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Symposia Part 2

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15th International Congress of Speleology

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United States of America
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Proceedings of the 15th International Congress of Speleology

Errata and Omissions

The Proceedings of the 15th International Congress of Speleology contain either abstracts or full papers of the 500 contributions presented at the Congress. The three volumes of the Proceedings total 2130 pages. The pathway to this mass of material was as follows: Prospective authors submitted an initial abstract to the ICS Science Committee. These abstracts were reviewed by the Committee to ascertain that the subject matter was appropriate for the Congress. The abstracts were then returned to the authors with suggestions and an invitation to prepare a full paper limited to six printed pages. Few papers were rejected, but some were withdrawn so that of 540 initial submissions, 500 were presented at the Congress. The draft papers were sent to the Science Committee who distributed them for review after which they were returned to the authors for such adjustments as the reviewers deemed necessary. The final papers were received by the Science Committee for formal acceptance and were forwarded to the editor. The edited papers were then transmitted to Production Manager for page layout and preparation for the printer.

All of this movement of abstracts and manuscripts was done electronically. In the process of transmittals, various reviews, and editorial handling, a few errors and omissions were created. The lists that follow contain the additions and corrections that have been brought to our attention. We have limited the corrections to matters of fact; small errors in spelling, punctuation, and formatting are not addressed. We apologize to the authors whose papers were mishandled in some manner.

The Editorial Team

Errata

Volume 1, Page 541

Cave Sediments Related to Cretaceous-Tertiary Paleokarst Developed in Eogenetic Carbonate Rocks: Examples from SW Slovenia and NW Croatia by Bojan Otoničar.

The abstract was truncated in printing with only the first few lines appearing in the Proceedings. The full abstract follows.

In the SW Slovenia and NW Croatia a regional paleokarstic surface separates the passive margin shallow-marine carbonate successions of different Cretaceous formations from the Upper Cretaceous to Eocene palustrine and shallow marine limestones of the synorogenic carbonate platform. Thus, the paleokarst corresponds to an uplifted peripheral foreland bulge, when diagenetically immature eugenetic carbonates were subaerially exposed and karstified.

Among the subsurface paleokarstic features vadose and phreatic forms are recognized. For the epikarst, pedogenic features and enlarged root related channels are characteristic. Vadose channels, shafts and pits penetrate up to a few tens of meters bellow the paleokarstic surface, where they may merge with originally horizontally oriented phreatic cavities. The latter comprise characteristics of caves forming in fresh/brackish water lenses. The phreatic cavities were found in different positions regarding to the paleokarstic surface, the lowest one being some 75 meters below it. Usually only one distinct paleocave level occurs per location, although indistinct levels of spongy porosity and/or irregularly dispersed cavities of different sizes have been noticed locally. The cavities had been subsequently partly reshaped and entirely filled with detrital sediments and flowstones in the upper part of the phreatic, epiphreatic and vadose zones. The internal cave sediments and flowstones may also occur as clasts in deposits (mostly breccias) that fill subsurface paleokarstic cavities and cover the paleokarstic surface. In general, the variety of cave infilling deposits and the amount of surface derived material decrease with the distance from the paleokarstic surface. Below the paleokarstic surface $\delta^{13}C$ and $\delta^{18}O$ values of cavity deposits usually exhibit good correlation with trend significant for meteoric diagenesis.

Relatively small phreatic cavities of the lowermost part of the paleokarstic profiles are commonly geopetally infilled with laminated mudstone derived from incomplete dissolution of the hostrock overlain by coarse grained blocky calcite of meteoric or mixing meteoric/marine origin. Somewhat larger phreatic caves located shallower below the paleokarstic surface usually exhibit more complicated stratigraphy. Although the lower parts of the caves are still mainly infilled with reddish stained micritic carbonate sediment, different types of flowstone, especially calcite rafts, become more prominent higher in the cave profiles. Gradually in the upper parts of the caves, sediments derived from the paleokarstic surface prevail over autochthonous deposits. Especially channels of the epikarst zone are almost entirely infilled with pedogenically modified material derived directly from the paleokarstic surface. Regardless of their origin, cave deposits had been often intensively modified by pedogenic processes while they were exposed to the paleokarstic surface by denudation. Just prior to marine transgression over the paleokarstic surface some cavities or their parts had been infilled by marine derived microturbidites. It will be shown that especially deposits related to denuded phreatic caves may be of great importance for the study of speleogenetic, geomorphologic and hydrogeologic evolution of a specific karst region.

Volume 2, page 650

Medical and Governmental Considerations of CO_2 and O_2 in Volcanic Caves by William R. Halliday

The final sentence of the first paragraph on page 652 contains incorrect wording. The sentence should read:

"The issue resurfaced when U.S. Geological Survey and National Park Service personnel applied OSHA standards to volunteers in volcanic caves with non-toxic levels of O_2 and CO_2."

Volume 2, page 662

Unusual Rheogenic Caves of the 1919 "Postal Rift" Lava Flow, Kilauea Caldera, Hawaii by William R. Halliday

The first paragraph on page 664 contains several errors and misstatements. The corrected paragraph should read:

"Noxious gas (probably HCl) was encountered only in one tiny cave on the edge of Halemaumau Crater. Presumed sulfate fumes were encountered in numerous caves but were found to be essentially non-toxic. Eye irritation rarely was encountered (Halliday, 2000b). Two types of CO_2 monitors previously untested in volcanic caves were required for the last five field trips. They were found to be useless in hyperthermal caves and no significant elevation of CO_2 was identified in normothermic examples (Halliday, 2007). In no cave was significantly elevated CO_2 identified by changes in normal breathing (Halliday, this volume)."

Volume 2, Page 785

Symposium #11, **Speleogenesis in Regional Geological Evolution and Its Role in Karst Hydrogeology and Geomorphology** was arranged by Alexander Klimchouk and Arthur N. Palmer (not by John Mylroie and Angel Ginés as listed on the title page of the symposium in the Proceedings).

Volume 2, Page 1033

Uranium Mapping in Speleothems: Occurrence of Diagenesis, Detrital Contamination and Geochemical Consequences

The correct authors for this paper are: Richard Maire, Guillaume Deves, Ann-Sophie Perroux, Bassam Ghaleb, Benjamin Lans, Thomas Bacquart, Cyril Plaisir, Yves Quinif and Richard Ortega. The names of Bassam Ghaleb and Yves Quinif were omitted in the Proceedings Volume.

Volume 3, Page 1307

Species Limits, Phylogenetics, and Conservation of *Neoleptoneta* Spiders in Texas Caves by Joel Ledford, Pierre Paquin, and Charles Griswold

James Cokendolpher, Museum of Texas, Texas Tech University, Lubbock, Texas was also a co-author for this paper.

Omissions

The Fossil Bears of Southeast Alaska by Timothy H. Heaton and Frederick Grady was inadvertently omitted in the final stages of page layout. The reviewed and edited paper follows:

THE FOSSIL BEARS OF SOUTHEAST ALASKA

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Southeast Alaska is home to brown bears (*Ursus arctos*) and black bears (*U. americanus*) with an unusual distribution. Both species inhabit the mainland, while only black bears inhabit the islands south of Frederick Sound and only brown bears inhabit the islands north of Frederick Sound. Brown bears of the northern islands belong to a distinct lineage and are genetically more similar to polar bears than their mainland counterparts. Bears are among the most common fossils found in caves in the region, and they indicate that both species made greater use of caves as dens when the climate was colder. But no bear fossils are known from the Last Glacial Maximum (LGM), even at On Your Knees Cave where foxes and marine mammals have been recovered across most of this interval. This begs the question of whether bears survived the LGM on coastal refugia or recolonized the islands after the ice retreated. No evidence has been found to settle the question for black bears. Black bears are far more common than brown bears in On Your Knees Cave for the period before the LGM, but they were slower than brown bears in expanding their range across the islands after the ice melted. The evidence for survival in a local refugium is much stronger for brown bears. While they are less common before the LGM, they had a greater distribution than black bears immediately following the LGM, including some of the outermost islands of the archipelago. The lack of brown bear fossils from mainland sites during early postglacial times may indicate that the mainland was not the source of this population. The distinct genetic character of modern island brown bears also suggests that they did not derive from the mainland. Two fossil brown bears from caves of Prince of Wales Island have had successful DNA extractions and match the distinct lineage that now lives only on the northern islands of Southeast Alaska. A refugium for brown bears may have been offshore on the continental shelf which was exposed during the LGM but was flooded by rising sea level in the early postglacial period.

1. Introduction

Our research in southeast Alaska began in 1991 after several bear skeletons were found in El Capitan Cave on Prince of Wales Island by a caving expedition (HEATON and GRADY, 1992, 1993). El Capitan Cave is Alaska's largest known cave and has passages that flood during storms, but the fossils were found in a quiet upper passage near the surface. One skeleton was complete and undisturbed, suggesting that the bears were denning in the cave, so cavers called this passage the Hibernaculum. It was apparent that the bears accessed the cave by an entrance that had become sealed with soil and logs, and we were able to reopen this entrance to conduct an excavation of the site. Soon cavers discovered skeletons in other caves of the region with similar dimensions, namely horizontal passages 1.5-2.5 meters in diameter. Several natural trap caves with bear fossils were also discovered. Although our research has expanded to include a variety of mammals, birds, and fishes (HEATON and GRADY, 2003), bears have remained a major focus, and our fossil discoveries have contributed to solving the question of whether animals survived the Ice Age in Southeast Alaska.

Most islands of Southeast Alaska are home to bears, but currently there is no more than one species per island. Black bears (*Ursus americanus*) inhabit Prince of Wales Island and most other islands south of Frederick Sound, while brown bears (*Ursus arctos*) inhabit the islands north of Frederick Sound, namely Admiralty, Baranof, and Chichagof (ABC) islands. Both species inhabit the nearby mainland (MACDONALD and COOK, 2007). Prior to the discovery of a fossil record, KLEIN (1965) proposed that this island distribution resulted from a postglacial colonization history: brown bears arriving from the north and black bears from the south. This hypothesis was based on the prevailing assumption that no land animals survived the Last Glacial Maximum (LGM, 24,000-13,000 radiocarbon years B.P.) in Southeast Alaska because of complete ice cover. Although the islands of Southeast Alaska exhibit a nested mammalian fauna suggestive of recent colonization (CONROY et al., 2000), fossil and genetic studies of bears have revealed a much more complex history in the region.

The complete skeleton from El Capitan Cave, as well as portions of several others, were of black bears, distinguished from the living bears on the island only by their large size. Their size seemed especially significant since they appeared to be females based on the lack of bacula and the gracile structure of their skulls. Even more significant was the discovery of even larger bear remains that we identified as brown bear. Finding that Prince of

Wales Island had been home to additional species in early postglacial time conflicted with the simple postglacial colonization model held by KLEIN (1965) and other biologists. In addition to brown bears, we also discovered fossil remains of Arctic fox (*Alopex lagopus*), red fox (*Vulpes vulpes*), and caribou (*Ranifer tarandus*) that no longer inhabit the island. Rather than lacking a fauna at the end of the Ice Age, Prince of Wales Island simply had a different fauna that was adapted to the colder and less forested habitat.

Following this initial discovery we set out to expand our dataset both geographically and chronologically by searching for caves with fossil deposits on different islands and the mainland, in diverse habitats, and of greater antiquity. During the 1990s fossil sites were brought to our attention by cavers exploring the region, often working with the support of Tongass National Forest and guided by forest agendas. After 2000 we began coordinating searches for caves specifically to fill in gaps in our dataset. In spite of limits imposed by limestone distribution and the difficulty of finding sites over 12,000 years old, a long history for both brown and black bears has emerged. During this same period geneticists began DNA studies on living bear populations in Southeast Alaska that complemented our work (HEATON et al., 1996), and we have worked in conjunction with ancient DNA researchers to trace bear lineages back in time. What has emerged is a greatly expanded, but not entirely complete, picture of bear history in Southeast Alaska.

2. Postglacial History

The postglacial record of bears in Southeast Alaska is spectacular. Following the discovery of black and brown bears in El Capitan Cave (130 m elevation), additional brown bear skeletons were found in two high elevation caves (over 500 m) on northern Prince of Wales Island: two juveniles in a natural trap called Blowing in the Wind Cave, and parts of 12 individuals in a horizontal tube called Bumper Cave, including skeletons of what appeared to be a mother and her two cubs (Table 1). By contrast, lower elevation caves (below 200 m) on the island, such as Kushtaka and On Your Knees caves (den sites) and Tlacatzinacantli Cave (a natural trap) contained only black bears from the postglacial interval (Table 2). This apparent partitioning of den sites by the two species must be kept in mind when considering other parts of Southeast Alaska where samples from diverse elevations are not available. This does not mean that brown bears were restricted to high elevations because their isotopic signature indicates a stronger marine diet than black bears (HEATON 1995; HEATON and GRADY, 2003).

Table 1. List of radiocarbon dated brown bear (*Ursus arctos*) fossils from caves of Southeast Alaska in order of age.

Laboratory #	**Age (years B.P.)**	**$\delta^{13}C$**	**Site**	**Island**	**Sample**
AA-15224	7,205 ± 65	-17.9	Bumper Cave	POW	Dentary
AA-56996	9,590 ± 95	-20.5	Deer Bone Cave	Coronation	Radius
AA-07794	9,760 ± 75	-18.0	El Capitan Cave	POW	Humerus
AA-10451	9,995 ± 95	-18.5	Blowing in the Wind Cave	POW	Ribs
AA-52223	10,700 ± 100	-17.1	Enigma Cave	Dall	Humerus
AA-15225	10,970 ± 85	-19.5	Bumper Cave	POW	Molar
AA-15223	11,225 ± 110	-16.8	Bumper Cave	POW	Humerus
AA-52221	11,600 ± 100	-14.6	Enigma Cave	Dall	Dentary
AA-44450	11,630 ± 120	-18.2	Colander Cave	Coronation	Humerus
AA-15222	11,640 ± 80	-17.8	Bumper Cave	POW	Rib
AA-15226	11,715 ± 120	-16.0	Enigma Cave	Dall	Humerus
AA-32122	11,910 ± 140	-18.1	El Capitan Cave	POW	Rib2
AA-52222	11,930 ± 120	-14.6	Enigma Cave	Dall	Skull
AA-10445	12,295 ± 120	-18.3	El Capitan Cave	POW	Pelvis
AA-33783	26,820 ± 700	-16.3	On Your Knees Cave	POW	Astragalus
AA-52219	29,040 ± 600	-16.3	On Your Knees Cave	POW	Rib
AA-52220	29,590 ± 980	-17.7	On Your Knees Cave	POW	M2/
AA-33792	31,700 ± 1900	-16.2	On Your Knees Cave	POW	Molar
AA-52218	31,900 ± 1,300	-19.6	On Your Knees Cave	POW	Claw
AA-52207	33,300 ± 1,500	-17.0	On Your Knees Cave	POW	Phalanx 1
AA-15227	35,365 ± 800	-15.9	On Your Knees Cave	POW	Femur
AA-52215	38,800 ± 3,000	-10.0	On Your Knees Cave	POW	Phalanx 2

AA-33791	39,400 ± 3100	-17.1	On Your Knees Cave	POW	Tooth
AA-52216	34,000 +	-17.4	On Your Knees Cave	POW	M/1
AA-52201	40,900 +	-16.8	On Your Knees Cave	POW	P4/
AA-52217	41,100 +	-15.4	On Your Knees Cave	POW	Vertebra

Table 2. List of radiocarbon dated black bear (*Ursus americanus*) fossils from caves of Southeast Alaska in order of age.

Laboratory #	**Age (years B.P.)**	**$\delta^{13}C$**	**Site**	**Island**	**Sample**
CAMS-27263	2,790 ± 60	-23.2	Kushtaka Cave	POW	Artifact
AA-57000	3,425 ± 50	-12.5	Lawyers Cave	Mainland	Humerus
CAMS-31068	3,960 ± 50	-20.7	On Your Knees Cave	POW	Dentary
AA-36637	4,847 ± 58	-21.2	Hole 52 Cave	Mainland	Skull
SR-5265	6,290 ± 50		Lawyers Cave	Mainland	Phalanx
AA-10447	6,415 ± 130	-22.1	El Capitan Cave	POW	Skull
CAMS-24967	8,630 ± 60	-21.4	Kushtaka Cave	POW	Rib
AA-18451R	9,330 ± 155	-23.9	Kushtaka Cave	POW	Femur
AA-32118	10,020 ± 110	-22.1	Tlacatzinacantli Cave	POW	Femur
AA-36641	10,080 ± 120	-21.6	Hole 52 Cave	Mainland	Phalanx
AA-33780	10,090 ± 160	-21.2	On Your Knees Cave	POW	Phalanx
CAMS-42381	10,300 ± 50	-20.7	On Your Knees Cave	POW	Artifact
AA-36636	10,350 ± 100	-18.9	Hole 52 Cave	Mainland	Skull
AA-36640	10,420 ± 110	-21.6	Hole 52 Cave	Mainland	Skull
AA-07793	10,745 ± 75	-21.1	El Capitan Cave	POW	Humerus
AA-32120	10,860 ± 120	-21.8	Tlacatzinacantli Cave	POW	Skull
AA-32117	10,870 ± 120	-21.8	Tlacatzinacantli Cave	POW	Ulna
AA-36638	10,930 ± 140	-19.8	Hole 52 Cave	Mainland	Skull
AA-32119	10,970 ± 120	-22.4	Tlacatzinacantli Cave	POW	Fragment
AA-33202	11,460 ± 130	-19.9	Hole 52 Cave	Mainland	Canine
AA-10446	11,540 ± 110	-20.0	El Capitan Cave	POW	Skull
AA-10448	11,565 ± 115	-18.7	El Capitan Cave	POW	Skull
AA-21569	28,695 ± 360	-20.7	On Your Knees Cave	POW	Calcaneum
AA-21570	29,820 ± 400	-20.8	On Your Knees Cave	POW	Vertebra
AA-33781	36,770 ± 2300	-18.6	On Your Knees Cave	POW	Femur
AA-33194	38,400 ± 3000	-18.4	On Your Knees Cave	POW	Humerus
AA-33198	39,000 ± 3100	-19.5	On Your Knees Cave	POW	Rib
AA-16831	41,600 ± 1500	-20.7	On Your Knees Cave	POW	Tibia
AA-36653	25,000 +	-22.0	On Your Knees Cave	POW	Premolar
AA-36655	27,000 +	-18.2	On Your Knees Cave	POW	Baculum
AA-33196	38,500 +	-19.4	On Your Knees Cave	POW	Scapula
AA-52206	38,500 +	-20.8	On Your Knees Cave	POW	Metapodial
AA-52204	39,100 +	-20.2	On Your Knees Cave	POW	Canine
AA-33200	39,400 +	-19.3	On Your Knees Cave	POW	Canine
AA-33195	40,100 +	-18.4	On Your Knees Cave	POW	Humerus
AA-33199	40,200 +	-19.9	On Your Knees Cave	POW	Canine
AA-44448	41,000 +	-21.7	On Your Knees Cave	POW	Molar
SR-5110	43,050 +		On Your Knees Cave	POW	Vertebra
SR-5111	44,940 +		On Your Knees Cave	POW	Skull

Several postglacial deposits have also been found on the mainland near the town of Wrangell and on two of the outermost islands of the Archipelago: Coronation and Dall Islands (HEATON and GRADY, 2003). Today only black bears inhabit Dall Island while no bears inhabit Coronation Island (MACDONALD and COOK, 2007). Three early postglacial cave deposits have turned up six individuals, all of which match brown bear (Table 1). Deer Bone Cave is a den cave while Colander Cave is a natural trap, and Enigma Cave is larger and more complex with bear skeletons both in horizontal den passages and at the bottom of pits. All these caves are at 200 m elevation or lower. By contrast, two postglacial cave deposits on the mainland, a den site called Lawyers Cave and a complex cave with horizontal passages and pits called Hole 52, contain only black bear remains (Table 2). Brown bears may have denned at higher elevation, but no such sites are known. The remarkable conclusion from these sites is that the two bear species had nearly the opposite distribution in the early postglacial period than they do today. Currently both species inhabit the mainland while only black bears inhabit the southern islands of Southeast Alaska. Shortly after the Ice Age only brown bears inhabited the outer islands, both species occupied the large Prince of Wales Island, and only black bears are documented from the mainland.

Discovering the postglacial history of bears in the northern islands of Southeast Alaska, where only brown bears live today, has been hampered by a paucity of limestone and a lack of any fossil discovery. Since brown bears thrived in the southern islands in early postglacial times, there is no reason to doubt their presence farther north. Whether black bears ever colonized the northern islands remains a mystery. To the south of Alaska a pattern similar to Prince of Wales Island has been documented by Canadian investigators. Haida Gwaii (Queen Charlotte Islands) and Vancouver Island are currently home only to black bears. Fossil black bears have been found dating back to 10,000 years B.P. on Haida Gwaii (RAMSEY et al., 2004; FEDJE et al., 2004) and from about 9,800 to 12,000 years B.P. on Vancouver Island (NAGORSEN et al., 1995; NAGORSEN and KEDDIE, 2000). Brown bears from Haida Gwaii have been found dating from 10,000 to 14,500 years B.P., showing that they once were widespread on coastal islands.

Another remarkable pattern visible in Tables 1 and 2 is the sheer number of early postglacial bears. With the exception of the sealed hibernaculum of El Capitan Cave, all of these sites remain open for potential denning today. Yet far more specimens of both black and brown bears date between 9,000 and 12,000 years B.P. than date to the 9,000 years since then. Most of these remains were exposed on the cave floors (not fully buried) so were not selected for dating based on their potential antiquity. Either bears were more numerous in early postglacial times or they were denning in caves much more regularly. The fact that natural trap caves (at least a third of the sites) show this same pattern suggests a high bear population. None of the other species we have studied show this distinct chronological pattern. Perhaps the early successional stages of forest development following the melting of the glaciers provided a high density of berries and other edible foods preferred by bears for the herbivorous part of their diet. Since climax forests are lacking in such foods, modern bears are attracted to forest clear-cuts, shorelines, and other disturbed areas where such plants grow.

3. Ice Age History

The single site in Southeast Alaska that has produced an extensive Ice Age record (prior to 13,000 radiocarbon years B.P.) is On Your Knees Cave. It is a small cave on the northern tip of Prince of Wales Island discovered during a logging survey and had only a few bones initially exposed. The significance of the site was only recognized when a partial brown bear femur was radiocarbon dated to 35,365 years B.P. (Table 1). Excavation began in 1996 and continued until 2004. An extensive record of mammals, birds, and fish was discovered covering at least the last 45,000 years (HEATON and GRADY, 2003) plus an extensive archaeological record including the oldest human remains from Alaska or Canada (DIXON et al., 1997). Devil's Canopy Cave on Prince of Wales Island is the only other site where we obtained an Ice Age radiocarbon date (on marmot), but extensive excavation produced only a few rodent and insectivore remains. Our extensive efforts to find an Ice Age site on the outer islands of Southeast Alaska have so far been unsuccessful.

For a single site, On Your Knees Cave provides a superb record of animals during the LGM and the preceding interstadial. As can be seen in Tables 1 and 2 many bone dates are beyond the radiocarbon limit, but uranium dates on speleothem fragments date back to 185,800 ± 2,800 years B.P. (DORALE et al., 2003). Both black and brown bears were present and probably used the cave as a den from at least 41,000 years B.P. until the approach of the LGM (Tables 1 and 2). We have not dated enough samples to be certain exactly when their use of the cave ceased, but no bear remains have been dated to the glacial maximum itself. A sample of 25 ringed seal (*Phoca hispida*) specimens were radiocarbon dated from 24,150 ± 490 to 13,690 ± 240 years B.P., which is the very interval that the

bears (and caribou) are missing. Arctic and red foxes, other marine mammals, and sea birds also date to the LGM, so the cave was available and used as a den (by foxes) during that interval. One ringed seal humerus has bite marks that match bear canines, but it could be a polar bear (*Ursus maritimus*) kill that was scavenged by foxes.

Black bear fossils outnumber brown bear fossils in On Your Knees Cave by a ratio of about 10:1. This is not evident in Tables 1 and 2 because we selected specimens of both species for dating. This difference could represent a greater abundance of black bears or a partitioning of den sites by elevation like we see during the postglacial period. Other elements of the fauna suggest that conditions during the interstadial were similar to the early postglacial interval before a climax forest was established.

4. Genetics

TALBOT and SHIELDS (1996) found that brown bears of Admiralty, Baranof, and Chichagof (ABC) islands (Southeast Alaskan islands north of Frederick Sound) are distinct from all other populations based on mitochondrial DNA and are more closely related to polar bears than to their mainland counterparts. Using nuclear microsatellite variations PAETKAU et al. (1998) confirmed this result for females but detected some exchange of males with the local mainland population. LEONARD et al. (2000) discovered a fossil from Yukon Territory matching the ABC bears and dating to 36,500 ± 1,150 years B.P., so this clade had a wider distribution before the LGM. Nevertheless, the current restricted range of this clade suggests that the islands of Southeast Alaska acted as a refugium for this population during the glacial maximum (HEATON et al., 1996). Further support for this hypothesis comes from early postglacial fossils of Prince of Wales Island and Haida Gwaii. After several failed attempts at extracting ancient DNA, BARNES et al. (2002) reported that a brown bear fossil from Blowing in the Wind Cave (AA-10451 on Table 1) belongs to the ABC clade. Further work by Sarah Bray (personal communication) also linked a bear from Bumper Cave (AA-16553 on Table 1) and ones from Haida Gwaii to the ABC clade.

STONE and COOK (2000) found that black bears from the southern islands of Southeast Alaska belong to a mitochondrial lineage that is also found on the islands and coastal mainland of British Columbia and down the coast to northern California. Several other mammal species have distinct coastal lineages with a similar range, but it remains unclear whether the source of these lineages was south of Cordilleran glaciers or on coastal refugia, possibly in Southeast Alaska (COOK et al., 2001, 2006).

5. Conclusions

The absence of a fossil record of bears from the LGM leaves open the question of whether they survived the glacial expansion in Southeast Alaska on coastal refugia or recolonized afterward. Cave faunas document that both brown and black bears were present during the preceding interstadial and reappeared in great numbers soon after the ice melted. Genetic evidence for a distinct coastal lineage, where refugial isolation is the simplest explanation, is strong for brown bears but more equivocal for black bears. Both bears are refugial species in the sense that they were adversely affected by glaciation and struggled to survive under unfavorable climatic conditions. By contrast, other carnivores such as ringed seals, Arctic foxes, and likely polar bears flourished and expanded their ranges during the LGM. The extent to which the Arctic and refugium faunas competed with one another is unknown, but their interactions could have been a factor in the temporary loss of black and brown bears from On Your Knees Cave.

What we learn from postglacial bears is that the species were able to move about freely and colonize territory that was favorable for them, rather than being restricted by barriers and competition. Solving the full puzzle of bear history in Southeast Alaska will require finding additional faunas of similar antiquity to On Your Knees Cave, as a single site cannot document the movements of species. During the LGM the expanding glaciers pushed mammal populations westward, while falling sea level opened up new habitat to the west and changed the configuration of the coastal corridor. The possibility that populations of bears and other mammals found suitable refugia to survive the LGM in Southeast Alaska is very possible.

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Symposium 9

LAVA CAVES

Arranged by:
Stephan Kempe
William R. Halliday

THE ANCIENT SPRING: WATER IN THE LAND OF FIRE

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A group of speleologists and archaeologists have studied an artificial cavity in Central Italy which dates back to the fifth century B.C. It is a former Etrurian aqueduct, bearing witness to the ancient civilization of the Etruscans, pre-dating Roman times in Tyrrhenian Italy.

The tunnel system was constructed in alkaline Quaternary volcanic deposits, rich in leucite, within the Roman Magmatic Province. They are characterized by a high potassium content (and therefore radiogenic K-40 as well) and fluoride. This kind of magma is very rich in incompatible elements erupting to the surface through fractures caused by crustal thinning, a consequence of the complex tectonic movements of the Italian peninsula that is still active. The eruptions date back 0.5 Ma and caused the formation of a landscape typical for Etruria.

This research revealed interesting archaeological details. The tunnel system is well constructed, complex, and compelled the builders to overcome difficulties by adopting hydraulic engineering solutions that are remarkable for this time. This is confirmed by the fact that the spring intercepted by the tunnels has supplied water to a village without interruption until the 1960s.

The chemical and radiological analyses revealed additional unexpected features. In the dry season, the spring discharges water exclusively of hypogenic origin, which exhibits a very high level of alpha radioactivity. It suggests that decomposition of the U-238 family is not the only source responsible for the high radioactivity, but that Th-232 is also an important source adding to the alpha activity.

The subject of our research is an artificial cavity located not far from the town of Orvieto, at the edge of a volcanic ash plateau, belonging to the Volsinian volcanoes, a system active in the Quaternary, between 0.6 and 0. Ma. This was a polycentric system, whose eruptions, mainly of explosive type, covered an area of about 2,000 hectares, at the centre of which is the lake of Bolsena, the largest European volcanic lake. During its history, this system has seen four different phases (some simultaneously):

(a) Paleo-volsinian phase, the most ancient, about 0.6–0.5 Ma,
(b) Bolsena-Orvieto phase, in whose bedding plane is located the tunnel we studied,
(c) Latera caldera phase,
(d) phreato-magmatic phase (Montefiascone phase).

The tectonic events which determined the rise of Volsinian volcanism and, broadly speaking, all the Tyrrhenian Quaternary volcanism, are the same as the origin of a highly seismic belt along the Apennine mountain chain, responsible of the dramatic earthquake that ravaged the town of Assisi in 1997. The Apennine belt is on a seismically active plane corresponding to a subduction line of the Adriatic plate, thrust by Tyrrhenian events. Responsible for such dynamic is the pushing force of the African plate on the Eurasian continent which is shifting the Italian peninsula in a counterclockwise movement, widening the Tyrrhenian Sea and contracting the Adriatic. Two seismic belts run N-S through the peninsula. One is aligned with the Apennines as far south as the Calabrian arch. It is known for high magnitude earthquakes. The other is along the Tyrrhenian area and has lower intensity earthquakes. The depth of the Moho is about 25 km under the Tyrrhenian belt, and considerably deeper under the Apennines. The subduction zone dips about 80° degrees. Its origin was in the Cretaceous, and it is still active. Crustal thinning caused upwelling of huge amounts of sub-crustal magma, which, on reaching the surface, gave origin to wide volcanic topography developed on NW-SE fractures (Fig. 1).

The converging plates (Adriatic subducting, Tyrrhenian thrusting) have produced wide volcanism, from Tuscany to the Somma-Vesuvio system. The process was in two distinct Quaternary phases which generated chemically distinct products: the ANATECTIC TUSCAN PROVINCE (PAT), and the later ROMAN MAGMATIC PROVINCE (PCR; Washington, 1906). Extension was particularly

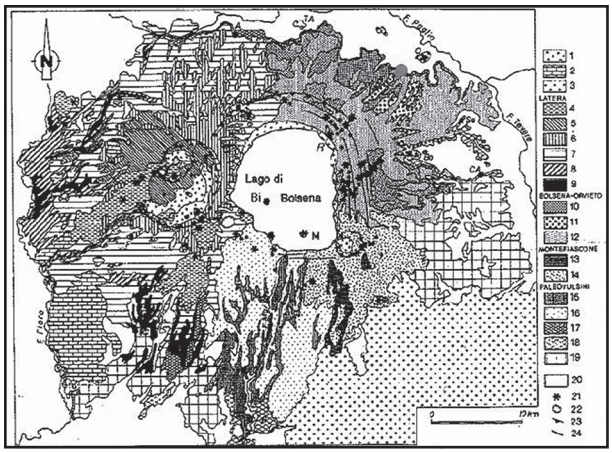

Figure 1: Geological map of the Volsinean system. The tunnel is located in the circled area.

active during the Tortonian-Messinian period. Main features are magmatic acidic eruptions, silica saturated (SiO2 > 60%) for the PAT, with domes at the surface and hypabyssal formations, due to high viscosity of lavas (Marinelli, 1961). Its age is between 4 and 1.3 Ma. The PCR was characterized by explosive features with rare emissions of lava, and the products are typically of the under-saturated, ultrapotassic, alkaline series, whose main mineral is leucite. Its main centers are the Volsinian, Vican and Sabatin at N of Rome, the Alban Hills by the capital, the Roccamonfina system at Caserta, the Campi Flegrei and the Somma-Vesuvio to the south. Almost all of these have been active beginning 0.6 Ma. Thus they were co-existant with Quaternary glaciations. While such magmatic regions are widely distributed, there are very few places on Earth with this particular type of alkaline magmatic bedding found in the PCR and the Leucyte Hills, in Wyoming.

The cavity which we studied belongs to the Volsinian system, part of the PCR. Our researches revealed a very high emission of alpha radioactivity. This particular kind of volcanism is notoriously rich in incompatible elements, coming from immediately below the aesthenosphere. Its origin can be attributed to partial fusion of the mantle caused by the ascent of fluids coming from the deep mantle, very rich in volatiles acting as carrier gases of incompatibles, including uranium and thorium. This particular process, called "mantle degasation", causes the fusion of material from upper parts of the mantle. It has been suggested that this mechanism happens at a depth of about 80 km. Ascending magma interacts with the embedding rocks with processes of metasomatism, thus changing considerably its composition. Such processes happen in the upper mantle or the lower crust and the result is the formation of so-called "glimmeritic" materials, sometimes referred to as MARID, standing for Mica (phlogopite), Amphibole (K-Richterite), Rutile Ilmenite,Diopside. This kind of rock crystallizes from magmas strongly enriched with volatiles. So the volcanic products characteristic of the PCR are particularly rich in uranium and thorium and also potassium-40. Uranium and thorium are present together in hypogenic environments but in superficial environments follow different courses. Uranium has two oxidation states, while thorium can be found only in the tetravalent state. When they enter the superficial environment, uranium shifts to the major oxidation state, and is soluble as a complex. Thorium is not. Thus we say that uranium is mobile, referring to this behaviour. Both are the progenitors of distinct radioactive families consisting mainly of alpha emitters, among which radon is gaseous and can be released without interacting significantly with the chemical environment. Radon is localized half-way along the U-Pb decay series, and is in turn the father nucleus of a narrow series of alpha and beta emitters characterized by short half lives.

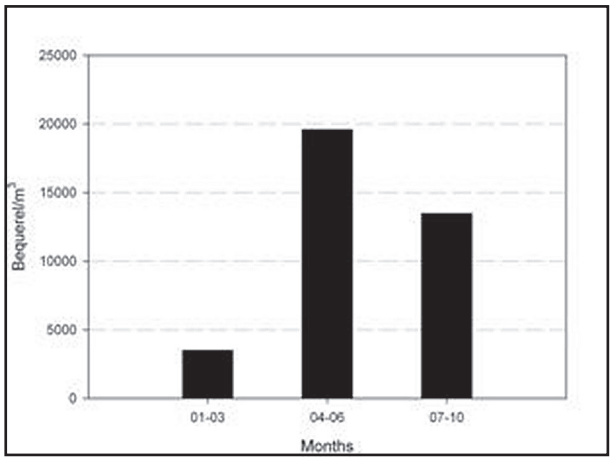

Figure 2: Radon concentration in air.

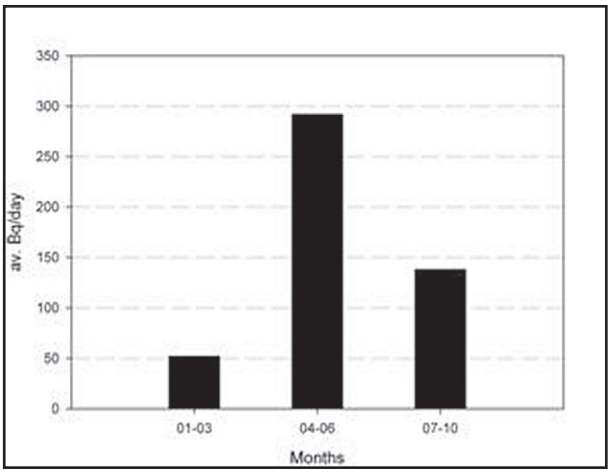

Figure 3: Average Rn concentration in Bq/day.

The histograms in Figures 2 and 3 show seasonal variation of radioactivity. Such seasonal nature is also present in the karstic environment at the Buso della Rana Cave at Vicenza. Here we have a completely different environment, and the main emission source is water, specifically its hypogenic component. In the hot season from May to October we have a long period of drought, and the tuff beds drain no surface waters. During such periods, the spring drains waters of exclusively hypogenic origin (cold thermalism: 13.1° C). These, before reaching the surface, undergo a deep water/rock interaction, absorbing radioactive elements from below. We performed radioactivity measurements using LR115 type SSNTDs (Solid State Nuclear Track Detector), closed in a container (Goblet A type) specifically designed to let only air flow inside, excluding solid matter, thus having measures of alpha particles coming exclusively from radon decay . The result, as developed and analysed in the laboratory of GT-Analytik of Innsbruck, is the measure of radon concentration. This suggests a seasonal nature of radon concentration in air, and what is most important, such variation follows the pattern of hypogenic origin in water: in the hot season, waters have almost exclusively a deep origin, and the radon concentration is higher than in the rainy season, in which we have mixed waters, hypogenic and meteoric. Further research will include a more detailed program, comparing SSNTD measures coming from different geological environments.

The object of our research is an artificial gallery at various angles. It follows the contact between an upper leucytic tephra level and a lower pyroclastic series. This artificial cave structure is well constructed and complex, and is divided in two sections: the main intercepts a perennial spring, the other gives access to a tank, nowadays inactive. The section is typically long and narrow, with an ogival vault, big enough to let an operator stand comfortably. The aim of the engineers was not to collect water dripping from the vault, but to intercept a stream. The stream is perennial and consistent. In the absence of a collection work, water found its way to the surface following two directions: vertically through fractures in the thick tephra bank, and horizontally between the tephra bank and the under-bedding layer of loose ash. In such conditions the spring would have split into a swampy surface along the vertical line, and more streams making a "buried spring" at the inter-bedding banks, along the horizontal line. This made rational utilization impossible, since scattered uncontrolled springs turned a wood into a marshland. The ancients made several other attempts to dig tunnels nearby (the longest being about ten meters). The successful tunnel is characterized by a long corridor parallel to the external lining, and by adjustments and changes of direction. It's remarkable that planimetry changes by right angles is the technique attested in southern Etruria, thus making the tunnel develop by right-angled lines. The only curve corresponds to a by-pass of probable Roman age, made to pass beyond a collapsed part of the tunnel corresponding to a change of direction. The chamber of the spring is a narrow space half filled by three settling tanks built less than a century ago, the first of which collects water directly from a hole in the rock, and the third drains to a small gutter on a side of the corridor by the exit, where a pipe conveys it to a fountain with a wash-basin. Deep inside the tunnel the walls are made of a sequence of unlithified ash. They are beds of pyroclastic surges, hard enough to sustain the weight of the overlying deposits formed by Peléan clouds and by the collapse of Plinian columns. The tunnel alternates between layers of fine ash and sharp cornered breccia. The lateral branch is affected by structural problems of instability making exploration dangerous because of high risk of slides.

As soon as one passes the narrow and partly collapsed access tunnel, the explorer finds himself in an irregular shaped passage showing visible evidence of slides. The ceiling is the floor of thick leucytic tephra that separates the tunnel from the ground surface, making exploration of this branch somewhat dangerous, but it can give information about the sedimentation surface. The deposition of tephra appears to have been uniform, suggesting a single eruptive event, while the lower beddings were in a sequence of very violent events, like Peléan clouds or Plinian columns. The walls of this latter part of the tunnel are made of clayish incoherent material incorporating sharp edged rocks, presumably not consisting of bombs, but of volcanic tuffaceous rocks included in the plastic bulk turned later into clay by the hydrolizing action of thermal waters on silicates

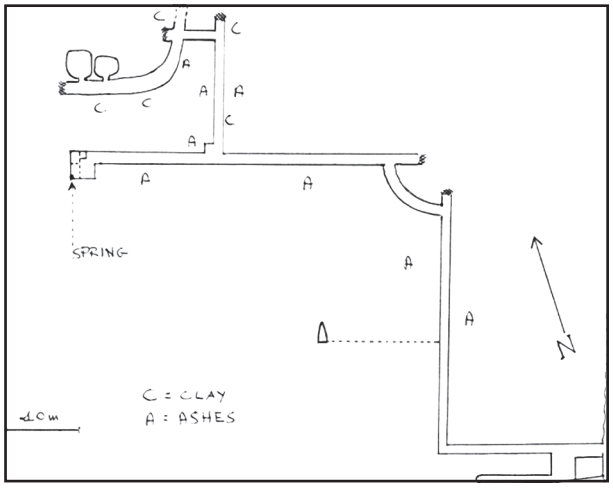

Figure 4; Sketch of the Etruscan tunnel.

While the Romans are known as "surface builders", Etruscans could reasonably be considered a population of "mining engineers." Both civilizations were involved in hydraulics, but the latter left us a huge number of hypogean works for collecting and conveying water, both spring and meteoric. In northern Latium area are numerous tunnels dug by the Etruscans for the control of waters, even in areas where the actual climatic conditions caused long periods of drought; indeed, most of those tunnels no longer drain water. Some of them had the function of draining meteoric waters, some others of collecting waters, others of tapping perennial springs as did the tunnel we studied. Tunnels made for collecting and conveying surface waters into basins far from the resurgence are just below the surface, between earthy and the tuffaceous horizons. Turf, although permeable, drains water much less than the earthy surface, so these pipes drained water dropping from the vaults and transferred it to storage basins at the foot of the hills. This is the classic type very well represented in the Campagna Romana (Roman Plains) and in southern Etruria, whose landscape is characterized by mild slopes. North, at the borders of the Vulsinian system, are harsh morphologies with hills abruptly interrupted by steep slopes, made of accumulations of volcanic deposits not always lithified and subject to slides, covering clay soils originated from Tyrrhenian Pliocenic sea floors. This is the typical landscape of the upper Viterbo region, giving to it an original characteristic of wilderness where mankind has changed very little of the natural landscape. The presence of many sliding surfaces, enhanced by many seismic events and gas emissions, has dramatically influenced settlement in the last two thousand years of recorded history. Striking examples are the cliffs of Orvieto and Civita by Bagnoregio: thick Pleistocene tuff on a stable layer of Pliocene clays.

Why did the ancient Etruscans dig such well-constructed works of hydraulic engineering where nowadays runs no water? This was because of conditions of paleometeorology. During the first millenium B.C., conditions were different from the present. It was cooler and a bit rainier. We call this sub-Atlantic weather. We have evidence of this from the study of ancient pollen, and we know that two thousand years ago forests were more widespread than today, mainly of oaks but of beech trees as well. Nowadays we have beech-woods only on the slopes of Mount Venere (Venus Mountain), a volcano by Vico caldera lake, and some other beech trees above Mezzano maar lake. It is likely that, two thousand years ago, beech woods were at the border between warm and cold climates, and in the last millennium the warm zone prevailed over the cold one. The Mediterranean weather of today with cool winters and droughty torrid summers, developed recently, in terms of centuries, and the climate in the Etruscan age was characterized by cooler summers and more rainfall than today, enough to justify the excavation of tunnels most of which nowadays are dry.

Acknowledgements

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PAHOEHOE AND LAVA TUBES IN PAYUNIA, NORTH PATAGONIA, ARGENTINA

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Payunia is a geographical region located in North Patagonia that includes parts of the Argentine provinces of Mendoza, Neuquén, and La Pampa. It owes its name to the Payún Matru volcano, located 280 km south of the city of Malargüe, Mendoza. The base of the volcano is 28 km in diameter and its elevation is 3800 m above sea level. Volcanologists describe the region as having the largest basaltic flows in the world, at nearly 180 km in length, which contain many unexplored lava tubes. Almost 800 volcanoes occur in the region that produced numerous pahoehoe flows, some extremely fluid, in which Argentine speleologists, in cooperation with British colleagues, have described several caves, the largest of which is 840 m long. One of these caves contains the richest suite of subterranean fauna in the region, made up largely of species not yet described. The main lava tubes explored to date are Cueva del Tigre, Cueva del Borne, Hoyo Dolo, Alero del Manzano, Cueva Doña Otilia (Mendoza province), Cueva de la Salamanca (Neuquén province), Caverna Halada (La Pampa province). Chacras de Aguado (Malargüe, Mendoza) is formed in a very low viscosity pahoehoe. Doña Otilia and Manzano are mineralogically and biologically important. Italian volcanologists have geophysically detected potentially longer lava tubes not explored yet in the 180-km-long lava flow in South Mendoza.

1. Introduction

Payunia is a North Patagonic region with more than 600 inactive volcanoes that were active in the Pleistocene. It is named for the volcano Payún Matrú, the largest of the region. All of the volcanoes are located in the Province of Mendoza, but the lava flows spread to the provinces of La Pampa and Neuquen. Known pahoehoe formations are located in the three provinces (Brojan et al, 1998; Benedetto, 1999, 2008; Brojan 2000), but the most important ones are located in Mendoza.

Llambías (2003) identified basaltic Quaternary effusions that have been sites of speleological explorations. The list of caves surveyed thus far are listed in Table 1 and demonstrate that the largest number of caves are concentrated near the volcanoes that gave them origin. Based on these data, maps were updated

Name	Province	Department	Elev. (m)
Borne	Mendoza	Malargüe	
Campana Mahuida	Neuquén	Loncopué	
Cerro Guacho	Neuquén	Loncopué	
Cueva del Zorro	Neuquén	Pehuenches	
Doña Otilia	Mendoza	Malargüe	1926
El Jagüel	Neuquén	Pehuenches	982
El Manzano	Mendoza	Malargüe	1350
Halada	La Pampa	Puelén	759
Hoyo Dolo	Mendoza	Malargüe	1650
La Escondida	Neuquén	Añelo	
La Salamanca	Neuquén	Pehuenches	
Los Gatos	Neuquén	Pehuenches	880
Pozo del Campamento	Mendoza	Malargüe	1264
Puesto La Barda	Mendoza	San Rafael	592
Tigre	Mendoza	Malargüe	1474
Zagal	Mendoza	Malargüe	1800

Table 1: List of caves explored.

The region is arid (precipitation of about 300 mm per year) and biogeographically is a transition from "Patagonia-Cordillera-Monte". The average surface temperature is between 10°C and 11°C, which coincides with the average temperature hypogeum measured in all visited caves.

2. Doña Otilia Cave

The Association CAE (Centro Argentino de Espeleología) mapped 838 m of galleries in an horizontal development in Doña Otilia Cave. This is the longest known lava tube in Argentina, located 70 km to the southeast of Malargüe city, and it is under the close supervision of the Family Zagal, the "farmers" not owners of the place. Speleologist can access the cave through a small hole in the floor, not easy to distinguish in epigean explorations, like almost all the basaltic caves of the region. In the inside, there are no major difficulties for exploration. The cavity ends in a chaos of blocks, but the

floor is comprises mostly sand and gravel. The penetration of roots from surface plants, which search to absorb the high humidity inside in the floor of the cave. The fauna noted to date have been grossly identified by Peralta and Benedetto (2007) as follows:

1. Animals associated with plants: -Order Collembola; -Class Oligochaeta; -Order Acariformes; Nematoda-Phyllum
2. Class Insecta: O.Diptera: Tipulidae (adult), other dipterans s / d; O. Blattaria, O. Coleoptera - Part of the exoskeleton (accidental)
3. Class Arachnida: O. Araneae, O. Opiliones (troglobitic?)
4. Class Chilopoda
5. Reptile bones and mammals (accidental?),

3. "Alero" El Manzano

"Alero" El Manzano is located on a basaltic wall in front of National Route 40, north of El Manzano, about 100 km south of Malargüe city. This is a small cavity with no more than 10 m of development, but where Paolo Forti (Benedetto et al, 1998) identified its importance as having the highest concentration of phosphate cave minerals in the world. There is a small colony of bats whose "guano" was, perhaps, the cause of these mineral formations

4. Hoyo Dolo Cave

Hoyo Dolo Cave, close of the farm (puesto) "Del Pozo", near the Dolo Vulcano, and on the southern tip of the province of Mendoza is a unique basaltic caves located within a "protected natural area" (Payunia). The CAE Association explored it and documented its 350 m length. The entrance is an opening of 20 m with a depth of 12 to 15 m. Inside, there are large blocks of collapses and toward the northeast and southwest are two large galleries where sunlight does not penetrate. The smaller gallery to the northeast is 20 m long with a height ranging from 5 - 15 m. The other gallery is 250 m long. The caved is a product of lava flows from Dolo Vulcano, and satellite-derived observations shows that the true development of galleries as almost 2.6 km. Speleologists could explore only 350 m inside, but the original extent was longer (Milillo, 1988).

5. Del Tigre Cave

Del Tigre Cave is the basaltic cave most visited by tourists, but it is not officially sanctioned to such activities. It is located 58 km southeast of Malargüe city. From the place of descent into the cave, the passage is divided into two branches: one goes to the north and the other one to the south. The second one ramifies towards the end and has numerous landslides. Most of the cave floor is bare sand. The first exploration in this cave was made by the CENTRO ARGENTINO DE ESPELEOLOGÍA (1973), but more explorations were done by the local Association INAE and the U.K.'s Mendip Caving Group. Joint explorations of Argentinian and British speleologists that sought to open the final collapses of the North gallery by following air flow were unsuccessful. Dr. Franco Urbani made an inventory of the minerals in the walls and ceiling of the cavity (Urbani & Benedetto, 1997) and, despite its extreme dryness, a biological survey in 1991 (Trajano, 1991) provided the following results:

F. Chordata: cl. Mammalia:

- O. Chiroptera: Vespertilionidae. Lasiurus sp: observed two individuals
- O. Edentata: Tolypeutes matacus.
- O. Rodentia: Lagidium sp.
- O. Carnivora: Canis familiaris, Felis concolor; Lyncodon patagonicus.
- O. Bovidae: Capra hircus

F. Arthropoda:

- Cl Hexapoda:
  - O. Diptera: Muscidae: puperios
  - O. Lepidoptera: Tineidae
- Cl Arachnida:
  - O. Araneae: Pholcidae

In 2008, during a visit by the Argentinian Federation, speleologists together with biologists of PCMA Project (Programa para la Conservación de los Murciélagos de Argentina) collected some bats in this cave, but not of the kind mentioned by Trajano, which suggests a greater biological importance (Daniela Rodríguez & Verónica Chillo, com. Pers).

6. Zagal Cave

Zagal Cave is located near Doña Otilia and Cerro Patahuilloso. Its name derives from the family that inhabits the region, the same family who takes care of Doña Otilia Cave. The 326 m long lava tube was explored and surveyed by the CAE. The access entrance is at the northern end of a circular depression that slightly slopes towards it. This entrance is narrow and upright for about five meters, reaching a room with a block collapse, then descends gradually and narrows. The floor is composed of sandy sediment, with evidence of water circulation.

7. Del Borne Cave

In 2007, the Instituto Argentino de Investigaciones Espeleológicas (IN.A.E.) explored a new cave near Cueva del Tigre that they called Cueva del Borne. Its entrances is a large "mouth", but the inner length is not remarkable. This cave was originally a lava tube but collapse has converted it to a clastic cave. The central structure (lava tube) confused with clasts. In a Project PCMA visit in late 2008, the entrance was detected by an overwhelming presence of fauna, especially chiroptera, birds, and mammals. In the first sampling, the cave revealed a kind of "natural museum" with a great variety of animal species that have been predated by older animals. The cavity appears to be a kind of "restaurant" of a puma (*Felis concolor*). The cave appears to be a natural repository information about past conditions on the surface of the region (Daniela Rodríguez & Verónica Chillo com. pers.).

8. Pozo del Campamento and Projections

In 2005, INAE participated with Giorgio Pasquaré (University of Milán - Italy) in the partial exploration of Pozo del Campamento, an artificial, 50 m deep, vertical pit in which stratigraphic observations were made in association with an almost 180 km long, the longest lava flow in the world (Pasquaré et al, 2008). The flow reaches Río Salado Valley (La Pampa province), maintaining a straight and narrow without following topography control. Pozo del Campamento is located in Salinillas, Malargüe, Mendoza, near the border with La Pampa province.

Lava tubes were detected that lacked previous access from the surface. These investigations revealed extremely long lava flows that originated in the Andean retroarc, forming in the late Quaternary. Pasquaré et al. (2008) describes the rock that forms the casting as a "hawaita" with a low content of olivine and plagioclase phenocrysts. During an exploration, the team of speleologists descended this artificial pit, which allowed the investigation of the strata in order to project information to all the region.

9. La Halada cave

In La Pampa province, near the flow described by Pasquaré et al. (2008), the association CAE explored La Halada Cave (also called "La Alada") (development 370 m, 10 m height difference) thirty years ago, but subsequently the GEA association made a second survey. Like the other basaltic cavities, its entrance is visible only from very close as it is along ground level. The entrance is circular, only one meter diameter, with a vertical, pipe-shaped tube about 2 meters long that reaches the floor of cavity. Passage development is horizontal with a slight slope inwards. The galleries are broad (width maximum is 22.90 m) with an average height of 1.60 m. It has a main duct that branches into three galleries

Cavern fauna were not observed but a lot of skeletons belonging to epigean fauna: birds, vizcachas, and small mammals.

Early geologic reports remark that the cave is formed in olivine basalts from Cenozoic casting corresponding to 8 to 12 meters thick. In the region, cast of basalts of various ages can be distinguished (Grupo Espeleológico Argentino, 2002, Martínez 1998).

10. Lava Tubes in North Neuquén

In 1983, the CAE explored Salamanca Cave which is few kilometers from Mendoza border and a few meters from National Route 40 to the East, in the province of Neuquén near Buta Ranquil city. The cave's entrance is similar to those described above. It formed in Cenozoic basalts, with a unilineal development of 204 meters. Subsequently, GEA explored the Jagüel Cave (development of 324 meters, -25 meters) and Los Gatos (312 m of development, 36 meters gap) near Rincón de los Sauces city. There are other data that have shown associations in Neuquen (Mahuida Campana, Cerro Guacho, Cueva del Zorro and La Escondida), which have the coordinates but not the full cadastral information at disposal. Speleology is forbidden now in Neuquén due to political problems, so we don´t know if cavers had explored other lava tubes in that area. The information of this communication was produced before the "prohibition".

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EXPLORATION OF MANU NUI LAVA TUBE, HAWAII, USA

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We have been exploring and surveying Manu Nui Lava Tube System since 2003, and so far have discovered over 3.5 km of passage, with a vertical extent of 347 meters. The cave, located in the rain forest above Kona on the Big Island of Hawaii, is unusual for several reasons: (a) it is profusely decorated with lava stalactites up to 1 m long, often hanging at significant angles from the vertical; (b) areas of vividly colored lava, ranging from black and dark brown through red and orange to ochre; (c) areas of extensive "fountaining", where lava splashed onto the walls and ceiling; (d) the slope of the passages is very steep for a lava tube system; and e) it contains bones from a now-extinct Hawaiian goose. In this talk, we will illustrate all of these features, and engage the audience in discussions of their origin.

1. Introduction

The Big Island of Hawaii is well known for its abundance of large and long lava tubes. Manu Nui is a lava tube system on Hualalai, one of the five volcanoes on the Big Island of Hawaii. The biggest volcano on this island is Mauna Loa, which is also considered to be the biggest volcano in the world. It rises to 4 km above sea level or about 9 km above the seafloor. Hualalai is the third youngest and third-most historically active volcano on the Island of Hawaii. Some 300,000 years ago, the summit of Hualalai was at sea level, and today it is at 2,521 m above sea level, making it the third tallest volcano on the island. Detailed mapping has shown that 95% of the surface area of this basaltic shield volcano is less than 10,000 years old. 80% is less than 5,000 years old, more than half is less than 3,000 years old, and 25% is covered by flows less than 1,000 years old. The most recent flow, which occurred in 1801, flowed over part of Manu Nui, so we are unable to know how far the tube system once extended. Hualalai is considered to be "dormant", and, according to the USGS Web site (USGS 2009), "is likely to erupt again in the next 100 years."

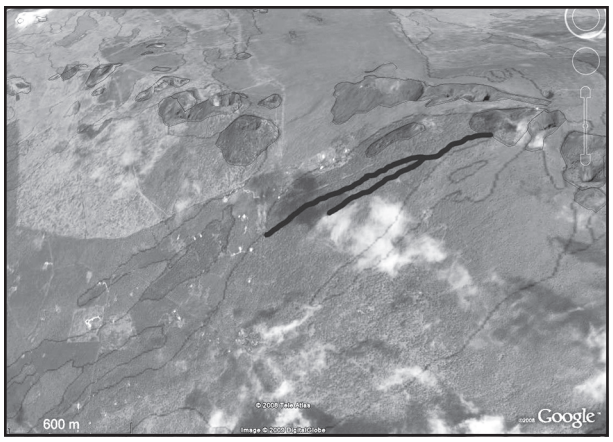

Figure 1: Google Earth view of Kaupulehhu crater area, with geologic overlay. Manu Nui cave system is shown as the dark black lines.

Manu Nui is a 3.5 km system on the western flank of Hualalai, noted for its steepness and colorful speleothems. Manu Nui is part of a flow that occurred about 2,200 to 2,300 years ago. The geologic setting is shown in Figure 1, where it can be seen that the cave starts just below the Kaupulehhu crater (elevation 1,870 m). The cave has two branches: the northern branch ends where it meets the 1801 flow. The southern branch is still being explored, and may continue down the main axis of the flow. The most striking feature of the system is its very steep grade, which averages 27 percent (or 16 degrees). This is considerably higher than the average 4 percent gradient of the famous Kazamura Cave.

2. Exploration History

The first recorded exploration of the lower part of the cave started in the late 1990s. The late Kathy Marcelius bought the lot that contains the lowest 500 m of the system, initially with the goal to preserve the natural flora and fauna of the tract. She discovered many *pukas* (collapse entrances), and named them after the various native plants that grew in or near these entrances (for example, the Alani, Koa, Palani, and Clermonita entrances). She explored much of the main passage, and was amazed by the many stalactites and colorful lava flows. Realizing that this cave might be quite exceptional, she contacted William Halliday of the Hawaii Speleological Survey (HSS). A visit by members of the HSS confirmed the interesting nature of the cave. In February 2003, Kathy guided Don Coons, Ric Elhard, Rose Herera, and the authors to the system, and the main passage between the Maile and Koa Tree and Clermontia entrances was surveyed. Many side passages were noted, and photos taken. Don, Ric, and Barb Capocy came back the next month and surveyed the main passage from the Maile

down to the Refrigerator entrance, again noting many side passages. Since the cave "flowed" from an upper lot onto her lot, Kathy bought the adjacent lot to prevent logging and development.

Over the next six years, the authors, together with Kathy and various friends, continued the cartography and surveyed most of the upper section of the main cave, and most of the small parallel tubes in both the upper and lower sections in a series of eighteen survey trips. On our most *mauka* (up-flow) trip, we came across some flagging tied around a tree. After some discussion with Doug Medville, it became apparent that he had been surveying the uppermost part of the cave, which had originally been explored by Rob Pacheco and friends. Doug joined us on a trip and helped us resurvey much of what he had done before noticing that he was duplicating his effort in the upper portion of the cave. In the process, Peter found an obscure route through a breakdown pile in one of the *pukas* that turned out to be the beginning of the parallel branch to the south. On the next trip, the authors and Kathy explored *makai* (down-flow) in the longest section of the system yet found with no entrances: *The Energizer Bunny Passage*. Sadly, this was to be her last trip, as she passed away less than a year later, a victim of cancer. The authors continued exploring and surveying the system *makai* in the southern branch in 2008 with her son, Donovan. As of this writing, several leads remain. The southern branch continues *makai*, and there are still some small side passages and parallel tubes to be surveyed in the northern branch.

3. Genesis of Some of the Lava Stalactites in Manu Nui

The western slope of Hualalai is notable for its steepness, which means that there are many lava falls (or cascades) in Manu Nui, and at the base of many of them there are, or were, lava plunge pools similar to those in the steepest parts of Kazamura, only smaller as the Manu Nui tube is considerably smaller than that of Kazamura. The western slope of Hualalai is also known for its high rainfall (60" to 70", or 150 cm to 180 cm, per year). Almost every afternoon, this slope is shrouded in mist and clouds when the rest of the island is clear and sunny. We speculate that pools of rainwater collected in the tube's dessicated plunge pools prior to the later flows of lava through the Manu Nui tube system. When very hot lava flowed through the tube, it would have mixed with the cold water, with spectacular results.

At present, the youngest of Hawaii's volcanoes, Kilauea, has actively flowing lava, which reaches the ocean. Thus, we can readily observe, today, how when flowing lava meets the ocean, we get spectacular "fountaining" of lava and huge plumes of steam. This is quite spectacular, especially when viewed at night, as not only is the lava thrown up into the air, but the sudden mixing of hot lava and cool water results in huge steam clouds. On the USGS website (USGS 2009), we read this explanation: "When lava pours into the ocean at high rates from a lava-tube entry, beautiful and spectacular explosions called tephra jets commonly occur. With temperatures higher than 1,100 degrees Celsius, lava can instantly transform seawater to steam, causing explosions that blast hot rocks, water, and molten lava fragments into the air. In general, the more intense the incoming waves, the more energetic the tephra jets." This source goes on to discuss four types of explosions when lava meets ocean water while a lava delta is being formed, namely tephra jests, blasts, bubble bursts and littoral lava fountains. Of interest to us is the statement: "When seawater and lava mix within the confines of a lava tube, pressure may build to cause explosions that blast a hole through the roof of the tube. Two types of steam-driven explosions may be generated in such a "confined" environment: littoral lava fountains and bubble bursts."

Litoral lava fountains are described as: "Spectacular and rare, this type of lava-seawater explosion produces fountains of molten lava and steam that reach heights of more than 100 m. The explosions of molten spatter, bombs, and smaller tephra fragments quickly build a circular cone on the subsided lava delta, sometimes in a matter of minutes. Originating from deeper within the subsided delta and closer to the shoreline than bubble bursts, littoral lava fountains are much more energetic and dangerous." (USGS 2009)

Bubble bursts are characterized as: "Sporadic bursts of molten, dome-shaped lava sheets emanating from a circular rupture in the roof of a tube a few meters inland from the shoreline. Individual bubbles can reach diameters of 10 m in less than 2 seconds before they burst. The bubble fragments continue on their radial trajectories for up to 10 m more before falling to the ground. At the end of a burst, a pool of lava that remains in the roof of the lava tube gradually drains away. These bursts are frequently accompanied by a loud boom that shakes the entire delta." (USGS 2009)

If we apply what the USGS vulcanologists have observed and documented when lava meets ocean water, we can begin to understand what might happen if hot lava met a pool of rainwater in a confined space, such as a lava tube, away from an ocean, and the meeting did NOT result in the blasting of a hole through the roof of the tube. We can imagine fountains of molten lava and great clouds of steam, but not

enough to damage the tube. Small and large fragments of molten lava would be thrown up randomly and splatter onto the tube's ceiling and walls, as illustrated in Figure 2. Parts of the larger fragments of molten lava would become elongated and start to resemble small stalactites. The pressure from the steam would instantly cause the fragments of molten lava to outgas, shrink, solidify and become permanent. If another fragment was to be projected onto a newly-formed stalactite, the process of sticking, elongating, outgassing, shrinking and solidifying would be repeated, and the stalactite would "grow" in length and volume. Since the fragments of liquid lava "fountained" up would be of varied sizes and trajectories, the growth of these stalactites would be very random – some would grow longer and thicker than others, and the shapes would vary greatly. However, the side of the stalactite facing the "fountain" would receive all additional fragments of molten lava, and the stalactite would grow in width in that direction, although gravity would ensure that it also grew in length.

As a stalactite grows thicker and longer from successive fragments, it would also shield some stalactites from receiving more fragments. It would be like a large tree in a forest blocking the sun from smaller trees. In other words, a large stalactite would throw a "shadow" over the stalactites no longer in the range of the lava fountain. Some of the fragments of molten lava may not reach the top of the stalactite, but instead stick to the bottom, or tip of the stalactite. In such cases, the stalactite's tip would "grow" towards the fountain, sometimes with a slight curl, which would get more predominant with successive fragments hitting and sticking to the tip of the stalactite.

This process would continue until the water in the pool had all evaporated into steam, or the flow of the lava was interrupted.

Today, when we visit Manu Nui, we observe that parts of the cave have a huge profusion of thick, oddly-shaped stalactites hanging away from the vertical (see Fig. 3).

We find stalactites growing like thick blades away from the

Figure 3: Lava stalactites up to 1 m long, hanging at significant angles from the vertical.

walls in the shape of sloping benches, and often reducing the width of the passage considerably. We find other areas that are covered with small fragments of different colored lava. The lava ranges from black through dark and light brown, red, butterscotch, dark and light orange to ochre. Some grayish and greenish tints are also seen. This has the effect of "color coding" the profusion of fragments so that we can better observe how some of them would have landed. For

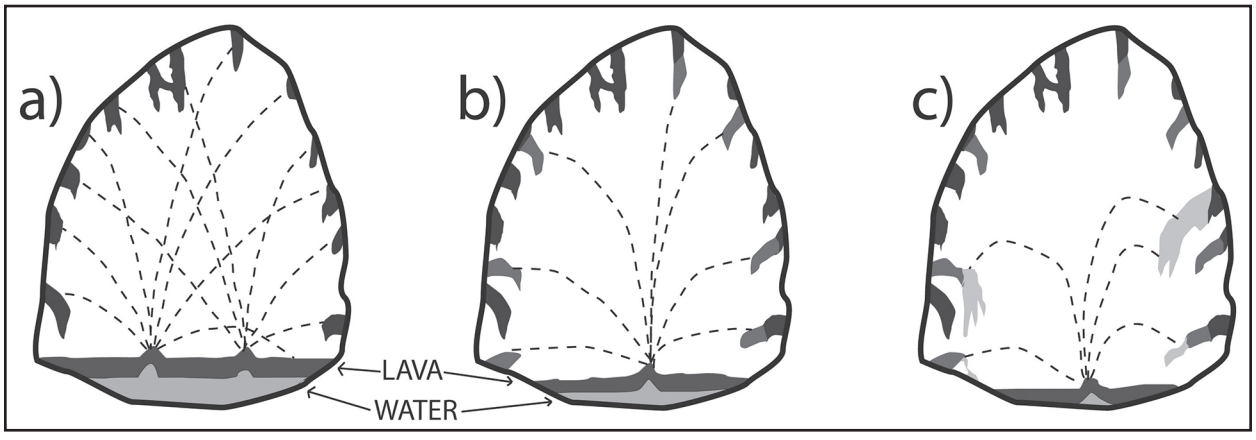

Figure 2: A series of diagrams, not to scale, illustrating the cross section of a lava tube, showing what could happen when lava fountains in a confined space: a) shows a pool of water trapped underneath flowing lava, turning to steam, and forcing random fragments of lava to hit the walls and ceilings in random trajectories; b) shows more fragments hitting walls and other fragments of lava, resulting in stalactite-like speleothems; c) The fountain is losing steam and trajectories are not as high. Stalactites grow towards the source of the fountain, and some are long enough to shadow the areas behind them.

example, we observe that one elongated ochre fragment, in the shape of a streamer, was about 25 cm long when it reached a wall some 4 m above the floor. The fragment was lying horizontally when it hit. About 8 cm landed against one stalactite, the middle 10 cm hit the wall, and the final 8 cm landed against another stalactite. We can easily observe the "shadow zone" caused by the two stalactites on the wall behind them. There are many hundreds of such fragments observable at one time. And because of the wide variety of size and color, we can observe a definite pattern in the direction of the blobs' trajectories (see Figs. 4 and 5).

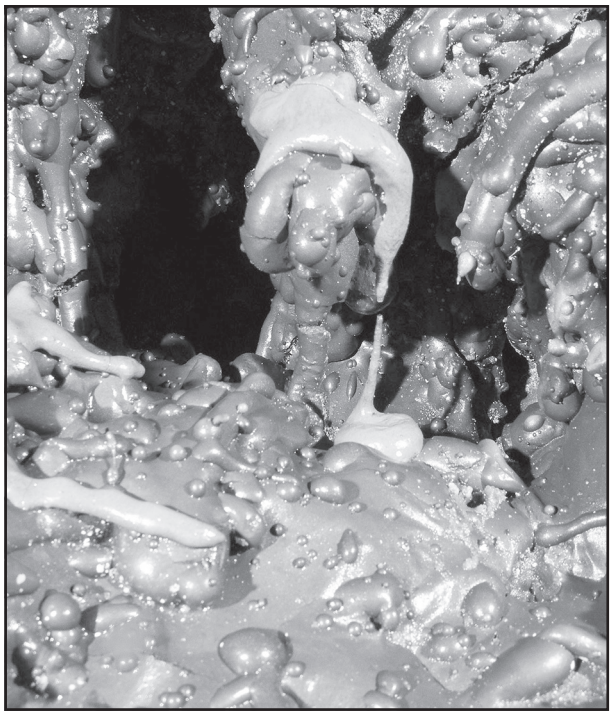

Figure 4: Splatters of vividly colored lava, ranging from black and dark brown through red and orange to ochre.

Space does not permit us to give a detailed description of each of the several places where fountaining in the cave is evidenced by a profusion of splatters, curved stalactites, or multi-colored blobs, but an observer with attention to detail and time on his hands could painstakingly document the occurrences where one color overlaps the other and perhaps reconstruct which colors flowed earliest, and which colors flowed last. Instead, we would prefer to seek answers to other questions, like "How can so many colors originate from one spot?" When we see lava flowing it is red, but it generally cools to black. Can Manu Nui be like Mary Poppin's jar of medicine, which poured a teaspoon of red medicine then, almost immediately, a teaspoon of blue? Disney jokes aside, could the answer lie in chemistry,

Figure 5: Sample spatters that indicate extensive "fountaining," where lava splashed onto the walls and ceiling.

heat, water, cooling time, steepness, or a combination of circumstances?

We know that the chemical composition of lava varies, not only among igneous rocks, but among basaltic rocks, and indeed among flows of lava from the same vent. The chemical composition of different flows has been likened to a fingerprint. The chemical composition of lava is, according to Wikipedia, composed by weight, 45% - 55% silicon dioxide, 5% - 14% iron oxide, 14% alumina, 5% - 12% magnesium oxide, 10% calcium oxide or lime, 2% - 6% alkalis, and 0.5 – 2% titanium dioxide. Iron oxide and magnesium oxide seem to be the chemicals with both a significant component and a significant variation, but can they account for such a wide variety of colors from black to ochre, via red and olive green? It is our understanding that lava has not been chemically analyzed to determine what causes the different colors. It is popularly held that magnesium causes the black lava and that iron causes the red color when it oxidizes, but can these two facts explain the kaleidoscope of colors in Manu Nui? It is also held that rapid cooling on the outside causes a veneer of black lava around an inner core of lighter-colored lava. So the color

black could indicate chemistry or genesis.

Dr. William Halliday told us that the chemical composition of lava is very similar to that of clay, and he had observed that 90-year-old lava had already decomposed to clay. We are not potters, but a cursory survey of ceramics websites informed us that the color of terra cotta is controlled by not only the chemical composition of the clays, but also the firing temperature, the composition of gasses in the kiln, and the water content of the clay. We read (CERAMICS 2009): *The iron-content of the clay used for earthenware gives a color which ranges from buff to dark red, or even cream, grey or black, according to the amount present and the atmosphere (notably the oxygen content) in the kiln during firing. Clays with low iron content can result in paler colors on firing, ranging from white to yellow.*

4. Description of Other Interesting Features

One unusual feature, which the authors have not seen in any other lava tube, is illustrated in Figure 6. It is a 'mini volcano', about 15 cm tall, with a 5 cm wide opening at the top. The mini-volcano seems to have formed above a small opening to a lower passage that crosses underneath, whose ceiling is less than a meter below the floor of the passage with the volcano. Apparently, there was a small opening during one of the last flows through the system, and lava welled up from below into the upper passage, and the strong wind kept the opening intact. The connection is still open today, as evidenced by a breeze blowing through the opening. We noticed the feature when a team surveying the upper passage was able to clearly hear another team in the lower tube.

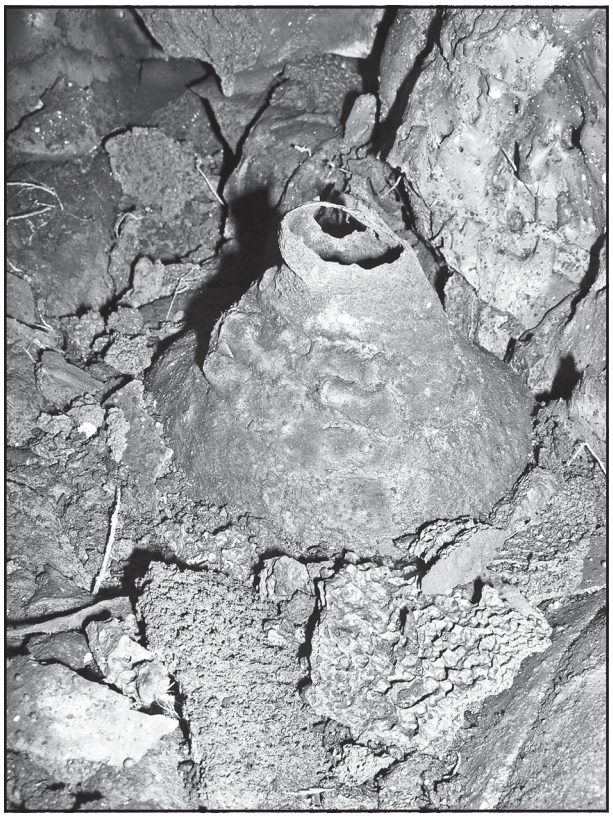

Figure 6: "Mini-volcano" feature, which is about 15 cm tall and connects overlain passages.

The initial explorations of the cave system revealed a variety of bones. While most of these are common (goats, pigs, cows, and small birds), one set of bones seemed quite unusual: see Figure 7. Don Coons initially identified these bones as having belonged to a large extinct goose, but this has yet to be confirmed. Kathy, an ardent lover of nature, named the cave for this avian friend who perished in her cave - Manu Nui means *Big Bird* in Hawaiian.

Figure 7: Bones from a large extinct Hawaiian goose.

4. Conclusions

More work remains to fully survey and document this fascinating cave system. We hope that it can be preserved for the future as Kathy would have wanted it to be. We gratefully acknowledge the leadership and generous support of Kathy Marcelius and her family.

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USGS 2009: http://hvo.wr.usgs.gov/hazards/oceanentry/delta explosions/and references therein.

CERAMICS 2009: http://www.visual-arts-cork.com/ceramics.htm

SOME ASPECTS OF SPELEOGENESIS IN EXTRATERRESTRIAL ENVIRONMENTS: 1-MERCURY AND MARS

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In this paper a general view of the aspects and problems of the extraterrestrial speleology is reported on the basis of the documents available from the Laboratory of Space Astrophysics (Italian Council of Research, CNR) in co-operation with NASA. In order to show the different aspects of the problem, some structures referred to speleogenetic processes observed on the surface of Mercury and Mars are here described. In the first case structures due to the effusion of volcanic lava are recorded; in the case of Mars the situation is more complicated because the evidence of erosion caused by fluid masses is associated to the volcanic phenomena. The fusion of permafrost in the underground of Mars could result in a pseudokarstic mechanism also able to produce extended caves.

1. Introduction

This paper is a revised and updated version of a paper delivered in 1978 at the 13th National Congress of Speleology held in Perugia, Italy, whose proceedings have never been published by the organizers, following a simple preprint without any illustration. Since Professor Vittorio Castellani, astrophysicist and speleologist, member of the Italian "Accademia Nazionale dei Lincei," died on May 20, 2006, this paper gratefully is dedicated to his memory.

2. Generalities

Speleology, as study of the different kinds of cavities found in the Earth, has gathered much information not only on the karst phenomena *sensu strictu*, but also on examples of parakarst and pseudokarst phenomena. Space explorations have shown the existence of similar examples on the surface of other planets of the solar system. Therefore, a new reason to investigate more deeply such phenomena on the Earth aroused in order to obtain a more detailed knowledge on the mechanism of their evolution with special regard to the environmental conditions.

In this paper a general view of the aspects and problems of the extraterrestrial speleology is reported on the basis of the documents available within the Laboratory of Space Astrophysics (Italian Council of Researches, CNR) in the framework of the co-operation with the NASA. In order to show the different aspects of the problem, in Table 1 the main characteristics of the so called "inner planets," which are similar to the Earth on account of their solid rock surface, are reported.

Venus, as well as the Earth, is the only planet with a real atmosphere. For this reason heavy clouds cover its surface and consequently the information on the surface morphology was obtained mainly by radar images. Pictures of the surface were taken by the Venera missions, which landed on Venus and returned pictures of area around the landing place to show a surface with basalt rocks of different size.

A study on the development of lava tubes in extraterrestrial conditions (Badino, 2008) is based on the heat released by

Order from the Sun	Name	Masse (Earth= 1)	Gravity (Earth= 1)	Atmospheric. pressure (millibar)	Temperature (K)	Craters	Lava	Volcanic structures
1	Mercury	0.055	0.38	0 (He trace)	440	Yes	Yes	Yes
2	Venus	0.816	0.82	9.10^5 (CO_2)	748	Yes	Yes	Yes
3	Earth	1.000	1.000	1000 (N_2+O_2)	293	(Yes)	Yes	Yes
3a	Moon	0.0123	0.165	0	245	Yes	Yes	Yes
4	Mars	0.11	0.38	6 (CO_2)	210	Yes	Yes	Yes
4a	Photos	-	Negligible	-	-	Yes	No	No
4b	Deimos	-	Negligible	-	-	Yes	No	No

Table 1: Characteristics of the planets similar to the Earth.

Planet	Convection w=10 ms^{-1}	Convection w=100 ms^{-1}	Irradiation	Total
Earth (ground level)	7	30	100	107-130
Moon	0	0	100	100
Mercury	0	0	100	100
Venus (ground level)	400	1600	80	480-1680
Mars (at 20 km)	1	4	100	101-104

Table 2: Heat loss of lava [kW m-2].

a lava flow. In case of the existence of an atmosphere the heat exchange is due to both convection and radiation, otherwise the release of heat is by irradiation only. On Mars and Venus the atmosphere is composed by CO_2 while on the Moon and Mercury the atmosphere is absent. In Table 2 the heat loss of lava in different planets is reported. The convection was evaluated for two wind velocities (w) of 10 and 100 ms^{-1} respectively and radiation for lava temperature (T) at 1000° C.

According these data a rather rough conclusion could be that the development of lava tubes in the different planets should not be much different from the Earth with the exception of Venus on account of its dense atmosphere. But, development of lava tubes depends on many other factors as the chemical composition of lava, the slope, the gravity, etc. An exhaustive evaluation of there factors is complicated and outside the scope of this paper; it will be further developed in the final version of Badino (2008). A global evaluation of the phenomenon can be obtained by a numerical calculation only since the radiation is proportional to T^4 while the convection is directly proportional to T. Therefore the lava flux must be analyzed along its whole pathway. If convection would prevail the lava tubes on Mars would be dramatically longer than on the Earth.

The surface of other planets is presently well known thanks to the space missions. Their surfaces have many craters due to the impact of meteorites. This fact is due to the absence of atmospheric effects which, on the Earth, acts as a shield for most of the meteorites and smoothes rather rapidly the craters formed on our planet. With the exclusion of Mars' satellites, which are nothing more than a couple of big boulders moving in the space, relevant volcanic phenomena seem to be widespread. Basalt rocks and detritus probably form planets' surface.

3. Mercury

Mercury, the least massive among the inner planets, shows many craters, which may be attributed to meteoric impacts. Among the most relevant examples, the so-called Caloris basin, a huge circular "sea" is the result of a catastrophic impact, which modified a wide part of the planet surface. It must be emphasized here that such events may produce a local fusion (or re-fusion) of the crust, so that meteoric impacts may be the origin of secondary effects of a non-endogen volcanism.

If evident volcanic craters are absent, there are wide covers of the original soil, which are generally supposed to be due to lava layers. In other words, an important effusive volcanism, with the lava, emerging from crust fractures, could have covered large areas of the planet surface. In Figure 1, a region of Mercury's surface is reported, where many indications support this hypothesis:

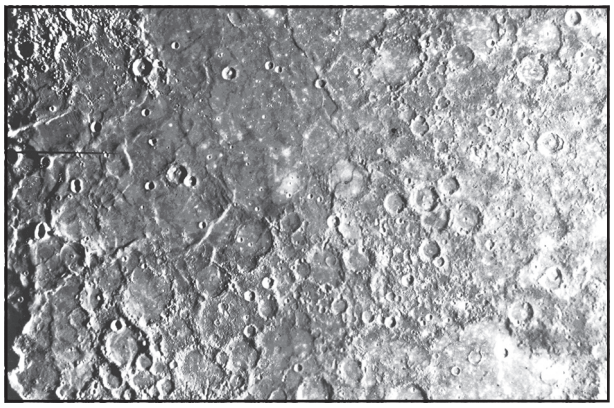

Figure 1: Lava waves on Mercury. Notice the crater covered in the upper left corner.

a. The area in the top, where there are practically no craters, can be assumed to have been successively covered by lava flow, since it cannot be assumed that this area was not originally hit by meteorites as well as the rest of the planet.
b. Typical ridges, laying north-south, are evident on such a cover, with the same appearance of the flow of a viscous fluid.
c. The existence of many craters filled and sometimes nearly smoothed by a fluid.

Sometimes the ridges rise above overlap the smoothed craters supporting the hypothesis that the covering layer is

successive to the formation of the crater. If the prevailing conditions of the planet are these, then tectonic caves and/or lava tubes could exist.

The presence of widespread fractures of the planet crust is evident in Figure 2 where a computerized photomontage of the area to the east of the Caloris basin is reported. A series of deep rills is seen on the left of the picture, as an evident consequence of the impact that originated the same basin. It is interesting to observe that the fracture, in the middle of the picture up to the basis of the typical group of four craters ("Mickey Mouse"), shows in the center top a series of interruptions suggesting the presence of tectonic caves. A support to this hypothesis is found in Figure 3 with a particular rill crossing the lower edge of the central crater of "Mickey Mouse". In the lower left corner of the picture, a channel between a substantially homogeneous plain and the center of the crater can be seen. It is interesting to observe that here the rill is formed by the union of a series of elliptical hollows as it happens when a lava tube collapses. This is an important criterion to distinguish surface collapses from a succession of micro-craters due to secondary ejecta from an impact crater.

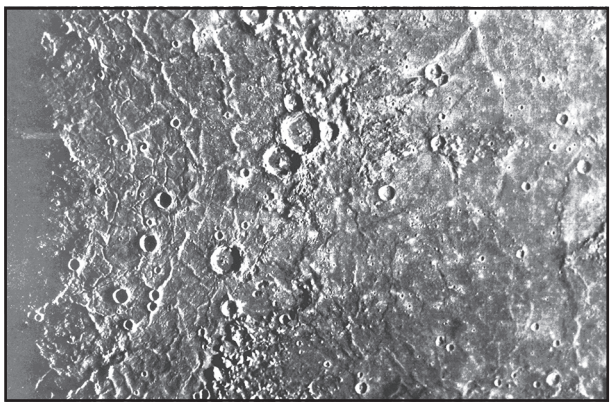

Figure 2: Computerized photo mosaic of the E edge of basin Caloris. A series of deep rilles are seen on the left of the picture.

Research of lava tubes is carried out on the same principles, on the basis as observations of surfaces with partially or totally collapsed lava tubes. Sometimes the winding of a series of micro-craters may give a rather precise indication of the presence of a lava tube below (Greeley, 1977: Fig. 3).

It is difficult to obtain a clear indication of the existence of volcanic caves by observing the surface of Mercury. Frequently the presence of some indication never reaches the level of a clear proof. Also in Figure 3, on the right of the channel mentioned above, a series of collapses can be seen as the result of a lava tube connected to the central

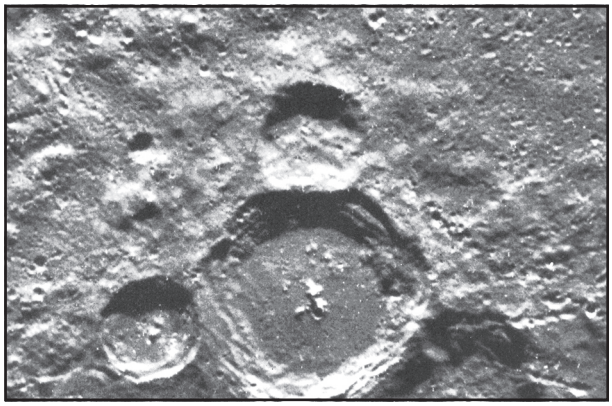

Figure 3: Particular of a group of craters (Mickey Mouse). In the lower left corner, channels can seem to be a series of elliptical hollows as it happens when a lava tube collapses.

crater. But perhaps it could be also a branch of the system of fractures already observed. The situation is much more uncertain because on Mercury there is a strict association between some craters and effusive phenomena. Figure 4 show a typical case: the craters in the picture appear to be filled by a homogeneous fluid but, nevertheless, the nearby soil and heights appear to be substantially untouched. The area appears to have been subject to lava flows, which locally filled hollows. In the center of the picture, two craters seam to be connected by a channel; as well lava channels could be the rills starting from the western ridge of the central crater and from the huge crater at the north-western border of the picture.

At the moment the existence of lava tube cannot be definitively proven. Perhaps, in the future, more detailed pictures could show important details. It is also possible that the nature itself of the volcanic phenomena on Mercury precludes to existence (or the observation) of lava tubes in this planet.

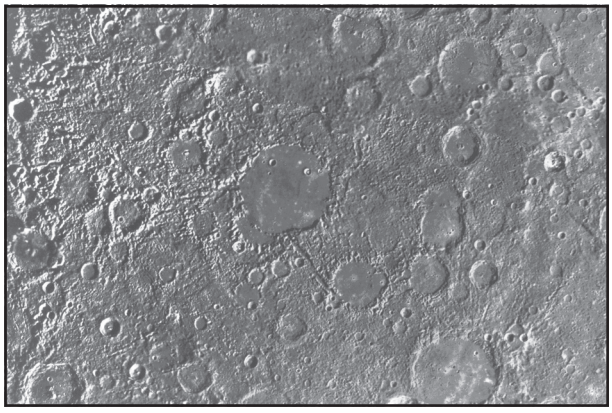

Figure 4 : In the middle, two craters connected by a channel. Other channels, sometimes covered, are seen at the top left.

4. Mars

The study of the surface structures on Mars is somewhat more difficult than the previous ones. In fact, in addition to the tectonic and volcanic structures, fluvial molding processes are evident supporting the hypothesis that liquid water exists on the surface of the planet (Leovy, 1977; Jakowsky & Haberle, 1992). Figure 5 shows a typical and striking example, where a fluvial mold on a surface with many craters can be observed. Note the strange dome-shaped structure inside the principal craters.

Tectonic structures are frequent both as a consequence of

Figure 5: Photo mosaic of Regio Crisis from 1,600 km; the structures around the craters are due to the flow of a fluid (water?).

strong meteoric impacts and as the result of a real planetary tectonics. The most striking example of such tectonics is given by the Vallis Marineris, a more than 1000 km long deep canyon in the Mars' surface.

Beyond these tectonic structures Mars shows the existence of strong volcanism with the largest volcanoes in the solar system, known up to now. The most imposing volcano (Olympus Mons) is more than 600 km wide and has a height from the planet surface of 26 km (Greeley, 1977: Fig. 17). The presence of wide areas without craters suggest the existence of a covering layer, which, in the case of Mars, could also be due to a water flow or to sand storms known to occur on this planet.

Close to volcanoes there are apparent lava tubes and volcanic caves. In Figure 6, the Arsia Mons, a volcano 19 km high and wider than 100 km is shown. In addition to a series of fractures in the upper right corner of the picture, three lava tubes appear to originate at the volcanic shield of the crater. Upstream, the central rill can be observed. It could be explained as the partial collapse of the lava tube that feeds the terminal channel. A more detailed study of the surface morphology suggests the existence of caves more exactly termed parakarstic. The landslides along the slopes of the Vallis Marineris (Fig. 7) have been interpreted as due to permafrost, i.e. to the existence of underground frozen deposits that under proper conditions (e.g., volcanic heat) can change into a liquid phase and result in a fluid flow under the thrust of the overlying layers (Coradini & Flamini, 1979). Good evidence of the existence of these phenomena is reported in Figure 8 where a fluid mass originating from a collapsed structure has covered the plain on the left of the picture. The fusion of permafrost in the underground of Mars could result in a pseudokarstic mechanism able to produce extended caves.

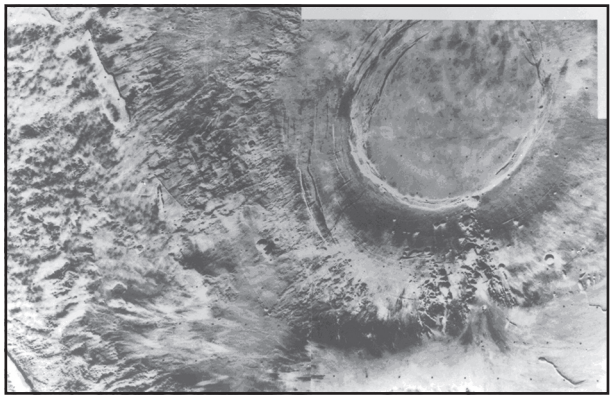

Figure 6: One of the Mars highest volcanoes, the Arsia Mons (diamater 100 km, and height 19 km). Notice the channels from the crater towards the center of the picture.

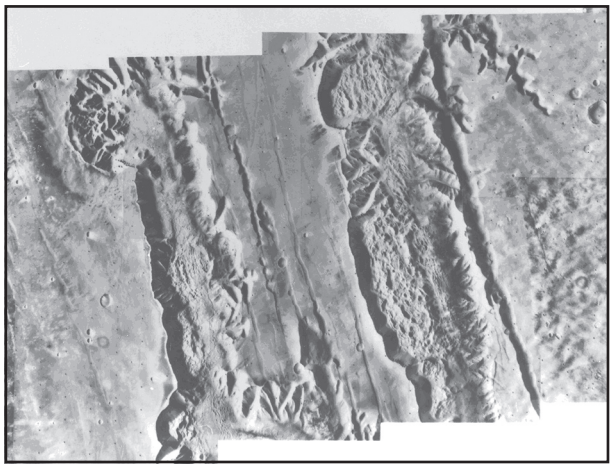

Figure 7: Photo mosaic of the area to W of Vallis Marineris from 4300 km. Notice the landslides along the slope or the valley and the channel due to the collapse of caves.

Up to now, only lava and tectonic caves (i.e., pseudokarst) had been identified or, at the most, some parakarst phenomena. Griffith and Schock (1995) proposed a geochemical model to explain the formation of hydrothermal carbonates on Mars from the alteration of

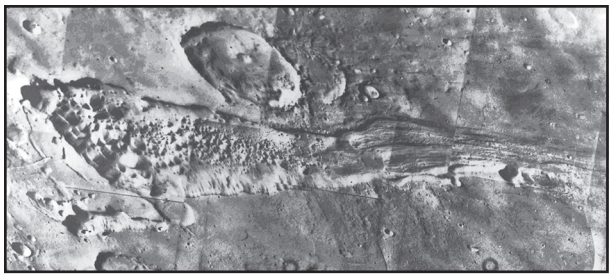

Figure 8: The landslides at the left of the valley originated the fluid mass that covered the plain on the bottom of the picture.

basalt. This model agrees perfectly with the observations when applied to Iceland rocks. In Mars conditions, the alteration of basalt in presence of water and CO_2, e.g., at a temperature of 250° C, could produce 7% carbonate, which could be found as vein-filling materials and mineral replacements. According to the above mentioned authors, if the hydrothermal processes developed, in areas where the water table intersect the surface, warm, CO_2-laden fluids should have degassed to produce locally extensive travertine. In this case, classic karst processes could have produced caves. Also, if the existence of hydrothermal systems on Mars seems to be assessed (Farmer, 1996), up to now no carbonates have been detected.

Recently, Halevy, Schrag and Zuber (2007) speculated on the possibility of an evolving Mars environment base on the sulfur cycle instead of the carbon cycle, as supported by the abundance of sulfur minerals on the Martian surface. In this case, caves could have developed in gypsum instead of limestone.

In Figure 9, the gullies eroded into the wall of meteor impact crater covered by soil (loess?) in Noachis Terra could start from the entrance of a cave. An image taken by NASA's Mars Reconnaissance Orbiter on 8 August 2007 shows the entrance of a pothole with a wall on this dark feature, suggesting it is a pit at least 78 meters deep (Shiga, 2007) (Fig. 10). The evidence of a surface layer with a round void (about 150 m in diameter) leading to an underground passage suggests the possibility of a skylight produced by the collapse of the roof of a lava tube or a wide passage. In any case, this feature is not an impact or a volcanic crater since there are no ejecta around it. Karst phenomena *strictu sensu* are probably absent due to the lack of limestone. Based on these assumptions, the above noted morphological characteristics of the planet's surface might hold speleological interest. Mars' satellites are not taken into account due to the absence of any mechanism of development.

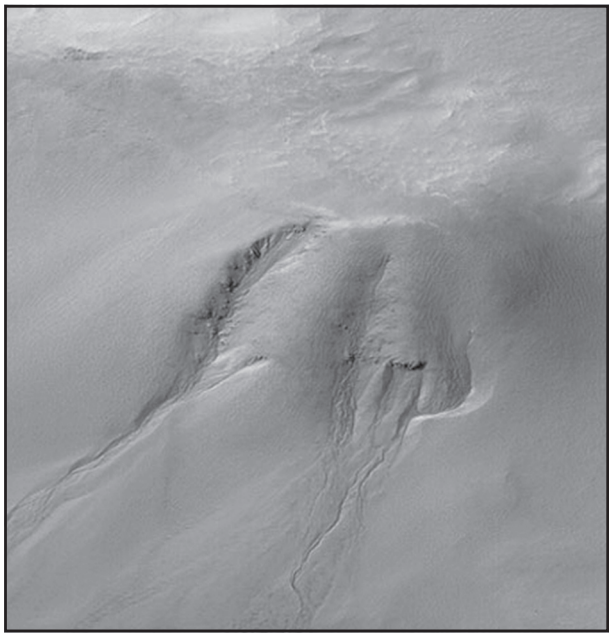

Figure 9: Gullies eroded into the wall of meteor impact crater in Noachis Terra could start from the entrance of a cave. (NASA/JPL/Malin Space Science Systems).

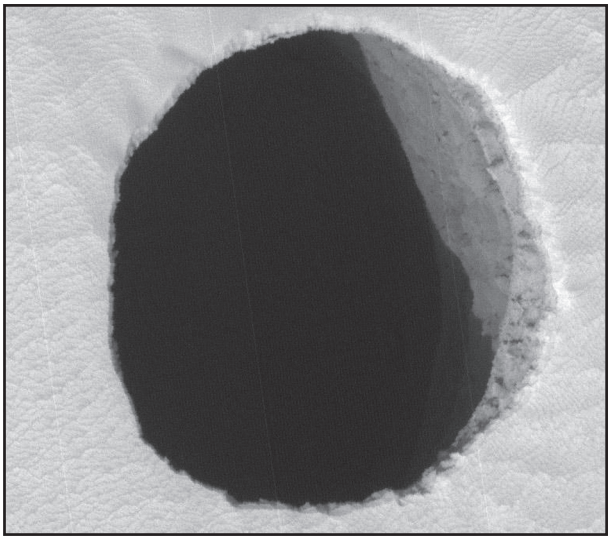

Figure 10: A pit at least 78 meters deep The evidence of a surface layer with a round void (about 150 m in diameter) leading to an underground passage suggests the possibility of a skylight produced by the collapse of the roof of a lava tube or a wide passage (Image: NASA/JPL/University of Arizona).

Along the Vallis Marineris there is some evidence of features that could be interpreted as long lava tubes (Fig. 11). In this case they could be the longest lava tubes in the solar system.

Also without a direct exploration, relevant indications support such a hypothesis. On the highlands, close to the slopes of the Vallis Marineris, and in addition to the landslides quoted above, there are typical pseudo-fluvial

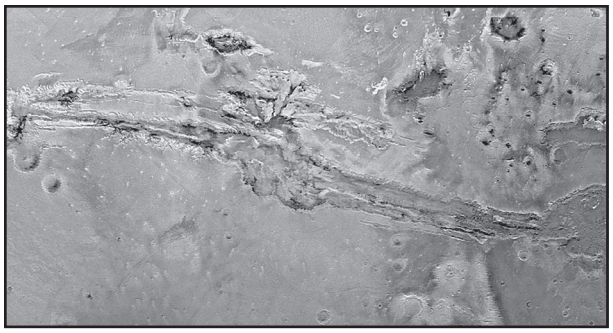

Figure 11: Another view of the Vallis Marineris; various structures, probably lava tubes, run parallel to the valley. Image from NASA (courtesy of Windows to the Universe, http://www.windows.ucar.edu).

valleys, which at first seem to be unjustified on account of the absence of any trace of the corresponding rivers.

If the existence of permafrost in the Martian subsoil is accepted, then such valleys can be attributed to the action of underground drainage channels along fusion lines of permafrost. Above these channels and close to the surface, collapse structures would have the shapes here observed (Fig. 12). In such a case, the Marstian subsoil could host pseudokarstic phenomena, although it is not possible to define their real importance.

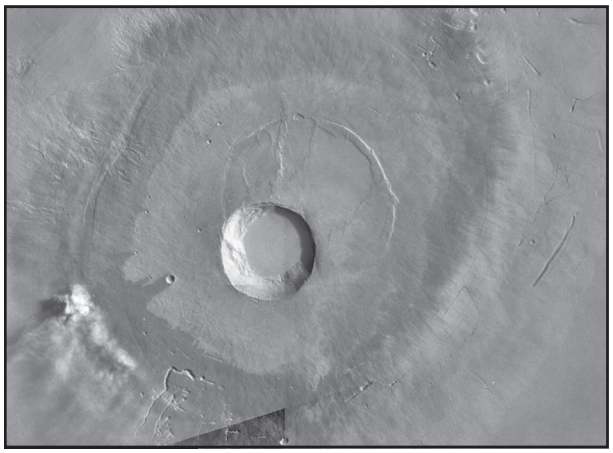

Figure 12: Caldera collapse pit at the summit of one of the large volcanoes on the Tharsis plateau. Image from NASA (Courtesy of Windows to the Universe, http://www.windows.ucar.edu).

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SOME ASPECTS OF SPELEOGENESIS IN EXTRATERRESTRIAL ENVIRONMENT: 2-MOON AND VENUS

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Some structures observed on the surface of the Moon are interpreted as resulting from speleogenetic processes. The volcanic structures are particularly prominent speleological features. Both lava tubes and tectonic caves have been identified. In particular, the lower gravity and the lack of an atmosphere relatively dense (and therefore able to drain negligible amounts of heat in short time intervals) allowed the formations of extremely long channels in these extraterrestrial environments.

Observations of Venus' surface, showed the existence of volcanic activity on this planet, and there are some indications about the possibility of the existence of volcanic caves as lava tubes. Nevertheless it must be taken into account the characteristics of this planet: if the high density of its atmosphere ($9*10^5$ millibar) would facilitate an exchange of heat, the high temperature (748° K) would reduce such an exchange. Therefore, the lava tubes could perhaps be larger than those on Earth.

1. Moon

On the Moon the volcanic structures are quite evident, as cupolas emerging above the soil surface or real volcanoes. Tectonic phenomena are also observed in the vicinity and inside some large impact craters. Figure 1 shows Maris Humorum, with a reported diameter of about 350 km. On the right side there are some ridges similar to those observed on Mercury, and on the left side there is a series of probable tectonic fractures.

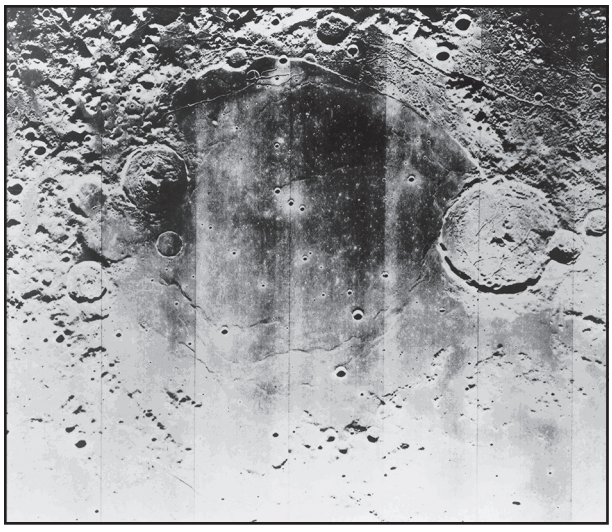

Figure 1: Mare Humorum (diameter about 350 km) in the middle; right: crater Gassendi, left: crater Vitello (23°30'S, 38°30'W) on the right some ridges are visible, on the left some rilles. The width of each path of the photo mosaic is 86 km.

It is interesting to observe that along the southwest edge of the principal crater there are some relics of craters filled by lava. Then, it seems that after the original formation of craters, further lava flows perhaps went off some fractures produced by the original event. On the west edge, in the inner zone, a series of rills with the very characteristics of lava tubes and covering relics of craters, support the hypothesis of a succession of lava flows. Somewhat above, the disappearance of half a crater, suggests that a lava flow from southeast stopped at a tectonic fracture.

Examples of clear lava tubes coming from wide craters are evident in Figures 2 and 3. Figure 3 show a general view of this area: from the structure reported above, a rill with many covers starts and extends till the near by "sea." The morphology of this rill leaves few doubts about its origin as a lava tube. The Circus of Plato is a crater filled by a "sea" about 100 km of diameter. The material inside the "sea" is also outside, without clear surface connections. For this reason already in 1970 an underground connection between the two areas was considered likely (Kosofsky & El Baz, 1970). Below, to the left, a large rill (lava tube?) seems to start from the slope of the principal crater. Above, to the right, there are a small crater and a stretched hollow that have evaded a clear interpretation.

Below, to the right, a peculiar formation (Vallis Alpinis), whose origin is clearly connected to a fluid flow, is still under discussion. In Figure 4, a view of the Vallis Alpinis (about 150 km long and 8 km wide) is reported with its evident connection to the higher Mare Imbrium. It could

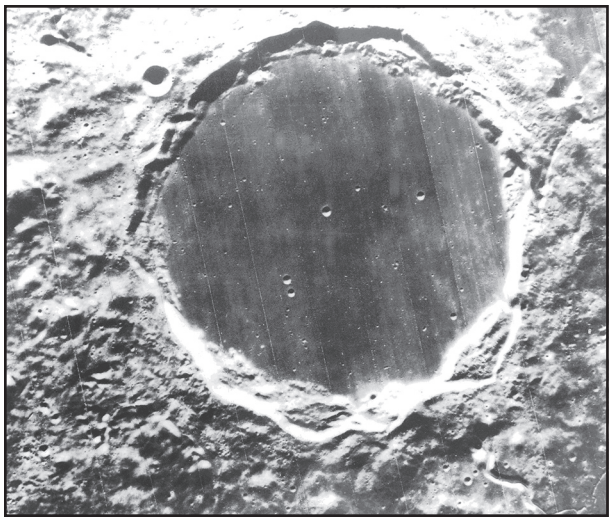

Figure 2: Crater Plato (diameter about 100 km). The material inside the "sea" is is found also outside, without clear surface connections. Perhaps there was an underground source of this material inside the crater or an underground connection connected the two areas. Below, to the right, a large rille (lava tube?). The width of each path of the photo mosaic is 12 km.

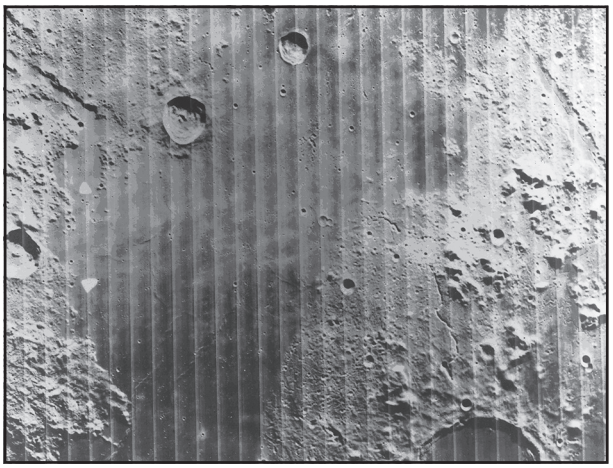

Figure 3: A long channel, sometimes covered, connects crater Plato (bottom lefy) to Mare Imbrium (centre). Vallis Alpinis is in the bottom right. The width of each path of the photo mosaic is 1 km.

be assumed that the valley acted to channel lava flow along a tectonic fracture to produce a central lava tube. On the right side of the picture and inside the same Mare Imbrium, there are other rills, which can be interpreted as lava tubes. Typical characteristics of the lunar volcanism is the frequent origin of lava tubes from hollows rather than from volcanoes. It is possible that this feature is a general phenomenon based on previous observations. For instance, one of the most prominent lunar rill (Rima Hadlet) appears to start from a deep hollow (Fig. 5). Another quite similar structure is seen in Figure 6. In this case, instead of the rill, there is a series of collapse structures attributable to a underlying cavity. It is very probable that it consists in lava tubes (notice the branch in the lower right part of the picture) due to a mechanism of lava effusion quite similar to the one observed on Mercury.

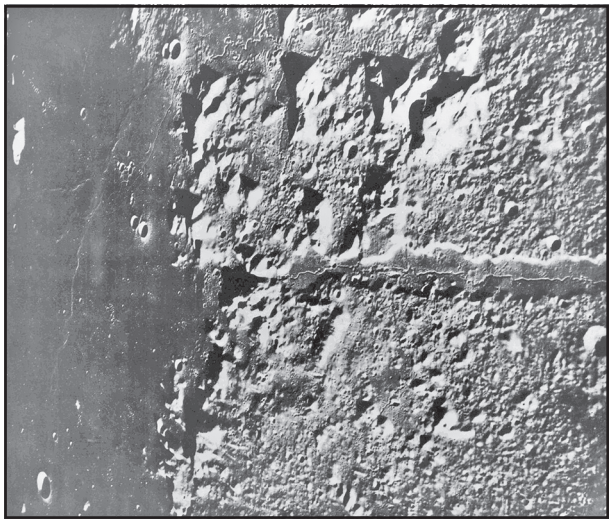

Figure 4: Mare Imbrium (left) and Vallis Alpinis (about 150 km long and 8 km wide) whose origin is much discussed. A channel with many meanders is along the valley; other channels are seen in the Mare and on the bottom.

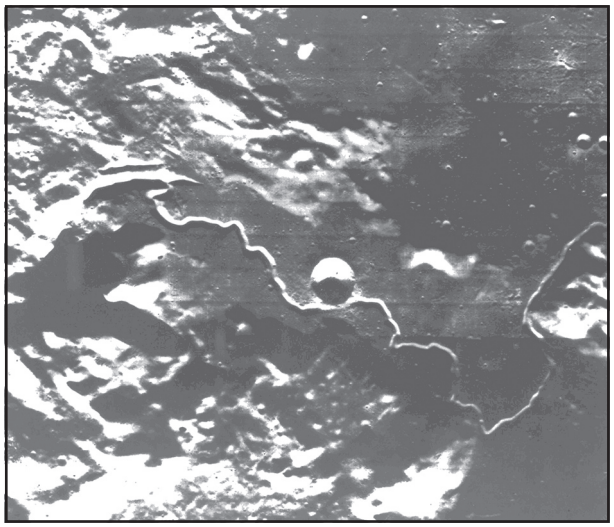

Figure 5: One of the most relevant Lunar channels (Rima Hadley) seems t start from a deep hollow. The width of each path of the photo mosaic is 4 km.

An interesting and typical example is given by the so called "Schroter Valley," a channel originating from a deep hollow at the base of a hill ("Cobras Head") about 1500 m high. The crater "Aristarcus" (about 40 km of diameter) is on the left and the crater "Erodotus" is on the right. The valley (Fig. 7) appears to be a long winding hollow with a flat floor, about 1,300 m deep. The whole area was evidently covered by a huge lava flow as supported by the presence of the relic of a crater in the lower left part and by the many rills. An enlarged view of the upper part of the valley (Fig. 8)

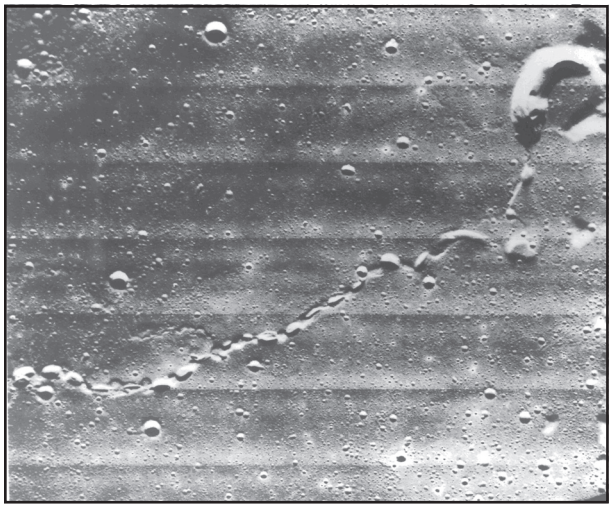

Figure 6: Series of hollows towards the hedge of the Oceanus Procellarum; they have the appearance of collapse structures attributable to a underlying cavity. The width of each path of the photo mosaic is 5.4 km.

shows that in its flat bottom there is a deep winding channel with the typical size of the rills to be noticed in the same zone (see the upper right side). The interpretation of this structure is not easy. The neat meanders of the inner channel seem to be due to an erosion by an absolutely non-viscous fluid. Such erosion may be connected to the genesis of the whole structure. It is also rather uncertain if the Cobras Head is the source vent of such a fluid. Some characteristics could suggest an opposite situation, so that the hollow in the upper part of the valley could be interpreted as a real lava pothole. In any case, it is evident that on the Moon there is an extended number of channels and lava tubes as well as tectonic caves to be still studied and explained in detail (Anelli, 1973).

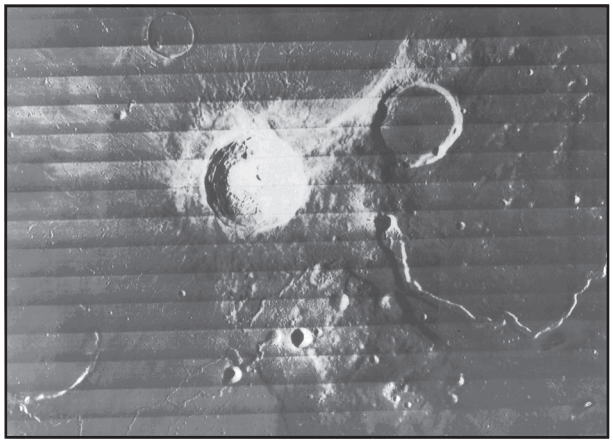

Figure 7: Crater Aristarcus (middle) (diameter about 40 km) and crater Erodotus to the right (diameter about 35 km) with a flat floor. The Valley of Schroeter (250 km long) starts from the Cobra's Head. The width of each path of the photo mosaic is 11 km.

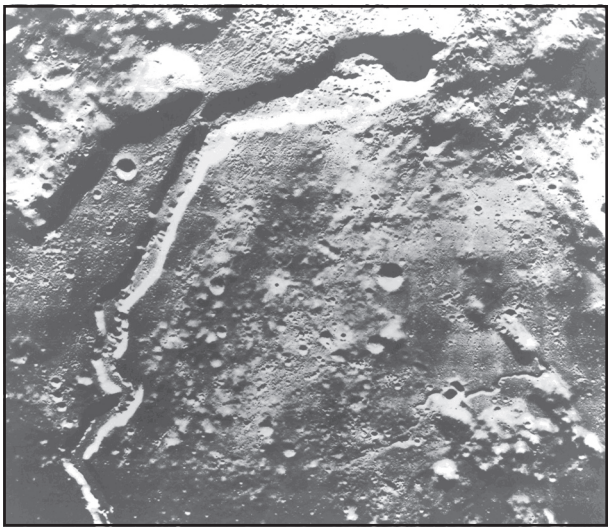

Figure 8: Particular of the Schroeter Valley about 1,300 m deep. The winding channel sometimes is covered by the slope of the valley. The width of each path of the photo mosaic is 4.3 km.

2. Venus

The first radar images of Venus (Saunders & Malin 1976) suggested the existence of craters. Successively detailed images confirmed this hypothesis. Because Magellan's radar viewed the Venusian surface from varying angles, 3-dimensional images of the planet's terrain were also possible in the early 1990s.

The Venera missions analyzed Venus' atmosphere and found that it is made up of about 96% carbon dioxide, with little oxygen. The 7th through the 14th Venera missions all successfully landed on Venus, each spacecraft spending a longer time on its surface than the previous one. Venera 10 sent back the first black and white photographs of Venus' terrain, while Venera 13 sent back the first color photos. The Venera missions also measured a surface temperature of 475° C, detected lightning, sampled the soil where it landed, and found a type of basalt that is common on Earth

In Figure 9 an image of a crater with multiple rings above the crater floor shows some channels in the upper left corner. In Figure 10, a very detailed image of the Lada Regio has many channels, particularly in the middle center flat area, that could be interpreted as lava tubes. Nevertheless it must be taken into account the characteristics of this planet: if the high density of its atmosphere ($9*10^5$ millibar) would facilitate an exchange of large amounts pf heat, the high temperature (748° K) would reduce such an exchange. Therefore, lava tubes could perhaps be larger than on the Earth.

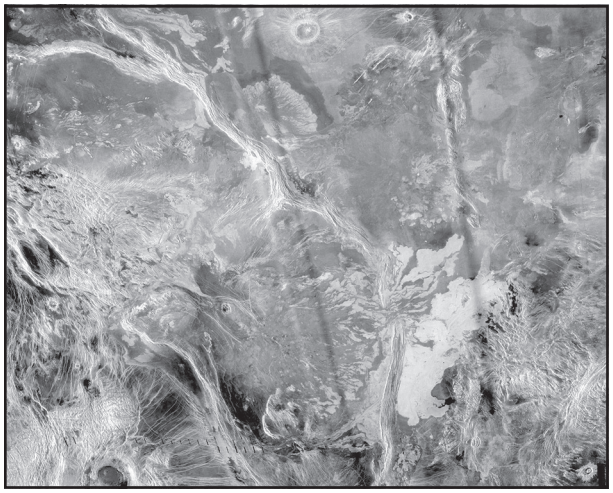

Figure 9: A crater on Venus with multiple rings that rise above the crater floor and some channels in the upper left corner. Image from NASA (Courtesy of Windows to the Universe, http://www.windows.ucar.edu).

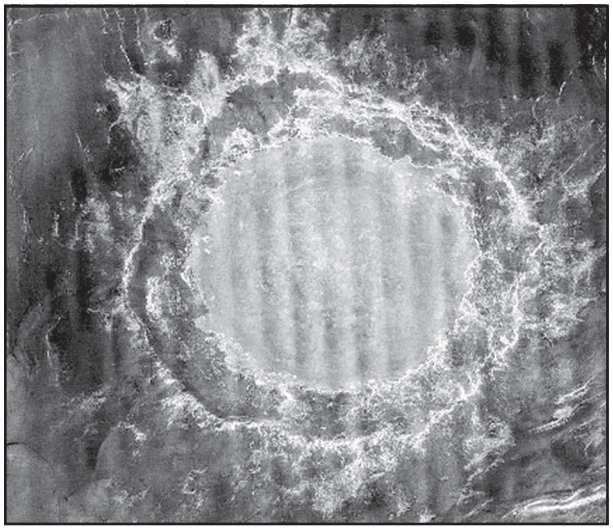

Figure 10: A very detailed image of Lada Regio with many channels, particularly in the middle centre flat area, which could be interpreted as lava tubes. Image from NASA (Courtesy of Windows to the Universe, http://www.windows.ucar.edu).

3. Conclusions

The framework here reported shows that earth-like speleogenesis may develop at the surface of many planets and satellites. A comparative study of these phenomena can explain the role played by the environmental conditions where the phenomena develop. The relevant parameters for this comparison are reported by Castellani and Cigna (these proceedings, Table 1). Many preliminary assumptions and working hypotheses may be easily listed. As an example, the large difference between Mercury and Mars must be emphasised notwithstanding the same gravity at their surface. Then it must be stressed the wide diffusion of volcanic phenomena also with different aspects.

The genesis of lava channels and tubes is characterised by various factors as it was reported by Wood (1977):

Flow rate
Flow speed:
- Viscosity
- Slope
- Gravity

Cooling velocity

Since some of these factors may vary largely in the different planets here considered, also the sizes of the structures described here may be very different from those observed on the Earth. In particular, the lower gravity and the lack of a relatively dense atmosphere (and therefore able to drain significant amounts of heat in short time intervals) allowed the formations of extremely long channels in the extraterrestrial environments here examined (Greely, 1976, 1977).

As it is not possible now to improve the knowledge of the phenomena by a direct observation, it is necessary to extend the study by developing models of the structures here described in function of known and measurable quantities.

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HIGH PRECISION U/TH DATING OF RECENT LAVA FLOWS USING SYNGENETIC NON-SILICATE CAVE MINERALS

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Precise radiometric dating of recent lava flows has been a problem due to the inability to resolve inherited geochemical isotopic signatures complicated by complex magma chamber residence histories. As a result, direct U/Th or K/Ar measurements of young basalts often yield ages with large uncertainties. Other techniques such as cosmogenic exposure ages require physical assumptions of erosion rates and production rates that are not always constrained, but are often the best or only techniques available. Syngenetic minerals, such as gypsum, occur in many lava tubes and may potentially provide reliable ages for young basalt flows.

Our first results come from Big Skylight and Four Windows caves, which are located in the Bandera basalt flow in the Zuni-Bandera volcanic field, New Mexico. In these caves thick gypsum crust (~0.5 – 1 cm) occur on primary tube surfaces. The Bandera lava flow has been well-dated using ^{14}C from charcoal underneath the flow (12.5 Ka) as well as ^{36}Cl and ^{3}He (11.2 Ka) . Initial results on the gypsum crusts show that U and Sr isotopic signatures are similar to those of the basalt. $\delta^{234}U$ values range from -6 to +30 ‰, which are moderately more positive than their basalt hosts, which is always 0 ‰ for unaltered basalts. The $^{87}Sr/^{86}Sr$ isotopic ratio for the gypsum crust average 0.7039149 $\pm$ 0.0003, which closely mirror published basalt value of $^{87}Sr/^{86}Sr$ = 0.703667 and which are lower than the $^{87}Sr/^{86}Sr$ ratio of 0.7075-.071226 for local soil. Slight differences of $\delta^{234}U$ and $^{87}Sr/^{86}Sr$ between the gypsum crust and basalt indicate some limited contribution from a non-basaltic source.

The oldest gypsum U-series ages range from 9–11 Ka, but some samples within these crusts also yield ages between 5-7 ka. Our initial results indicate that U-series ages of these gypsum crusts could potentially provide a new method for dating young basalt flows, if we are able to delineate pristine samples from those that experienced cryptic alteration.

1. Introduction

Radiometric dating of Quaternary (2.0 Ma to present) lava flows is important for cosmogenic exposure age techniques, which are used to constrain erosion rates, as well as neotectonics, hazard assessment, evolution of magma chambers, and magma recurrence intervals.

K/Ar (Ar/Ar) method, cosmogenic nuclide dating of surfaces, and in cases where eruption related charcoal can be found the ^{14}C method have been used to date volcanic rocks. The K/Ar method suffers from problems due to the low abundance of K in the basalts, as well as ideal conditions for the entrapment and isolation of radiogenic argon from atmospheric argon, particularly in basalts that are aphinitic(Sims et al, 2007). Cosmogenic nuclides have been successfully applied to many young basalts where erosion rates and cosmogenic production rates have been independently determined, and exposure (or lack thereof) to cosmogenic rays is well known. For basalts that overly charcoal deposits, a lower limit on eruption age can be determined from ^{14}C measurements, but only up to the upper limit of ^{14}C dating (50 ka).

Direct uranium series dating of young lava is problematic due to the unfavorable U/Th ratios in volcanic rocks. Daughter nuclide disequilibria of ^{238}U and ^{230}Th have been successfully used to date carbonate rocks up to 500,000 years (Cheng et al., 2000), but lava flows require isochron techniques because of their high Th/U ratios and have large errors (i.e., ±50%, Sims et al, 2007). Moreover such the ages do not differentiate between timing of magma chamber residence, transfer to the surface and flow emplacement. Syngenetic non-silicate minerals potentially can overcome these limits to the extent that many minerals, such as gypsum have favorable U/Th ratios and they do form at the time of eruption.

Primary igneous sulfates have been directly observed as anhydrite in a number of localities and settings (Luhr, 2008). To determine if our samples are pristine and from

a magmatic source, we focus on U, Sr and S isotopic measurements on the well-dated Bandera flow from the Zuni-Bandera volcanic field in northwestern New Mexico, USA. Data on U and Sr from the Bandera basalt are known (Asmerom, 1999) and should be reflected in eruption products. The S isotopic composition should near 0 ‰ for a high temperature source (Sakai et al, 1982). The Bandera flow has ^{3}He, ^{36}Cl, ^{14}C, as well as an aberrantly older K/Ar ages.

2. Sample Description

The Bandera flow is branched and segmented, with all samples collected from the Big Tubes recreation area in El Malpais National Monument, with a majority of samples collected and analyzed from the largest cave, Big Skylight cave (Fig. 1). Other samples were collected from nearby Four Windows Cave and Giant Ice Cave. Gypsum crusts were not observed on any broken surfaces on the cave walls or on breakdown blocks. The crusts were located near entrances and skylights, where preservation of the gypsum is presumed to be highest because of low humidity as opposed to deeper into the cave systems where higher relative humidity might form condensates that remove these easily dissolvable crusts. Samples were collected in-place, as well as broken pieces along lava shelves. When multiple lava benches were present, samples were collected at multiple levels. Gypsum crusts were also present on the primary ceilings of the caves, but not accessible.

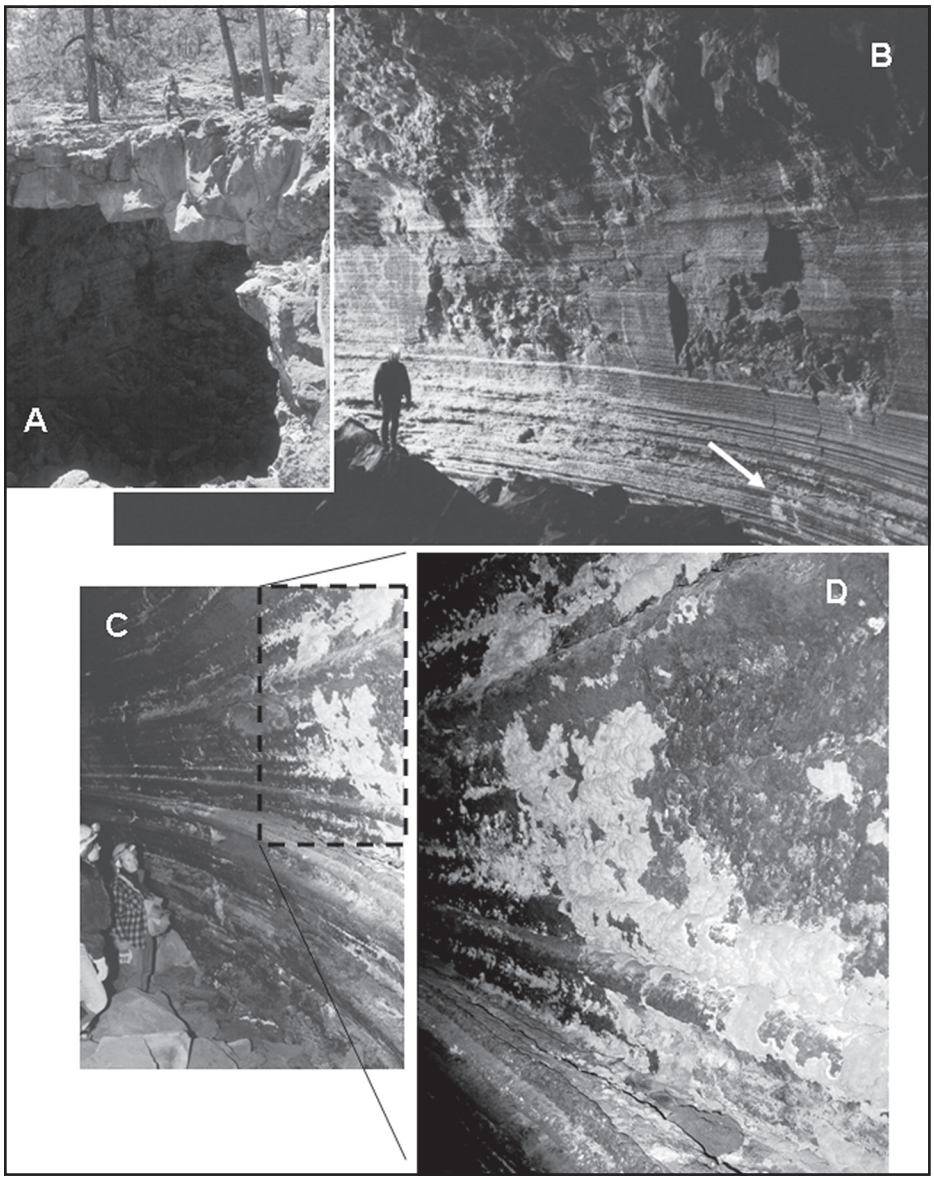

Figure 1: (A) Big Skylight Cave entrance. (B) Lava Grooves and shelves (flow lines) illustrating well-preserved passage walls in Big Skylight Cave. The white arrow points to gypsum crust (site 2). (C,D) Gypsum crust on cave walls in Big Skylight Cave (site 1).

The gypsum crusts were up to 1 cm thick in places, and as thin as 5 mm. Crusts were locally continuous, and showed a rosette texture of crystal terminations on surfaces. Some samples, after collection, showed voids between the basalt surface and gypsum surface. A sample of soil was collected from directly above the entrance of Big Skylight Cave for $^{87}Sr/^{86}Sr$ comparisons.

3. Methods

Gypsum crust samples were lightly powdered and dissolved in 1N HNO_3. This process took 24-48 hours. The gypsum solutions were spiked with a mixed ^{233}U-^{236}U-^{229}Th spike for the U-Th dating and ^{84}Sr spike for Sr concentration determination. U and Th were coprecipitated from the spiked solutions for U-series analyses. All separates were analyzed using a Thermo-Neptune multi-collector ICPMS.

Table 1. Uranium-series data – lava tube gypsum crusts

Sample	^{238}U (ng/g)	^{232}Th (ng/g)	$^{230}Th/^{232}Th$ activity ratio	$^{230}Th/^{238}U$ activity ratio	measured $\delta^{234}U$ (‰)	initial $\delta^{234}U$ (‰)	uncorrected age yr BP	corrected age yr BP	$^{87}Sr/^{86}Sr$
5-7 Ka Group									
BS-2-L	444.35 ±1.1	29.09 ±0.1	3.18 ±0.02	0.068 ±0.0005	17 ±1	17 ±1	7569 ±58	5680 ±942	0.70397
BS-5	749.65 ±2.7	29.37 ±0.1	4.64 ±0.0	0.060 ±0.0005	31 ±4	31 ±4	6492 ±59	5381 ±557	0.70384
BS-3-L	370.65 ±1.5	16.72 ±0.1	4.20 ±0.1	0.062 ±0.0010	14 ±1	14 ±1	6894 ±120	5592 ±660	0.70384
BS-2-U	319.89 ±0.8	53.39 ±0.1	1.96 ±0.02	0.107 ±0.0012	22 ±1	22 ±1	12106 ±150	7249 ±2406	0.70397
9-11 Ka Group									
BS-1-5K-U	434.12 ±1.1	59.37 ±0.1	2.55 ±0.0	0.114 ±0.0007	28 ±2	29 ±2	12855 ±83	8370 ±2221	0.70389
BS 6 – 3	1867.97 ±4.2	40.23 ±0.1	11.97 ±0.1	0.084 ±0.0009	9 ±1	9 ±1	9534 ±113	8911 ±331	0.70395
FW - 1	355.38 ±2.5	29.10 ±0.1	3.81 ±0.2	0.102 ±0.0044	9 ±2	9 ±2	11650 ±537	9263 ±1299	0.70392
BS-1-5K-L	576.25 ±1.4	26.19 ±0.1	6.31 ±0.04	0.094 ±0.0005	13 ±1	13 ±1	10613 ±65	9300 ±658	0.70390
BS-1 2008	1157.87 ±4.4	12.17 ±0.1	24.95 ±0.2	0.086 ±0.0005	9 ±2	9 ±2	9707 ±59	9403 ±163	0.70392
BS 6 – 2	2914.58 ±6.5	61.32 ±0.2	12.88 ±0.1	0.089 ±0.0009	9 ±1	10 ±1	10035 ±109	9427 ±322	0.70391
BS-4	112.76 ±0.4	7.95 ±0.0	4.71 ±0.1	0.109 ±0.0016	28 ±5	29 ±5	12194 ±199	10181 ±1020	0.70388
Soil over Big Skylight Cave									
QC - 1									0.71226

Corrected ages use an initial $^{230}Th/^{232}Th$ atomic ratio = 4.40 ± 2.2 ppm. Years before present = yr BP, where present is AD 2007. All errors are absolute 2σ, $^{87}Sr/^{86}Sr$ are >.001% 1σ. Subsample sizes range from 85 to 105 mg.

Table 1: Uranium series data: lava tube gypsum crusts.

4. Results

Our apparent ages from cave speleothems show a bimodal distribution, with an upper group of 9-10 ka, and a lower group of 5-7 ka (Table 1). For the initial Big Skylight samples with sufficient thickness, top and bottom age profiles of the crusts were also analyzed yielding the same ages within error. $\delta^{234}U$ values range between +9 and +30. $^{87}Sr/^{86}Sr$ isotope ratios are tightly clustered between 0.703659 - 0.7039974 with Sr concentrations ranging from 300 to 1400 ppm, with the exception of sample FW-1, which was has anomalously low Sr abundance. Our soil $^{87}Sr/^{86}Sr$ value is 0.712255 ± .00076% (1σ). Cosmogenic ages (Table 2) are from Dunbar and Phillips (2004), and McLaughlin (1994). $^{40}Ar/^{39}Ar$ ages are from McIntosh (1994).

5. Discussion

The age of the Bandera basalt flow is established by multiple methods to be 9-12 ka (Dunbar and Phillips (2004). Given that our gypsum crusts are speleogenetic (having formed as a product of the cave's origin), then they should yield U-series ages within the same age range as the other methods. Our results show a bimodal distribution of ages with the younger being about half the reported age and the older representing an age close to the expected age. The bimodal distribution of

Table 2. Bandera Flow Ages

Dating System	Apparent Age (Calendar y.b.p)
U-series of gypsum 5- 7 ka group	5549 ±380
U-series of gypsum 9-11 ka group	9936 ±330
[1] ^{3}He	11200 ±1100
[2] ^{36}Cl	11200 ±600
[1] ^{14}C	10700 -12500
[3] $^{40}Ar/^{39}Ar$	41000 ±7000

U/Th ages are weighted averages. Y.b.p = years before present

[1] from McLaughlin, 1994

[2] from Dunbar and Phillips, 2004

[3] from McIntosh, 1994. Excessively old ages are thought to be contamination from atmospheric ^{40}Ar (Dunbar and Phillips, 2004)

Table 2. Bandera flow ages.

ages forces the question of – are these indeed speleogenetic or are they speleothemic crusts? Field observations and isotopic analyses provide additional insights.

Speleothems in the lava tube caves of El Malpais National Monument are opalline and calcitic coralloids, crusts, and moonmilk. With the exception of some occurrences of calcite moonmilk, all speleothems in these caves seem to be significantly thinner and smaller than the gypsum crusts. The gypsum crusts are relatively thick in comparison and seem to have no obvious secondary origin. For instance, coralloids form readily from condensates and sprays which are observed in these caves today. The calcite moonmilk deposits are also located in areas where condensates occur. But the gypsum crusts seem to be located in areas where secondary deposits are absent or rare. They are also located on original tube surfaces, and not found on breakdown.

The gypsum crusts, if formed by final volcanic activity related to the lava tube, should have inherited isotopic signatures similar to the basalt/volcanic gases. $\delta^{234}U$ values of the crust are low (9-30 ‰), and while higher than the basalt (0 ‰), they are still reasonably low enough to have formed from the volcanic gases associated with the origin of the lava tube. The $\delta^{234}U$ values for coralloids and moonmilk are respectably higher (~133-226 ‰, LaPointe personal communication). $^{87}Sr/^{86}Sr$ isotope measurements for the gypsum crust (0.703659 - 0.7039974) also match the published Bandera basalt values of 0.703667 (Asmerom, 1999), and differ significantly from the soil (0.712255, our value for soil above Big Skylight Cave; 0.71066-0.7122, Van der Hoven and Quade (2002)). The U isotope ratios and Sr isotope ratios of the gypsum and Bandera basalt are similar enough to explain their origin from a magmatic source rather than from surrounding pedogenic soils. Slight differences may be due to inheritance of groundwater signatures of the surrounding basalt, but given the young age of the lava flow and the thickness of the sample sizes as well as the consistency in ages from the upper and lower samples, we find it unlikely that secondary deposition would be possible to deposit a sufficiently thick gypsum crust in the allotted time, especially since top and bottom subsamples of the crusts are the same age. Furthermore, no gypsum crusts have been observed on broken lava ceiling surfaces, suggesting one depositional event.

The variation in ages is attributed to secondary alteration, which gypsum is highly susceptible to, or to later anhydrite-to-gypsum transition. Current research is on identification of alteration signatures, with emphasis on the stable isotopes of S. Other possible explanations for the bimodal cluster of ages include a subsequent pulse of volcanic activity around 5 ka, consistent with the McCarty's flow in the Zuni-Bandera volcanic field. However, the McCarty's flow uses a different vent system entirely, and the Bandera flow tube system is heavily segmented with no indication of subsequent pulses of volcanism. Also, preservation of two stages of gypsum crusts is highly unlikely. Our field observations and geochemical results show that the gypsum is not a secondary deposit (speleothem) and support that it is speleogenetic. We interpret our highest ages to represent the age of the gypsum crust emplacement and timing of the end of Bandera volcanic activity.

6. Conclusion

The recent recognition of deposition of primary igneous sulfates has provided an opportunity to use U/Th disequilibrium techniques as a way to determine meaningful ages of quaternary volcanism. Isotopic signatures of the gypsum crust samples from the Bandera flow indicate a magmatic source, while apparent ages agree with previously published cosmogenic exposure ages as well as underlying charcoal ^{14}C. Due to the unstable nature of gypsum or early anhydrite-to-gypsum transitions, analyses of multiple samples increase reliability of apparent ages. Application of gypsum crust dating may be applied to other lava tube systems once the system is better understood.

Acknowledgments

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MEDICAL AND GOVERNMENTAL CONSIDERATIONS OF CO_2 AND O_2 IN VOLCANIC CAVES

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Occurrences of hypercarbia in carbonate caves are well comprehended in most of the global speleological community. In some volcanic caves, a different scenario also must be considered: simple addition of magmatic CO_2 to ambient air. In this scenario, hypoxia plays a minimal role, if any. In others, simple percent for percent replacement of O_2 by CO_2 may occur, just as in carbonate caves. In addition, other toxic gases of magmatic origin may exist in volcanic caves, but their toxic manifestations are easily detected clinically.

Basic investigations of separate effects of various levels of hypoxia and of hypercarbia were conducted so long ago that they cannot readily be retrieved electronically. Medical textbooks of the mid-20th Century summarized such studies in volunteer healthy adult males. At approximately 4% atmospheric CO_2. breathing is alarmingly increased, with the limit of tolerance in highly motivated test subjects between 7 and 9%. Eventual unconsciousness occurs at 10–12%. No such early warning sign exists for hypoxia; even reduction of O_2 to 10% (which is lethal eventually) causes only a slight increase in breathing. Such textbook summaries, however, fail to emphasize the wide individual human variations in response to hypoxia and to hypercarbia clearly specified in the original reports.

Congress assigned a politically charming but technically impossible task to the Occupational Safety and Health Administration (OSHA): setting standards which would provide safe work places for all American workers - young and old alike, and both healthy and terminally ill cigarette smokers. OSHA chose to set standards that would protect most workers in most workplaces, with selective enforcement. This allows volcanologists to run great risks on volcanoes, for example. Inevitably, its standard for CO_2 responded to anxiety produced by breathing a mere 4% CO_2 and its impact on workers, their union shop stewards, the general public and even concerned employers. A wide safety margin was included to protect aged workers and those with breathing impairments. This likely included some with a financial stake in maximizing their symptoms. Further, OSHA determinations were developed to apply to closed work spaces much like the scenario seen in carbonate caves, where hypercarbia gives the alarm but hypoxia kills. Thus, OSHA standards probably bear little resemblance to medical principles in healthy, highly motivated volunteers in volcanic caves. While the promulgated figures vary slightly from country to country, this pattern exists broadly across developed, socially conscious nations.

This issue surfaced in 1990 when Howarth and Stone found a notable ecosystem in a cave with 6% CO_2 (60,000 ppm) and 15% O_2, and recommended that fellow biospeleologists seek similar caves for comparative studies. However, working in such environments runs contrary to law and OSHA regulations. The issue resurfaced when the U.S. Geological Survey and National Park Service administrators of two national parks applied OSHA standards to volunteers in volcanic caves with nontoxic levels of O_2 and CO_2. However, medical research suggests that establishing minimum blood saturation limits and using portable oximeters would provide more effective protection than applying OSHA standards and requiring CO_2 detectors while working in volcanic caves.

1. Hypercarbia and Hypoxia in Closed Spaces

Occurrences of hypercarbia in carbonate caves are well comprehended in most of the global speleological community. In some parts of Australia, cavers encounter 8% CO_2 and sometimes more. In such caves, simple percent for percent replacement of O_2 by CO_2 occurs. The same

effect exists in closed work spaces, and OSHA has set exposure limits to protect American workers. With some minimal variations, similar standards exist broadly across developed, socially conscious nations. Two other American regulatory agencies also have promulgated such standards: the Environmental Protection Agency (EPA) and National Institute for Occupational Safety and Health (NIOSH). In the past, the OSHA standards were difficult to access electronically, and statements by manufacturers of gas monitors were commonly consulted. Some manufacturers have restated the OSHA standards to conform to the inherent capabilities of their particular devices but some others (e.g., InspectAPedia) provide independent information.

OSHA currently permits a maximum concentration of 1% CO_2 (10,000 ppm) for a ten hour work shift and a maximum of 3% (30,000 ppm) for any ten minute period (OSHA 2008). Also, it promulgated a minimum O_2 level of 19.5%, which would mean a maximum CO_2 of 1.4%. In contrast, EPA recommends a maximum concentration of 0.1% CO_2 for continuous exposure (InspectAPedia, 2009).

All these maxima and minima correlate poorly with basic medical investigations of various levels of hypoxia and hypercarbia. Basic research on separate effects of various levels of hypoxia and hypercarbia was conducted so long ago that it cannot be readily retrieved electronically. At approximately 4% atmospheric CO_2, breathing becomes alarmingly increased, but the limit of tolerance in highly motivated, healthy young test subjects was found between 7 and 9% (Sollman, 1942). Eventual unconsciousness is reached at 10 to 12%. No such early warning sign exists for hypoxia. Even reduction of O_2 to 10% (which is lethal eventually) causes only a slight increase in breathing. Early basic studies also noted wide individual human variations in responses. This is sometimes ignored in later restatements.

2. Hypercarbia and Hypoxia in Volcanic Caves

A more benign scenario is encountered in some (but not all) volcanic caves with hypercarbia. Some lava tube caves (e.g., the Undara system, Queensland, Australia) are overtopped with such impermeable layers of rock or soil that they function as closed spaces like those commonly encountered in karstic terrains. At the other extreme, many caves in the flows of Kilauea volcano, Hawaii, USA, are within flows with plentiful connections to extratubal spaces and to the surface. Winds blow through even single-entrance caves in such flows, and reverse abruptly with little lag time from the surface. Yet such caves are permeable to magmatic CO_2. This may produce a significantly different scenario of additive hypercarbia, quite different from the replacement hypercarbia characteristic of closed work spaces and karstic caverns (Table 1). For example, cave air containing 6% CO_2 also contains 19.5% O_2, which is an insignificant decrease. Anyone slowly dying from a CO_2 concentration of 10% in such caves still has plenty of oxygen.

This issue surfaced in 1990 when Howarth and Stone (1990) found a notable ecosystem in a volcanic cave with

ADDITIVE HYPERCARBIA AND HYPOXIA IN THE VOLCANIC CAVE ATMOSPHERE

Total CO_2 concentration in Cave atmosphere	Total O_2 concentration in cave atmosphere	Total RF concentration in cave atmosphere
1%	**20.75%**	78.25%
2%	**20.50%**	77.50%
3%	**20.25%**	76.75%
4%	**20.00%**	76.00%
5%	**19.75%**	75.25%
6%	**19.50%**	74.50%
10%	**18.50%**	71.50%
24%	**15.00%**	61.00%

Source: Smith, Garry K. 1997. Naked flame tests for CO2 in limestone caves and the effect of CO_2 and O_2 on humans. Papers, 1997 Australian Speleological Federation Conference. Quorn, South Australia, pp 40-52.

Table 1: Additive hypercarbia and hypoxia in the volcanic cave atmosphere.

6% CO_2 and 15% O_2 and recommended that fellow biospeleologists seek similar caves for comparative studies. Medical principles indicate that, for healthy volunteers not subject to OSHA constraints, this would be an unpleasant experience but within functional limits. For persons conducting such studies in the course of employment, however, it would be unlawful. The issue resurfaced when US Geological Survey and National Park Service personnel applied OSHA standards to volunteers in volcanic caves with non-standard levels of O_2 and CO_2.

3. Application of OSHA and EPA Standards to Investigators in Volcanic Caves

The intention of the U.S. Congress in creating OSHA was to provide safe work places for all American workers; young and old, healthy and terminally ill alike. This was a politically charming but technically impossible task. OSHA chose to set standards that would protect most workers in most work places, most of the time. Selective enforcement is inherent in the process. Without flexibility, volcanologists would be barred from risky field studies on active volcanoes, for example. Inevitably, OSHA's standard for CO_2 responded to the anxiety produced by breathing a mere 4% CO_2 and its impact on frightened workers, their union shop stewards, the general public and even concerned employers. A wide safety margin was included to protect aged workers and those with breathing impairments. This likely included some with a financial stake in maximizing their symptoms. Thus, these standards have little relevance to speleologists and other investigators – especially volunteer investigators. Basic medical data cited above suggest that establishing minimum blood saturation limits and using portable oximeters would provide more effective protection than blindly applying OSHA standards and requiring CO_2 detectors in well-aerated volcanic caves, especially in caves where investigators undergo no significant increase in respiration.

Acknowledgment

Australian caver Garry K. Smith is the originator of the concept of two scenarios for increased CO_2 in caves.

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A STEEPLY INCLINED PLIOCENE (?) LAVA TUBE CAVE IN DEATH VALLEY NATIONAL PARK, CALIFORNIA

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Gneiss Cave is a misnamed ancient lava tube cave which opens on a cliff in the northwest end of the Mormon Point Turtleback of Death Valley National Park. While small, it is especially significant because of its location in a fault-bounded block of basalt of uncertain but clearly pre-Pleistocene age. Several geologists have mapped this area, with notably different interpretations. One of these maps shows the cave area as gneiss, hence the name of the cave. It is entered through a comparatively spacious chamber which opens widely on the cliff face. From it, a tubular passage about 1 m in diameter extends upward at about 45° for a total length of 11.7 m. It is notable for a dusty sheet of banded brown flowstone about 2.5 cm thick which does not react to acid. A pathognomonic central ridge of cauliflower lava extends along the floor of the tubular section of the cave and the upper part of the entrance chamber.

Other documented lava tube caves of pre-Pleistocene age are (1) Pahihi Gulch Cave, Maui Island, Hawaii, USA, and (2) an apparently unnamed lava tube cave on the Pacific Island of Truk, reported by Rogers and Legge. One or more ill-defined caves in Pliocene basalt in Colorado (USA) and some small lava tube caves opening on a cliff in Jalisco, Mexico, are under study. Three well-known, heavily marine-eroded horizontal caves near sea level on the Hawaiian island of Kauai also may qualify.

1. Location and History of Gneiss Cave

The entrance room of mis-named Gneiss Cave is easily seen by visitors driving on California State Highway 178 just south of Mormon Point in Death Valley National Park, about 30 m above the highway (Figs. 1, 2). Because the scramble to it is steep and rubbly, it has had few visitors and is free of graffiti and trash. It was named Gneiss Cave because a geological map showed the bedrock surrounding the cave to be gneiss. When the junior author was transferred to Death Valley National Park in 2005, he became confident that it is not in gneiss. But, he was unable to classify the surrounding bedrock or the cave itself. In 2007, the senior author joined him in a further study of the cave (Halliday, 2008) (Fig. 3). Because of the presence of a central longitudinal ridge of cauliflower lava (Larson, 1993) extending nearly the entirety of the length of its floor (Fig. 4), it now is considered a lava tube cave, the only example identified in this national park. An accreted tube lining

Figure 1: About 30 m above a state highway and salt pan, the entrance of Gneiss Cave is in a fault-demarcated block of mafic rock, presumably basalt or metabasalt. With a hand lens, an accreted tube lining is easily seen.

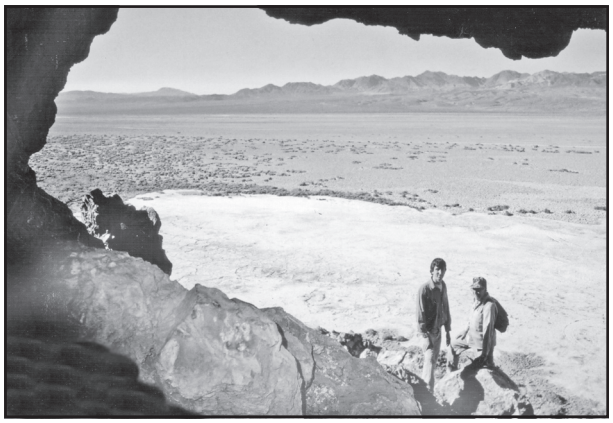

Figure 2: Looking back down from the entrance to the salt plan on the floor of Death Valley.

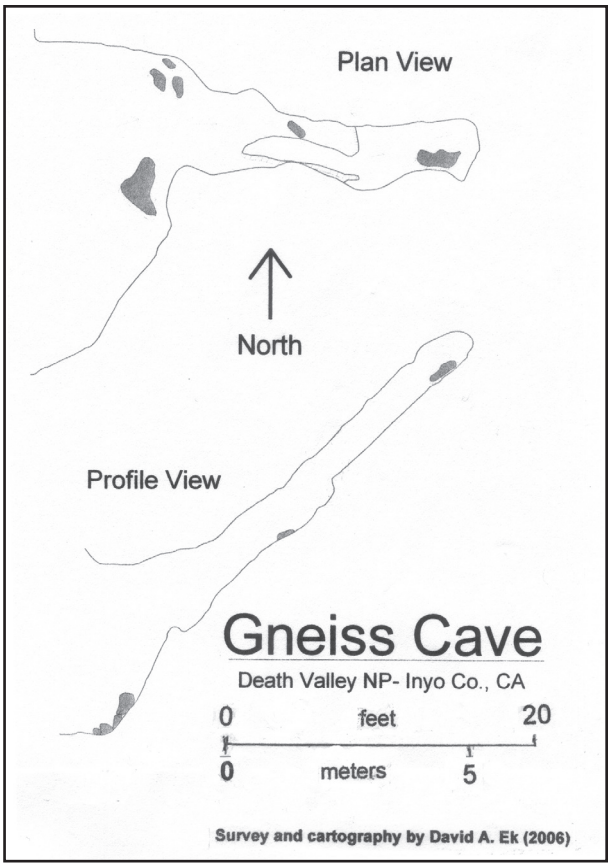

Figure 3:. Map of Gneiss Cave.

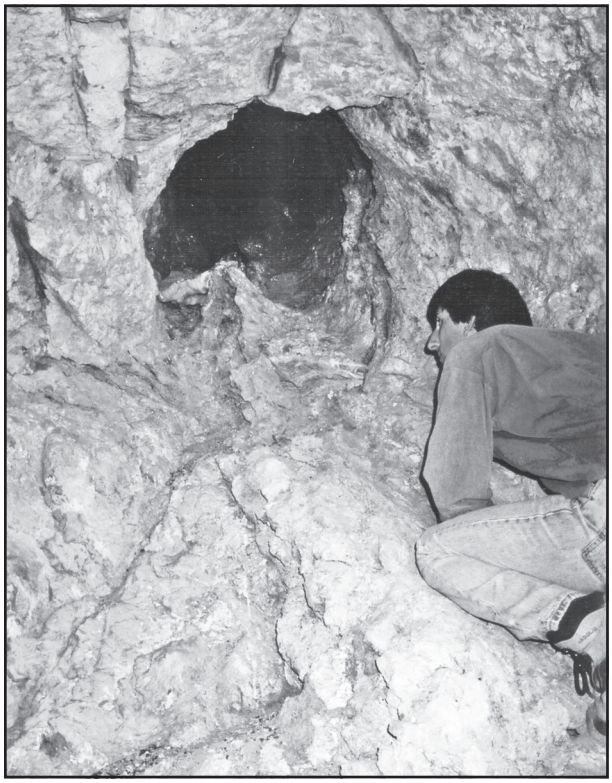

Figure 4: A central longitudinal ridge of cauliflower lava extends down the tubular passage and into the entrance room.

several centimeters thick also is present.

2. Features of Gneiss Cave

This is not a large cave. The comparatively spacious entrance room (Fig. 5) is no more than 7 m wide and about 3 m long, with a ceiling height of about 2 m. From it, a tube-shaped passage extends upward at an angle of 45° to a tapered end 11.7 m from the drip line. The upper section contains a sheet of banded brown flowstone (Fig. 6) which does not effervesce with acid. It is 1 to 2 cm thick and partially covers the longitudinal ridge and a now-eroded space alongside the ridge. It closely resembles banded siliceous flowstone and dripstone seen in some lava tube caves of southwestern Washington State. Plentiful rodent and bird droppings are present, and a little amberat.

Figure 5: Looking diagonally across the entrance room to the lower end of the tubular passage.

3. Geology of the Area of Gneiss Cave

The geology of the cave area is unusually complex, and the age of the cave will be difficult to determine conclusively. Several geologists have mapped the area, with notably different interpretations (e.g., Otton, 1974; Wright et al., 1974, Gregory and Baldwin, 1988). Everyone agrees that it is on the northwest end of the Mormon Point Turtleback, but even the definition of "turtleback" is less than fully agreed upon. The AGI Glossary of Geology (Jackson, 1997: 684) defines the term as "an extensive smooth curved topographic surface, apparently unique to the Death Valley (Calif.) region that resembles the carapace of a turtle or a large elongate dome with an amplitude up to a few thousand meters". Wright et al. (1979) consider them to be "colossal fault mullions" resulting from severe crustal extension localized along undulating, northwest-plunging zones of pre-existing weakness coinciding with anticlinal folds in Precambrian metasediments. From the western foot of the turtleback, the cave appears to be in an unmapped gully-filling basalt flow plunging steeply down

Figure 6: Sheet of banded brown flowstone which does not react to acid, located near the top of the tubular passage. The length of the pocket comb used for scale is 115 centimeters.

the Black Mountains, but this is something of an optical illusion. From a greater distance, it is seen to open on the near-vertical side of the turtleback in the lowest of several fault-demarcated blocks of basalt or metabasalt (Fig. 7). The intricate faulting in this vicinity is especially well-described in Wright et al. (1974). The basalt or metabasalt may be part of the mid-Pliocene Furnace Creek Formation (McAllister, 1970) or a local basalt member of the Pliocene Furnace Formation exposed a few kilometers farther north (Gregory and Baldwin, 1988). The possibility of much greater age cannot be ruled out. Its lithology and relationship to other bedrock differs markedly from that of Cenozoic basalt seen on Recent surfaces nearby and it is clearly pre-Pleistocene.

4. Other Pre-Pleistocene Lava Tube Caves

Gneiss Cave is a member of a very small group of recorded pre-Pleistocene lava tube caves. These include (1) Pahihi Gulch Cave on the island of Maui, Hawaii, shown on the Stearns and Macdonald (1942) map of Maui as being within Tertiary lava, an apparently unnamed lava tube cave on the

Figure 7: The northwest end of Death Valley's Mormon Point Turtleback, with the Black Mountains in the background. Large and small blocks of mafic rock are clearly seen. Gneiss Cave is just above the valley floor near the center of the photograph.

Pacific island of Truk (Rogers and Legge, 1985) and perhaps three well-known horizontal caves near sea level near Haena, Kauai Island, Hawaii, which are heavily marine-eroded (Halliday 1981). Recently, several ill-defined caves have been reported in Pliocene basalt in Colorado, USA (Medville and Medville 2008). At least one probably is a remnant of lava tube. In Jalisco, Mexico, several small lava tube caves open in a bluff of uncertain age (John Pint, e-mail communications, 2008–2009).

If Gneiss Cave is in metabasalt, it is the first lava tube cave to be identified in this rock. Despite reports to the contrary, (e.g. Alexander, 1980: 78), no lava tube cave has been found in 1.1Ga metabasalt that are notable for other, remarkably preserved pahoehoe features on the north shore of Lake Superior (John C. Green, written communication, 2008). Consequently, this small cave merits especially intensive additional studies.

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MINERAL-LINED THERMAL EROSION CHANNELS IN A HOLLOW TUMULUS COMPLEX, KILAUEA CALDERA, HAWAII, USA

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Sharply incised dendritic channels up to several centimeters in depth and width were found in the sloping floor of a chamber of Fractured Tumulus Cave, a cavernous hollow tumulus complex in Kilauea Caldera, Hawaii Island, USA. Much of these channels is lined with a silvery, iridescent optically active mineral or minerals. While the occurrence of thermal erosion now is widely accepted, these may be the first recorded examples of small-scale eroded channels in a cave. Very low concentrations of Na_2O and K_2O indicate that their linings and thence the lava in which they are incised are early eruption products. Backscatter and other commercial electron microscopy revealed six groups of oxides in one of the linings. Group 1 may be a magnesiocuprous ferrite. The oxide in Group 2 is primarily Fe_2O_3. Group 3 apparently is a complex oxide such as $TiFe_2O_5$. Group 4 appears to be ilmenite. Group 5 may be a titanomagnetite and Group 6 is a pyroxene.

1. Introduction

Hollow tumulus caves are a comparatively uncommon volcanic landform but several examples exist in the 1919 Postal Rift lava flow in Kilauea Caldera (Fig. 1). They perhaps were first described by James Dana (1891). In the United States, other examples exist in Idaho (e.g., Abo Dome) and presumably elsewhere. The Postal Rift lava flow is located directly below the Hawaiian Volcano Observatory of the U.S. Geological Survey and probably is the most-studied part of the floor of Kilauea Caldera. As discussed in a companion paper (Halliday, this volume), the Hawaii Speleological Survey has identified a total of about 250 rheogenic caves in this flow. Some are complexes containing more than one hollow tumulus. Fractured Tumulus Cave is a comparatively large example of hollow tumulus complex. It consists of two hollow tumuli with a subterranean crawlway connection through stable breakdown (Fig. 2). Its entrance room is unusually large for this type of cave (Figs. 2, 3) but the notable features in this study are in the smaller inner chamber.

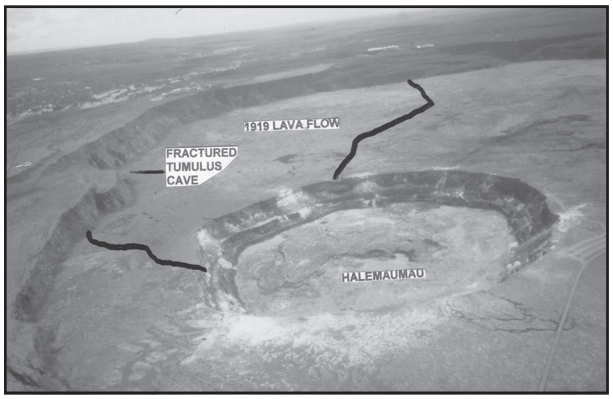

Figure 1: Aerial view of Kilauea Caldera looking north. The 1919 "Postal Rift" lava flow is on the left (west) beyond the large inner pit.

Figure 2: The entrance room of Fractured Tumulus Cave is nearly 30 meters wide. The inner room is much narrower, and its floor slopes at about 20 degrees.

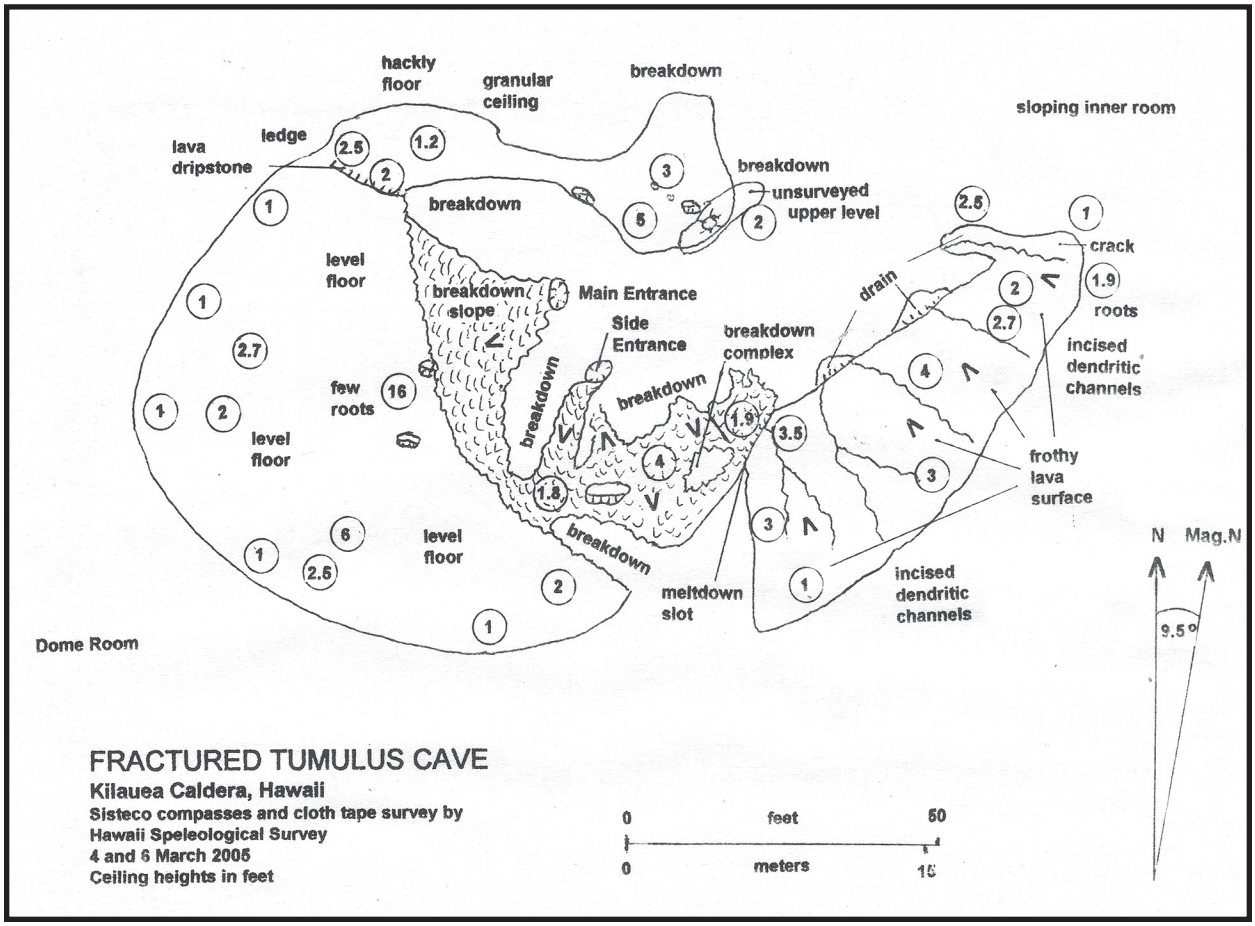

Figure 3: Map of Hollow Tumulus Cave. The inner room containing the incised channels is reached by crawling through stable breakdown.

2. Thermal Erosion Channels in Fractured Tumulus Cave

To date, Fractured Tumulus Cave is unique in Kilauea Caldera in that it contains dendritic thermal erosion channels up to several centimeters in depth and width (Figures 2, 4). These channels are sharply incised into the sloping floor of the chamber within the smaller of the two tumuli. While the general concept of thermal erosion now is widely accepted, this may be the first recorded example of small-scale thermally eroded channels in a cave. They are especially notable for linings of silvery, iridescent and optically active mineral or minerals (Fig. 5). This silvery material also formed flowstone and crack fillings, and small ponds. It resembles fragments up to 1 cm thick observed as float in a breakdown area of Jonathan's Cave, Puna District, Hawaii, not yet studied Very low concentrations of Na_2O and K_2O indicate that these linings and thence the lava in which they are incised are early eruption products (Scott Cornelius, e-mail communication, 2007).

3. Procedures and Findings

Under a National Park Service research permit which required on-site supervision by Don Swanson of the US Geological Survey, small examples were collected for study. Using a binocular microscope, Swanson subsequently identified platy surface minerals as magnesioferrite and titanomagnetite (Don Swanson, oral communication, 2007). Commercial electron backscatter (BSE) and reflected light microscopy at Washington State University identified six groups of oxides in the channel lining (Scott Cornelius, e-mail communication, 2007):

Group 1. "The mineral contains major Cu, and may be a magnesio-cuprous ferrite." It should be noted that small quantities of copper minerals have been found as dripstone in other caves in Kilauea Caldera and elsewhere in Hawaii.

Group 2. "The oxide is primarily Fe_2O_3".

Group 3. "For the formula, five oxygens seemed to work best, as in $TiFe_2O_3$."

Group 4: "..appears to be ilmenite."

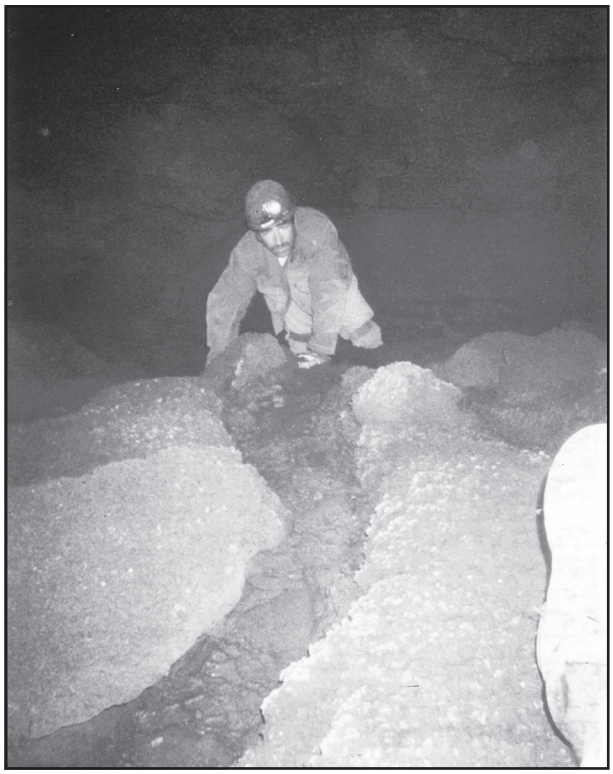

Figure 4: Looking down one of the incised channels of the inner room. The brown object on the lower right is my boot. Note that with illumination at this angle, the silvery, optically active lining of the channel appears tan. In less oblique light it appears nearly indigo.

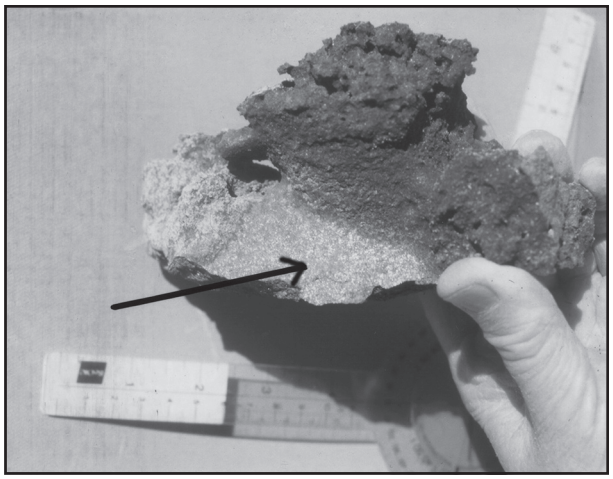

Figure 5: The specimen analyzed is marked by an arrow. In direct light it appears silvery and iridescent.

Group 5: "..may be a titanomagnetite."

Group 6: "..a pyroxene, the location of which is off the photos."

Numerical data substantiating these conclusions are presented in Tables 1 and 2, and the tested loci are shown in Figures 6 to 10. Color renditions of these figures will be supplied by e-mail upon request.

	Na For	Mg For	Al Forn	Si Forn	Fe Forn	Mn For	Ti Forn	K Forn	Ca Forn	Ni Forn	Cr Forn	Cu Forn	Totals
group 1	ions based on 4 oxygens												
Un 143, 1 of 2	0.004	0.562	0.042	0.002	1.959	0.066	0.005	-0.001	0.006	0.001	0.000	0.349	6.994
Un 143, 2 of 2	0.014	0.578	0.041	0.000	1.943	0.068	0.006	0.000	0.004	0.001	0.000	0.354	7.009
Un 148	0.008	0.555	0.055	0.002	1.946	0.072	0.004	0.000	0.005	0.000	0.000	0.352	6.998
group 2	ions based on 3 oxygens												
Un 144	-0.002	0.024	0.014	0.000	1.932	0.006	0.025	-0.002	0.002	-0.001	0.000	0.001	5.000
Un 145	0.000	0.155	0.030	0.001	1.478	0.008	0.285	0.000	0.001	0.000	0.001	0.001	4.959
Un 146	0.015	0.118	0.040	0.027	1.621	0.014	0.141	0.001	0.007	0.001	0.000	0.023	5.009
Un 149	-0.003	0.015	0.025	0.002	1.925	0.005	0.026	-0.001	0.000	0.000	0.000	0.002	4.996
Un 150	-0.001	0.110	0.020	0.000	1.706	0.013	0.139	0.000	0.003	0.001	0.000	0.008	4.998
group 3	ions based on 5 oxygens												
Un 151, 1 of 3	0.009	0.195	0.098	0.069	1.457	0.010	1.152	0.001	0.011	-0.001	0.001	0.002	8.006
Un 151, 2 of 3	0.002	0.160	0.059	0.011	1.665	0.010	1.101	0.000	0.016	0.000	0.001	0.005	8.028
Un 151, 3 of 3	-0.003	0.160	0.058	0.001	1.626	0.010	1.145	-0.004	0.015	-0.001	0.002	0.000	8.008
group 4	ions based on 3 oxygens												
Un 101	0.001	0.14	0.03	0.008	0.828	0.007	0.983	0.002	0.002				4.998
group 5	ions based on 4 oxygens												
Un 102	0.001	0.12	0.01	0.007	1.339	0.022	0.525	0.001	0.001				5.019
group 6 - no phot	ions based on 6 oxygens												
Un 147 pyx	0.035	0.780	0.135	1.869	0.393	0.009	0.052	0.000	0.754	0.000	0.001	0.000	10.028

Table 1: WWU ion analysis of selected study points.

	Line I	Na2O	MgO C	Al2O3 C	SiO2 O>	Fe2O3 (	MnO O>	TiO2 O>	K2O Ox	CaO Ox	NiO Oxi	Cr2O3 (	Cu2O C	Oxide T
group 1		probe results - oxide weight percent												
Un 143, 1 of 2	2556	0.06	10.33	0.98	0.05	71.29	2.14	0.18	-0.03	0.14	0.04	0.01	12.65	97.84
Un 143, 2 of 2	2557	0.19	10.65	0.95	0.01	70.98	2.21	0.20	0.00	0.11	0.04	0.01	12.88	98.25
Un 148	2562	0.12	10.28	1.29	0.04	71.41	2.34	0.14	0.00	0.13	0.02	0.00	12.86	98.62
group 2						Fe2O3								
Un 144	2558	-0.04	0.60	0.44	0.02	96.65	0.25	1.25	-0.05	0.05	-0.03	0.00	0.07	99.23
Un 145	2559	0.00	4.16	1.03	0.02	78.88	0.39	15.23	0.00	0.03	0.01	0.03	0.03	99.81
Un 146	2560	0.30	3.09	1.33	1.07	84.07	0.66	7.33	0.02	0.27	0.04	0.01	1.18	99.37
Un 149	2563	-0.05	0.38	0.81	0.06	96.26	0.24	1.28	-0.03	0.01	-0.02	0.01	0.08	99.04
Un 150	2564	-0.03	2.83	0.64	-0.01	86.76	0.60	7.06	-0.01	0.09	0.02	-0.01	0.40	98.36
group 3						Fe2O3								
Un 151, 1 of 3	2565	0.13	3.41	2.16	1.80	50.38	0.30	39.87	0.03	0.28	-0.03	0.04	0.07	98.43
Un 151, 2 of 3	2566	0.03	2.70	1.26	0.27	55.87	0.29	36.97	-0.01	0.38	0.01	0.02	0.17	97.95
Un 151, 3 of 3	2567	-0.04	2.70	1.23	0.03	54.44	0.29	38.35	-0.07	0.36	-0.03	0.06	0.02	97.34
group 4						FeO								
Un 101	204	0.02	3.73	0.88	0.30	38.88	0.30	51.34	0.05	0.07				95.57
group 5						Fe3O4								
Un 102	205	0.02	3.12	0.24	0.27	68.10	1.01	27.65	0.02	0.04				100.47
group 6 - no photo location						FeO								
Un 147 pyx .	2561	0.48	13.77	3.02	49.21	12.37	0.28	1.83	0.00	18.54	0.00	0.02	-0.01	99.503

Table 2: WWU oxide analysis of selected study points.

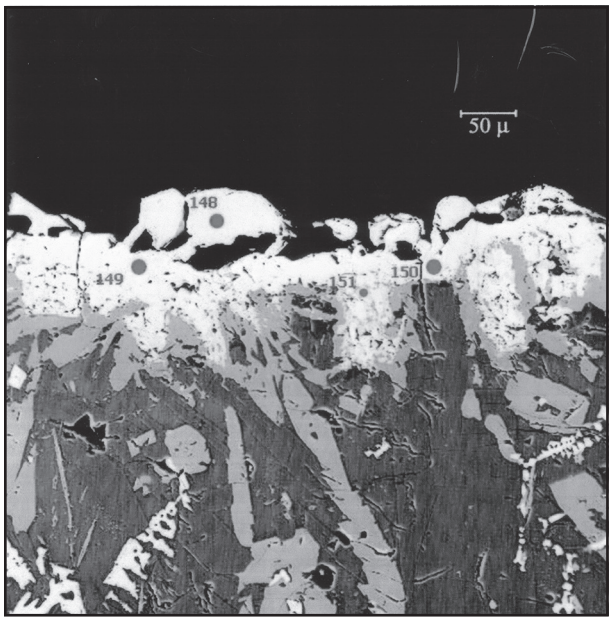

Figure 6: Back scatter electron microphotograph (BSE) of lining shown in Figure 5. Numbers refer to analysis sites listed in Tables 1 and 2. Electron microscopy by Scott Cornelius, Washington State University (WWU).

Cornelius noted that for these oxides, reflected light microscopy "in some ways" seems better than BSE. He explained that the contrast in BSE is due to differences in the average atomic number of the phases present. The data are on a thermal scale, "with brighter colors (yellow to white) representing phases with the highest average atomic number." "The light brown are mostly or all pyroxenes, olivines or other ferro silicates. The dark brown

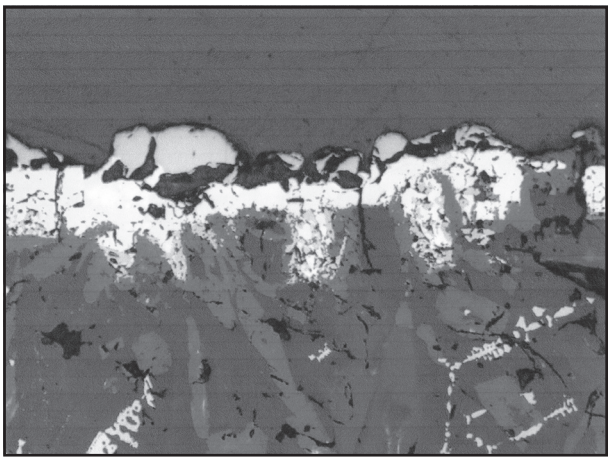

Figure 7: Same as Figure 6, by reflected light.

are undifferentiated feldspar and glass. The black is epoxy mounting medium."

4. Optical Properties

The unusual optical properties of this lining were not studied. Depending on the angle of illumination, it appears silvery, tan, or indigo.

5. Conclusions

Data presented here demonstrate that Fractured Tumulus Cave contains mineralogical and other features not found in other caves in the Postal Rift lava flow. Further study is strongly indicated.

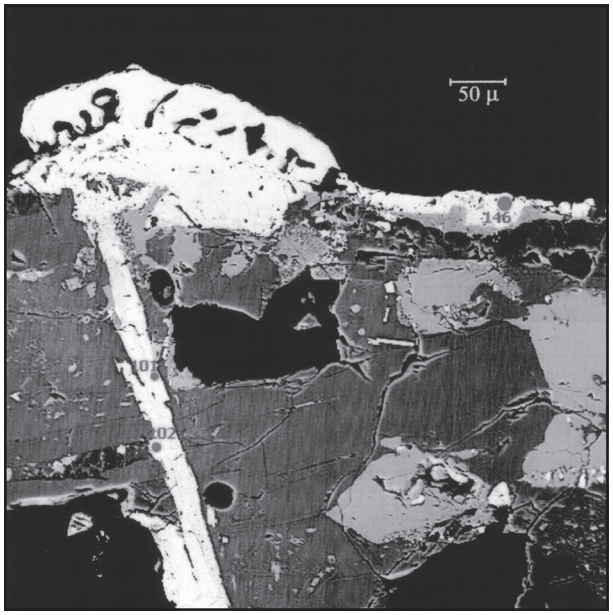

Figure 8: BSE of another section of lining shown in Figure 5.

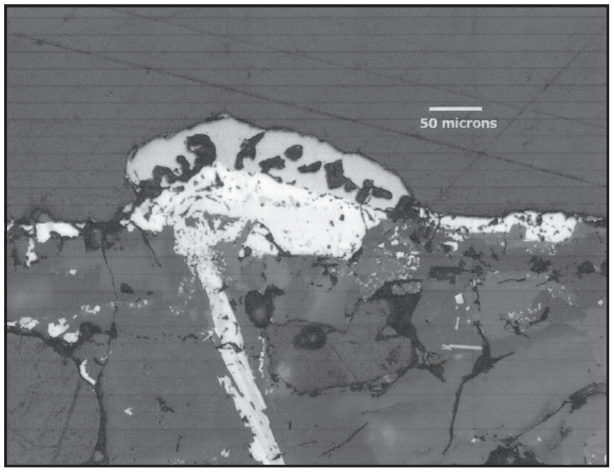

Figure 9:. Same as Figure 8, by reflected light.

Acknowledgments

My profound thanks to Don Swanson of the U.S. Geological Survey for invaluable field assistance and laboratory studies, to Harry Shick for notable field assistance, to Scott Cornelius of Washington State University for going beyond the call of duty in analyzing the specimen, and to Jim Martin, former Superintendent of Hawaii Volcanoes National Park for encouraging the Hawaii Speleological Survey to conduct studies in Kilauea Caldera. All work described here was self-funded.

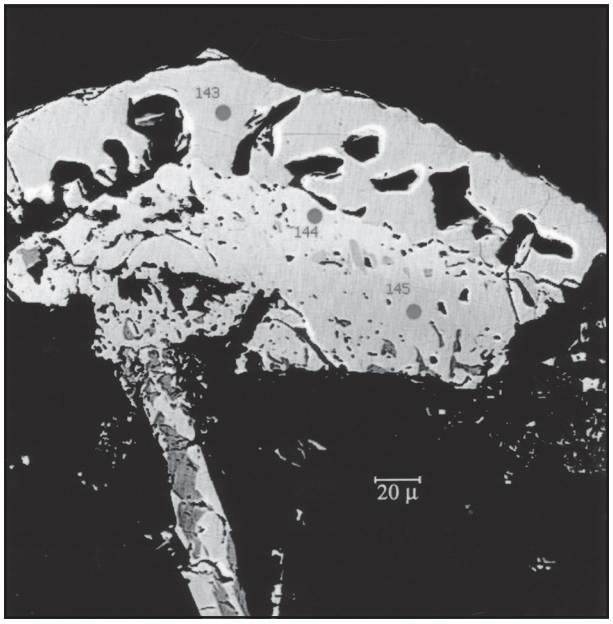

Figure 10: Enlargement of section of Figure 8.

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Halliday, William R. (this volume) Unusual rheogenic caves of the 1919 "Postal Rift" lava flow, Kilauea Caldera, Hawaii.

UNUSUAL RHEOGENIC CAVES OF THE 1919 "POSTAL RIFT" LAVA FLOW, KILAUEA CALDERA, HAWAII

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In follow up of a 1991 study by George P. L. Walker of the surface of a small part of the 1919 "Postal Rift" lava flow in Kilauea Caldera, Hawaii Speleological Survey teams studied the entire 1919 flow. Walker described and discussed "'tumuli, 'lava rises,' 'lava rise pits,' and 'lava inflation clefts.'" He described and depicted one hollow tumulus and noted the presence of one subcrustal grotto in a lava rise. In our intermittent 12-year study of the entire flow, Hawaii Speleological Survey teams identified and studied approximately 250 rheogenic caves and a few crevice caves. Most of the rheogenic caves are shallow cavities drained after subcrustal injection of lava rather than classical lava tube conduit caves: flow lobe caves, lava rise caves, hollow tumuli and the like. Only two lengthy lava tube caves were identified, and one of these shares morphological characteristics with some hollow tumuli. In and near Walker's study area, we identified and mapped (1) a second hollow tumulus with a sizeable "melthole" connection to the one identified and mapped by Walker, (2) a complex circumferential cave in the perimeter ridge of a lava rise whose surface features he identified and mapped, (3) a penetrable crevice cave which drained a lava pond in a second lava rise which he identified, and we mapped and inventoried several other hollow tumuli and other lava rise caves just outside his study area. The internal morphology of the lava rise caves differs significantly from that of the hollow tumuli, thus substantiating Walker's differentiation of lava rises from tumuli and providing additional insight into the emplacement of pahoehoe flow fields.

1. History and Techniques of the Study

In 1991, George P.L. Walker published a notable paper on inflation features of a small part of the 1919 "Postal Rift" lava flow in Kilauea Caldera, Hawaii Island, Hawaii (Walker, 1991). He described and depicted one hollow tumulus and noted the presence of one sub-crustal grotto in a lava rise. In an intermittent 12-year study from mid-1994 to Spring 2006, teams of the Hawaii Speleological Survey continued his work and expanded it to the entire lava flow (Figs. 1-5). We undertook 180 ten to eleven hour day trips in the course of 23 field seasons. Approximately 251 caves were identified and 83% of these were investigated with forms reported here. Of the others, eleven (4%) were too tight, eleven (4%) too hot, ten (4%) were both too hot and too tight. Three (1%) were bypassed because of fragile features and three

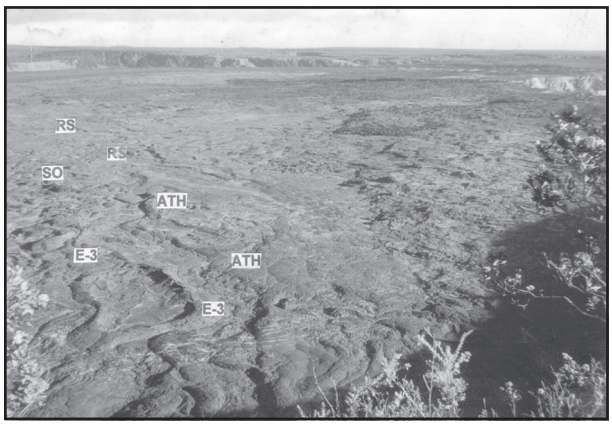

Figure 1: Looking southeast across the 1919 Postal Rift lava flow from the rim of Kilauea Caldera. The south (uphill) end of Walker's study area is in the immediate foreground. Shown are Lava Rise Cave E-3 (E-3), Almost Too Hot Cave (ATH),.Red Slope Cave (RS), and Sleeping Ohia Cave (SO). Sleepings Sister Cave is just to the left of Sleeping Ohia Cave, out of the photograph.

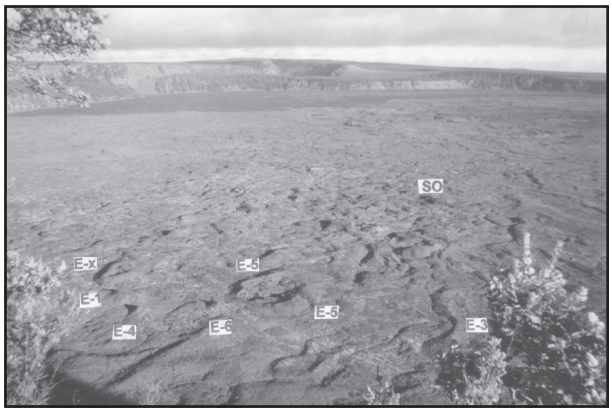

Figure 2: Looking east across the 1919 Postal Rift lava flow from the caldera rim. The north end of Walker's study area is in the immediate foreground. Shown are Lava Rise E-3 (E-3), Lava Rise E-5 Caves (E-5), Tumulus E-4 (E-4), Tumulus E-6 (E-6), Tumulus E-1 (E-1) and Lava Rise E-x Caves (E-x).

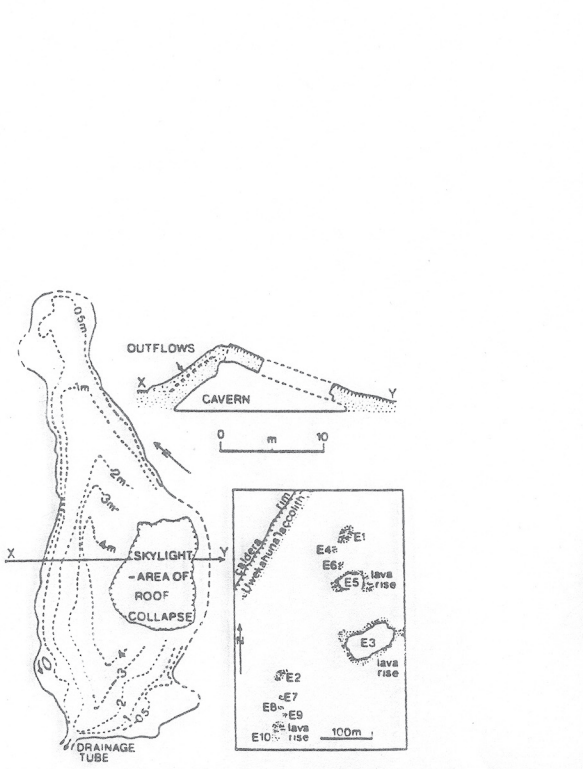

Fig. 11. a Plan view of the cavern in drained-out tumulus E1; the contours of cavern roof height are based on 320 measurements. b Profile across tumulus E1 on the same scale. c Sketch map of part of Kilauea caldera floor showing the locations of E1 and other measured tumuli and lava rises in relation to the well-known Uwekahuna "laccolith" on Uwekahuna Bluff

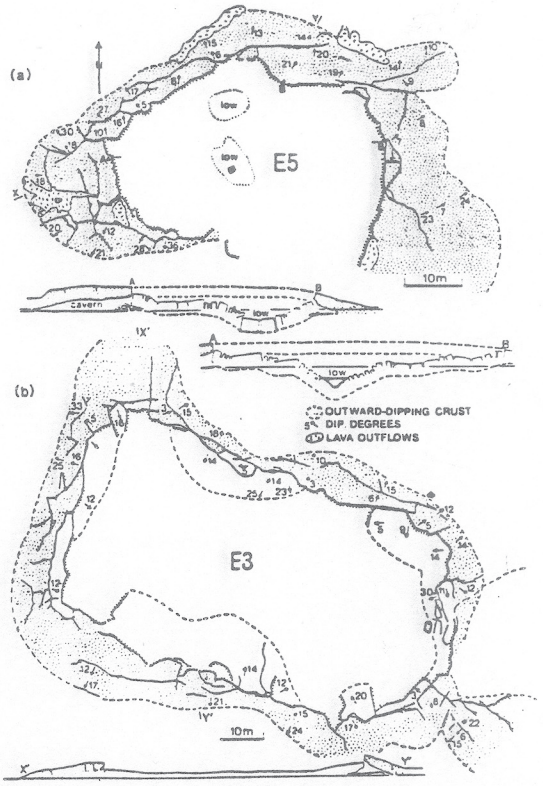

Fig. 12. Sketch maps, not on the same scale, of collapsed lava rises E5 (a) and E3 (b), and profiles across the structures. *Stippled areas* represent the outwardly dipping and non-collapsed outer parts of the rises. *Arrows* give dip direction and amount in degrees

Figure 3: Selected maps from Walker (1991) showing his study area and features. No cavernous features have been found in his southern group (E-2, E-7–E-10).

(1%) were found to be tectonic rather than rheogenic. Two (1%) were lost or forgotten, and permission was denied for entry into approximately four caves (2%).

Figure 4: View of Tumulus E-1 from Lava Rise E-x. The latter is outside Walker's study area. Tumulus E-6 also is seen on the left.

Many of the caves are hyperthermal (up to 77° C), with 100% relative humidity, thermostratification, and/or changing underground wind currents. This required development of new exploration techniques including identification and use of relatively cool layers of air for escape routes of one minute or less. Core temperatures were monitored. Sublingual temperatures of 38° C were found to cause serious impairment of critical functions requiring emergency replacement of fluids and electrolytes as well as cooling. Symptoms from core temperatures of 37.5° generally benefited from these replacements. Some individual variations were found in the exposure needed to cause such hyperthermia. Tables of broadly tolerable exposure to various temperatures were developed empirically and published (Halliday, 2000a) but occasionally were exceeded briefly by participants with especially high heat tolerance. Light weight, hard weave cotton clothing was used at all times, together with a variety of face masks in hyperthermal caves.

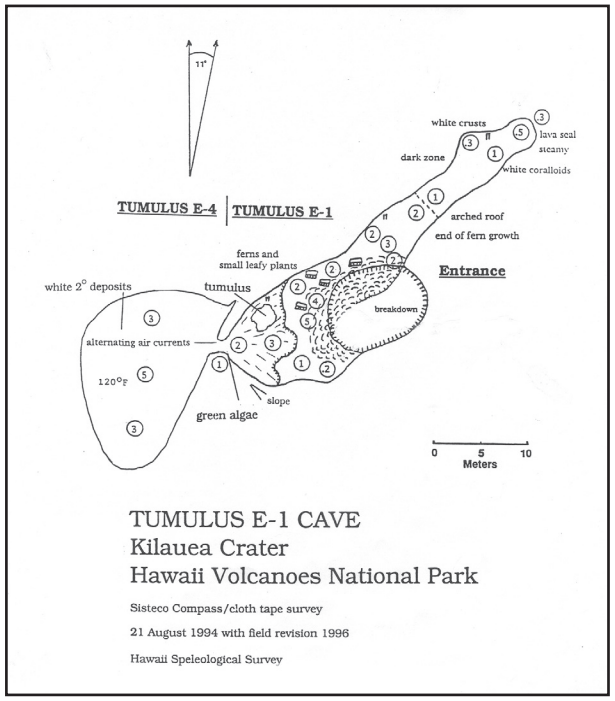

Figure 5: Plan of Tumulus E-1 Cave showing melt hole connection to chamber in Tumulus E-4. Ceiling heights are in meters.

Noxious gas (probably HCl) was encountered only in one tiny cave on the edge of Halemaumau Crater. Presumed sulfidic fumes were encountered in numerous cave but were found to be essentially non-toxic. Eye irritation rarely was encountered (Halliday, 2000b). Use of two types of CO_2 monitors was required in previously untested volcanic caves for the last five field trips. They were found to be useless in hyperthermal caves and no significant elevation of CO_2 was identified in normothermic (normal body temperature) examples (Halliday, 2007). In no cave was significantly elevated CO_2 identified by changes in normal breathing (Halliday, this volume).

2. Types of Rheogenic Caves

One major lava conduit system consisting of three individual caves was identified, inventoried and mapped: the Postal Rift System (Fig. 2). With a total length of 1,081 m, it is the master conduit for the 1919 flow in the caldera but extends for less than a third of the length of the flow. Directly beneath the US Geological Survey's Hawaiian Volcano Observatory, its 1919 origin from overflow of Halemaumau pit crater was documented in detail in early serial publications of that institution. Nearly all the other non-tectonic caves in this flow were formed by drainage of sub-crustal injection and lava breakout. These form a continuum between rough-shaped hollow breakouts a few meters in diameter and approximately a meter in height, hollow tumuli of several types, and drained injection spaces, the largest of which have some characteristics of a partially developed conduit tube. Drained lava rises, drained flow lobes and drained lava tongues are common. Meltdown of short-lived lava between adjoining cavernous landforms has produced complex floor plans and limited vertical development. No hollow pressure ridges comparable to those in the Myvatn region of Iceland were found.

3. Forms of Rheogenic Caves

Several very small tumuli and flow lobe caves were found with maximum ceiling heights of 1 to 1.5 m and diameters of a very few meters. The Puka X group of caves are little more than hollow breakouts. Lehua Cave is an example of a larger, igloo-shaped hollow tumulus. More commonly, such tumuli are elongated in the direction of flow. New Cave is an example almost completely buried by flows subsequent to its development.

Some larger hollow tumuli are oblong and are oriented transversely to the flow. Black Hole Cave is an unusual example. Only its outer shell is essentially intact. Beneath it, breakdown is so extensive that little of the original domed space remains. Hollow "whale back" tumuli are larger and even more elongate. Sleeping Sister Cave is a prototype. Its upper end is a very small sub-crustal tube. It curves and soon enlarges to a width of more than 15 m within a whaleback ridge. The outer chamber of Tumulus E-1 Cave was studied by Walker (Fig. 3). Our study found the orifice he labeled "drainage tube" to be a melt hole of lava originally separating cavities in Tumuli E-1 and E-4 (Fig. 5).

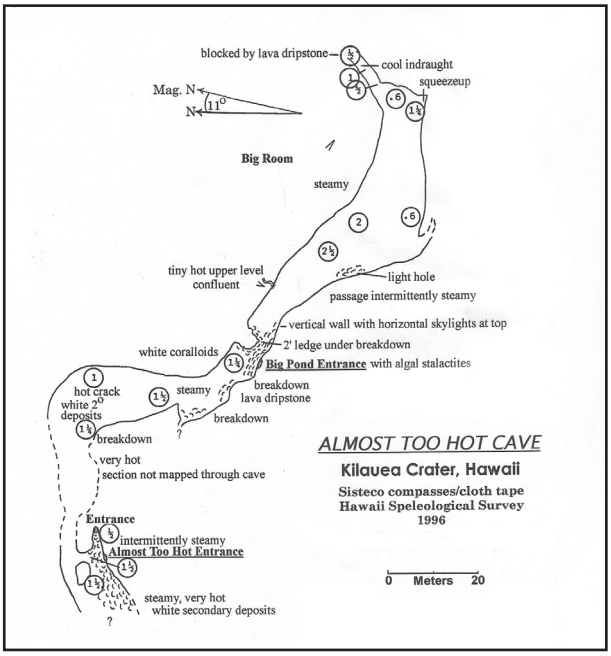

Figure 6: Plan of Almost Too Hot Cave. Ceiling heights are in meters.

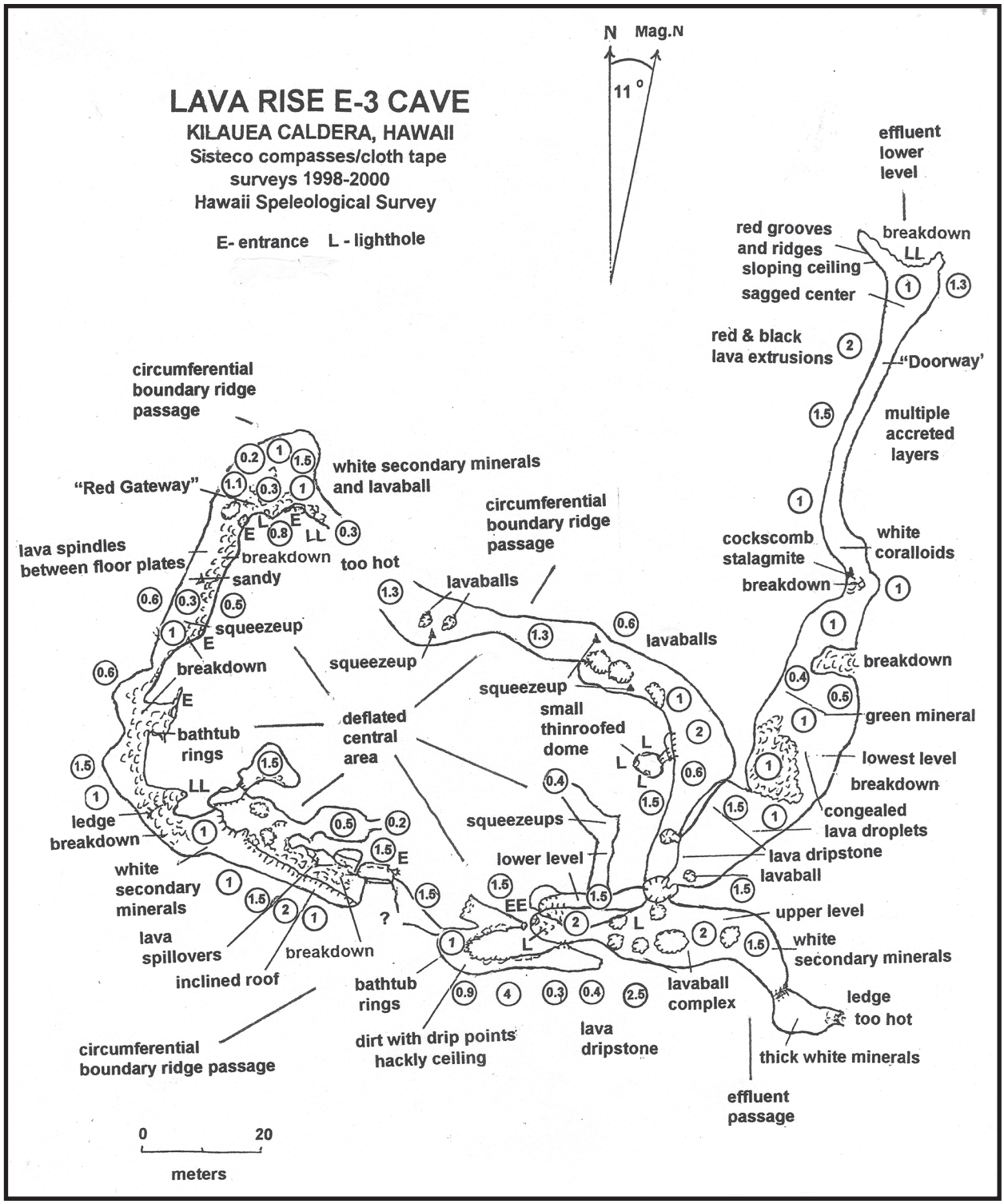

Figure 7: Plan of Lava Rise E-3 Cave. Ceiling heights are in feet.

Hollow sinuous tumuli and "feeder" and "drainage" tubes are common. Almost Too Hot Cave also has a wide terminal room but is an illustrative example of hollow sinuous tumulus (Fig. 6). About half of its height rises above the local lava surface. Much of Red Slope Cave has the same form, but it is more complex. Much of it is the product of deflation of a seemingly ordinary lava tube conduit cave, with a somewhat tubular residual passage along one edge of the original tube. Locally, the original roof slumped irregularly, producing up to three sub-parallel passages. The original cave was immature, and brief periods of overload produced local upper levels, breakouts, and small tumuli.

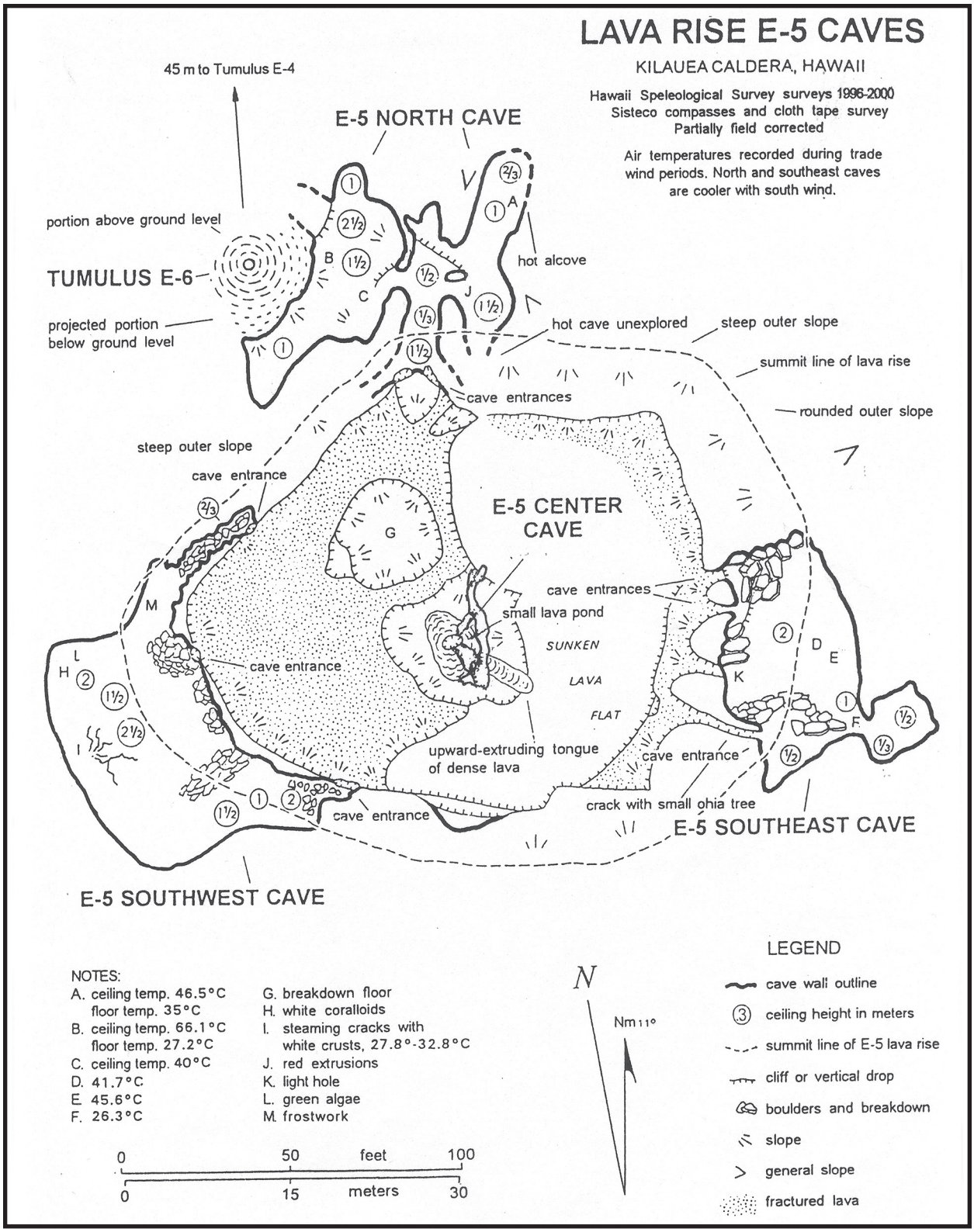

Figure 8: Plan of Lava Rise E-5 Cave.

A small melt hole connects it to an originally separate cave. Christmas Cave is even more complex. Its main entrance is at the lower end of a lava trench formed by similar slumping of the roof of an ordinary lava tube cave, and its long southern extension is in the preserved margin of that cave. This cave is of special interest because of its nesting of

drained flow lobes ("pancake rooms"), as theorized by Hon et al. (1994) as an important factor in the homogenization of pahoehoe flow fields. Other parts of this complex cave include a hollow hornito and hollow flow lobes connected to the its northeastern section through a melt hole at the eastern extreme of the mapped portion. Merry Go Round Cave also has a hornito-like structure protruding upward from its main passage. The original connection solidified, and feathery lava extrusions are present on the cave ceiling.

Flow lobe caves tend to reflect local topography during the emplacement of the parent flow. Plywood Cave extends down the side of a solid tumulus, retrograde to the direction of general flow. New Entrance Cave is a flow lobe cave with budding of a secondary chamber or passage. A slumped area draining into the budded passage demonstrates the speleogenetic sequence. Big Ell Cave is within a hollow tumulus with a deep surface indentation above the point of budding of a large side passage formed by this process. Natural Bridge Cave and nearby South Twin Puka Cave uniquely consist of budded crawlways reflecting large terminal toes of the flow.

Lava rise caves appear to have originated through a mechanism also seen in Red Slope and Christmas caves. These are largely perimeter caves, circumferential to large deflated areas (Figs. 7, 8), characteristically containing numerous lavaballs. Lava Rise E-3 Cave is especially notable for its lengthy peripheral and short central drain passages. Lava Rise E-5 Cave has a central cavernous crevice from which very fluid pahoehoe was forced late in the speleogenetic process. The base of Tumulus E-6 can be inspected in the north cavern of Lava Rise E-5 Cave.

Acknowledgments

My heartfelt thanks to Jim Martin, former Superintendent of Hawaii Volcanoes National Park, for long-term encouragement and actual participation in this study, and to Bobby Camara, Cave Specialist of that park, who assisted notably. Don Swanson of the U.S. Geological Survey and Ken Hon of the University of Hawaii, Hilo Branch, made valuable suggestions in the field. Too many members and cooperators of the Hawaii Speleological Survey participated in field studies to name them all here, but without their generous assistance, the project would not have been possible. It was self-funded by participants.

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PRINCIPLES OF PYRODUCT (LAVA TUNNEL) FORMATION

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Shield volcanoes owe their shape to the fact that low-viscosity, high-temperature lavas form internal tunnels in which the lava can be transported for tens of kilometers. Originally described as tunnels and termed pyroducts (in analogy to aqueducts) they are integral features of pāhoehoe lava flows. The term "lava tube," implying that lava is simply piped downhill, should be avoided. Contrary to the popular idea that lava tunnels form by the crusting over of lava channels, they form at the tip of the lava flow by a repeated process of advance and inflation. Within the stack of lava sheets formed initially, the hottest conduit will attract most of the flow. Soon after the lava will start eroding downward, thus creating an underground canyon-like tunnel with a river of low viscosity lava at the bottom. Back-cutting lavafalls can quickly enlarge this canyon uphill. Collapse of the primary roof can open skylights ("pukas") that allow convective cooling of the lava. It reacts by freezing over, forming a secondary roof, under which the flowing river is once more protected from heat loss. Field investigations suggest categorization into single-trunked, double(or multiple)-trunked and superimposed-trunked systems. First category examples are some of the very long caves like Kazumura, Ke`ala and Ainahou Caves (all Kilauea, Hawai`i). Double-trunked systems operate contemporarily side-by-side influencing each other. One known example is the interaction between the upper part of the Huehue Flow and the Mystery Flow (Hualalai, Hawai`i). The final category includes superimposed tunnels all active at the same time. Such systems can come about by an increase in lava volume during an eruption causing new tunnels to form on top of the old ones that also stay active but cannot swallow the increased flow. Such a system most likely is represented by Kulakai Cave (Mauna Loa, Hawai`i).

1. Introduction

Transport of lava through interior tunnels of pāhoehoe lava flows is an important volcanic process. It allows lava to flow over long distances. Within the tunnel, heat is lost only conductively while surface lava looses heat convectively at the upper and conductively at the lower interface. Lava transport through tunnels is therefore the reason why basaltic shield volcanoes attain very low slopes (often <2°,

Cave	Total length, km	Main trunk length, km	End-to-end bee-line, km	Sinuosity	Vertical distance m	Slope	Volcano
Kazumura Cave	65.50	41.86	32.1	1.30	1101.8	1.51°	K, A
Ke'ala Cave	8.60	7.07	5.59	1.25	186	1.51°	K, A
J. Martin/Pukalani System	6.26						K, A
Epperson`s Cave	1.93	1.13	0.80	1.41	-	-	K, A
Thurston Lava Tube	0.490	0.490	432	1.13	20.1	2.4°	K, A
Ainahou Ranch System	7.11	4.82*	4.27	1.13	323	3.83°	K, A?
Ke'auhou Trail System	3.00	2.27	1.99	1.13	213.3	5.36°	K, A?
Charcoal System	1.5		1.4		60	2.6°	K,
Earthquake System	0.34				33	4.7°	
Huehue Tube	10.8	6.17	5.13	1.2	494.6	4.58°	H, HH
(Clague's Cave**)	2.73	1.39	1.18	1.15	157.1	6.49°	H, HH)
Pa'auhau Civil Defense C.	1.00	0.58	0.50	1.14	49	4.87	MK

*horizontal; ** upper part of Huehue

Table 1: Comparison of some morphological indices of some of the Hawaiian lava tunnels (for sources of data see KEMPE, 2002). (K,A: Kilauea, Ai-la`au; H, HH Hualālai, Huehue flow of 1801; MK: Mauna Kea).

compare Table 1) and why large continental lava plateaus fed by multiple eruptions can form. These facts are known, even though many volcanology textbooks do not mention them or deal with them only marginally. Overall, a pāhoehoe "lava flow" is stationary, growing only at its tip One can walk across its active tunnel without even noticing it. A`a flows on the other hand move like glaciers, shoving down-hill in their entire width. These flows do not develop a tunnel.

The first to describe a lava tunnel after having inspected it by himself was apparently OLAFSEN (1774–1775) who visited Island 1752 to 1757 (KEMPE, 2008). In his description of Surtshellir (§ 358, p130; later almost verbally copied by ROSENMÜLLER & TILLESIUS, 1799) we read: „*Der fließende Hraun ist wie ein Strom durch diesen Canal geflossen*;..." (the running lava flowed through this channel like a river..."). TROIL (1779; p 225) who visited Island with Joseph Banks and Daniel Solander in 1772 wrote: "*Die obere Rinde wird bisweilen kalt und fest, obgleich die geschmolzene Materie noch unter derselben wegläuft, dadurch entstehen große Höhlen, deren Wände, Betten und Dach aus Lava besteht, und wo man eine Menge Tropfstein aus Lava findet*." („The upper crust sometimes cools and solidifies, even though the molten matter keeps running underneath; in this way large caves form, the walls, floors and ceiling of which are composed of lava and where a lot of dripstones of lava occur"). The first one to report seeing an active tunnel was COAN (1844) who in 1843 ascended Mauna Loa: "*But we soon had ocular demonstration of what was the state beneath us; for in passing along we came to an opening in the superincumbent stratum, of twenty yards long and ten wide, through which we looked, and at the depth of fifty feet, we saw a vast tunnel or subterranean canal, lined with smooth 'vitrified matter, and forming the channel of a river of fire, which swept down the steep side of the mountain with amazing velocity. The sight of this covered aquaduct – or, if I may be allowed to coin a word, this pyroduct – tiled with mineral fusion, and flowing under our feet at the rate of twenty miles an hour, was truly startling."* Thus Coan used the term "tunnel," but he also coining a new one: "pyroduct". This is a specific term for a very specific natural phenomenon and should take precedence over younger terms. On the other hand famous geologists like James Dana continued to use "tunnel," while J.W. Powell introduced "volcanic pipes" and Tom Jaggar used "tunnel" as well as "tube"; only after 1940 the term "lava tube" became standard (pers. com. J. LOCKWOOD). In this contribution I will go back to the old term "tunnel" and, for reasons of rules of scientific nomenclature, "pyroduct" as well. There is also good reason why to avoid the term "tube," because it invokes the picture of pipes in which lava can flow up and down under pressure like in a plumbing system. Furthermore, "tube" implies a circular cross-section that is only rarely found.

The discovery of long lava flows on Moon, Venus and Mars and even active volcanoes on Io has increased the interest in pyroducts in the last few decades. On Earth the longest surveyed lava tunnel is Kazumura Cave (65.5 km) (Hawai`i, Kilauea Volcano) (ALLRED et al., 1997) and the longest terrestrial tunnel-fed flow is that of Undara/Australia (ATKINSON, 1993). The author's group explored and surveyed many other caves on Hawai`i (KEMPE, 2002) and in Jordan (KEMPE et al., 2006a) that give opportunity to study formation and evolution of pyroducts from the inside.

2. Formation of Pyroducts

In many text books lava tunnels are described as having formed by "crusting over channels" (e.g., Francis, 1993). Such caves do exist, but they are clearly in the minority. Mostly they form short, roofed sections of open-surface lava rivers contained in levees. In cross-section such cave roofs show accreted layers growing from the sides inward and having a central vertical parting where the growing lateral shelves met.

The long lava tunnels form, however, by "inflation" (HON et al., 1994). It is a process that is incremental and it starts at the distal tips of the pāhoehoe flows where hot lava rapidly covers the ground in thin sheets. The sheet will cool quickly, causing the dissolved gases to form bubbles, decreasing the overall density of the rock. The next pulse of advancing lava will lift this sheet up ("inflation" by buoyancy) before forming the next distal surface sheet. Multiple advances can occur, forming a primary roof with several sheets, separated by sheer interfaces (only the first or top sheet will have subaerially formed ropy structure) (Fig. 1). The "oldest" lava sheet is therefore on top of the stack in contrast to normal stratigraphic conditions. Below the primary roof the lava can stay hot and can keep flowing. This is the initial tunnel. Thus these caves are characterized by roofs build of one or several, sometimes more than ten continuous sheets of lava. This roof structure can be studied at roof collapses, called "pukas" in Hawai`i.

2. Internal development

If the area to be covered by the first advance is rather flat, many small, parallel conduits can develop Each of them can start to erode down soon after. One of the threads will, however, erode fastest and attract the largest flow volume. It will then drain the other parallel ducts one by one of their lava, often leaving them as small-scale labyrinths high above the final floor (Fig. 2). Since these mazes are drained from

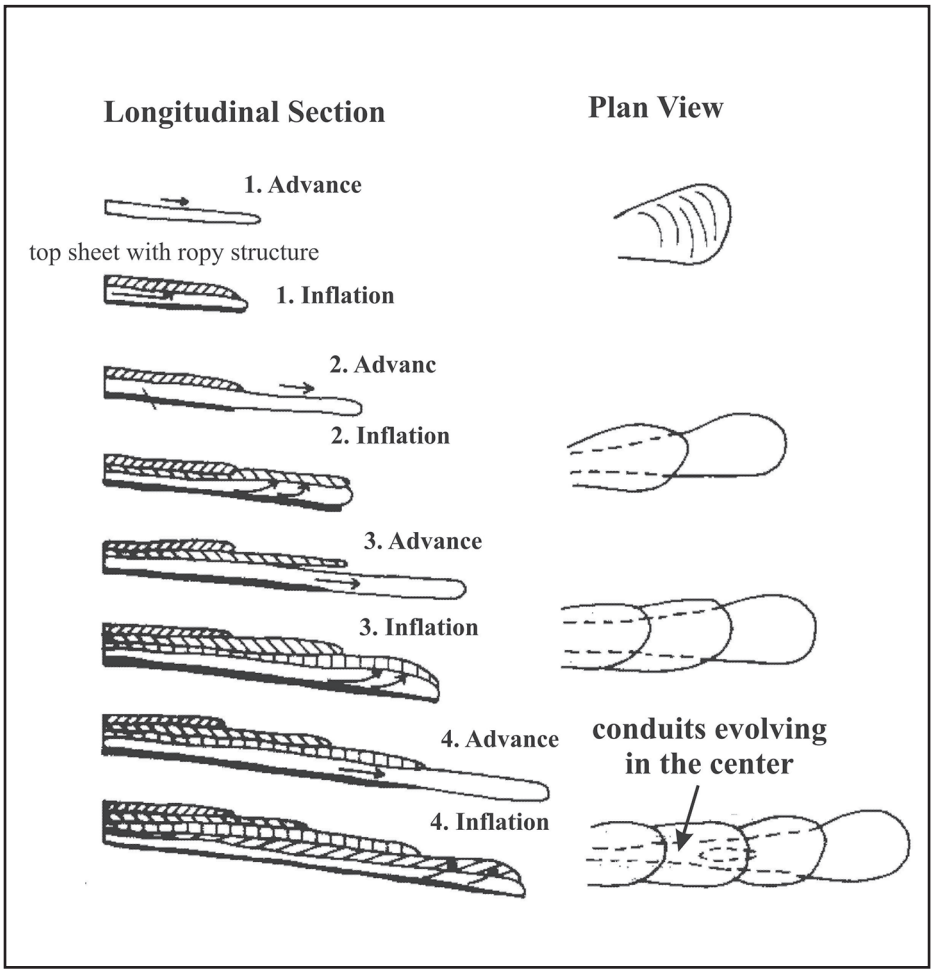

Figure 1: Sketch illustrating pyroduct (lava tunnel) formation. At the tip of a pāhoehoe flow lava advances quickly in form of a delta of thin, ropy lava. The next pulse of lava lifts the first sheet up (inflation). This process is repeated until a stack of lava sheets (the primary roof) is formed, below which the hottest flow thread becomes the later tunnel.

their lava when the whole system is still very hot, their floors are mostly smoother than that of the later main tunnel.

As the erosion continues, the lava runs with an open surface in a self-generated underground canyon. This canyon is cut into older rocks, not associated with the current eruption. This fact can be studied at places, where the thin lining of the side walls has fallen away (e.g., GREELEY et al., 1998; KEMPE, 2002). Often we find a`a blocks behind or even ash layers, both certainly not integral parts of pāhoehoe flows. Downcutting is facilitated by a variety of processes. One of the more spectacular processes is canyon formation by backcutting lavafalls (KEMPE, 1997; ALLRED & ALLRED, 1997) (Fig. 3). These are quite common in the long Hawaiian caves, but none are yet found in Jordan. The falling lava hammers out the rubble from the floor. It consists of less dense rocks that float up and are transported on the surface of the river. Thus, other than in a water river, the bed is not protected by bedload and therefore prone to continued erosion. The mobilized blocks are cool and receive a coating of lava forming lavaballs. Some of the lavafalls seem to be stationary forming large plunge-pools and chambers (ALLRED & ALLRED, 1997). Thus the tunnel will grow in depth and width in an uphill direction. The passage above the lava falls is quite small in contrast. As one proceeds uphill, the canyon will become larger and larger until one enters the next plunge pool chamber. It is not quite understood how much mechanical erosion and how much melting of the river bed occurs (e.g. GREELEY et al., 1998; and citations in KEMPE, 2002). Other enlarging processes may occur, such as small phreathic explosions, blowing out sections of the wall or floor as groundwater is vaporized.

As the downcutting continues the river meanders, undercutting walls and destabilizing the roof. Breakdown falling into the flowing lava is also carried away. If the primary ceiling collapses entirely, a skylight or "puka" opens up If the flow is still active, the rubble can be carried away and we speak of a "hot puka." If the collapse occurs after the termination of the flow, there will be a breakdown pile, sometimes giving easy access to the cave below, sometimes sealing it completely this is termed a "cold puka". If a puka opens up during activity then hot gases can escape from the tunnel and heat exchange can occur convectively. The heat exchange is specifically efficient if two pukas open up Then the upper one will serve as an exit or chimney of hot gases, while cold external air is drawn into the cave at the lower puka. This intrusion of cold air causes the surface of the lava river to freeze over, forming a secondary ceiling in the canyon (Fig. 3). The secondary ceiling will split the passage into two levels, one on top of each other extending between the two pukas but not very much further. This process can occur several

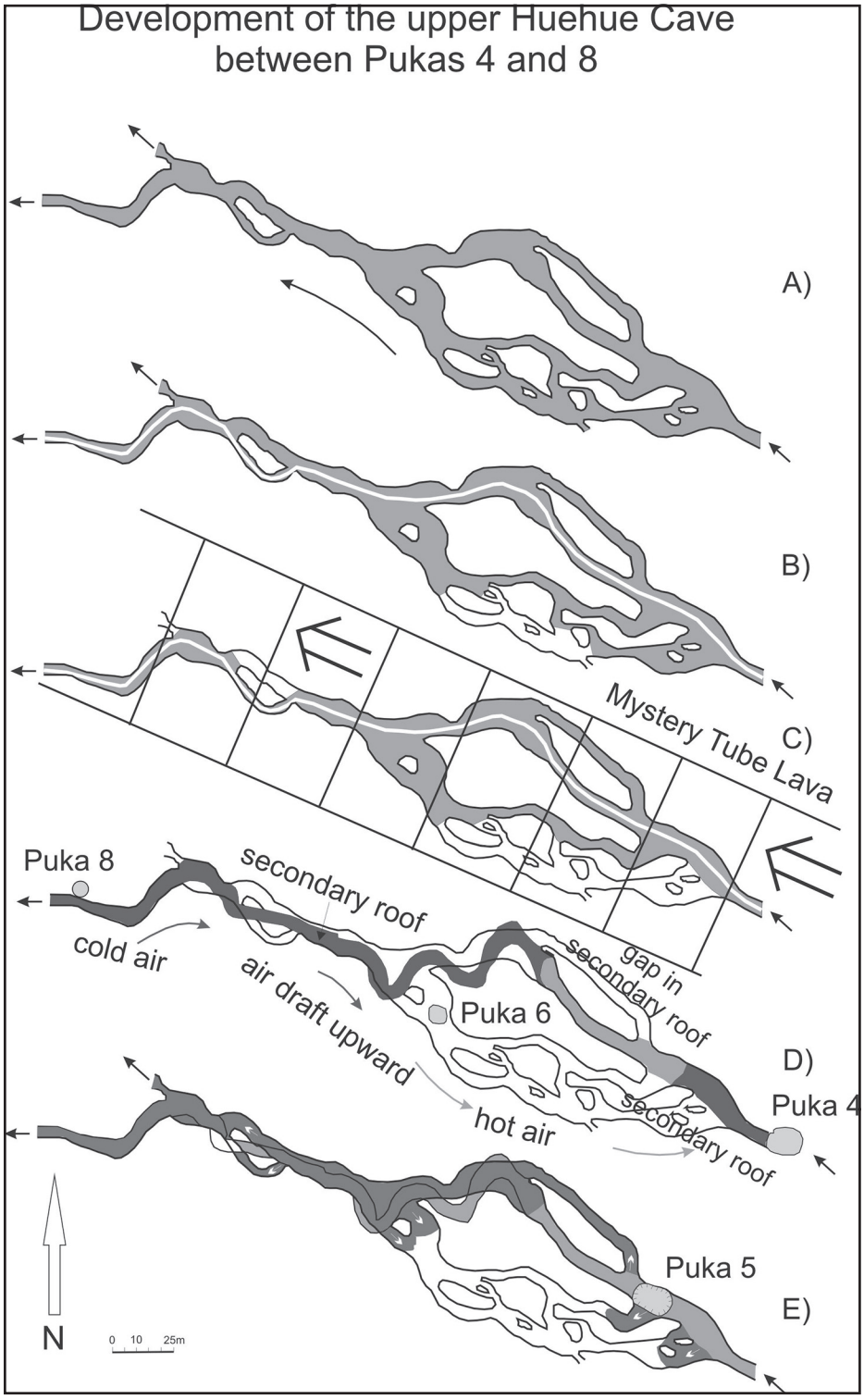

Figure 2: Detail of the ground plan of the Huehue Cave illustrating how a primary maze of parallel lava threads (A) was drained until the master trunk that cut down fastest remained (E). (A) Initial pattern of lava tunnels, flow was from right to left in up to five parallel conduits. (B) The southern-most conduits were drained first. (C) Further downcutting reduced the number of active conduits to three. At the same time, lava from a parallel flow (Mystery Flow) covered the area. (D) Only one tunnel remained (following the thick line in B and C), its bed 2 m below the original surface. The added overburden caused collapse of pukas (labeled 8, 6 and 4) the breakdown of which was removed by the lava river. Now external air began flowing uphill from Puka 8 to 4. As a consequence a secondary ceiling froze out above Puka 8 and below Puka 8. (E) Various spill-events reinforced the secondary roof, even spilling into the already drained upper conduits, closing the northern-most one. These spilled lavas were oxidized by the passing surface air and attained various shades of red caused by the crystallization of very fine-grained hematite. The last event was the collapse of puka 5 while the tube cooled. Its material is still in place.

times consecutively, forming e.g. a tertiary ceiling. Later spills from below through breakdown holes or from the upstream end of the secondary ceiling can reinforce it from above. In Ke`ala Cave, Hawai`i, one section of secondary ceiling is over 1 km long. Very often the upstream end of the secondary ceiling is sealed. This is caused by lavaballs floating on the lava river that are too buoyant to be dragged below the secondary ceiling. Instead they strand on the upper edge of the secondary ceiling. The accumulated blocks are then welded together by splashed-up lava. Floating blocks can be very large, in Waipouli Makai Cave there is a block about 12 m wide, 8 m long and 5 m thick welded into the ceiling of the cave (KEMPE et al., 2006b). The cold, oxygen containing external air that is drawn into the

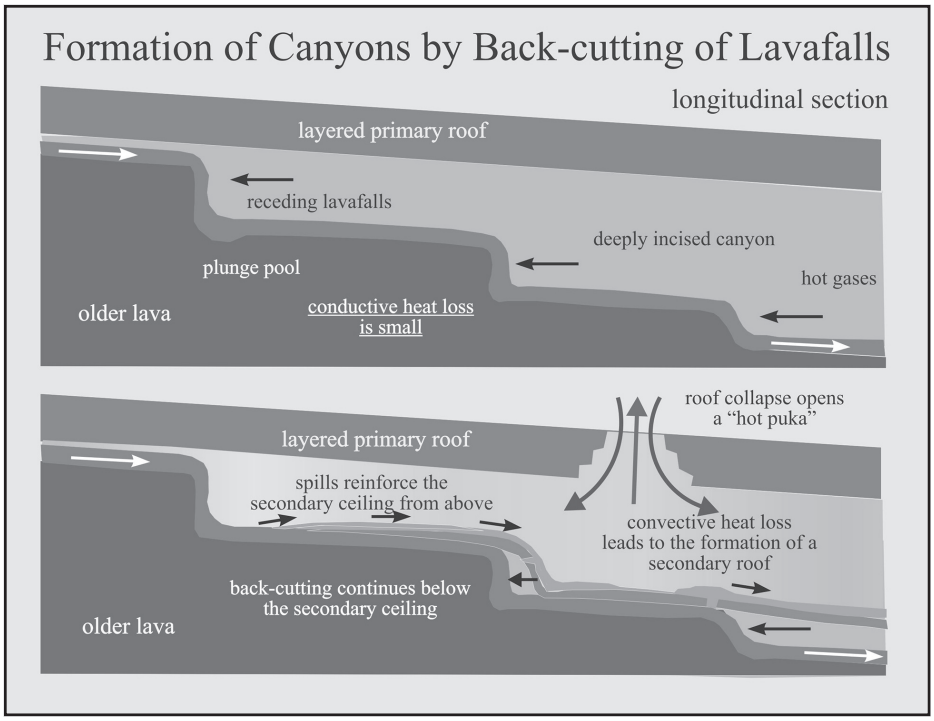

Figure 3: Longitudinal section of an evolving lava tunnel. Top: Erosional enlargement of the underground canyon by backcutting lavafalls. Bottom: Upon static failure and partial collapse of the primary roof a skylight (puka) opens up, allowing cold air to enter the tunnel, freezing an internal secondary roof below which erosional enlargement can continue. Spills from uphill or through holes reinforce the secondary roof.

cave can oxidize lava surfaces that are still hot. The iron, contained in the volcanic glass, is oxidized to fine-grained hematite, tinting the surfaces of secondary ceilings in various hues of red. Thus, red lava is not any different from the lava in the tunnel, it just was exposed differently to oxygen during cooling.

Hot pukas can also serve as temporary rootless vents when the tunnel below is obstructed or even closed entirely. Lava can then flow out of them, forming relatively rapidly cooling, thin, ropy pāhoehoe. The "Puka 17 Flow" out of the lower part of the Huehue tunnel (Fig. 4) is an example. Pukas, cold or hot, can also serve as entrances for lava of later flows. The upper and lower ends of Ke`ala Cave were plugged by later lava invading into pukas.

All these processes act to form caves of complex pattern, morphologically not representing "tubes" at all. Also the total length of the caves is usually much larger than the simple distance along the main tunnel. Table 1 gives some basic morphometric data, such as sinuosity and slope for some tunnel systems.

3. General Types of Pyroducts

Overall, we can differentiate several general types of lava tunnels. Here I would like to introduce three new terms to describe the general functioning of the lava tunnels. These are:

(a) **single-trunked systems**, (b) **double(or multiple)-trunked systems** and (c) **superimposed-trunked systems**

Most of the lava tunnels yet documented in enough detail appear to belong to the **single-trunked** category. They are fed by one eruption vent and the meso-morphological internal structure can be explained by the processes discussed above. The tunnel size depends on the lava discharge rate and on the length of activity (days, weeks, months and possibly even years), i.e., on the time available for erosion. If the eruption stops or the tunnel collapses or is blocked, the tunnel will cool. The next or even - in case of a blocked tunnel - the same eruption will then create a new pyroduct. Normally, it will be situated to either side of the previous flow because it now forms a topographic ridge (flow lobe). Typical examples of single-trunked systems are Kazumura, Ainahou Ranch, Ke`ala and others of the long Hawaiian caves. If lava from the new tunnel should spill through a puka, or break (because of its overburden) into any older, underlying tunnel, then the older tunnel will be filled by lava cooling in the same pattern as at the surface.

Double-trunked systems are comprised of two lava tunnels, active side by side at the same time and fed by two separate eruption points. Such tunnels can interact and cause more complex morphologies than described above. One example is the interaction between the Huehue Flow and the Mystery Flow (Fig. 4; KEMPE, 2002). In this case the Huehue flow established its tunnel first. Then a second eruption point (the very inconspicuous, low Mystery Shield) erupted lava, establishing a small tunnel system to the side of the Huehue flow lobe. Part of the Mystery lava formed surface lavas that quickly cooled forming a`a flows. These superseded the upper part of the Huehue tunnel to the left.

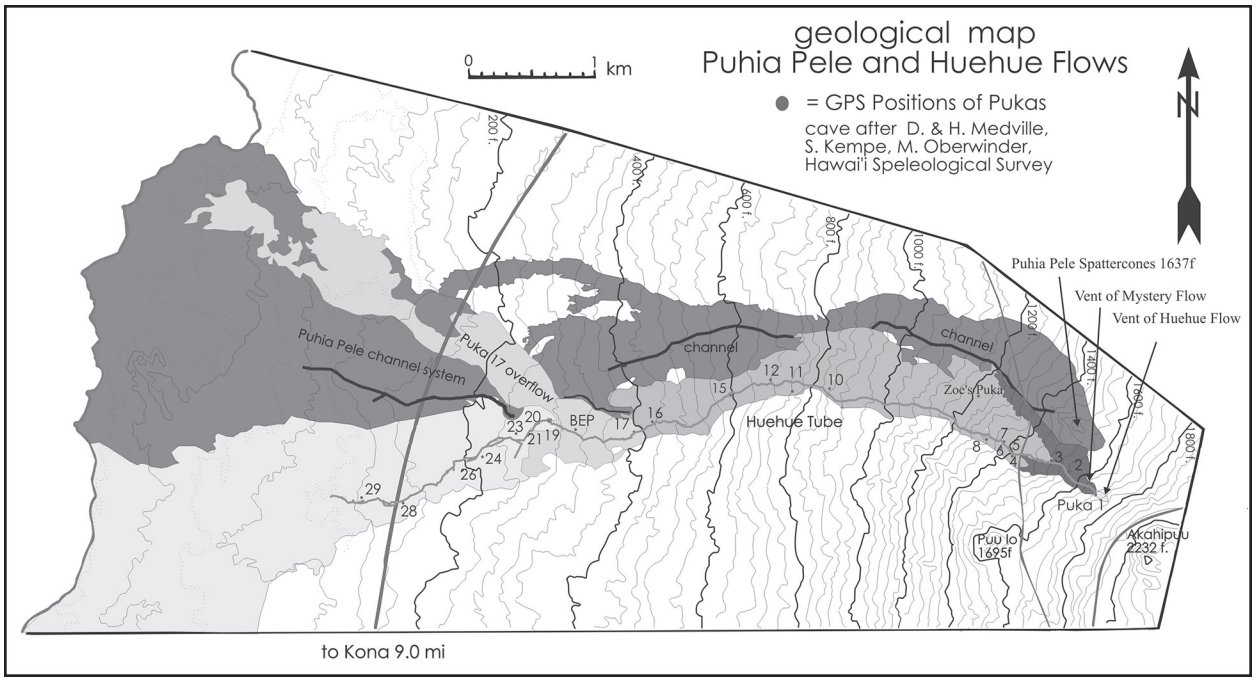

Figure 4: Geological map of the Huehue flow (Hualalai Volcano, Hawai`i) of 1801 according to surveys of the author's group Flow was from right to left, vertical distance 500 m. Oldest are the lavas (light grey) of the Puhia Pele vent (a series of spectacular spatter cones) that was gas-rich and formed an open channel system (with a few roofed-over sections). After its termination the Huehue Flow erupted (numbers label pukas on the Huehue Cave, thick line; lava light middle grey left and at Puka 1) accompanied by the Mystery Shield eruption that was active for only a short time (upper right) and covered much of the upper part of the Huehue Flow (dark middle grey). Zoe's Puka is a tunnel belonging to the Mystery flow. From Puka 17 a surface flow issued (dark grey) and the terminal lava from the mystery shield formed several short a`a flows (dark grey at the right).

Once thick enough, the primary, sheeted roof of Huehue collapsed and left a roof composed of Mystery a`a lava. The resulting breakdown was removed with the active lava river. Due to the large, hall-like cavity that formed, a secondary roof froze out over the active flow of Huehue. Later rockfall covering the newly formed "false floor" gives the upper passage the appearance as if the tunnel was formed in a`a, an impossibility near to a vent issuing very hot basaltic lava.

The least understood and documented category is the **superimposed-trunked** system. It is defined as a set of lava tunnels superimposing and crossing each other, all being all active at the same time. The upper tunnels stop their activity first, so that the lower ones carry on for some time before they also stop operating and become emptied. There may even be connecting openings between the levels exchanging lava between cross-overs. Such systems could arise when a volcanic vent increases its output volume during an ongoing eruption. Then the already established pyroducts cannot accommodate the increased flow volume and a new story of independently operating tunnels is build on top of the already active one. To my knowledge the Kulakai System on Hawai`i is an example of such a superimposed-trunked system.

4. Conclusions

In spite of the tremendous progress made in lava cave exploration, we still are far from understanding all the features and processes that interact during lava tunnel formation. It is clear, that the concept of a "tube," simply piping lava downhill, is far too simple to explain the observed morphologies. Furthermore, many published lava cave maps are rather useless because they are not linked to a geological map of the flow; many of them do not even offer morphological details and cross-sections (if they are made at all) do not show the structure of the lava flow itself. Thus, much more process-oriented analysis is needed in order to advance lava cave research.

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INTERPRETING THE GENESIS OF THURSTON LAVA CAVE, KILAUEA, HAWAI`I

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Thurston Lava Tube (alias Keanakakina), discovered east of the Kilauea Iki Crater on Hawai`i in 1913, soon became an attraction in the Hawai`i Volcanoes National Park. It is visited daily by many tourists who get here their only chance to experience a true pyroduct. Nevertheless, not much is known about Thurston's speleogenesis and previously published maps are not very detailed. We resurveyed the cave in 1996 with high precision, establishing its morphometry (horizontal length 490 m, direct distance 432.5 m between ends, sinuosity 1.13, vertical drop 20 m, average slope 2.4°, width 10.5 to 3.5 m, height 11.5 to 1.6 m). Two lava falls with a total drop of 1.8 m are encountered. Volcanologically, the cave is important because it is situated near the vent of the Ai-la`au Shield, which at 1,195 m a.s.l. that yielded the last massive summit eruption of Kilauea 350 years ago and produced Kazumura Cave. The cave appears strangely dull; the typical smooth, continuous glazing normally found is missing throughout. The cave ends at a lava sump, posing a puzzle because lava seems to have upwelled from below. No other cave downhill can be linked with Thurston. The lava falls show that Thurston is not just the upper part of a larger canyon, separated by an internal, secondary roof. However, it is possibly an independent tunnel created on top of the original lava tunnel during a burst of activity of the Ai-la`au Shield and that the upwelled lava came from this lower tunnel.

1. Introduction

On Hawai`i, only a few caves are accessible to the general public. There are two show caves (sections of Kula Kai and Kazumura caves) that offer ecologically and conservatively oriented tours for small groups and one cave in Kaumana State Park that people can visit at their own risk. In addition, Hawai`i Volcanoes National Park offers guided educational tours to a few selected caves. Otherwise, the visitor to the Hawaiian volcanoes can go underground only in Thurston Lava Tube (or Keanakakina, i.e. Tunnel of Thurston, *keana* meaning "the cave" and *kakina* being the Hawaiian Name of Thurston). It is a popular tourist attraction in the Hawaii Volcanoes National Park and visited daily by hundreds, if not over a thousand tourists. In spite of its many literature references, not much is known about its speleogenesis and previously published maps lack detail (POWERS, 1920; WOOD, 1981; HALLIDAY, 1982). We therefore re-surveyed the cave on March 9th, 1996, in high precision by digital compass and level mounted on antimagnetic tripods to keep instruments at a fixed distance from the rock (Figs. 1, 2). Using forward and backward shots served to eliminate any magnetic influence of the rock (which is small anyway according to our survey experience in Hawaiian caves). Width and heights were recorded every 5 m. Table 1 gives the most important results.

The cave was discovered in 1913. A report signed by Wade Warren Thayer in the visitors' book of the Volcano House says: *"On Aug.2nd a large party headed by L.A. Thurston explored the lava tube in the twin Craters recently discovered by Lorrin Thurston, Jr. Two ladders lashed together gave comparatively easy access to the tube and the whole party, including several ladies, climbed up. No other human beings had been in the tube, as was evidenced by the perfect condition of the numerous stalactites and stalagmites. Dr. Jaggar estimated the length of the tube as slightly over 1,900 feet. It runs northeasterly from the crater and at the end pinches down until the floor and roof come together..."* HALLIDAY (1997).

The primary entrance to the cave today is reached across a bridge. It opens in the wall of an elongated depression called Kaluaiki, possibly a pit crater collapsed over the original magma chamber that delivered the lava producing the cave. The present exit is a roof collapse where the tourists leave the cave via stairs. The tourist section has yellow electric lighting to minimize lampenflora and the floor is covered with gravel. Beyond the stairs, an open gate is found with a sign advising to carry proper lighting when visiting this 343 m long back section (more correctly 357 m).

2. Volcanological importance

Volcanologically, the cave is important since it is situated

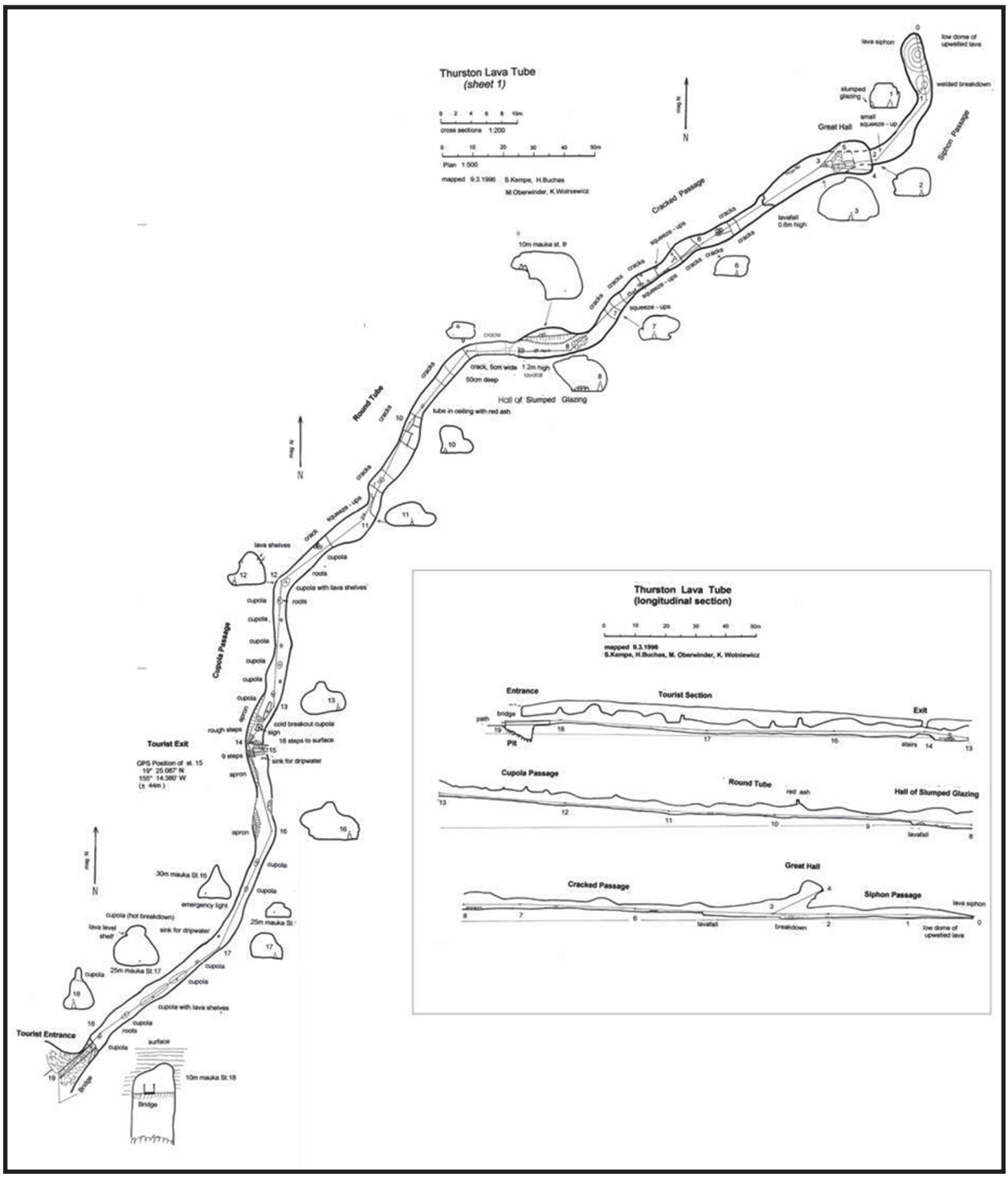

Figure 1: Map of Thurston Lava Tube.

very near to the original vent of the Ai-la`au Shield, the site of the last massive summit eruption of Kilauea (HOLCOMB, 1987) that lasted from about 500 to 350 aBP. The Ai-la`au lavas cover a very large area east of Kilauea Caldera all the way to the ocean near Hilo. These tube-fed pahoehoe lavas contain not only the longest lava cave known (Kazumura Cave) but also a number of other very long lava tunnels (Keala Cave, John Martin Cave, Pahoa Cave). Since Thurston runs underneath the highest point of the Ai-la`au shield (the 3,840 foot contour), it appears to be the tube that sustained the last active flow, possibly producing the lava which reportedly invaded Kazumura (ALLRED and ALLRED, 1997). Thurston is heading 45° N, ending just inside the park boundary. It is aiming at a prominent flow

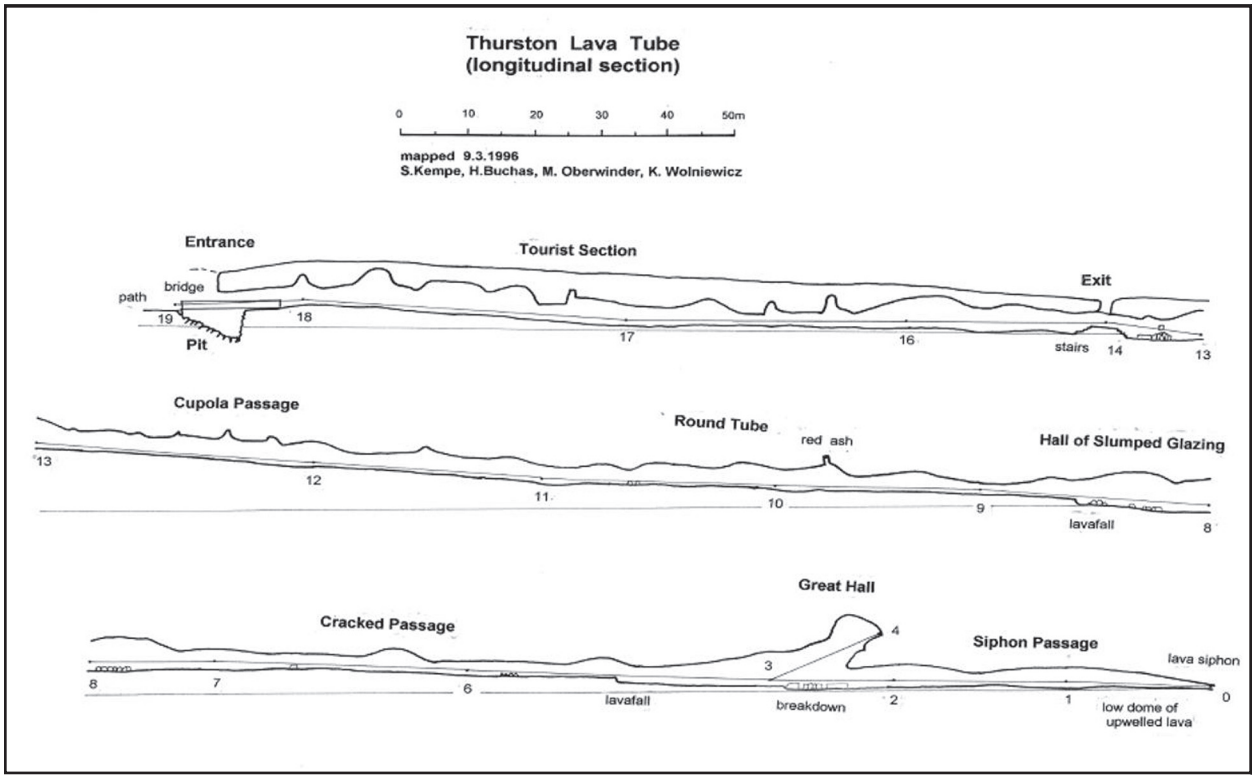

Figure 2: Longitudinal section of Thurston Lava Tube.

Length (from the beginning of cave roof - which is 13.5 m upslope of Station 18 above entrance bridge - to lava sump end at Station 0)	**Inclined**	**Horizontal**
Total cave (m)	490.84	490.08 (Station 0 to Station 18= 476.576 m)
Wild section (m)	357.43	356.76
Tourist section (m)	133.41	133.32
Total survey length (m)	531.75	(total of 19 stations)
Linear extent (m)	432.5	
Sinuosity (490.076/432.5)	1.133	
Vertical extent (m) (Station 0 at lava sump to floor at Station 18 at downslope end of bridge)	-20.08	
Width (m)	max. 10.5	min. 3.5
Height (m)	max. 11.5	min. 1.6
Total lava fall height (m)	1.8	8.96% of total vertical extent
Slope (°) ($\tan^{-1}$ (20.08/476.576))*	2.413	
Entrance: side of collapsed crater at ca.1195 m (3920 ft) elevation	End: lava sump	

* Because the cave roof starts earlier than the cave floor, we can use only the cave floor length, which is shorter than the total cave length, in order to calculate slope.

[for comparison, length by POWERS (1920): 1494 feet total (455 m), straight: 1360 feet (425m); slope 2.5°].

Table 1: Survey data for Thurston Lava Tube.

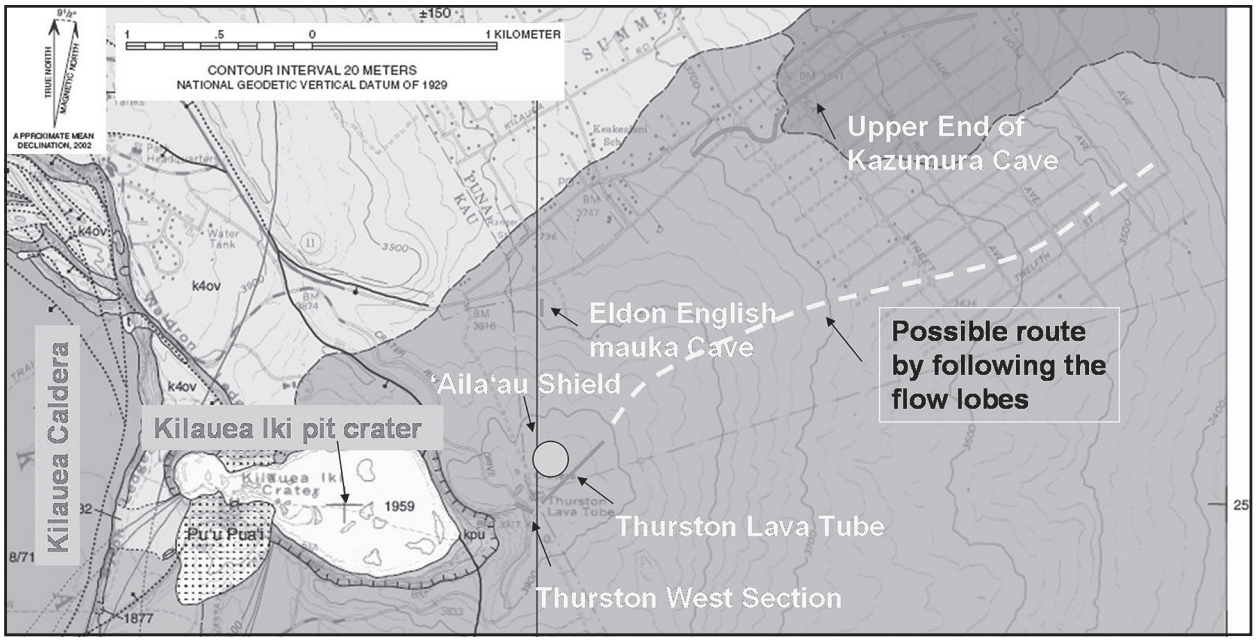

Figure 3: Modified clip of USGS Kilauea geological map (NEAL and LOCKWOOD, 2004).

Lava Cave	Total length, km	Main passage length, km	End-to-end length, km	Sinuosity	Vertical extent, m	Slope deg.	Volcano
Kazumura Cave[1]	61.0	41.86	32.1	1.30	1101.8	1.51°	K, A
Keala Cave[2]	8.60	7.07	5.59	1.25	186	1.51°	K, A
John Martin/Pukalani System[3]	6.26						K, A
Eppersons Cave[4]	1.93	1.13	0.80	1.41	-	-	K, A
Thurston Lava Tube[5]	0.490	0.490	0.432	1.13	20.1	2.4°	K, A
Ainahou Ranch System[6]	7.11	4.82*	4.27	1.13	323	3.83°	K, A?
Keauhou Trail System[7]	3.00	2.27	1.99	1.13	213.3	5.36°	K, A?

Table 2. Topographic data of some of the tubes from the Ai-la`au flows. 1: ALLRED et al., 1997; 2: KEMPE 1997; 3 4; 5: unpublished data; 6: WOOD, 1980; 7: KEMPE et al., 1997. Volcano: K, A: Kilauea, Ai-la`au.

bulge at the NE of the Shield. The upper end of Kazumura runs in parallel, slightly less than a kilometer further to the north near the highway (ALLRED et al., 1997). This makes is unlikely that both caves belong to the same lava flow, unless the northward turn of Thurston shortly before its end indicates a sharp bend in the tunnel system (Fig. 3).

When comparing the sinuosity and slope of the cave with those of others in the flow field (at least for those for which we have data) Thurston shows similar characteristics (Table 2).

When inspecting the cave, a series of questions arise. For the casual observer the cave appears strangely dull, without many detailed features. Also the typical smooth, continuous glazing found in lava tubes is mostly missing. And finally the cave ends at a kind of lava "sump," which poses quite a puzzle (Figs. 1 and 4).

Figure 4: Thurston Lava Tube ends in a Chamber where the ceiling sinks below the floor that appears to consist of material up-welled from below forming a low bulge.

3. Features of the cave

Nevertheless that cave shows several interesting details like two lava falls (Fig. 5), below which the cave is wider and higher than above. Looking mauka (uphill) the undercutting of the former bottom sheet and of the wall linings is noticed. Ledges bending downward at the lip of the lava fall can be followed for some distance upstream, indicating that the final flow in the cave did not fill it entirely.

Figure 5: The first lava fall viewed mauka. The undercutting of the bottom sheet is clearly visible.

The cave also features ceiling cupolas of different sizes. POWERS (1920) noted that the cupolas become larger and wider along the tube. For those nearer to the entrance he suggested that they resulted from a "blow torch effect," i.e. from the melting of the primary ceiling by hot gas jets escaping from the flowing lava beneath. However, the blow torches should have been moving makai (downhill) with the flow and elongated cupolas or ceiling notches should have been formed. Some of the cupolas are elongated, others not. For the cupolas further down, Powers suggested breakdown as their cause, the blocks of which have been carried out of the tube during its activity. Most of the cupolas have received a new lining and some have horizontal rims, indicating former lava stands. We found (Figs. 1, 2) seven cupolas in the first two thirds of the tourist section and eight in the beginning of the wild section. None occur further in and they do not become wider. There are smaller and more cylindrical and larger and more elongated cupolas in both sections. All of them occur in the center of the passage. This, and their forms, speak (at least for the cylindrical) against their origin as breakout cupolas. We suggest that they are former hornitos, vents in the primary ceiling that allowed hot gases and spatter to escape. Thin secondary overflow, reinforcing the roof may have buried and closed them in the final phase of the eruption.

POWERS (1920) suggested that the "Great Hall" (Figs. 1, 2), shortly before the end of the cave, is actually a window caused by breakdown of the intervening ceiling in between and up into another tube above Thurston, again an observation that we could not corroborate.

The floor is almost devoid of flow lobes, indicative of very hot conditions when the flow stopped, not allowing sufficient cooling of the surfaces skin to be rippled. Many cooling cracks are noticed in the makai section extending into the floor deeper than the thickness of the bottom sheet of the cave (which is just a few cm thick), again indicative of very hot conditions far beyond the bottom sheet of the cave. There are also a significant number of squeeze-ups (termed "volcanoes" by POWERS, 1920) (Fig. 6), partly related to the cracks, forming very flat, glazed mounds, again indicating very hot conditions when they where extruded from the underlying lava by the expanding gas during solidification. On the walls many runners occur, partly "bleeding" in series out of horizontal partings in the wall.

Figure 6: One of many low, dome-and-cone-shaped mounds on the floor that seem to be squeeze-ups from below.

Overall, ceiling, walls and floor are irregular on the centimeter scale. The millimeter-thick, continuous, and shining glazing, so typical for most lava caves, is missing, possibly being destroyed by the ongoing degassing of the lava surrounding the cave after the evacuation of the cave, again speaking for sustained and very hot conditions. Also the typical cylindrical lava stalactites are missing, save for short stumps. They may, however, have been removed over the years by visitors since the initial description of the cave talks of a "rich decoration" (see above).

4. Discussion of speleogenesis

A lava "sump" seals the cave makai (Fig. 4) and it appears as if lava welled up from underneath (POWERS, 1920,

"convex" surface). Flow lobes or ropy textures are missing which would indicate that the flow in the cave just filled it to the roof at a low spot. Thus it is conceivable that Thurston represents an upper level of a much larger conduit system, as suggested by HALLIDAY (1982), stating that the cave is part of a "Jameo System," i.e. a multi-level lava conduit. If this is so, then the two caves were above each other and not created by down-cutting and consecutive formation of a secondary ceiling separating a canyon-like tunnel. Such separations are clearly later additions and can be recognized at cross-sections (KEMPE, 2002). Inspection of the lava below the entrance of the cave shows that floor is not a secondary ceiling. If Thurston belongs to a multi-storied cave system, then it must have formed during an increase in eruption volume, exceeding the capacity of the lower tube and establishing a contemporaneous upper conduit above it, which, when lava supply subsided, fell dry and was sealed at the end by lava up-welled from the lower conduit.

Another feature speaks also against the hypothesis that the floor of Thurston is a secondary ceiling and that is the presence of the two lava falls. They indicate that the floor formed by active flow because these falls show clear signs of their back-cutting (Fig. 5). Thus, if we assume the presence of multi-storied conduits, then they must have been established by consecutive overflow events, creating several caves on top of each other. Such situations have rarely been documented. Parts of Kulakai Cavern could represent such a cave type, based on the geological mapping of its surface by our group.

On the far side of the collapse crater another section of cave was found, as reported by W.R. Halliday and J. Martin (HALLIDAY, 1992) (Fig. 3). It has a NW–SE direction, at a 90° angle from Thurston. Its relation to Thurston and to a presumed multi-story tube system remains unclear from the available map (HALLIDAY and MARTIN, unpublished).

The correct interpretation of the nature of Thurston lava tube is intimately associated with the question of where the Ai-la`au vent exactly was. HOLCOMB (1987) suggests it was at the eastern notch of the Kilauea Iki collapse structure. There vertical lava sheets are preserved. However, the topographic high is to the east of it, above Thurston Lava Tube (Fig. 3). Therefore it is conceivable, that Kilauea Iki served as a gas vent, while a second vent produced the final lava flows. It could have been below the Kaluaiki collapse crater. Otherwise one would need to explain how the topographic high came about. This question and some of the others posed in this paper, suggest that we do not understand the speleogenesis of Thurston Lava Tube very well, in spite of the fact that it may be the most visited and the most often mentioned lava tube world-wide.

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ARCHAEOLOGY AND ^{14}C DATES OF THE KAMAKALEPO/WAIPOULI/ STONEHENGE AREA, NAHALEHU, HAWAI`I

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The archaeology of Hawaiian lava caves is poorly documented. Here we report about a small area south of Na`alehu, Hawai`i, near the coast. On aerial photos, a small outcrop of ash is clearly visible. It belongs to the agriculturally valuable "Pahala Ash" sites that sustained early Hawaiian populations. The area called Kamakalepo is just east of South Point, where similar soils provided for some of the earliest settlements on Hawai`i. It contains unique archaeological features both above and below ground and was studied by the authors over the last several years. We now have two ^{14}C carbon dates setting time constrains on the time of settlement in the Kamakalepo area.

A large cave system consisting of four sections of a once much longer tunnel in Mauna Loa lavas was used extensively by the native Hawaiians. The system is entered through two pukas (ceiling collapses): Lua Nunu o Kamakalepo (Pigeon Hole of the Common People) and Waipouli (Dark Waters). Both pukas give access to uphill (mauka) and downhill (makai) caves, totalling 1 km in length. Two further pukas belong to the system, "Pork Pen Puka" (mauka of Lua Nunu) and "Stonehenge Puka" (makai of Waipouli) for which no local names are known. Pork Pen Puka is a depression set into the roof of Lua Nunu Mauka Cave, the bottom of which is a secondary ceiling to the cave below. Stonehenge Puka is a large root-less vent with rafted blocks around its perimeter, 60 m x 40 m wide and up to 20 m deep.

Underground, the Lua Nunu caves are the ones used primarily. The main features are two large defensive parapets across the cave erected from breakdown blocks. The wall in the Makai Cave, 40 m inside the entrance, collapsed mostly but the one in the Mauka Cave, approximately 60 m into the cave, is well preserved. It is approximately 2 m high and up to 1 m thick; because it was erected on breakdown it reaches 3.7–5.5 m above the floor. It has a length of 25 m from wall to wall with a doorway slightly off the middle. The wall could be defended from a platform behind by throwing sling stones (polished beach pebbles) and spears. Further in, Bonk counted 102 sleeping platforms, extending well beyond the zone of light. Charcoal, seafood shells and some fish bones can be found, suggesting that the place has in fact served its purpose. In the far back of the cave, we opened a crawl, giving access to more than 100 m of additional cave. Even here we found charcoal bits on the floor, suggesting that the Hawaiians had already explored this section, albeit by a now collapsed crawl. A piece of charcoal was dated to 282±31 years. This places the exploration of this section of the cave at around A.D. 1600 (1σ cal A.D. 1523–1656, 2 σ cal A.D. 1495–1793), i.e., into the time of the highest population density of the pre-discovery Hawai`i.

Both of the Waipouli Caves show little signs of Hawaiian presence. Mauka, just a few bits of charcoal and seafood shells are found. The floor is too rough to be of any use. The makai part is filled by brackish water that is caped by freshwater at times of high groundwater flow. Underwater, at a depth of 10 m we recovered a whale vertebra, now dated to 524±50 years (1σ cal A.D. 1327–1439, 2σ cal A.D. 1303–1451). Since the bone may have been washing in from the beach, it would mark a time prior to which the last flow in the area, a black pahoehoe lava, covered the area and closed Waipouli Makai by intruding it from the downhill Stonehenge Puka.

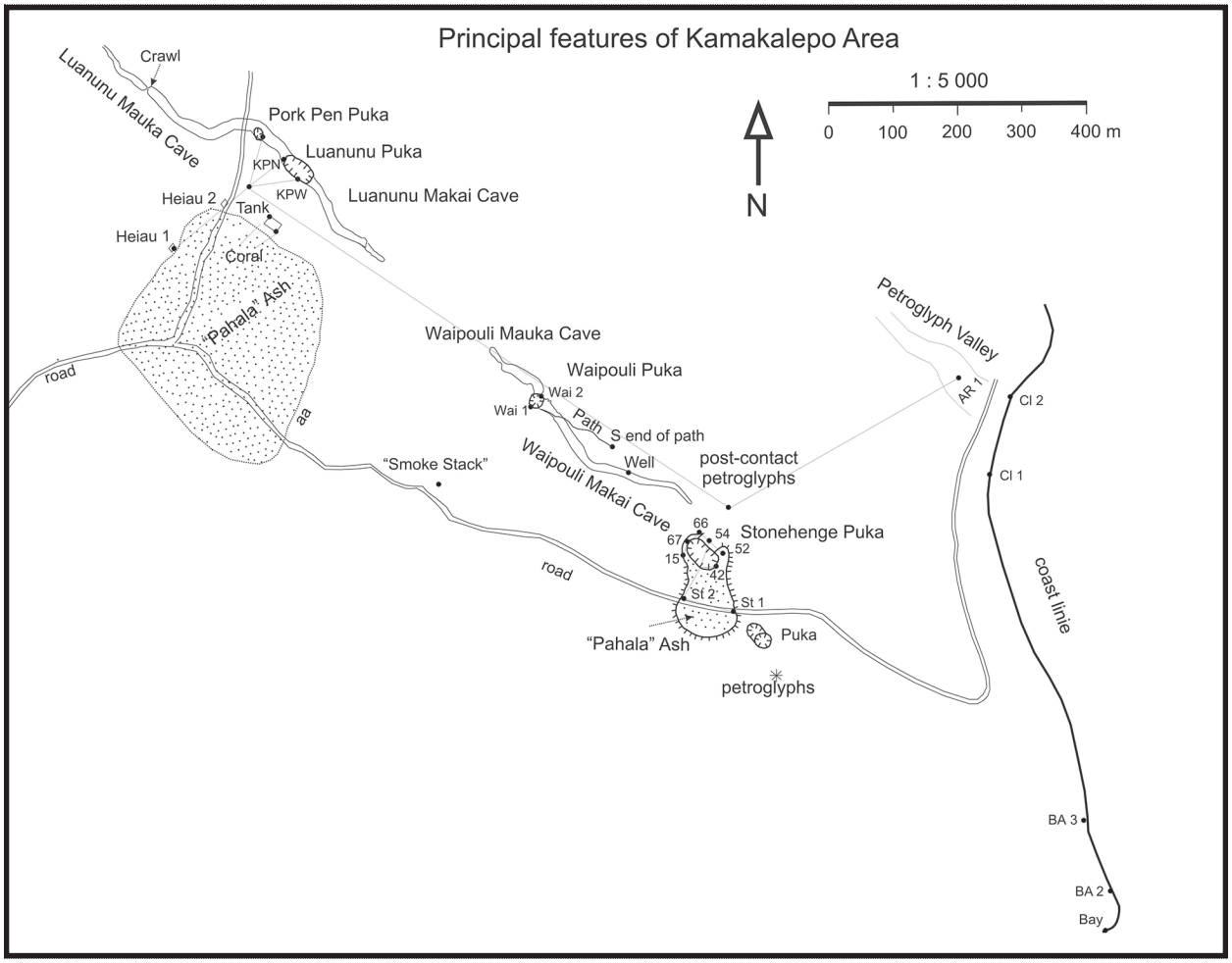

Figure 1: Situation of Kamakalepo area with important landmarks, caves, and their GPS fixes (dots).

Kind	Male	Female	undecided
Simple stick man, hands down	3A2;2A3;2A4; 5A5; 3A7; **Σ=15**	2A2;2A3;1A4; 4A5; 1A6; 2A7; 2A10; **Σ=14**	1A3, 3A3; 1A6; 4A9; 4A10; **Σ = 13**
Simple stick man, one hand up	1A2; 2A7;1A10;Σ = 4	1A5	
Stick man, legs spread	1A1; 2 A7	3A7; 3A10	
Triangular or square bodies		1A1; 2A2;1A3; 1A6; 1A8; **Σ = 6**	
Full head, double line body	2A8	3A4; 1A7; 4A8	1A6; 8A8
Filled frontal		1A6	
Lateral views with outlines			1A4?
Lateral views filled bodies	1A7	1A7	
Monkeys	1A6	1A8	
Rectangular basins			2A1
Others (many lines but unclear)			3A7

Table 1: Classification of petroglyphs (Petroglyph Valley, Kamakalepo) (read: 3A2 = 3 specimens in Area A2).

1. Introduction

East of Southpoint, Hawai'i, and south of Na`alehu is an outcrop of agriculturally valuable "Pahala Ash" forming a lemon-shaped area on aerial pictures. It is one of the sites that sustained early Hawaiian populations (Kirch, 1985).

The area under investigation (Fig. 1), called Kamakalepo, contains unique archaeological features both above and below ground (Bonk, 1967; Kempe, 1999; Kempe et al., 2006a).

A large cave system of a once much longer tunnel in Mauna Loa lavas (Kempe et al., 2006b) was used extensively by the native Hawaiians. It consists of four sections, that can be entered through two ceiling collapses ("pukas"): Lua Nunu o Kamakalepo (Pigeon Hole of the Common People) now overgrown by acacia shrubs and Waipouli (Dark Waters). Both of these pukas give accesses to uphill (mauka) and downhill (makai) caves, all-in-all 1 km in length (Table 1 and Figs. 5 to 8 in Kempe et al. 2006b) Two further pukas belong to the system, "Pork Pen Puka" (mauka of Lua Nunu) and "Stonehenge Puka" (makai of Waipouli) for which no local names are known. Pork Pen Puka is a depression set into the roof of Lua Nunu Mauka Cave, the bottom of which is a secondary ceiling to the cave below. Stonehenge Puka is a large root-less vent with rafted blocks around its perimeter, 60*40 m wide and up to 20 m deep (Kempe et al., 2006b).

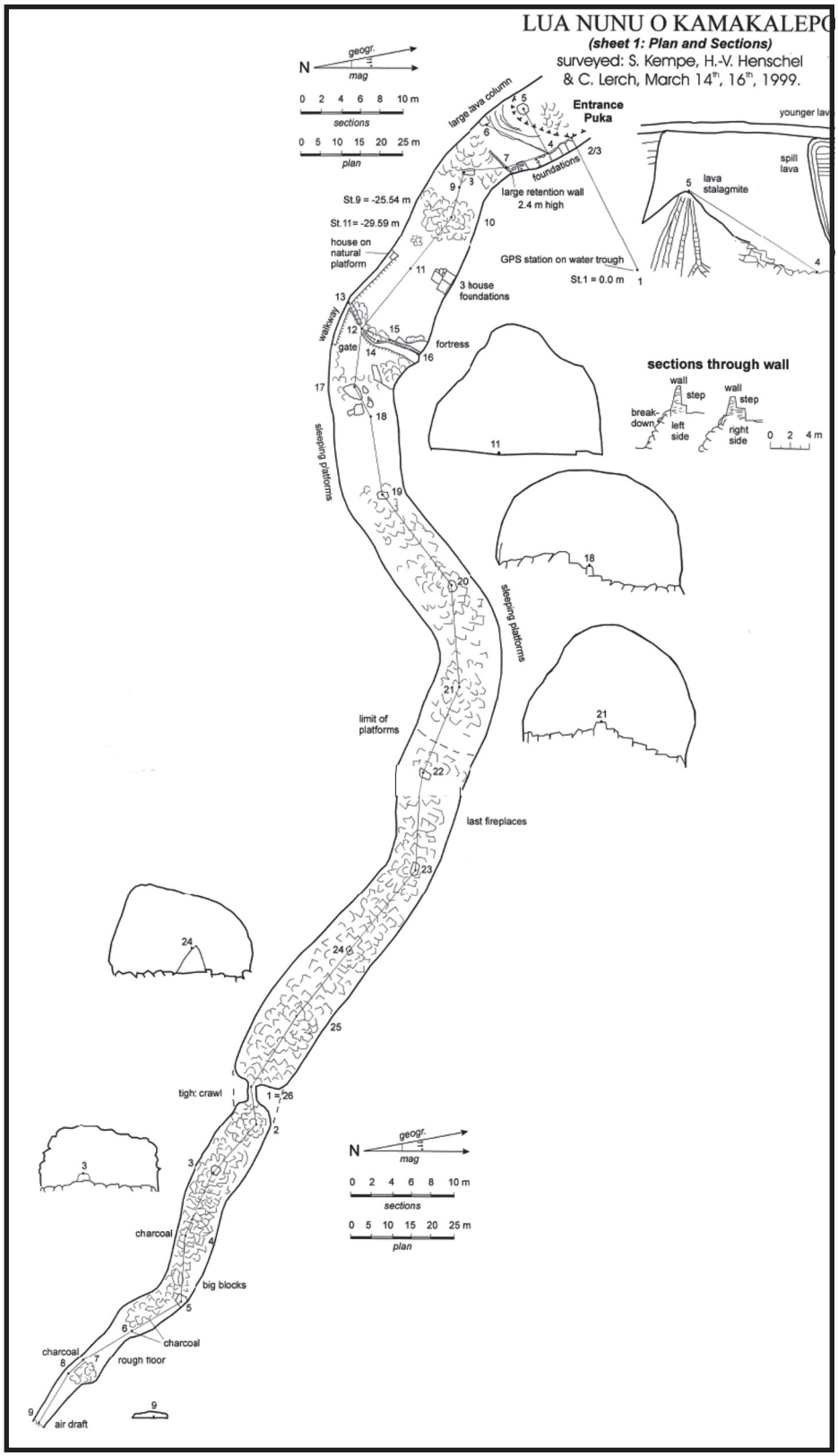

Figure 2: Map of Lua Nunu o Kamakalepo Mauka Cave. Note archeological details.

2. Usage of caves

Underground, the caves of the Lua Nunu are the ones used primarily (Figs. 2 and 3). An old, now mostly obliterated path led down from the northeast rim with the other sides overhanging. Within the puka small outcrops of Pahala Ash exist, possible former field plots or agropits. Retaining walls are found at both entrances providing for level ground, on which foundations of huts are found. In both caves large defense walls were erected by stacking breakdown blocks. The wall in the Makai Cave, 40 m from the entrance, collapsed mostly but the one in the Mauka Cave,

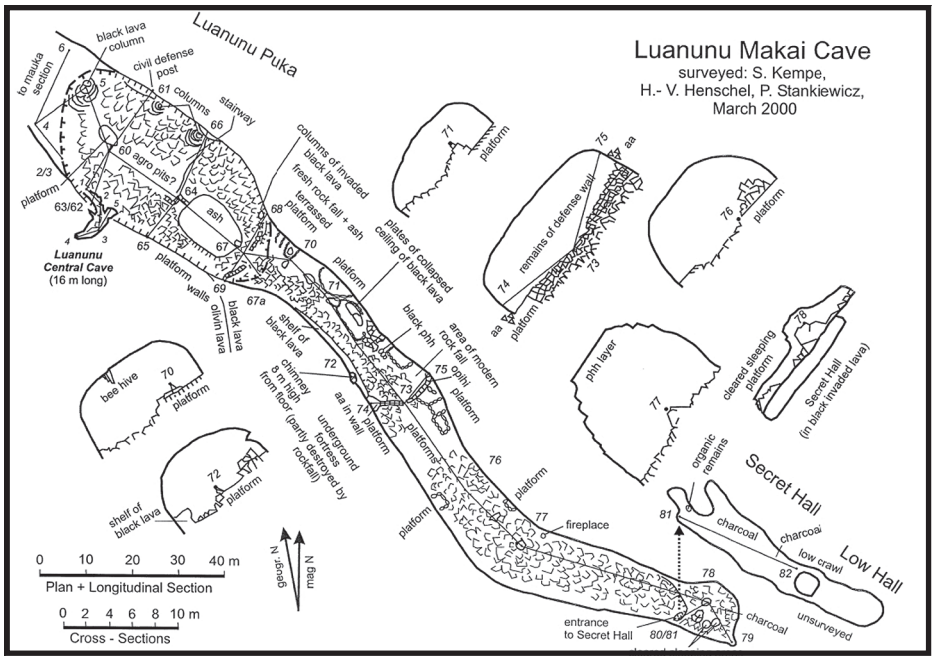

Figure 3: Map of Lua Nunu o Kamakalepo Makai Cave. Note archeological details.

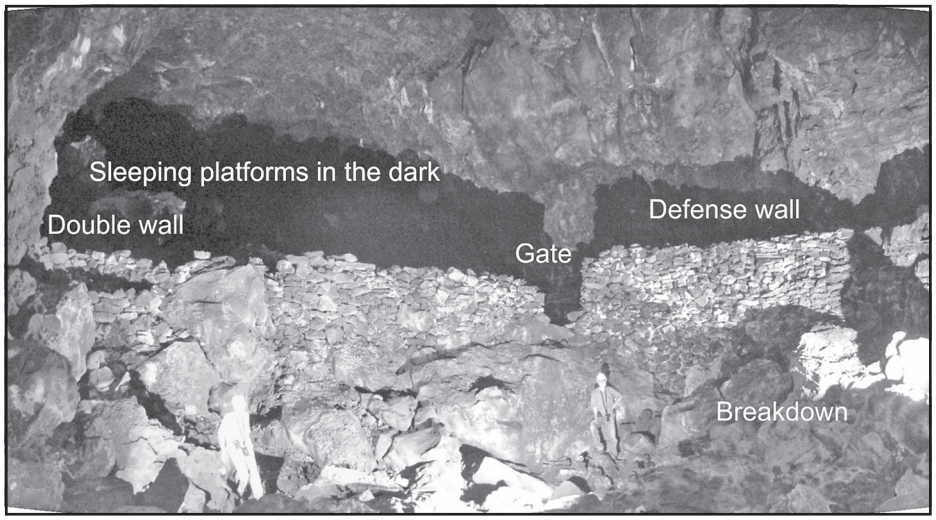

Figure 4: View mauka of the 25 m long defense wall in the Lua Nunu o Kamakalepo Mauka Cave. Note persons for scale and gate at the center of the wall.

approximately 60 m into the cave, is well preserved. It has all the characteristics of a medieval defense wall: It is about 2 m high and up to 1 m thick. Because it was erected on breakdown, it reaches 3.7 and 5.5 m above the floor (Fig. 4). It stretches from wall to wall and, due to its convex-mauka curvature, reaches a length of approximately 25 m (the cave being 23 m wide and 14 m high in its center). A doorway, slightly off center, admits access and platforms behind the wall permit the defenders to throw sling stones and spears at any attacker. Sling stones (wave-worn pebbles) are still found on the floor. While the defenders would stand in the dark, the attackers would be outlined by daylight providing good aims. Behind the wall, Bonk (1967) counted 102 sleeping platforms that extend well into the zone of complete darkness. Charcoal, seafood shells and a few fish bones can be found everywhere, suggesting that the place has in fact served its purpose. Artifacts were collected in 1908 by Meineke and 1967 by Bonk. In the far back of the cave, we opened a crawl, giving access to more than 100 m of additional cave. Even here we found a few charcoal bits on the floor, suggesting that the Hawaiians had already explored this section, albeit by a now collapsed crawl. A piece of charcoal was dated to 283±31 a BP. This places the exploration of this section of the cave at around A.D. 1600 (1σ cal A.D. 1523–1656, 2 σ cal A.D. 1495–1793), i.e. into the time of the largest population density of pre-discovery Hawai'i. Similar dates have now been obtained for charcoal from the Pa`auhau Civil Defence (Kempe et al., 2003): Hd 26237: 270±34 aBP; 1σ cal AD 1524-1792, 2σ cal A.D. 1495-1951; and Hd-26276: 211±32 a BP; 1σ cal A.D. 1650–1951, 2σ cal A.D. 1643–1952) also indicating dates centered to late pre- or early post-contact occupation times.

Underground fortifications have been described from other caves on Hawai'i (e.g., Kennedy & Brady, 1997). An elaborate example is the Cave of Refuge on the Hakuma Horst (Kalapana, Puna District). There the defense function was obtained by narrowing the entrance to the cave to a crawlway that could be entered by attackers only one at a time (Kempe et al., 1993). La Plante (1993) reported about fortifications (defense walls, fortified crawlways) from the Puna District (most probably Pahoa Cave) without giving details about locations or constructional dimensions. Small

defense walls, now crumbled seem to have protected the cave passages below Keala Pit as well (Kempe & Ketz-Kempe, 1997). More data probably exist in internal reports of various agencies without ever having been published.

The Lua Nunu o Kamakalepo Makai Cave has also been fully explored by the Hawaiians. Platforms and fire places extend almost 100 m into the cave. At the makai end, the black pāhoehoe lava that intruded the puka secondarily (see Kempe et al., 2006b) forms a separate, less than a meter high cave. It was also entered by the Hawaiians as bits of charcoal on the floor reveal. We found its entrance closed artificially by rocks, probably to hide the entrance of this chamber of last refuge (see "Secrete Hall" on map, Fig. 3).

Both of the Waipouli Caves show little signs of Hawaiian presence. In the mauka sections, just some charcoal is found and a few bits of seafood remains. The floor is too rough to be of use. The makai part is filled by a brackish water lake that is caped by freshwater at times of high groundwater flow. We found one large beach stone on the steep entrance slope and a whale vertebra mid-lake at a water depth of about 8 m

Both of the Waipouli Caves show little signs of Hawaiian presence. Mauka, just a few bits of charcoal and seafood shells are found. The floor is too rough to be of any use. The makai part is filled by brackish water that is caped by freshwater at times of high groundwater flow. Underwater, at a depth of 10 m we recovered a whale vertebra (Fig. 5), now ^{14}C dated to 524±50 a BP (1σ cal A.D. 1327–1439, 2 σ cal A.D. 1303–1451) (data courtesy of Dr. Bernd Kromer, Heidelberg). Since the bone may have been washed in from the beach, it would mark a time prior to which the last flow in the area, a black pāhoehoe lava, covered the area and

Figure 5: Weathered whale vertebra from the deeper part of the lake in Waipouli Makai Cave.

closed Waipouli Makai by intruding it from the downhill Stonehenge Puka (Kempe et al., 2006b).

The water was pumped up in the 20th Century for cattle. A concrete platform at the entrance is all that is left. Also, further makai an over 20 m deep well was dug through the cave roof and the water was pumped up by a wind-driven pump. Part of its collapsed trestle fell into the well and landed in the water, where it now forms interesting "rusticles."

Stonehenge Puka was also used by Hawaiians: Its southern wall is overhanging and providing a natural shelter. Here a few very small platforms were erected.

3. Above-ground usage

Above ground, the area shows many signs of usage as well. First of all there is a beach stone paved path, giving access to the area from the west (mauka). The area south of Lua Nunu is covered by ash and could have been used for agriculture, explaining the presence of the underground settlement. At the western rim of the ash plain, on the overlaying bare lava, we found two small heiaus, compact stone platforms used either for dwelling huts or religious purposes (Fig. 1 for location). The Pork Pen Puka has stone walls along its perimeter and throughout its centre, suggesting that it was used to keep pigs. At the eastern side of the ash outcrop, there is a rectangular structure build from pāhoehoe plates which probably also was a pen either for pigs, or for goats and cows if erected after contact. Nearby, a shallow cave was found, showing also signs of occupation.

Paths connected the Lua Nunu with Waipouli (mostly overgrown now) and led towards the coast from Waipouli eastward. At the end of the path a large carbonate-cemented beachrock was placed, obviously a well-visible signal to guide the traveler to the beginning of the path across the Waipouli a`a.

4. Petroglyphs

Within the studied area, three petroglyph sites were found. The one furthest south has mostly animal figures. The second one, north of Stonehenge, is composed of post-contact petroglyphs: It displays a pentagram, a large cross made from five squares each of it inscribed with a + and a X, and a saber with a two line inscription reading: "KA IEIE PALA" and "IKA UA NOE" (the Mellow IeIe, a plant, and Strong Misty Rain; possibly the names of two lovebirds).

To the north, at the seaward end of a shallow valley, ten groups with almost a hundred petroglyphs occur within an

area of 50*50 m. There simple stickman occur next to more complicated full body pictures, both in frontal as in lateral views. Two of the larger figures have long tails, possibly pictures of monkeys (one of them clearly a male specimen) (Fig. 6), thus placing the petroglyphs into the early post-contact time. Marks made by sharpening tools occur as well as many pound marks, some almost obliterating some of the glyphs. A total of 92 glyphs were identified that distribute among several types (Table 1).

Figure 6: The picture of a male primate being with a long tail, possibly a monkey brought by sailors to the island in the early post-contact period.

Many different styles are present: The group of simple stickmen with arms and legs bend at right angles dominates; male and female glyphs occur with a similar frequency (Fig. 7; Table 1 first line). One of the male stickmen has two lines extending down its head, like indicating long hair. Five stickmen have one hand raised as if in greeting. A few stickmen have simple spread legs like in an inverted "Y." The triangular-bodied figures appear all without a penis and could therefore reasonably be labeled as female. The figures with open circle heads and a double-lined body have a variety of hands, mostly with three fingers, but one even has five fingers and toes. Interesting are figures shown in side-view, among them a large figure in Area 8. The two ape-like glyphs are among the largest. One, with a penis, is shown laterally (A6), the other (A8) in frontal view with a long thin tail between its legs. Otherwise, no other animal pictures are seen, except a possible goat head (triangle and two curved lines).

Overall, the site seems to be restricted (with the exception of the two monkeys and the goat) to glyphs of humans, both female and males. Circular depressions and rings are missing, so prominent in other Hawaiian petroglyph sites, and in spite of the proximity to the sea, no marine animals are depicted (Cox & Stasack, 1977).

Area 9 features a vertical slab which is pounded upon forming a spot about 1 m in diameter (Fig. 8); the surfaces

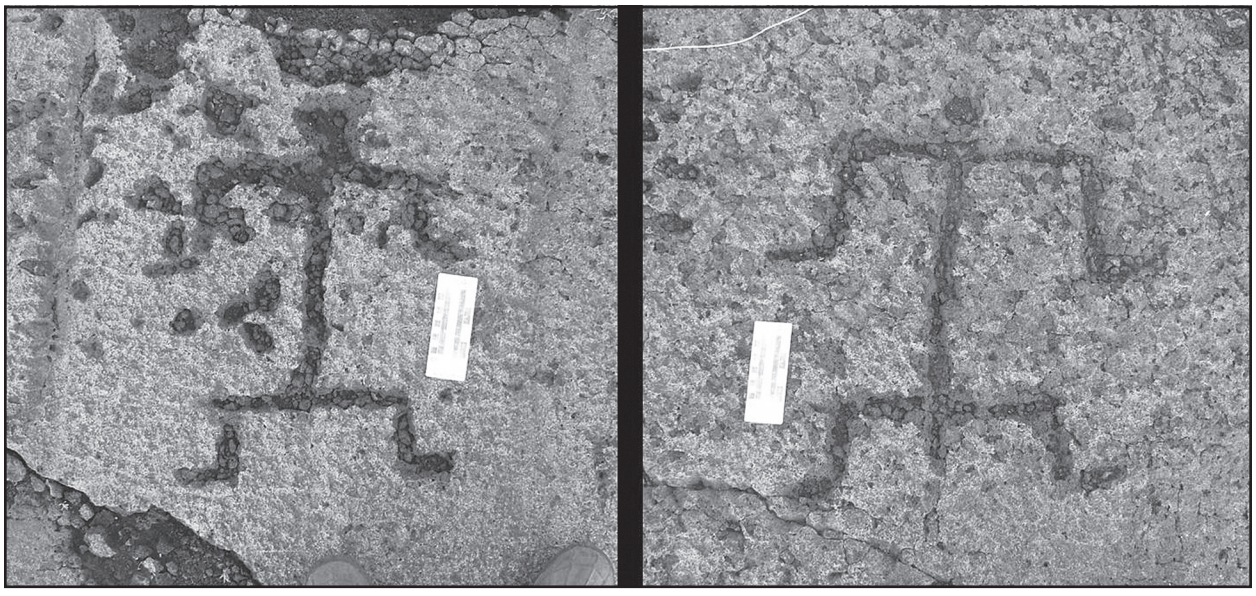

Figure 7: Examples of simple stickmen petroplyphs, right with a penis (male) left without (female).

Figure 8: This near-vertical slab features multiple pound-marks, possibly a training target for shooting sling-stones.

of the inclined slabs below are also heavily abraded. Both slabs contain traces of almost erased stickmen. We interpret this area as a sling-stone practice target. Behind the slabs, an approximately 5 m long cave extends, which contains four bamboo poles of unknown age.

The valley is also heavily impacted by Hawaiian quarrying: all along the rims of the valley the upper lava layers have been dug up, partly down to 2 to 3 m, and piles of broken rocks litter the perimeter of the quarries. Quarrying has been going on also in the area between the Petroglyph Valley and Lua Nunu. Many of the sites display longitudinal grooves caused by grinding. What exactly the rock was quarried for remains unknown since no intermediate products were noticed.

5. Conclusions

The archeological evidence - specifically the number of sleeping platforms behind the defense walls - suggests that the Kamakalepo area sustained a sizeable population. At peak times it may have counted hundred or more people. Clearly the area was still settled in early post-contact times as illustrated by petroglyphs of monkeys, a saber, a Christian (?) cross and an inscription. Writing was introduced to the islands only after 1820. The only directly accessible water in the area is the lake in Waipouli. Paths leading towards it suggest that it was used by the Hawaiians intensively, in spite of the fact that not much archeological evidence is found inside. Any stairways or walls may have been obliterated either by later rock fall or by the farmers in the early 20th century. This water supply is, however, treacherous and in times of drought the water turns brackish, salty enough to make it even unfit for cattle. In times of drought drip water in the caves ceases also, which is, in other areas of the island, a major source of water (compare Martin, 1993; Kempe & Ketz-Kempe, 1997). Therefore the Kamakalepo settlement may have been sustainable under a different climate condition, such as during the Little Ice Age in the 17th and 18th century, when more groundwater may have been available. The dated charcoal (1σ cal A.D. 1523-1656, 2 σ cal A.D. 1495–1793) from one of the caves substantiates this interpretation. Because the dated whale bone was found deep inside the lake of Waipouli it may not be an artifact at all. Its age (1σ cal A.D. 1327–1439, 2 σ cal A.D. 1303–1451) may mark the time when it was washed into the Waipouli tunnel from the sea. Thus it indirectly gives a date after which the tunnel was closed by the black pāhoehoe flow that invaded and closed the seaward section of the Waipouli tunnel via Stonehenge Puka.

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JORDANIAN LAVA CAVES AND THEIR IMPORTANCE TO UNDERSTAND LAVA PLATEAUS

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The Arabian plate is covered by large Cenozoic (Oligocene-Quaternary) basalt fields, the "Harrats", over a north-south distance of about 3000 km from Jordan and Syria through Saudi Arabia to Yemen with an estimated volume between 10^3 and 10^5 km^3. These are among the largest basalt plateaus worldwide. We study the Jordanian Harrat Al-Shaam, the most northern of these plateaus that covers about 45,000 km^2. It forms a gently undulating plateau dotted with tephra cones, shield volcanoes, pressure ridges and crossed by a few, up to 80 km long dikes. The, with < 4°, northwest-southeast dipping plateau drops from approximately 1100 m to 700 m at Al-Mafraq and to 550 m asl in the Al-Azraq area. It forms a succession of flow sheets, the youngest of these is over 400 ka old (Al-Fahda area). The Harrat is covered by a 1-2 m thick loess layer that has been washed into the depressions forming playas (locally known as Qa'). In these lavas we explored, surveyed, and studied a total of 17 lava caves since September 2003. 2824 m of passages were surveyed as of spring 2008. Nine of these are lava tunnels, six are pressure ridge cavities and two are of doubtful origin. The discovery of these lava tunnels is surprising considering their old age and the fact that the loess is easily washed into caves filling them eventually. The presence of the lava tunnels underscores the fact that the Harrat consists to a large part of tube-fed pahoehoe, thus explaining its overall low slope.

1. Introduction

The Arabian plate is covered by seven larger and several smaller Cenozoic (Oligocene-Quaternary) basalt fields, the "Harrats." They stretch over a north-south distance of about 3000 km from Jordan and Syria through Saudi Arabia to Yemen. The estimated volume of eruptive material equals to between 10^3 and 10^5 km^3. These wide-spread, poorly studied basalt fields are considered to be among the largest of predominately alkali-olivine basalt plateaus in the world (e.g., AL-MALABEH, 1994).

Our group studies the lava caves contained in the Jordanian section of the Harrat Al-Shaam, the 700 km long, most northern of these plateaus that covers about 45,000 km^2 (approximately 25% of the Arabian Harrats) (Fig. 1). This Harrat is in Jordan approximately 220 km wide in the N and 30–50 km in the south. Geomorphologically it forms a gently undulating lava plateau dotted with prominent tephra cones, low shield volcanoes, numerous pressure ridges and crossed by a few, up to 80 km long eruptive fissures. The plateau generally dips to the south and southeast, starting at an elevation of approximately 1100 m (asl) along the Syrian border and dropping down to 700 m at Al-Mafraq and to 550 m in the Al-Azraq area. The overall slope is at most 4°.

The structure of the basalt plateau is a succession of flow sheets which form stepped cliffs along wadi walls or faults. The youngest of these flows are over 400 ka old (Al-Fahda area) (TARAWNEH et al., 2000). It, and the other younger lava fields, does not show wadi incision yet, while the older flow series are heavily incised. The Harrat is covered by a 1–2 m thick loess layer that has been washed into the depressions forming playas (locally known as Qa') giving the less incised areas a mottled appearance.

2. Lava Caves

In these lavas we explored, surveyed and studied a total of 17 lava caves since September 2003. 2824 m of passages were surveyed as of spring 2008 (KEMPE et al., 2008) (Table 1).

Of the total 1,486 m, or close to 53%, was surveyed in September 2005, among them the 923.5 m long Al-Fahda Cave, currently the longest cave in Jordan. Eight of the lava caves are lava tunnels. One cave (Treasure Pit) is pit dug by treasure hunters that probably leads into a sediment-filled lava tunnel. Six caves are pressure ridge cavities and two caves (Beer Al-Wisad and Uwaiyed) are of unusual origin.

2.1 Lava tunnels

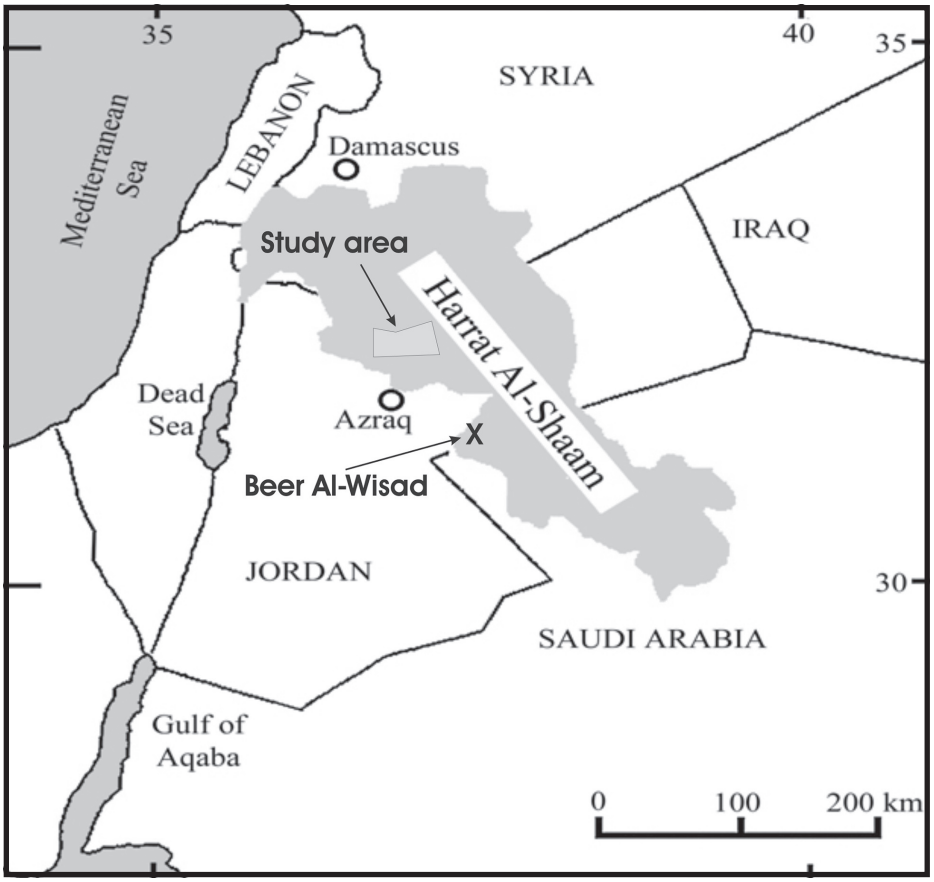

Figure 1: Map of the Harat As Shaam Lava field in the north of the Arabian plate.

Al-Fahda ("the lioness") Cave (AL-MALABEH et al., 2006) was named after the local name for one of the youngest lava fields (K–Ar age 0.46 ± 0.01 Ma sample HAS-7; TARAWNEH et al., 2000) in the Harrat. It was first mentioned without any speleological details by HELMS (1981, p.138) as El-Mughara in connection with the investigation of the famous Bronze Age desert city Jawa. Helms described a channel that leads to the entrance of the cave, apparently dug in an attempt to store water in times of plenty in the cave for times of need. This channel led to the rediscovery of the cave by the second author, who followed it from Wadi Rajil (830 m asl)

Name of Cave	Type	Length m	Depth m	Hyena presence
Al-Fahda Cave	Lava Tunnel	923.5	6.7	+++
Al-Badia Cave	Lava Tunnel	445.0	17.2	++
Hashemite University Cave	Lava Tunnel	231.1	10.0	-
Al-Ameed Cave	Pressure Ridge	208.0	4.0	++
Dabié Cave	Lava Tunnel	193.6	1.8	+++
Abu Al-Kursi East	Lava Tunnel	153.7	12.2	++
Kempe Cave	Lava Tunnel	139.4	11.3	+++
Al-Howa	Lava Tunnel	97.1	10.8	-
Obada Cave	Pressure Ridge	90	3.4	++
Al-Hayya Cave	Pressure Ridge	81.3	4.2	+++
Abu Al-Kursi West	Lava Tunnel	77.1	8.1	++
Azzam Cave	Pressure Ridge	44.1	4.2	-
Al-Ra'ye Cave	Pressure Ridge	42.0	3.5	-
Dahdal Cave	Pressure Ridge	28.9	0.0	+
Beer Al-Wisad	Pit (unknown)	11.4	11.5	-
Uwaiyed Cave	Upward stooping (?)	11	3.1	+++
Treasure Pit	Tunnel ?	7.2	5.8	-
Total		2,824		

Table 1: List of presently (spring 2008) surveyed lava caves in Jordan (altered after KEMPE et al., 2006b).

Stations	Horizontal	Length m	Stations		m
2-54a	Main survey downslope	488.60		End-to-end (as the crow flies)	**684.0**
8-11	Back of entrance	18.68		Sinuosity (771.03/684)	1.13
19-22	To second entrance	14.46	2-54a	Vertical (entrance to deepest point)	-6.74
50-51a	W-passage of terminal split	28.45	71-54a	Vertical extent of Main Passage	-8.41
4-5	Connection	6.05	71-54a	Horizontal length	755.12
5-71	Upslope passage	266.21	**Slope 1**	slope (°) ($\tan^{-1}$ (8.41/755.12)*	0.64°
67a-79	Mahmoud's Test Passage.	101.07	**Slope 2**	slope (°) ($\tan^{-1}$ (8.41/684)	0.70°
Total		**923.52**	**Width**	Maximal at St. 8	17.5
	Main Passage length			Minimal at St. 64	3.55
4-54a	Downslope passage	482.86		Mean of main passage (39 stations)	7.51
4-67a	Upslope passage	187.10	**Height**	Maximal St. 14	4.67
67a-79	Mahmoud's Test Passage	101.07		Mean of main passage (39 stations)	1.21
Total		771.03			

Table 2: Survey results of Al-Fahda Cave (AL-MALABEH et al., 2006).

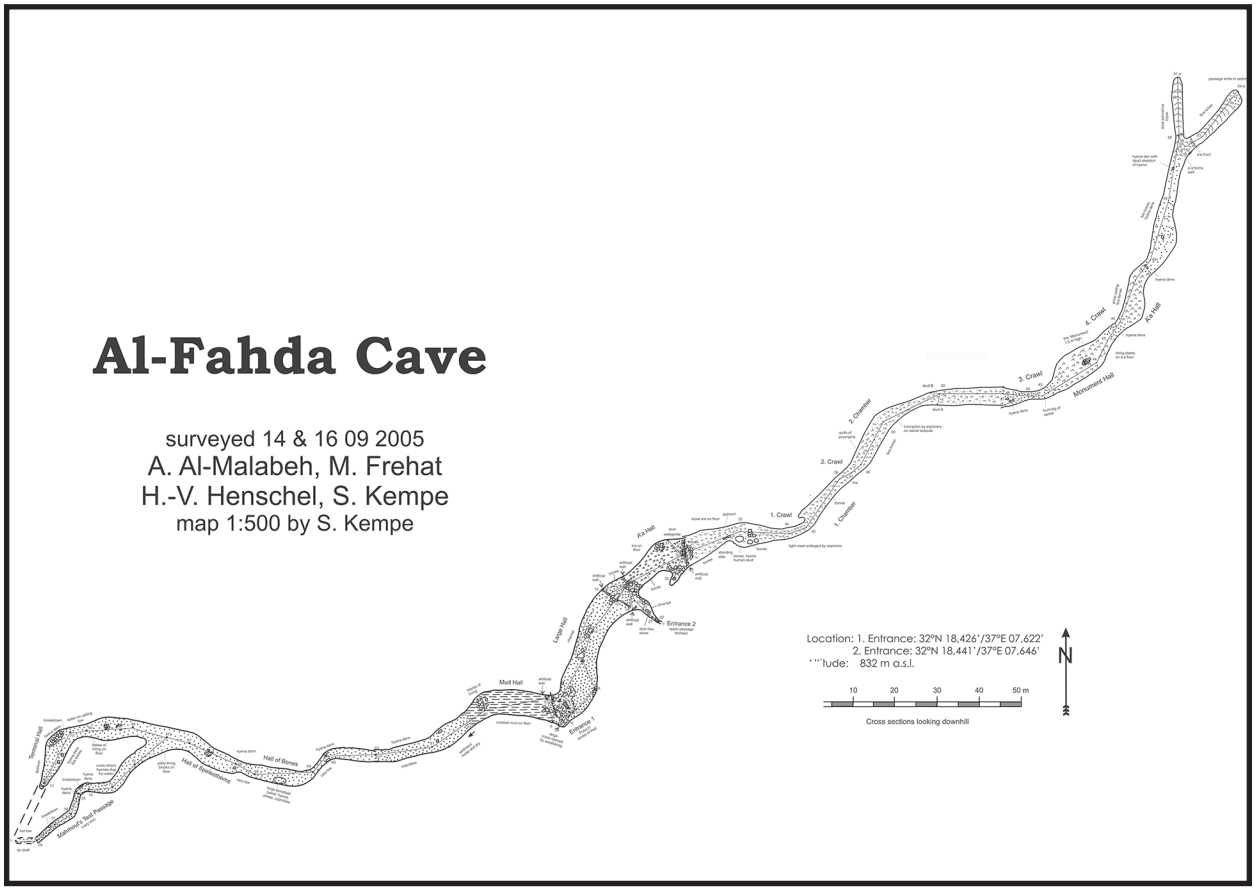

Figure 2: Map of Al-Fahda Lava Cave, longest lava cave in Jordan.

in the north downslope to the main entrance (730 m asl) (AL-MALABEH et al., 2006) and surveyed by us in 2005 (Table 2; Fig. 2). The cave is also known under the name of Khsheifa Cave and was surveyed in parallel by FRUMKIN et al. (2008) yielding astonishingly similar results (their length 920 m).

The cave has a very low slope, according to our survey of about 0.7°. Such a low slope is typical for tube-fed pahoehoe flows. Al-Fahda Cave is unusually wide but very low and has

a very flat floor (at least were the rock floor is visible) (Fig. 3). It appears that this was caused by a later invasive flow filling the lower part of the tunnel. It shows a blocky surface and ends in two flow lobes shortly before the cave itself ends. It remains unclear if this fill is autochthonous, i.e, generated within the tunnel as a terminal slump of a higher viscosity, or allochthonous, i.e. caused by an invasion of a later flow of the Al-Fahda flow field through a ceiling hole (above the current accessible section of the cave). The main entrance to the cave today is through a late central ceiling collapse, exposing a cross section through the primary roof. It is composed of two relatively thick layers, in contrast to other caves that have up to 12 sheets in the primary ceiling (in case of Abu Al-Kursi) (for a more detailed study of the cave see AL-MALABEH et al., 2006).

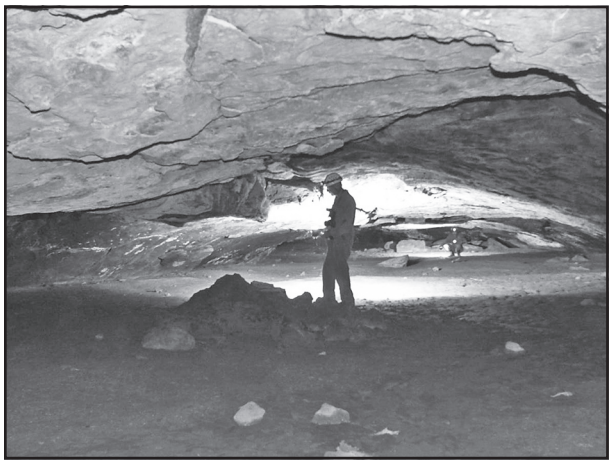

Figure 3: View up-slope into Al-Fahda Cave from the entrance. Note flat, sediment covered floor and low and wide character of the tunnel (persons for scale).

Hashemite University Cave is speleologically interesting also; it is reached through a collapse hole at the crest of a ridge. There the primary, 7 m thick roof is exposed consisting of only three pahoehoe layers. The uphill passage running NW is blocked by breakdown but from the north another low passage filled with sediment joins. The downhill tunnel is 180 m long before it opens up to a nearly circular room approximately 20 m in diameter. There, the cave ends in a lava sump. In a way, this is similar to the terminal lava sump of Thurston Lava Tube (see KEMPE et al., this volume). It poses a structural riddle since one would expect that the back-up of the residual flow in the tunnel should close the cave at a narrow point but not at a wide passage. One possible solution could be assuming that the floor is a secondary ceiling (KEMPE, 2002). A blowhole, situated near station 26, indicates that there could be an open passage underneath, giving some credibility to this hypothesis.

In case of Kempe Cave, we can identify the source volcano for the first time in Jordan (Fig. 4) (KEMPE et al., 2008). It is a low shield volcano in between larger stratovolcanoes. The crater is 120 m across and the rim is very even, suggesting that it once held an overflowing lava lake. The slope between crater (976 m asl) and cave (936 m) is only 1.2°. The cave itself (Fig. 5) is very low and curves around in half-circle; it is the most sinuous among the caves yet explored. Due to the fact that it is the cave furthest east and therefore the driest it also contains unusual speleothems, among them curvy gypsum flowers.

2.2 Pressure ridge caves

A group of caves not showing any clear direction of slope nor any signs of horizontal flow, is grouped as “pressure

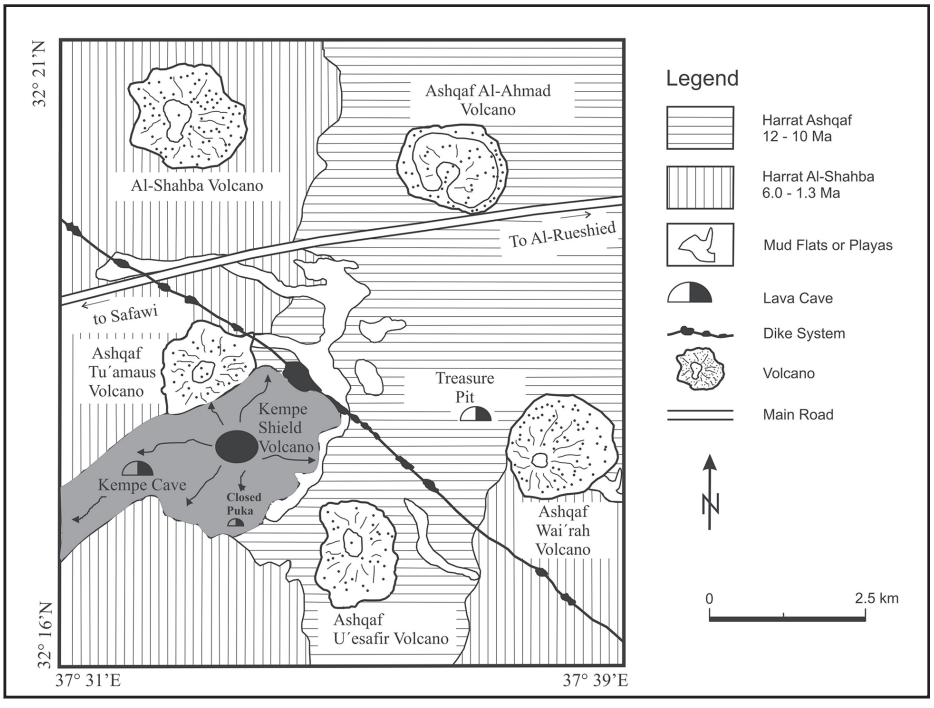

Figure 4: Geological map of the Kempe Volcano (Map by Al-Malabeh and Kempe based on Field observations and Google Earth images).

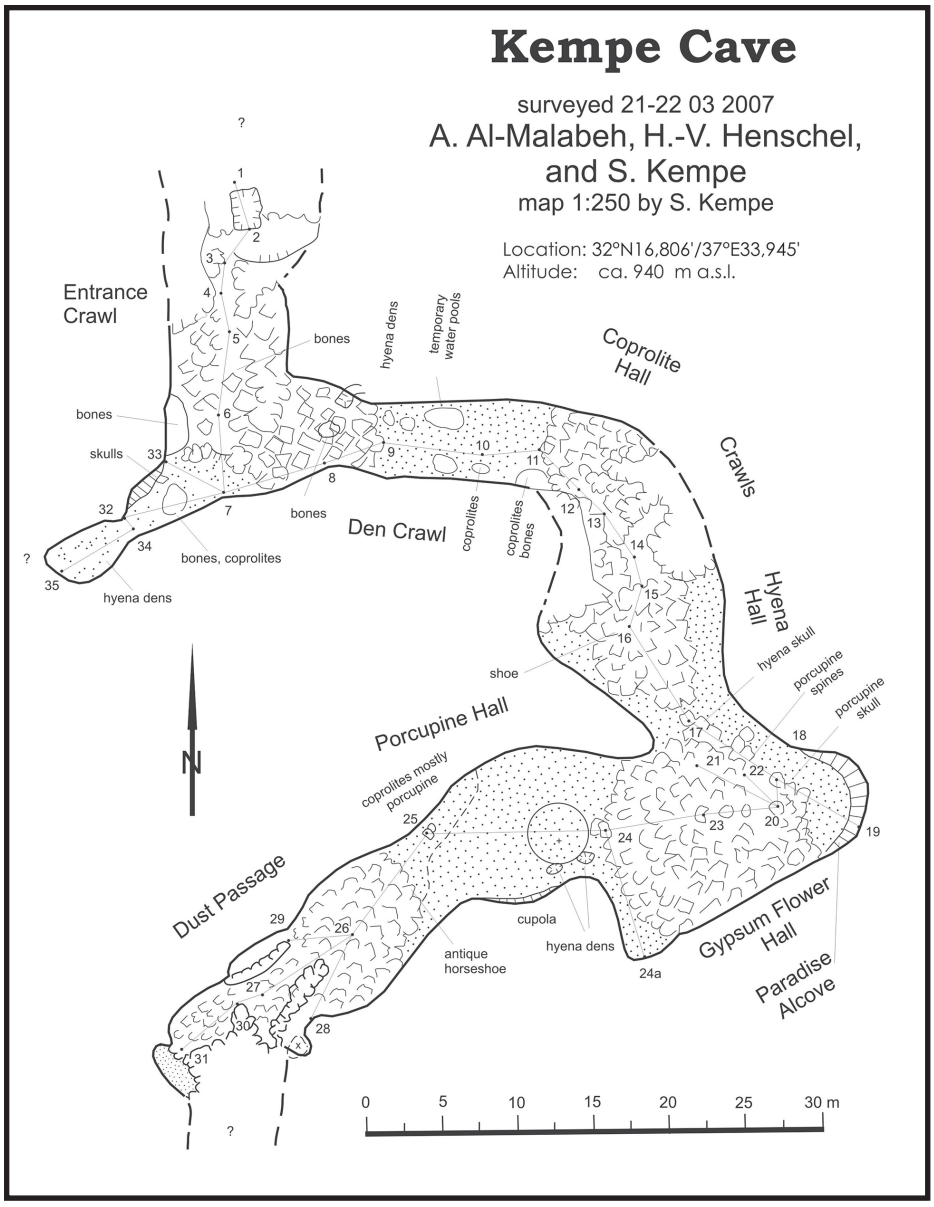

Figure 5: Map of Kempe Cave.

ridge caves." They can be quite long (Fig. 6, map of Al-Ameed Cave), are very wide and low in general and can have several branches, petering out at their ends. Similar caves are kwon from Hawaii, but are not well documented. Pressure ridge caves apparently form when half-solidified surface sheets possibly yield to the shoving of the hotter lava below by doming upward, often with axes perpendicular to the direction of pressure. The caves are however, not bound to pronounced tumuli put can occur under low, dome-like rises.

2.3 Other lava caves

Uwaiyed Cave is a circular 10 m wide chamber in highly weathered old basalt that may be caused by upward stooping of a hypogene, collapsed limestone cave at depth (KEMPE et al., 2009) (Fig. 7). Another (Beer Al-Wisad) one is an 11 m deep pit, also in very old lava, of unknown origin.

3. Conclusions

The discovery of so many lava tunnels in the Harrat is surprising considering their old age and the fact that the loess is easily washed into caves filling them eventually. Al-Fahda, Hashemite University, Dabie, Kempe and the two Abu Al-Kursi Caves are all closed by sediments. Only Al-Howa Cave is terminated on both ends by roof collapse due to the loading of a later a`a lava flow.

Al-Fahda, Al-Badia (Beer Al-Hamam), and the two Abu Al-Kursi Caves are rather wide, while Al-Howa, Hashemite University, Kempe and Dabie Caves are of smaller dimensions. All have very low gradients. Lava falls and plunge pools, so often encountered in Hawai'i (KEMPE, 1997; KEMPE this volume), were not found in these caves. A secondary ceiling is possibly present only in Hashemite University Cave. Benches and shelves marking older flow levels occur in Dabie Cave, Al-Fahda and in one place in Hashemite University Cave. Branching is rare, apart from Al-Fahda Cave only Hashemite University and possibly Kempe Cave display branching.

The presence of the lava tunnels underscores the fact that the Harrat consists to a large part of tube-fed pahoehoe, thus explaining its overall low slope. Compared to Hawaiian tunnels (see data in KEMPE, 2002; Kazumura, Keala and Huehue, some of the longest caves on Hawaii have sinuosities of 1.30, 1.25 and 1.2), most caves show a rather

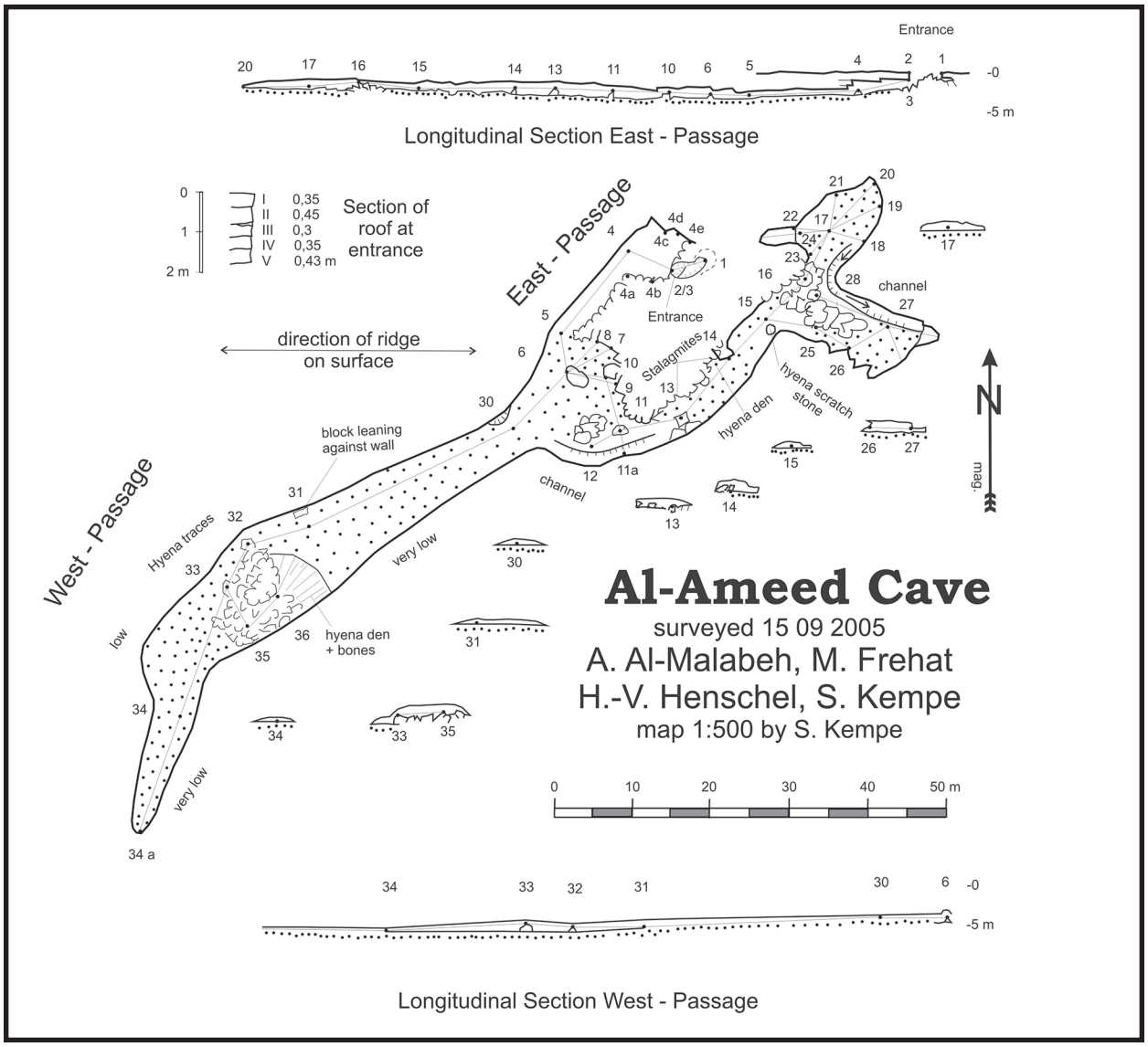

Figure 6: Map of Al-Ameed Cave.

low sinuosity (Al-Fahda: 1.13), in spite of the fact that it has a lower slope than the mentioned Hawaiian caves (1.51°, 1.51°, 4.58° respectively). The hypothesis that there should be a reverse relation between slope and sinuosity can, therefore, not be substantiated. The winding of the cave should have provided for a "Thalweg", i.e. a path along which the lava flow was maximal with slip-off and undercut slopes to the sides depending on curvature.

The high proportion of "pressure ridge caves" and their length are another interesting finding. One of the reasons for this high proportion of caves not formed by underground linear flow of lava may be the low slope of the terrain being in places even below 1°.

Many of the caves (compare Table 1) have been used by hyenas, wolves, foxes and porcupines. Specifically hyenas left many bones of their prey, abundant coprolites, dens dug into sediment and scent marks (KEMPE et al., 2006a). The caves therefore are also of high paleontological and taphonomic importance.

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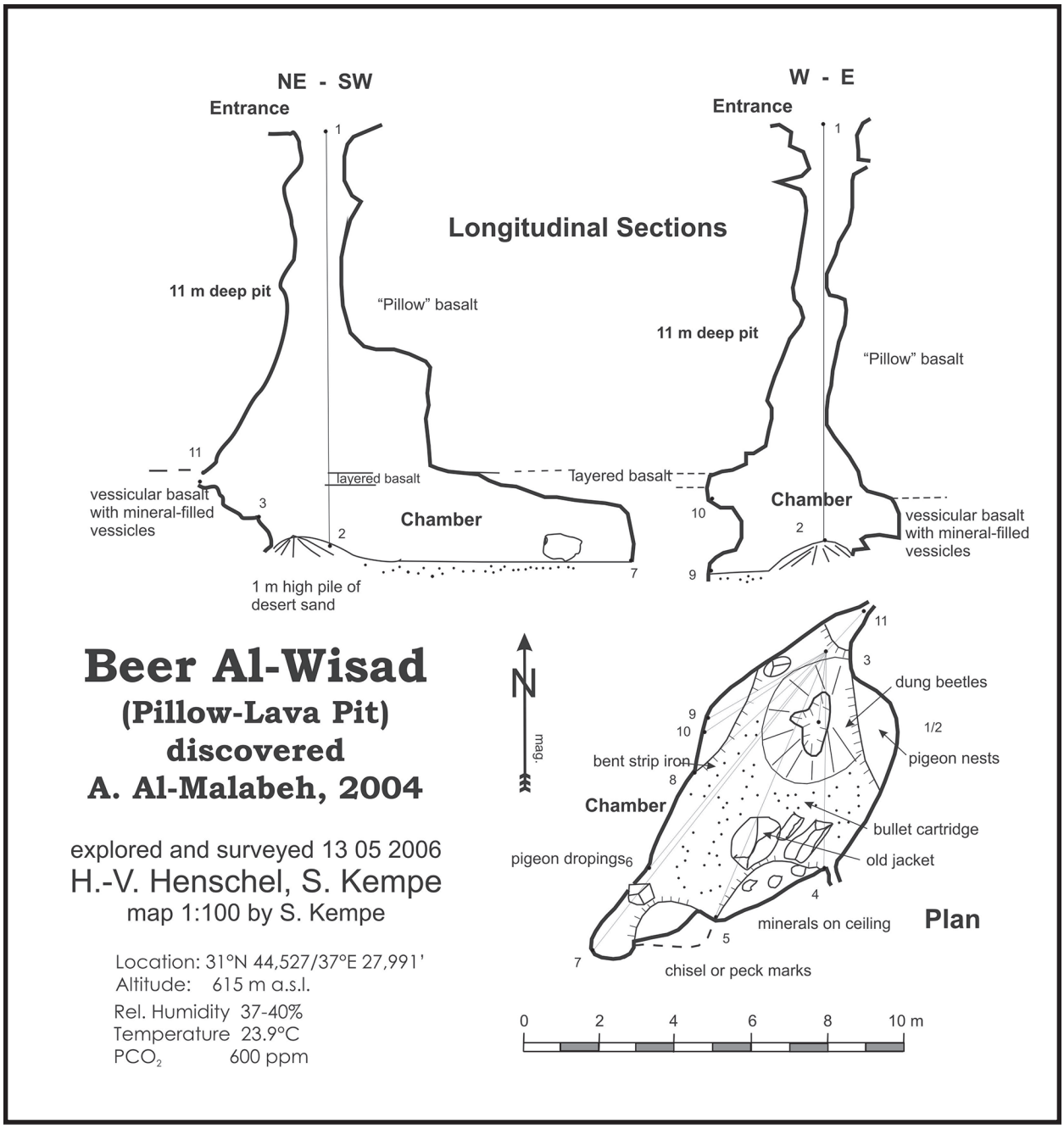

Figure 7: Map of Beer Al-Wisad.

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POSSIBLE LAVA TUBE DEVELOPMENT IN THE SAN LUIS VALLEY AND SOUTHEASTERN SAN JUAN MOUNTAINS, COLORADO

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Entrances to what appear to be lava tube caves are observed on two Pliocene shields in south-central Colorado: the Culebra Volcano on the Taos Plateau volcanic field in the San Luis Basin and Los Mogotes; a shield in the southeastern San Juan Mountains, 42 km to the west.

The Culebra volcano is a 2 km^2 isolated shield on the east side of the Rio Grande River. Entrances to ten short lava tube segments up to 20 m in length occur along the base of two 8 to 10 m high escarpments on the west side of the shield. The chemical composition of four groundmass samples taken from inside the caves indicates that the tubes are in a silicic alkaline basalt (SiO_2: μ = 52.9%, $Na_2O + K_2O$: μ = 5.2%). Although estimated to be age-equivalent to the 3.4-3.9 Ma Servilleta basalt to the south and east, the age of the Culebra Volcano has not been determined. Based on their position with respect to the Rio Grande River and the exposure of the host rock on the opposite bank of the river, the tubes appear to predate the draining of historic Lake Alamosa (440 ka) and to have been exposed following incision of the modern Rio Grande into the flow.

Entrance to possible lava tube segments up to 10 m in length are also observed in basaltic rock on the flanks of a 270 km^2 shield volcano (Los Mogotes) in the southeastern San Juan Mountains. The entrances are exposed in a sequence of up to 12 escarpments in 4.4- 4.75 Ma Hinsdale trachybasalts on the south side of the shield where the Conejos River has exposed individual flow units. Deformed rock around entrances, oval shaped passages, and the presence of a feature resembling a levee in one of the cave segments may be evidence of genesis by flowing lava. A K/Ar date of 4.4 Ma was obtained by USGS for an exposure 1.25 km west of the entrances and at the same elevation. If this date is representative of the age of the flow episode containing the entrances, the observed lava tube remnants could be among the oldest in the U.S.

1. Introduction

The Taos Plateau volcanic field in the southern San Luis Valley and the adjacent southeastern San Juan Mountains, both in south-central Colorado, contain several late Tertiary (Pliocene) to early Quaternary (Pleistocene) shield volcanoes composed of silicic alkalic basalts, andesitic basalts, and trachybasalts. Entrances to what appear to be lava tube caves are observed on two of these shields; the Culebra Volcano on the Taos Plateau and Los Mogotes; a shield 42 km to the west in the southeastern San Juan Mountains. The locations of these features are shown in Figure 1 with the town of Alamosa in the central San Luis Valley shown at the top of the figure.

2. Culebra Volcano

The Culebra Volcano is a 2 km^2 isolated shield on the east side of the Rio Grande River, 6 km south of the San Luis Hills and on the Costilla Plain of the Taos Plateau. This low shield was named by BURROUGHS (1971) and is labeled as a Tertiary olivine andesite on the map by THOMPSON and MACHETTE (1989).

The summit is at elevation 2,357 m and rises only 70 m above the Costilla Plain. The age of the Culebra Volcano is not known but is postulated in THOMPSON et al. (2007) to be age equivalent to the Pliocene Servilleta basalt (3.5–4.2 Ma). Flows from this small shield are exposed in two escarpments, each up to 10 m in height along the west side of the volcano, where the Rio Grande River has incised into the flow, exposing it on both sides of the river in a two kilometer long and 20 m deep canyon labeled "The Box" on topographic maps. The eastern escarpment contains entrances to ten short cave segments up to 18 m in length. The entrances to the largest of these segments are 4–5 m wide and 3–4 m high (Fig. 2) and are at the base of the lowest cliff, only 1–2 m above river level. The passages in these caves parallel each other, are perpendicular to the river, and slope upward toward the top of the shield, where within only 20 m they become choked with rock fall and animal midden. A third short cave, shown in Figure 3, is 7 m in length and is found at the base of an upper escarpment, directly above the two entrances shown in Figure 2. The directional orientation of this short segment is the same as the lower caves.

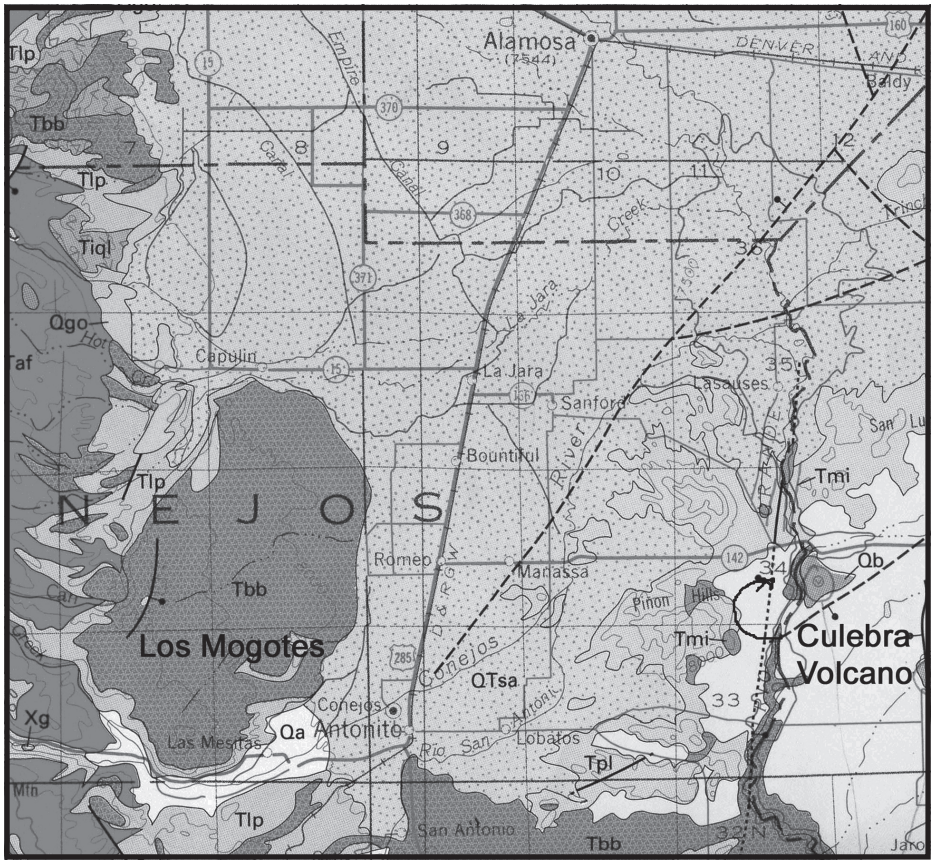

Figure 1: Map of south-central Colorado showing Los Mogotes and the Culebra Volcano.

existing material which was subsequently removed following exposure of the entrances by the downcutting Rio Grande River, resulting in a mold having the form of the pre-existing object.

The caves do not exhibit many of the flow related features usually observed in lava tubes; perhaps as a result of weathering and spalling of original wall rock near the entrances and passage modification resulting from back flooding of the Rio Grande into the caves. Away from the river and toward the accessible end of the largest two caves, the passage morphology becomes more tube-like with smooth curved ceilings (Fig. 5).

Figure 2: Possible lava tube entrances on Rio Grande River below Culebra shield volcano.

Figure 3: Low entrance to cave at base of upper flow unit on east side of The Box.

In Figure 2, deformation of the host rock around entrances can be observed. Liquid lava flowing through a molten core may have exerted lateral pressure on the surrounding viscous lava, resulting in plastic deformation of this slowly cooling material and inflation of the malleable crust immediately above the tube as noted in KAUIHIKAUA et al. (1998). This may explain the curvilinear texture of the flow cross section seen around several of the cave entrances as illustrated in Figure 4. An alternative interpretation (Kauahikaua, pers. comm.) is that lava flowed around pre-

As a result of midden fill, soil blown into the caves, and deposition of sediments by the Rio Grande River, the original bedrock floors of the caves cannot be observed, hindering interpretation.

2.1. Groundmass composition

The composition of the Culebra Volcano flows have been variously described as an olivine andesite in

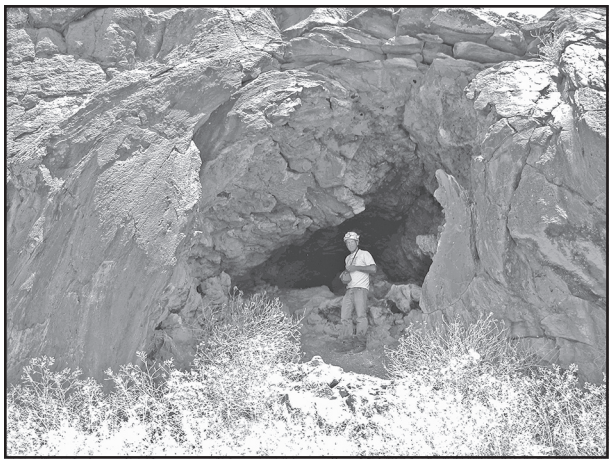

Figure 4: Curved/deformed beds around entrance below Culebra shield volcano.

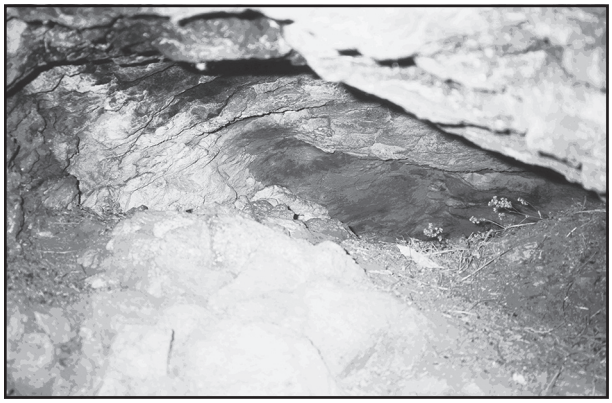

Figure 5: Curved ceiling at back of cave below Culebra shield volcano.

THOMPSON and MACHETTE (1989), and andesitic in BURROUGHS (1971). To determine the chemical composition of the rock, four groundmass samples were taken, two from the interior of caves in the lower escarpment and the other two from the interiors of caves in the upper escarpment. LUISZER (2008) used X ray fluorescent spectroscopy to identify the constituents of each sample. Results obtained indicate little variation between upper and lower escarpment samples. The alkalinity (Na_2O + K_2O) and silica content (SiO_2) for each sample indicate that the tubes are in a silicic alkalic basalt/trachybasalt with mean SiO_2 percent weight of 52.9% and mean alkalinity (Na_2O + K_2O) of 5.2%. This material is more viscous than Hawaiian basalts.

2.2. Cave age

To determine the age of the flow in which the tubes are found, $^{40}Ar/^{39}Ar$ radiometric dating was carried out on a wall sample taken from the largest of the tubes. As of the preparation of this paper, results were not available, but are expected to indicate an age that is comparable to that of the nearby and more widespread 3.4 Ma to 3.9 Ma Servilleta basalt as suggested in THOMPSON et al. (2007). If correct, the Culebra Volcano would be considerably older than the nearby Mesita Hill shield, 5 km to the southeast, where a $^{40}Ar/^{39}Ar$ age of 1.03 +/- 0.01 Ma was obtained by APPELT (1998).

The distal end of the flow in which the caves are found is buried beneath Quaternary deposits on the west side of the Rio Grande River, where a 12 m escarpment and 50 m wide surface exposure above it are seen. The flow predates the modern Rio Grande River, which occupied its current course as a result of the draining of a 105 km long, and 48 km wide Pleistocene paleolake (Lake Alamosa), dammed by the San Luis Hills, 6 km to the north of the Culebra Volcano as described in MACHETTE et al. (2007). The elevation of shoreline deposits and calcic soils on barrier bars indicate a maximum elevation of 2330–2340 m for Lake Alamosa and overflow through a gap in the San Luis Hills and onto the Costilla Plain around 440 ka, well after the emplacement of the Culebra Volcano flows and its lava tubes. Bisection of the flow by the modern (post- 440 ka) Rio Grande exposed the observed lava tubes and beheaded them at their lower ends since there is no evidence of continuations of any of the tubes on the west side of the river.

3. Los Mogotes

Los Mogotes is an east-dipping 130 km^2 shield volcano in the southeastern San Juan Mountains, 42 km. SW of the Culebra Volcano. Basaltic rocks on the Los Mogotes summit (elev. 3010 m asl) have been dated by APPELT (1998) with $^{40}Ar/^{39}Ar$ dates of 4.75 +/- 0.28 Ma obtained. The eastward flowing Conejos River, 490 m below the summit, has cut across the south flank of the shield, exposing a sequence of at least 12 flows as a series of 6- to10-m high cliffs (Fig. 6) in late Cenozoic Hinsdale Formation silicic alkalic basalts and basaltic andesites, described by LIPMAN and MEHNERT (1975).

Figure 6: Exposed beds of basaltic rock on south side of Los Mogotes.

Numerous openings are observed in these cliffs with typical cross sections being circular or oval shaped. Passages can only be followed for a few meters before being choked by cemented rounded blocky material, possibly fill from younger flow episodes at higher elevations on the shield. These openings may be remnants of lava tubes dating back to emplacement of the Hinsdale Formation basaltic rocks.

The largest of the caves- Los Mogotes Cave- has an entrance that is 5 m wide and 4 m high and can be followed for 10 m to a rock choke (Fig. 7). A laterally protruding fin of rock that can be seen on the right wall of this short cave segment resembles a levee as described and illustrated in LARSON (1993): "a free standing lateral remnant of a lava tongue or flow caused by cooling along the edges and subsequent evacuation". If this is the case, it provides evidence for genesis of the cave by flowing lava. A second cave entrance is in a bed 8 m below the one containing the Los Mogotes Cave and is few meters offset from the former. A 1.5 m high and 2 m wide entrance leads to an alcove and a curved passage segment 12 m long, ending at a choke in blocky, ashy material. The bedrock around several of the entrances on the south side of Los Mogotes has the same appearance as seen around the Culebra Volcano entrances: deformation of the host rock around the entrances.

3.1. Groundmass composition

Los Mogotes basalts are both silicic and alkalic. The

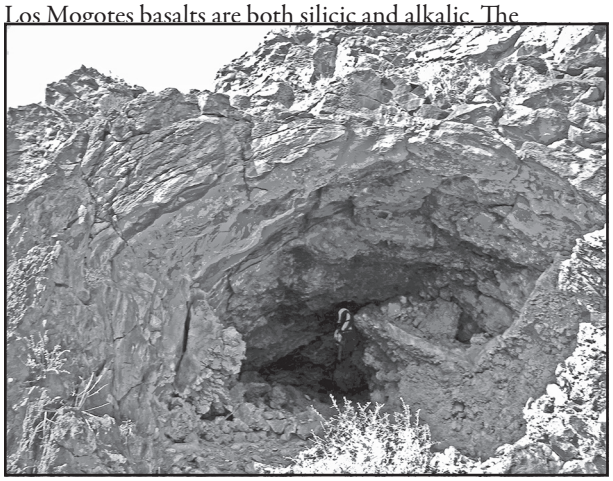

Figure 7. Five meter wide, four meter high entrance to Los Mogotes Cave with deformed beds around the entrance.

composition of eleven samples taken from this shield is plotted in Figure 8 of LIPMAN and MEHNERT (1975). These have a mean SiO_2 content of 51.6% and a mean $Na_2O + K_2O$ content of 4.9%. For this study, a sample was taken from the wall of Los Mogotes Cave and another from the wall of a 12-m long cave in the flow unit immediately below the one containing the Los Mogotes Cave. X ray fluorescent spectroscopy analysis of the composition of the two samples (LUISZER, 2008) indicates that the host rock is a trachybasalt having a mean SiO_2 content of 49.97% dry weight and a mean $Na_2O + K_2O$ content of 6.23% dry weight; somewhat more alkalic and less silicic than the samples analyzed in LIPMAN and MEHNERT (1975).

3.2 Cave age

Although $^{40}Ar/^{39}Ar$ dating was not carried out for this study, LIPMAN (1975) provided a K/Ar date of 4.4 Ma from an exposure 1.25 km west of the entrances and at about the same elevation as the Los Mogotes cave entrances. If the entrances and short passage segments seen on the south side of Los Mogotes are remnants of lava tubes and if, as appears to be the case, some of them are in the same bed as the dated sample, these features could be among the oldest lava tubes in the United States.

4. Conclusions

Openings to what appear to be short and truncated lava tube segments in late Pliocene basaltic rocks (3.5 Ma to 4.4 Ma) are observed on the flanks of two shield volcanoes in south Central Colorado. These are the first lava tubes to have been documented in this State and appear to be among the oldest in the United States.

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SEVENTEEN YEARS BENEATH HUALALAI: A SUMMARY OF CAVING EXPERIENCE

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Hualalai, a shield volcano on the western side of the island of Hawai`i, rises to an elevation of 2521 m and has a surface area of about 751 km^2. In the seventeen year period 1992-2009, 485 lava tube caves have been recorded beneath 30 of the 173 Hualalai lava flows and over 111 km of passages have been surveyed in 203 of these caves. The Hualalai lava tubes are found in flows ranging from just over 200 years to over 10,000 years in age and vary greatly in pattern from simple linear conduits to multi-level braided and branching complexes that present exploration and survey challenges.

Hualalai contains some of the world's longest and most vertically extensive lava tubes, including the deepest single pit in the United States (Na One, 263 m deep), the 24 km Hualalai Ranch tube complex with 452 m of relief, the 10.8 km Hu`ehu`e Cave in the historic 1801 flow with 498 m of relief, Pueo Cave, a highly braided lava tube containing over 6 km of passages, and the 10.7 km Lama Lua-Ka`upulehu cave complex extending over a linear distance of 5.4 km and having a relief of 370 m. The surveyed distance from the Lama Lua entrance to the end of one of its passages is 2.65 km and is entirely in darkness; this is perhaps the greatest traversable distance in total darkness for any lava tube on earth.

Above 1200 m elevation, the gradients of the flows increase to up to 15 degrees and several long and vertically extensive lava tubes have been surveyed in upland dry forests. Notable caves include: (a) Umi`i Manu, the second most vertically extensive lava tube on Hawaii, extending for a linear distance of 3.4 km and having a vertical relief of 570 m, (b) Ambigua Cave, having a linear extent of 1.3 km and a vertical relief of 306 m, and (c) Manu Nui, a steep and decorated lava tube having a surveyed length of 3.7 km and a vertical relief of 352 m.

1. Introduction

Hualalai, a shield volcano on the western side of the island of Hawai`i (Figs. 1-A, 1-B) reaches an elevation 2521 m (8271 feet) and covers an area of 751 km^2 (290 mi^2); about 7.2% of area of the island. A majority of the lava flows on Hualalai are Holocene in age (10,000 years bp or younger), a few are Pleistocene in age (>10,000 years bp) and one is historic. The historic flow occurred in ca. 1800 and produced two flow fields; the Hu`ehu`e flow field seen one km. north of the Kona International airport and the somewhat older Ka`upulehu flow field 8 km. to the north. The Hu`ehu`e field in turn, consists of two historic flows: the primarily pahoehoe Manini`owali flow and the primarily a`a Puhi-a-Pele flow.

Of the 173 Hualalai flows that contain some pahoehoe, only 30 have been examined for caves. However, beneath these 30 flows, 485 caves have been found of which 203 have been surveyed. The combined survey length of these caves is 111 km (69 miles). The caves are found at all elevations on Hualalai and cave temperatures range from 30° C on the Pacific coast to 20° C on the upper slopes of Hualalai.

2. Significant Lava Tubes on Hualalai

The lava tubes found on the slopes of Hualalai are among the longest and most vertically extensive on earth with five of these caves having a vertical extent of over 300 meters. Several of the more notable caves on Hualalai are described below, starting with caves at and just above sea level to those found at elevations of up to 2000 meters above sea level on Hualalai's upper slopes.

2.1 Under the Wall Cave

Located a few km south of the Kona International airport, this fine unitary tube extends for a linear distance of 2.5 km and has a vertical range of 125 meters. The upper part of the cave consists of a 10 meter wide and 6 meter high tunnel containing a variety of man-made features including walls,

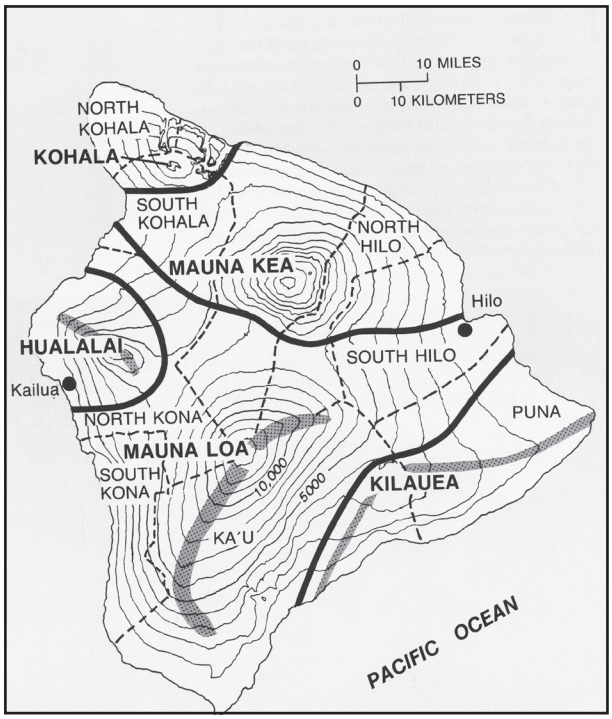

Figure 1-A: Map of Hawai`i showing location of Hualalai Volcano (credit: USGS).

Figure 1-B: Hualalai Volcano, Hawai`i (credit: USGS).

ramps, and platforms. A description and map of the cave are provided in MEDVILLE (2002).

2.2 The Hu`ehu`e (Manini`owali) Cave

The Huehue Cave, found in the historic 1801 flow 2 km north of the Kona International airport, was surveyed in the 1992-96 time frame by teams of American and German caver/speleologists led by D. Medville and Prof. S. Kempe, respectively. The cave and its geology are documented in OBERWINDER (1996), MEDVILLE and MEDVILLE (1997), and KEMPE and OBERWINDER (1997).

Although braided in places, the cave usually consists of a single large conduit. The cave originally consisted of four separate segments but in a series of three trips made in March 1997 by S. Kempe, M. Oberwinder, D. and H. Medville, and W. Storage, the segments were connected, resulting in a single tube with 10.8 km. of surveyed passage and 498 meters of vertical relief extending over a linear distance of 6.1 km. The cave is about 8 meters beneath the surface and contains passages that are generally 5-6 meters in width and 4-5 meters in height (Fig. 2).

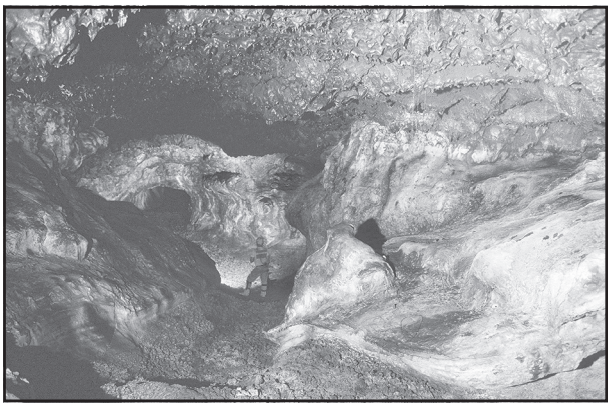

Figure 2. Passage in Hu`ehu`e Cave (Photo by Dave Bunnell).

2.3 Hualalai Ranch Cave System

This is a huge distributary system that contains over 24 km of passages in a 3,000-5,000 year old flow and as such, is the largest lava tube known to exist on Hualalai. Although the source of the flow containing this cave is a vent- Puu Alauawa at elevation 660 meters asl, the cave is terminated by a local highway (Route 190) at its upper end at elevation 634 meters. Here, a single passage can be followed downhill for over 450 vertical meters, branching into a multi-level complex of parallel passages. At its mid-section, the cave contains numerous parallel passages up to 20 meters beneath the flow and extending laterally for 600 meters across the flow. The cave has a linear extent of over 4 km. and was explored and surveyed in the 1997-2007 time period by J. Rosenfeld, N. and J. Davis, P. Carter, J. Wilson, R. Pacheco, B. Liebman, D. Coons and many others. The project is described in ROSENFELD (2001) and DAVIS (2003).

2.4 The Ka`upulehu/Lama Lua Complex

Adjacent to the historic (1800-1801) Ka`upulehu a`a flow and on its eastern margin, a 1,500-3,000 year old flow contains another complex of large caves. Although 19.2 km of passages have been surveyed in 58 caves, half of the total (10.5 km.) is found in two long, aligned caves extending over a linear distance of nearly 6 km. The upper of the caves, Lama Lua, has 5.5 km. of passage and four entrances, three of which require vertical equipment to enter. The cave was

explored and surveyed in the 1997-2004 time frame by N. Davis, J. Davis, J. Rosenfeld, M. Kramer, P. Carter, D. Medville, H. Medville, G. Clemmer, D. Bunnell, R. Pacheco, and T. Lappin. A description and map of the cave are provided in MEDVILLE and DAVIS (2007).

The highest of the entrances is a collapse pit, 10 meters in diameter and 10 meters deep. This leads to a 15 meter wide and 10 meter high passage nearly 20 meters beneath the surface. This passage can be followed down the flow for nearly 3 km to lower entrances. A parallel passage 700 meters below the Lama Lua entrance (Fig. 3) extends to the ENE for over 2 km before ending at a lava seal. The surveyed distance to this point from the Lama Lua entrance is 2.65 km., entirely in darkness and possibly the greatest known distance in darkness from an entrance for any lava tube on earth. The two parallel passages in Lama Lua are 550-600 meters apart, comparable to the lateral extent of the Hualalai Ranch complex.

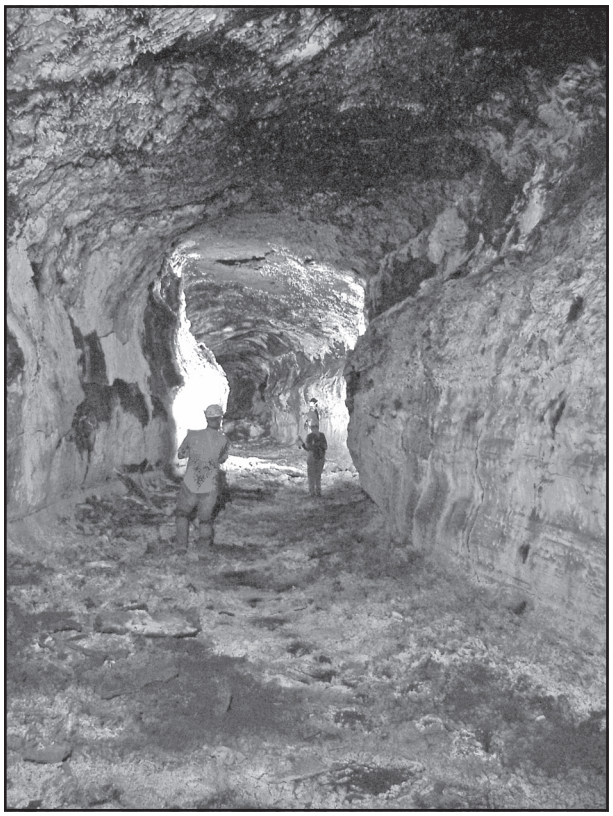

Figure 3: Passage in Lama Lua (Photo by Nevin Davis).

The lower of the two caves; the Ka`upulehu System, has nearly as much surveyed passage (5 km.) and is a continuation of the Lama Lua Cave, separated from it by two shattered rock rings 275 meters apart. The shatter rings are a result of filling of the tube beneath and a breakout to the surface with subsequent draining of lava back into the tube as described in KAUAHIKAUA et. al. (1998). This cave extends from the lower of the two shatter rings to within 200 meters of the coastal highway over a linear distance of 2.2 km. The cave was explored and surveyed by D. and H. Medville in 1993-97.

2.5 Kiholo Bay Caves

A 3,000-5,000 year old flow crosses the coastal highway (Route 19) at the Kiholo Bay scenic viewpoint at mile post 82. This flow contains a concentration of 105 caves in an 18.5 km^2 area. During the time period 1992-2009, 43 of these caves were surveyed, the longest of which has a length of 1.3 km. Unlike the flows described above, this flow does not contain a single massive conduit but rather numerous shallow (4-6 meters beneath the surface) and shorter caves that parallel each other with no apparent overall pattern. The caves are found between sea level and an elevation of 250 meters with several of the sea level caves containing pools of brackish water. The most notable of these is informally called "Peles Water Cave" and contains a sea level pool extending for mm meters (Fig. 4). Another such cave, the Keanalele Water Hole, is found on the shore of the Pacific Ocean and is a local tourist attraction.

Figure 4: Water Cave above Kiholo Bay (Photo by Dave Bunnell).

2.6 Pueo Cave

In the vicinity of Pu`u Wa`awa`a and at an elevation of 500 meters asl, a 3,000-5,000 year old flow extends for nearly 9 km. toward the ocean. The caves in this flow are shallow: only 3-5 meters beneath the surface and contain numerous small entrances. These caves however, are highly braided and complex, perhaps indicating lava flowing in multiple diverging and recombining lobes before the molten cores of these lobes were evacuated with a resulting braided tube remaining. The largest of the tubes in this flow, Pueo Cave, contains over 6.5 km. of passages in an area less than 0.2

km^2. The cave contains over 40 loops and is one of the most complex of the Hualalai caves. It was surveyed in 2004-2007 by D. and H. Medville, N. and J. Davis, and S. Smith and is described in MEDVILLE (2008). A similar cave (Two Owl Cave) is 150 meters below Pueo Cave but unconnected to it and contains over 2 km of surveyed passage.

2.7 Mauka Hualalai: Umi`i Manu and Ambigua Caves

Higher on Hualalai the gradients of the flows increase and the tubes tend to be vertically extensive. One example of such a tube is Umi`i Manu, literally Bird Trap, named after the numerous skeletal remains of the extinct Hawiian flightless goose, collected in this cave by ornithologists from the University of Hawai`i and the Smithsonian Institution. This goose was three to four feet in height and the bones have been radiocarbon dated to 500-900 years bp.

The upper end of the cave is at an elevation of 1890 meters and is only 300 meters below the source vent for the flow containing the cave. At this elevation the average gradient on Hualalai is 13 degrees. The cave extends for a linear distance of nearly 3.4 km and has a vertical extent of 570 meters, arguably the second most vertically extensive lava tube known, after Kazumura Cave. Umi`i Manu consists of a single large conduit, generally 5 meters wide and high and follows the steepest gradient of the flow for its entire length. In addition to the goose bones, the cave contains the skeletal remains of other birds, including rails, petrels, and nenes. The cave is a good example of a high gradient conduit with very little meandering or braiding of passages. An outline map and summary are provided in MEDVILLE (2003).

Another example a few km to the north is Ambigua Cave where the local gradient is about ten degrees. As is the case with Umi`i Manu, Ambigua Cave is generally a single large conduit; it has a vertical extent of 306 meters and a surveyed length of 1.96 km. A map and description are provided in SZUKALSKI (2008).

2.8 Below Kaupulehu Crater: Manu Nui and Bealls Cave

Also on the steep upper flanks of Hualalai and in an area receiving over 90 cm. of rainfall per year are two other extensive and complex cave systems: Manu Nui and Bealls Cave. Manu Nui, surveyed by P. and A. Bosted, K. Marcellius (the owner), D. Coons, and others, is an extremely colorful, complicated, and steep tube system containing over 3.5 km of passage and having a vertical extent of 347 meters. The cave is braided and contains long, dagger-like stalactites (Fig. 5). A discussion of the cave's exploration and the genesis of its lava stalactites is given in BOSTED, A and P. BOSTED (2009).

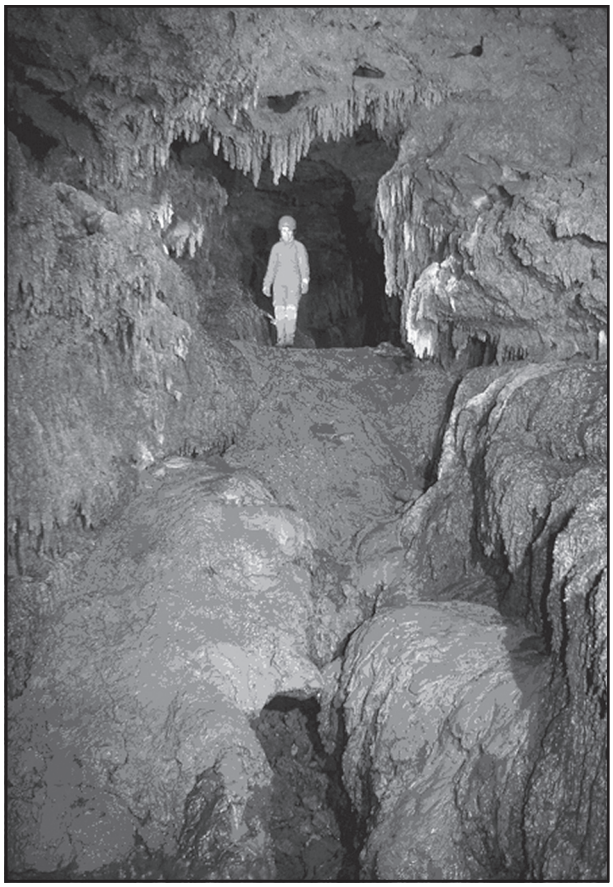

Figure 5: Passage in Manu Nui (Photo by Peter and Ann Bosted).

Somewhat lower in elevation (800 meters asl) and in an adjacent prehistoric flow, Bealls Cave contains over 2.1 km of passage extending over a vertical range of 105 meters. As a result of the humid tropical climate at this elevation, Bealls Cave is wet and contains numerous colorful slimes. The cave was surveyed in the period 2004-2006 by D. and H. Medville, N. and J. Davis, and others.

3. Pit Craters and Open Vertical Volcanic Conduits

In addition to lava tubes, Hualalai is known for the numerous pit craters and open vertical volcanic conduits along its rift zones and on its summit area. Some of these are described below.

The historic Ka`upulehu flow field contains ultramafic xenolith nodules, the primary constituents of which are clinopyroxene-olivine and olivine. These nodules are embedded in the walls of several pits having vertical extents of up to 30 meters. These pits, at an elevation of 1000 meters

asl, were explored and surveyed by W.R. Halliday and others in the mid-1990s and are interpreted as breakouts from a lava tube that transferred the nodules from near-vent regions.

The source of the 1800-01 Hu`ehu`e flow, Puhi-a-Pele consists of an aligned series of hollow spatter cones/spatter vents containing vertical openings, the deepest of which has been explored by J. Rosenfeld, N. Davis, P. Carter and others to a depth of 130 meters beneath the local surface via a series of elongated pits. This vertical cave has not been followed to an ultimate bottom due to the decreasing width of the passage, a lack of rigging points (many rebelays and redirections are required), and generally incompetent rock.

At an elevation of 1870 meters asl on the NW rift zone of Hualalai, the Ka`upulehu crater is a 70 meter diameter vent within which a 5 meter diameter inner pit descends to a depth of 112 meters. The pit's base consists of a chamber, 15 meters wide and 30 meters long with a downsloping rubble covered floor. The pit was descended and surveyed by P. Carter and N. Davis in February 2004.

The deepest of the Hualalai pits, Na One, is on the volcano's southeastern rift at an elevation of 1850 meters. A combination pit crater and open vertical volcanic conduit, Na One has a vertical extent of 263 meters. The entrance is a 180 meter wide pit crater, roughly 100 meters deep. An opening in the floor of this pit leads to the top of a 160 meter deep shaft. The debris floor of the chamber at the bottom of this pit is 30 meters wide and 60 meters long. When rigged with a Tyrolean traverse across the top, Na One can be descended in a single free drop, the deepest pit known in the United States and among the deepest volcanic pits on earth (Figure 6). There has only been one descent of Na One, in February 1994 by K. Allred and D. Coons.

Figure 6: Na One on Hualalai (Photo by Dave Bunnell).

4. Summary

Hualalai Volcano in West Hawai`i, contains one of the world's greatest concentrations of long and vertically extensive lava tubes and volcanic pits. Although over 110 km of passages have been surveyed in over 200 caves, including five having a vertical extent of over 305 meters (1,000 feet), a large majority of this shield volcano has yet to be investigated. New discoveries, exploration, and surveys are expected for many years to come.

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COMPOSITION OF BACTERIAL MATS IN EL MALPAIS NATIONAL MONUMENT, NEW MEXICO, USA: COMPARISON AND CONTRASTS WITH BACTERIAL COMMUNITIES IN HAWAI`I LAVA TUBES

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Cave bacterial mats cover the walls of lava tubes around the world, including the lava tubes in New Mexico, yet little is known about their bacterial composition and role in the ecosystem. We undertook a study of the differently colored bacterial mats found in Pahoehoe, Four Windows, and Roots Galore Caves in El Malpais National Monument (ELMA), located southwest of Grants, New Mexico. To determine the bacterial community composition and the phylogenetic relationships of the bacterial mats found in these three caves, we aseptically sampled bacterial mats found in the twilight and dark zones of each cave. Bacterial DNA was extracted and purified, the 16S rRNA gene was amplified using polymerase chain reaction (PCR), and approximately 1400 bases were sequenced from clone libraries. Bacterial identities of the closest relatives were found using Ribosomal Database Project II and BLAST, while a maximum parsimony phylogenetic tree was constructed using PAUP.

Our results reveal the presence of a diverse bacterial community comprising the differently colored lava tube mats that includes members related to the *Actinobacteria, Gammaproteobacteria, Alphaproteobacteria Acidobacteria, Firmicutes* and *Chloroflexi*.. There exists common overlap in bacterial communities across the three cave sites, but most notably within the Actinobacteria, the bacterial group that produces many of the antibiotics in use today. In comparison with a parallel study in Hawaiian lava tubes, ELMA microbial mats were less diverse, but overlapped in some phyla present. Our studies show that there is less diversity in yellow bacterial mats than white bacterial mats in both the New Mexican and Hawaiian lava tubes. Putative *Actinomyces* were found among the *Actinobacteria*, which suggests that heterotrophy occurs in these lava tubes. In addition, putative *Nitrosococcus* were found among the *Gammaproteobacteria*, suggesting that ammonia oxidation may also occur. Our studies are shedding light on the nature of these communities and their possible roles in the ecosystem.

1. Introduction

The colorful mats that exist in caves and lava tubes all over the world are known to be microbial thanks to culture studies, scanning electron microscopy, and culture-independent molecular phylogenetic techniques. Until recently scientists used only culture-based techniques to study microorganisms in environments such as caves. Researchers have assumed that the microbial mats in lava tubes are primarily composed of actinomycetes. However, our preliminary studies have revealed many new microbial species waiting to be identified in these mats. These unidentified species could have some useful medicinal value as has been shown in actinomycetes. Some types of actinomycetes are medicinally and culturally significant because they excrete antibiotic products to repel invaders (Lazzarini et al. 2000). The antibiotic properties of many bacteria species make them promising biotechnology targets.

Humid lava tube caves contain highly visible mats of bacteria and other microorganisms, nicknamed "lava wall slime," but they have been studied even less than limestone caves (Northup and Welbourn 1997; Northup et al. 2008). Howarth (1981) has suggested that nutrient recycling (e.g. nitrogen) occurs in the microbial mats. Ashmole et al. (1992) have found microbial mats present in humid caves in the Canary and Azores Islands, but never in caves lacking moisture. Staley and Crawford 1975 have found microbial mats consisting of different species of bacteria, including actinomycetes in the genus *Streptomyces* in research done in lava tubes in Washington

We have had limited success in culturing microorganisms from the environment, including caves, using standard microbiological media (Northup et al. 1994; Amann et al. 1995; Hugenholtz et al. 1998). Molecular phylogeny, using the 16S ribosomal rRNA gene, has revolutionized our understanding of the great diversity and distribution of life present in the environment (Pace 1997). Many

novel bacterial and archaeal species have been detected as a result of this new technology in a variety of environments. Bacteria have been found in some of the most extreme areas including deep-sea hydrothermal vents, kilometers below the surface of the Earth in rock, and in caves. These microorganisms are important participants in the precipitation and dissolution of minerals in caves (Northup and Lavoie 2001; Barton and Northup 2007) and in a variety of surface settings (Ehrlich 1999). However, researchers have barely begun to characterize the microbial diversity of caves and the roles of microorganisms in the subsurface. Additionally, we know little of what abiotic factors control the lava tube microbial diversity. We feel that investigating these mats, using culture-independent techniques, will provide valuable insights into the nature of these communities and what determines their diversity.

This study intends to identify many novel bacterial species that inhabit the walls and ceiling of several El Malpais lava tubes and compare them to the parallel study of the bacterial communities in Hawai`i lava tubes (Garcia et al., this volume). This study will advance our knowledge of the differences and similarities found among lava tubes with varied age flow, surface conditions and different colored bacterial mats.

2. Methods

The three lava tubes sampled at El Malpais National Monument, Four Windows, Pahoehoe, and Roots Galore, occur in the Bandera lava flow, which is approximately 10,000 years old. El Malpais National Monument is located southwest of Grants, New Mexico, USA. Age of flow and average area rainfall data for Hawaiian and El Malpais lava tubes were ascertained using a variety of online resources and from previous investigations (Laughlin and Woldegabriel, 1997).

We recorded entrance elevation and GPS coordinates, and cave temperature and humidity were measured using an IMC Digital Thermometer probe. Small samples of wall rock covered with bacterial mats were collected from the three El Malpais Lava tubes under a National Park Service collecting permit. Samples were covered with sucrose lysis buffer to preserve the DNA and transported to the lab where they were stored in a -80°C freezer until DNA extraction. Yellow and white microbial mats were sampled from Pahoehoe and Roots Galore Caves, and white and gold microbial mats from Four Windows Cave, in the El Malpais National Monument.

DNA was extracted and purified using the MoBio PowerSoil™ DNA Isolation Kit using the manufacturer's protocol (MoBio, Carlsbad, CA). Extracted DNA was amplified with universal bacterial primers 46 forward (5'-GCYTAAYACATGCAAGTCG-3') and 1409 reverse (5'-GTGACGGGCRGTGTGTRCAA-3')(Vesbach, personal communication). Amplicons were cleaned and

Figure 1: Parsimony tree of bacterial clone sequences from a yellow microbial mat from Pahoehoe Cave in El Malpais National Monument. Numbers on the branches indicate bootstrap values from 1000 re-samplings and indicate the degree of support for this tree topology.

purified using the Qiagen PCR cleanup kit (Qiagen, Germantown, Maryland) and were cloned using the TOPO TA Cloning kit (Invitrogen, Carlsbad, CA) and sent to Washington University Genome Sequencing Facility for sequencing with primers M13F and M13R. Once received, sequences were edited and contiged with Sequencher 4.8. (Gene Codes, Ann Arbor, Michigan). To check the orientation of our sequences and to convert from antisense to sense, OrientationChecker (www.cardiff.ac.uk/biosi/research/biosoft/) was used. Chimeras were detected using the Mallard software (http://www.bioinformatics-toolkit.org/Mallard/). Rarefaction curves were generated using Dotur (http://schloss.micro.umass.edu/software/dotur.html) to ascertain whether sequencing had detected a comprehensive set of community members. Sequences were analyzed using BLAST (NCBI; Altschul et al. 1997) to identify closest relatives. Initial alignment was completed with Greengenes (greengenes.lbl.gov/) and manually corrected using BioEdit editor (http://www.mbio.ncsu.edu/BioEdit/bioedit.html), guided by 16S primary and secondary structure considerations. Parsimony analysis was performed using PAUP (version 4.0b10, distributed by Sinauer; http://paup.csit.fsu.edu/) and bootstrap analyses were conducted on 1000 re-sampled datasets using PAUP.

Samples of the lava tube wall rock covered with microbial colonies were examined on a JEOL 5800 scanning electron microscope (SEM) equipped with an Oxford (Link) Isis energy dispersive x-ray analyzer (EDX). Rock samples with adherent bacterial colonies were mounted directly on an SEM sample stub while in the cave and then coated by evaporation with Au-Pd in the lab prior to imaging.

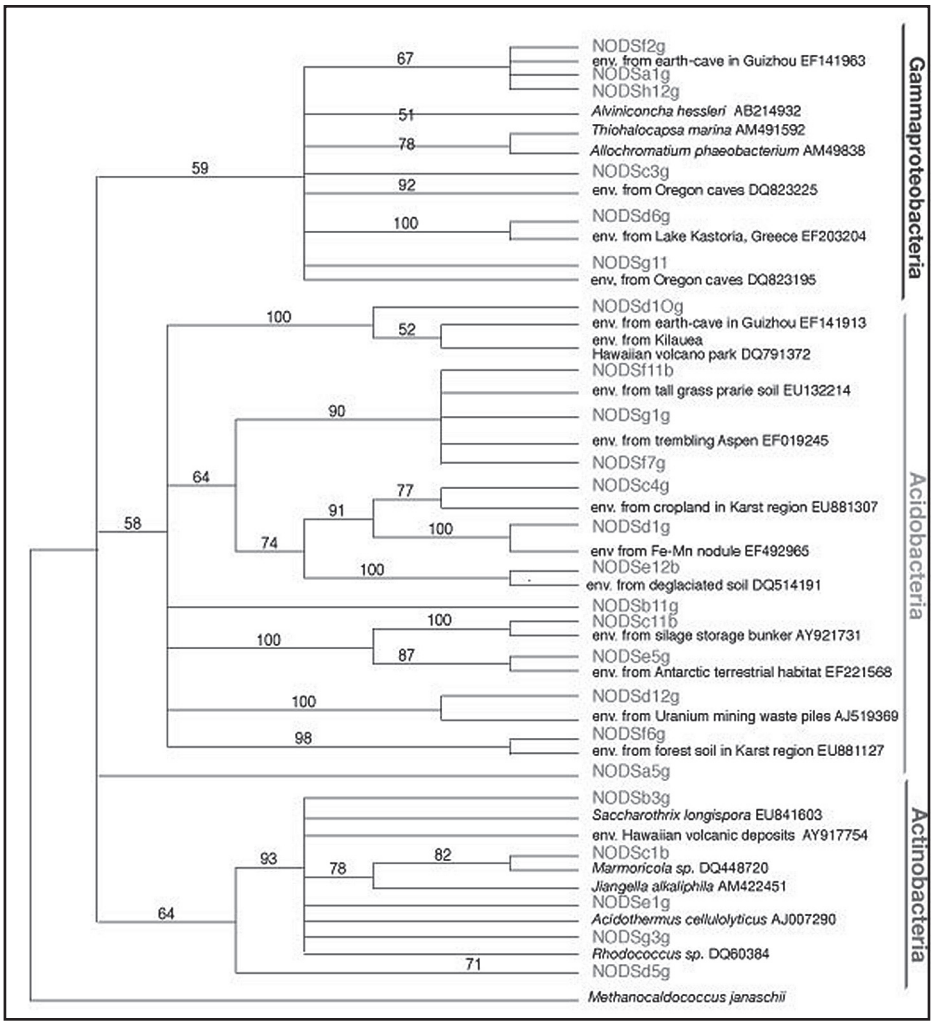

Figure 2: Parsimony tree of bacterial clone sequences from a yellow microbial mat in Roots Galore Cave in El Malpais National Monument. Numbers on the branches indicate bootstrap values from 1000 re-samplings and indicate the degree of support for this tree topology.

3. Results and Discussion

The phylogenetic analysis of yellow microbial mats from Pahoehoe and Roots Galore Caves revealed that the sequences group within six phyla: *Actinobacteria, Gammaproteobacteria, Alphaproteobacteria Acidobacteria, Firmicutes* and *Chloroflexi.* Pahoehoe Cave yellow bacterial mats are more diverse than the Roots Galore mats, which only contacted sequences from the *Actinobacteria, Gammaproteobacteria,* and *Acidobacteria* phyla,. Interestingly the Pahoehoe phylogenetic tree (Fig. 1) and the Roots Galore tree (Fig. 2) overlap in the *Gammaproteobacteria, Acidobacteria* and *Actinobacteria.* Some of the close relatives that group with our sequences were isolated from other caves around the world, such as Frasassi cave (*Actinobacteria)* and Oregon caves (*Gammaproteobacteria).* Other closest relatives were environmental isolates from a variety of soils.

In Figure 2 the *Actinobacteria* clone sequences from our study have mainly cultured closest relatives, something that is rarely encountered in our environmental studies where novel species are common. Also, there are close relatives that came from Oregon caves and Hawaiian lava tubes. In addition, there is a close relative that came from an Fe-Mn nodule, suggesting the presence of possible iron and manganese oxidizing microbes in this lava tube. Because of the iron in the basalt of the El Malpais lava tubes, this is not a surprising finding and reinforces the idea of using various iron media to isolate iron bacteria for further physiological and biochemical study.

In comparing results from this study and a parallel study by Garcia et al. (this volume) of microbial mats in lava tubes on Hawai`i, we see a combined diversity that spans 13 phyla, including four of the subdivisions of the *Proteobacteria.* The greatest overlap amongst New Mexican and Hawaiian lava tubes occurred among the *Actinobacteria* and *Acidobacteria* phyla (Table 1), with all but one lava tube with closest relatives found within those phyla. The second most abundant group found was *Gammaproteobacteria,* which had eight lava tubes with closest relatives among this phylum. There is a slight trend for yellow microbial mats to be more diverse than white mats, but more sequencing and analyses are needed before a definitive assessment can be made.

Scanning electron micrographs revealed the presence of many different possible microbial cell shapes, including cells in the shape of rods (e.g. Fig. 3), filaments, and spores. The fuzzy rods seen in Figure 3 are one of the more common morphologies seen and may indicate the widespread presence of *Actinobacteria* in these mats.

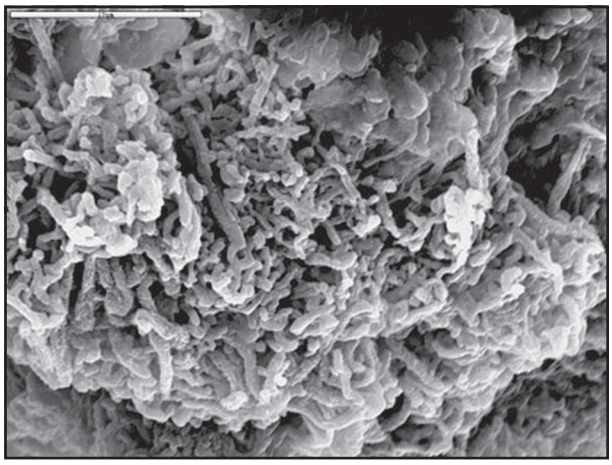

Figure 3: Scanning electron micrograph of a yellow microbial mat in Pahoehoe cave. The presence of the rods suggests a microbial presence. Scale bar is 10 microns.

4. Conclusions

We conclude that the Hawai`i lava tube microbial mats are quite diverse, overall containing 13 phyla of bacterial life as opposed to seven phyla for the New Mexico lava tubes. Hawai`i receives considerable more moisture, especially on the eastern side of the island, than does the region of New Mexico where El Malpais National Monument is located. Additional moisture will infiltrate the lava tubes and may bring additional nutrients to fuel some microbial metabolic lifestyles. The Hawai`i lava tubes samples are several thousand years younger than are those of El Malpais, but whether this is a factor in the decreased diversity

Phyla / *Cave*	*Actn*	*αP*	*βP*	*γP*	*δP*	*Acd*	*Clfx*	*Cyan*	*Nit*	*Ver*	*Gem*	*Planc*	*Bact*	*Dein*	*OP11*	*Firm*
4W	§		§				§			§						
Pahoe	#	#		#		#	#									#
RG	#§	§		#§		#§					§					
Bealls	#/§	#/§	#/§	#/§	#/§	#/§		#/§	#/§		#/§	#/§	#/§		#/§	
BP	§	§		§	§	§	§		§							
Epper	><	><	><			><	><		><					><		
Kau	/\			/\	/\	/\										
Kula	#			#		#							#			
Maels		*	*	*	*	*			*	*		*				*

*Table 1: Comparison and contrast of Hawai`i and El Malpais caves by bacterial phyla. Actn- Actinobacteria, αP- Alphaproteobacteria, βP- Betaproteobacteria, γP- Gammaproteobacteria, δP- Deltaproteobacteria, Acd- Acidobacteria, Clfx- Chloroflexi, Cyan- Cyanobacteria, Nit- Nitrospirae, Ver- Verrucomicrobia, Gem- Gemmatimonadetes, Planc- Planctomycetes, Bact- Bacteroidetes/Chlorobi Group, Dein- Deinococcus-Thermus, OP11 and Firm- Firmicutes. The symbols represent a different color of microbial mat as follows: *- blue/green ooze, #- yellow, §- white , #/§- yellow and white, >< - orange and /\- purple.*

will need to be determined by additional sampling and sequencing of older lava tubes on Hawai'i. Many novel species were detected in the clone libraries and many of the sequences from this study are from other volcanic or cave environments. Our knowledge of lava tube microbial mats is increasing as a result of these studies and we know know that the microbial mats can be quite diverse in their phylogenetic makeup.

Acknowledgements

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UMM JIRSAN: ARABIA'S LONGEST LAVA-TUBE SYSTEM

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This system is located in Harrat Khaybar Lava Field, 130 km north of Medina in the Kingdom of Saudi Arabia. The system consists of three lava-tube passages separated by two collapses and measures 1481.2 m in length with a typical passage height of 8–12 m and a maximum passage width of 45 m. Sediment covering the cave floor was measured at 1.17 m deep.

Wolves, foxes, swifts and snakes inhabit or use the cave. Caches of human and animal bones are found in many places, lying on the surface of the floor sediment. Carbon dating revealed that various human skull parts are from 150 to 4,040 years old and the oldest animal bone dates 2,285 years BP.

Many basalt fragments of a size and shape useful for gouging or scraping were found inside the longest cave passage, about 180 m from the closest entrance. It is conjectured that older bones and tools might lie beneath the sediment and digging under the guidance of an archaeologist is recommended.

Umm Jirsan is one of at least 40 strings of collapses appearing on the most accurate geological map of Harrat Khaybar. Some of these strings are over 15 km long, suggesting that other, much longer lava tubes may be found in this area.

1. Introduction

Al-Malabeh et al. (2006) reported that Al-Fahda Cave in Jordan had been surveyed with a total passage length of 923.5 meters. This was, at the time, the longest known surveyed cave on the Arabian Peninsula. In 2007, Umm Jirsan Lava-Tube System in Saudi Arabia was measured to be 1,481.2 meters long with features of possible archaeological significance. Mapping and limited studies of Umm Jirsan System were carried out by members of the Saudi Geological Survey and the author during five days.

2. General Description

Umm Jirsan System is located near the center of Harrat Khaybar Lava Field (Fig. 1), which lies due north of Al Madinah (Medina) in western Saudi Arabia. These lavas have an area of approximately 12,000 km^2 and are mildly alkaline with low Na and K content and include alkali olivine basalt (AOB), hawaiite, mugearite, benmoreite, trachyte, and comendite. The age of Khaybar lavas range from ~5 Ma to historic (Roobol and Camp, 1991). The age of the lava flow in which Umm Jirsan is found has not been determined, but volcanologist M.J. Roobol suggested it may be three million years BP (Roobol, 2007).

Figure 1: Location of Harrat Khaybar Lava Field in Saudi Arabia.

The main passages of the Umm Jirsan System system extend east and west of Collapse 1, which measures 89 m long by 55 m wide with a depth of 13 m and which is shown in Figure 2. A breakdown slope on the south side of this collapse supports a narrow path from the surface to the floor. In many places along this path, the basalt has been polished, perhaps by the feet of human visitors.

Figure 2: Collapse 1, with a view of the entrance to the west passage.

The entrance to the east passage (shown in Figure 2) measures 10 m high and 35 m wide. A shallow water channel can be seen along the north wall of the entrance room and mounds of rock-dove guano along the opposite

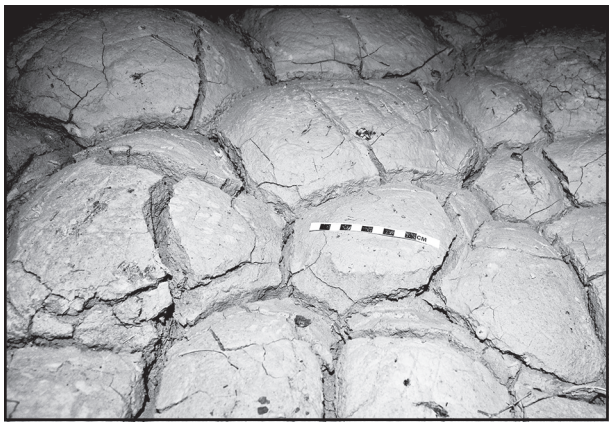

Figure 3: Mounds on the floor of the east passage.

side. Sediment covers the original floor of the cave. This was found to be 1.17 m deep at station 3, with the measurement taken in the center of the passage. North of station 4, much of the surface of the passage floor takes the form of mounds roughly 15–30 cm in diameter and varying in height. XRD analysis showed one of them to be composed principally of quartz, albite and kaolinite as well as nontronite, biotite, microcline and augite with traces of saponite, montmorillonite and hematite. A number of these mounds are shown in Figure 3.

Figure 4: A human figure provides scale in the entrance to the west passage.

Lava stalactites as well as gypsum and calcite speleothems are found in several parts of the passage. The maximum height of the passage is 12 m and the maximum width 45 m. The length of the passage is 948.6 m. An air temperature of 24° C was recorded at station 5 on May 18, 2007.

The west passage has only one entrance (Fig. 4) and measures 341 m in length with a maximum passage width of 45 m and maximum height of 12 m. Lava levees are prominent in this section of the system and the sediment mounds are notably lacking. Moist spots are found in both of the cave's long passages, with evidence of water flow particularly noticeable in the east passage. A third passage, 34 m long with a maximum of 20 m wide and 4 m high connects Collapse 2 to Collapse 3.

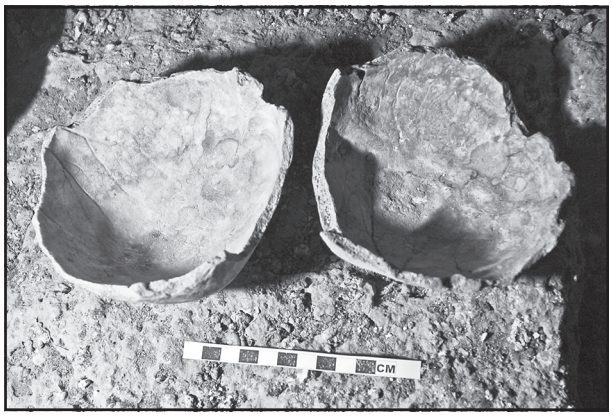

Figure 5: Fragments of two human skull caps found in the Wolf Den in the west passage.

3. Bones and Coprolites

Coprolites and guano indicate that wolves, foxes, hyenas, rock doves, bats, sheep or goats, and swifts have inhabited the cave at some point in its history. Swifts (possibly *Apus pallidus*) and bats (not identified) were seen in the west passage of the cave and a swift nest measuring 9 cm in diameter was found on the passage floor. Animal sounds thought to be wolf growls were noted in this same passage. Recently made fox and snake tracks were seen in the east passage.

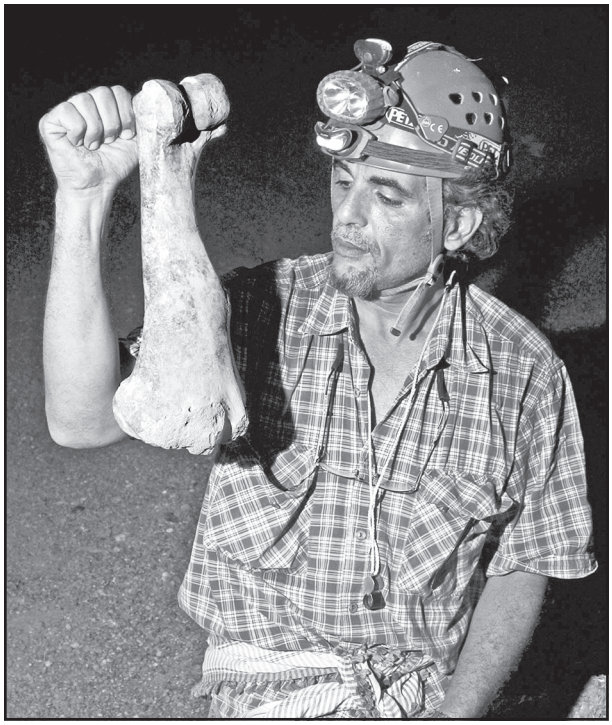

Figure 6: This bone, over 2000 years old, is still awaiting identification.

Bones, presumably carried in by predators, were found throughout the cave but were particularly concentrated at the extreme western end of the system in the same place (the Wolf Den) where growls were heard. From among many bones lying on the surface, a human skull, two human skull-cap fragments (Fig. 5), one particularly large animal bone and one springy, curved stick were collected, removed from the cave and radio-carbon-dated. The results are shown in Table 1. One of the human skull fragments was dated at 4040±30 years BP and the still unidentified animal bone (Fig. 6) was found to be 2285±30 years old. Since these items were found lying on the surface of the sediment layer covering the original floor, it is speculated that still older human and animal remains might be found by excavations carried out by competent investigators.

4. Tool-Shaped Basalt Fragments

At station 5 in the east passage, 180 m east of Entrance Collapse 1, up to 20 fragments of basalt were found lying on the surface within one meter of one another. These items either had a point at one end or a sharp edge on at least one side. Most of them ranged in length from 7 to 13 cm and were of a shape that fits comfortably in the human hand. So far, no sign of chipping has been detected in these items, but the concentration of so many fragments usable as tools in one small area, raises the question of whether primitive people without tool-chipping skills may have gathered usefully shaped fragments of basalt (the most common rock in the area) for use as simple tools, perhaps for removing

Sample record index No.: 2334
Job number: NB-186?RMF-1/2007

No.	Sample name	Lab. No.	Age ^{14}C (BP)	Calibrated age range 68.2%	Calibrated age range 94.5%
1	OO.STK.1	GdA-1155	300±25	1522AD (50.0%) 1574AD 1627AD (18.2%) 1646AD	1495AD (69.9%) 1602AD 1616AD (25.5%) 1651AD
2	OO.SKU.1	GdA-1156	150±30	1670AD (12.8%) 1695AD 1727AD (29.3%) 1779AD 1799AD (7.9%) 1813AD 1854AD (4.3%) 1867AD 1918AD (13.9%) 1943AD	1667AD (16.3%) 1709AD 1718AD (31.5%) 1784AD 1796AD (30.3%) 1890AD 1910AD (17.3%) 1951AD
3	OO.SKU.2	GdA-1157	4040±30	2618BC (5.6%) 2609BC 2598BC (1.4%) 2595BC 2583BC (19.3%) 2560BC 2537BC (41.8%) 2491BC	2832BC (2.2%) 2821BC 2631BC (93.2%) 2474BC
4	OO.SKU.3	GdA-1158	3410±30	1749BC (68.2%) 1668BC	1867BC (2.8%) 1848BC 1774BC (92.6%) 1624BC
5	OO.BON.1	GdA-1159	2285±30	399BC (56.9%) 360BC 274BC (11.3%) 260BC	404BC (60.7%) 352BC 295BC (33.0%) 228BC 221BC (1.7%) 211BC

Table 1: Radio-carbon dates for items collected in the Wolf Den, courtesy of Radiocarbon Laboratory, Gliwice, Poland.

meat from bones. It should be noted that thin layers of basalt naturally spall off the cave walls in Umm Jirsan. Breaking these plates may have provided cave visitors with a source of fragments from which to select simple tools. No search for similar sites has yet been undertaken in the Umm Jirsan System, nor has digging been undertaken.

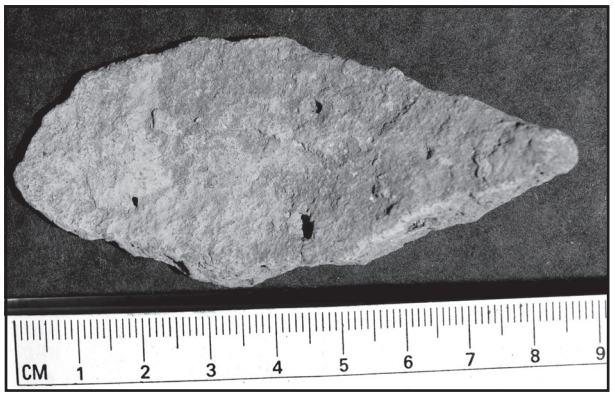

Figure 7: One of many pointed or sharp-edged basalt fragments found near station 5.

5. Stone Walls

The remains of a stone wall bisect the short passage between Collapses 2 and 3 at its narrowest point. What appear to be the foundations of a rectangular stone building were found at the east end of the east passage. It should also be noted that the breakdown slope on the south side of Collapse 1 may have been reshaped by human hands in order to accommodate the footpath. None of these things have been investigated by experts.

6. Conclusions and Suggestions

Umm Jirsan appears to be significant not only because of its size but also for its archaeological potential. Although the cave was mapped and a few studies were carried out, much remains to be done: the age of the cave has yet to be determined; archaeologists have yet to visit the cave; investigations of what lies beneath the surface of the sediment should be carried out; biologists, micro-biologists and mineralogists ought to do a preliminary study. The few such studies undertaken in other lava caves in Saudi Arabia have resulted in the discovery of artifacts, bones and a human skull (Pint, 2006) and cave minerals rare enough for Saudi Arabia's Ghar Al Hibashi to be included among the world's top ten volcanic caves for hosted minerals. (Forti et al., 2004).

In addition, a search for other lava caves in the area should be undertaken. Roobol and Camp (1991) show at least 40 strings of collapses on Harrat Khaybar, some of them up to 15 km long. The existence of intact lava tubes between the Umm Jirsan collapses suggests that other, longer volcanic cave systems may be found in the same lava field.

At present, no Saudi organization has plans to continue vulcanospeleological studies in Harrat Khaybar, but proposals from non-Saudi entities for organizing and financing such studies might be accepted by Saudi universities or the Saudi Geological Survey.

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IDENTIFICATION OF THE MICROBIAL COMMUNITIES ASSOCIATED WITH ROOTS IN LAVA TUBES IN NEW MEXICO AND HAWAI`I

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Although roots have been found to be an essential energy source in lava tubes around the world, the role of the roots and their microbial communities in the cave environment is largely unknown. We investigated bacterial communities found on roots and walls in two lava tubes in the El Malpais National Monument, New Mexico, USA, and two lava tubes in Hawai`i, USA, using culture-independent methods. Root, wall, soil and water samples were collected to determine carbon levels and for DNA extraction. Root and wall samples were collected for scanning electron microscopy (SEM) to look for presence of microorganisms. All samples were collected with permits or permission of landowners. Samples of these communities were taken aseptically and stored on site in sucrose lysis buffer to lyse the cells and for preserve the DNA. DNA was extracted and purified using the MoBio Power Soil DNA Extraction Kit, amplified using polymerase chain reaction (PCR), cloned using Topo TA Cloning and sequenced using Big Dye Terminator v1.1 sequencing. Closest relatives were identified through searches of the NCBI BLAST database. Alignment was done using Greengenes and neighbor joining phylogenetic trees with 100 bootstrap replicates were constructed using Paup version 4.0b10. Bacterial communities of the roots and walls were compared using presence/absence charts. Preliminary results show that the water drips collected from the roots had three times the amount of dissolved organic carbon as drips collected from the walls, suggesting that the roots are an area of increased nutrients in the lava tube. SEM analysis found evidence of bacteria and fungus associated with the roots while only bacteria were noticed on the samples of wall using SEM. Both root and wall samples from the New Mexico lava tubes had closest relatives within the *Acidobacteria*, *Alphaproteobacteria* and *Actinobacteria*. However, only the wall bacterial communities had closest relatives in the *Gammaproteobacteria* and *Firmicutes,* while only the roots had closest relatives in *Deltaproteobacteria*, *Bacteroidetes* and *Betaproteobacteria*. This study suggests that the roots support a diverse microbial community in the lava tubes and is one of the first projects to look at root-associated microorganisms in cave environments.

1. Introduction

Few studies have examined the role of roots growing into caves, aside from their use as the sole food source of the troglobitic planthopper *Oliarus polyphemus* in Hawaiian lava tubes (Howarth, 1972), and no studies have investigated the microbial communities associated with the roots growing into caves. Traditionally cited sources of energy in caves include organic debris entering the cave via sinking streams, gravity or floods (Poulson, 2005), drip water percolating down into the cave, or remains of any type left by trogloxenes visiting the cave (Gillieson, 1996). In addition, chemoautotrophs, use elements from the cave walls or soils as an energy source (Barton and Northup, 2007). However, it is unlikely that roots growing into caves have no effect or bearing on the cave environment and food web. Indeed, we believe roots are another significant source of food for the cave environment, especially in oligotrophic, or nutrient poor, lava tubes.

While plant roots withdraw and store essential nutrients from the surrounding soil matrix, they can also affect the local area around them. Surrounding all plants' roots is an area called the rhizosphere, a layer of soil up to 20 mm thick that is affected biologically, chemically and physically by the presence of the roots and is rich in microorganisms directly or indirectly associated with the plant root. Roots excrete numerous exudates and produce dead material in the form of fine root turnover, and this nutrient input results in higher levels of microbial diversity and activity in the rhizosphere compared to that of root/rhizosphere free soils (Madigan et al., 2008). Roots growing into a lava tube cave bring in their at least part of their rhizosphere, including its load of carbon, nutrients and numerous new microbes, into the cave environment. While the presence of roots affects the cave environment, growing into the cave environment also affects the rhizosphere of the roots. As the root grows out of the soil of the epikarst and into open

air of the cave atmosphere the rhizosphere loses much of it accompanying soils. It can be assumed that the microbial community associated with the root is altered by this change in the rhizosphere; however, no research has looked at how the rhizosphere changes as it grows into the cave. The roots' (and rhizosphere's) incursion into the lava tube cave may "seed" the cave with novel microorganisms. In order to shed more light on the role of roots growing into the lava tube cave environment, we plan to address the following questions:

1. What is the composition of the microbial communities associated with roots growing into lava tubes in New Mexico and Hawaii?
2. Are the roots an area of increased nutrient (e.g. carbon, nitrogen and phosphorus) levels in the lava tube environment?
3. How related are the wall and root microbial communities? Which groups are similar or different in the two cave habitats?

2. Materials and Methods

2.1 Cave description and sample collection

Two caves in New Mexico and two caves in Hawai`i, all with active root growth, were selected as collection sites. Roots Galore Cave and Pahoehoe Cave are located in the El Malpais National Monument in northwestern New Mexico. Thurston Lava Tube and Kula Kai Caverns are located on the Hawaiian Islands. Root samples from each cave were collected aseptically from active root growth near the root apex. Small samples of rocks from the walls and floors at least 2 meters from any noticeable root growth were collected from each cave. All samples were collected aseptically, under an official collecting permit or landowner permission and were stored on site in sucrose lysis buffer (SLB) to ensure preservation of the DNA. Samples were then transported back to the lab and stored at -80° C until DNA extraction. Additional samples were collected aseptically and stored on site in dry tubes for scanning electron microscopy and nutrient analysis.

2.2 SEM imaging and nutrient analyses

Samples for SEM imaging were coated with Au/Pd and viewed using a JEOL 5800 LV SEM at the University of New Mexico. Dry samples collected for nutrient analysis were desiccated, ground, and inorganic carbon was removed by HCl fumigation (Harris et al, 2001). Percent nitrogen and percent carbon was determined by high temperature combustion; the resulting gases were eluted on a gas chromatography column, detected by thermal conductivity and integrated to yield carbon and nitrogen content. Analysis was performed on a ThermoQuest CE Instruments NC2100 Elemental Analyzer (ThermoQuest Italia Sp.A., Rodano, Italy (Pella, 1990)). Soil extractable nitrogen was determined by extraction with 2N KCl followed by analysis for NH_4-N using method 98–70W(1a), 4500-NH_3-G(2) and NO_3-N using method 100–70W (1b), 4500-NO_3-F (2), on a Techincon AutoAnalyzer II (Mulvanery, 1996). Total phosphorus was determined by combustion at 500° C for one hour, followed by addition of 1N HCl and incubation at 80° C for 30 minutes. After dilution the aliquots were analyzed for PO_4 using method 94-70W (1c), 4500-P-F (2), on a Technicon AutoAnalyzer II. Total organic carbon (TOC) samples were analyzed using the persulfate digestion method (APHA, 1998) method on a Shimadzu TOC-5050A instrument. All analyses were completed at the UNM Biology Annex Labs.

2.3 Phylogenetic studies of microbial communities associated with walls and roots

DNA was extracted and purified using the MoBio Power Soil DNA Extraction Kit (MoBio Laboratories, Inc., California). The 16S rRNA gene was amplified using universal bacterial primers 46 forward (5'-GCYTAAYACATGCAAGTCG-3') and 1409 reverse (5'-GTGACGGGCRGTGTGTRCAA-3') with an amplification reaction mixture that contained 30mM Tris-HCl (pH 8.3), 50 mM KCl, 1.5 mM MgCl2, 5 mg bovine serum albumin (Boehringer- Mannheim), 200 mM (each) deoxynucleoside triphosphates, 100 pmol of each primer and 0.5 U of *Taq* polymerase (AmpliTaq LD; Perkin-Elmer) in a final reaction volume of 25µl. Amplicons were cleaned and purified using the Qiagen PCR cleanup kit (Qiagen, Germantown, MD) and were cloned using the TOPO TA Cloning kit (Invitrogen, Carlsbad, Calif). RG71 samples were sequenced using ABI PRISM Big Dye Terminator v1.1 sequencing kit (Perkin-Elmer, Foster City, Calif), while RG88 and PH1 and TH10 samples were sent to Washington University Genome Sequencing Facility for sequencing with primers M13F and M13R. Orientation of all sequences was checked using Orientation Checker (http://www.bioinformatics-toolkit.org) and sequences were screened for possible chimeric artifacts using Mallard (http://www.bioinformatics-toolkit.org). Closest relatives of the genetic sequences were selected using NCBI Blast. Alignment using 650bp was developed using GreenGenes (http://greengenes.lbl.gov/cgi-bin/nph-index.cgi) and manually refined using BioEdit multiple sequence editor (http://www.mbio.ncsu.edu/BioEdit/ BioEdit.html). Neighbor joining and unweighted maximum parsimony phylogenetic analysis was performed using PAUP version 4.0b10. Bootstrap analyses were conducted on 100 resample datasets.

3. Results and Discussion

3.1 SEM imaging and nutrient analyses

There were significant differences in root length and lushness of associated fungal and microbial mats between New Mexican and Hawaiian lava tube caves in which we sampled. In Roots Galore Cave, roots grew approximately 20 cm into the cave and were covered with white fungal and bacterial mats (Fig. 1). Roots growing into Pahoehoe Cave were shorter, with only 5 to 8 cm of growth and showed minimal white microbial mats. The roots in the Hawaiian lava tubes typically were between one and four meters, some even growing through the cave and back into the floor of the cave. However, they did not show the thick white fungal mats found on the roots growing into the New Mexico lava tubes, as seen in Figure 2. Samples from Roots Galore Cave viewed by SEM showed fungal growth associated with the root, included one fungal mass appearing to grow into the root (Fig. 3). The root also appeared to have a thick mat of microorganisms growing over most to of the root outer surface (Fig. 4).

Figure 1: Macroscopic photographs of the roots in Roots Galore Cave, New Mexico. The roots have about 20 cm of growth and the thick white microbial maps are visible in the photograph. Photos copyright © 2007 and 2008, Kenneth Ingham.

Figure 2: Macroscopic photographs of the roots in Kula Kai Caverns, Hawai`i. Unlike the roots in Figure 1, the Hawaii roots are 2 meters long and do not appear to have microbial mats associated with them. Photos copyright © 2007 and 2008, Kenneth Ingham.

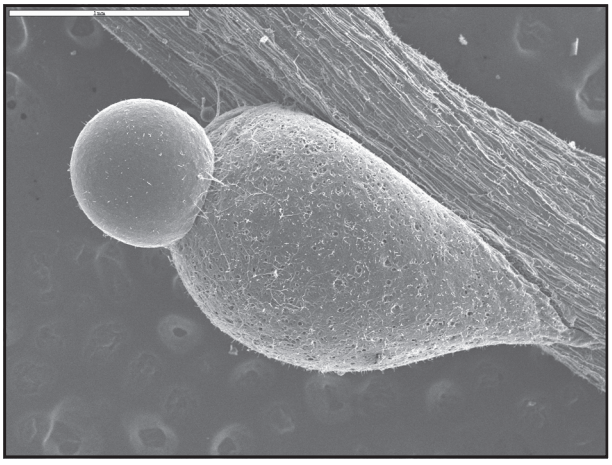

Figure 3: SEM images of root samples from Roots Galore. The scale bar in the image is 1mm long. Notice how the fungus appears to be growing into the root at the bottom of the image while other strands anchor the mass to the roots.

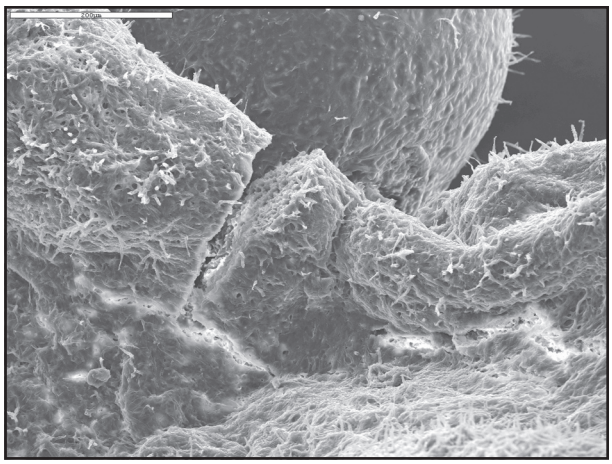

Figure 4: SEM images of root samples from Roots Galore. The scale bar is 200µm long. Microbial mats, including both fungus and bacteria, cover the surface the root and help increase the surface area exposed to soil of the root.

Preliminary TOC levels were determined for drip water in Roots Galore Cave. Our results showed that the TOC levels in the water dripping from the roots to be three times greater than that dripping down from the ceiling where no roots were growing. These preliminary results suggest that the roots are providing additional carbon to the cave.

3.2 Phylogenetic studies of microbial communities associated with walls and roots

The microbial communities on roots in the New Mexico lava tubes were associated with *Pinus ponderosa* roots growing into the lava tubes. Closest relatives to the microbial communities associated with the roots grouped within five phyla: *Bacteroidetes, Actinobacteria, Acidobacteria, Alphaproteobacteria,* and *Betaproteobacteria*. Figure 5 shows a phylogenetic tree of the Roots Galore root microbial mats. 44% of the 18 unique clone sequences grouped within the *Acidobacteria*, while 33% grouped within the *Alphaproteobacteria*. A number of the clones had closest relatives that were known rhizosphere bacterial species. For example, RG88B09, RG88B02 and RG71A10 all had closest relatives that have been associated with trembling Aspen roots. Other sequences were more closely related to soil microbes, such as RG71B12, which had a closest relative from Holocene lake sediment. Surprisingly, some microbes found on the roots had closest relatives that were common in other caves with no root samples. RG88B11 has a closest relative found in a Hawaiian lava tube bacterial mat and RG71C09 grouped with bacteria found in Roman catacombs. Closest relatives of clones from the Pahoehoe Cave wall sample grouped in six phyla: *Actinobacteria, Alphaproteobacteria, Gammaproteobacteria, Acidobacteria, Firmicutes* and *Chloroflexi* (Fig. 6). The closest relatives of the clones were fairly evenly distributed among the six phyla. Most of the clones had closest relatives that resided in other lava tube caves or soils, such as one clone with a closest relative found associated with trembling Aspen.

Bacteria found on roots in Hawai`i lava tubes had closest relatives that grouped in *Alphaproteobacteria*, *Betaproteobacteria* and *Cyanobacteria*. A majority of the clone sequences had closest relatives that live associated

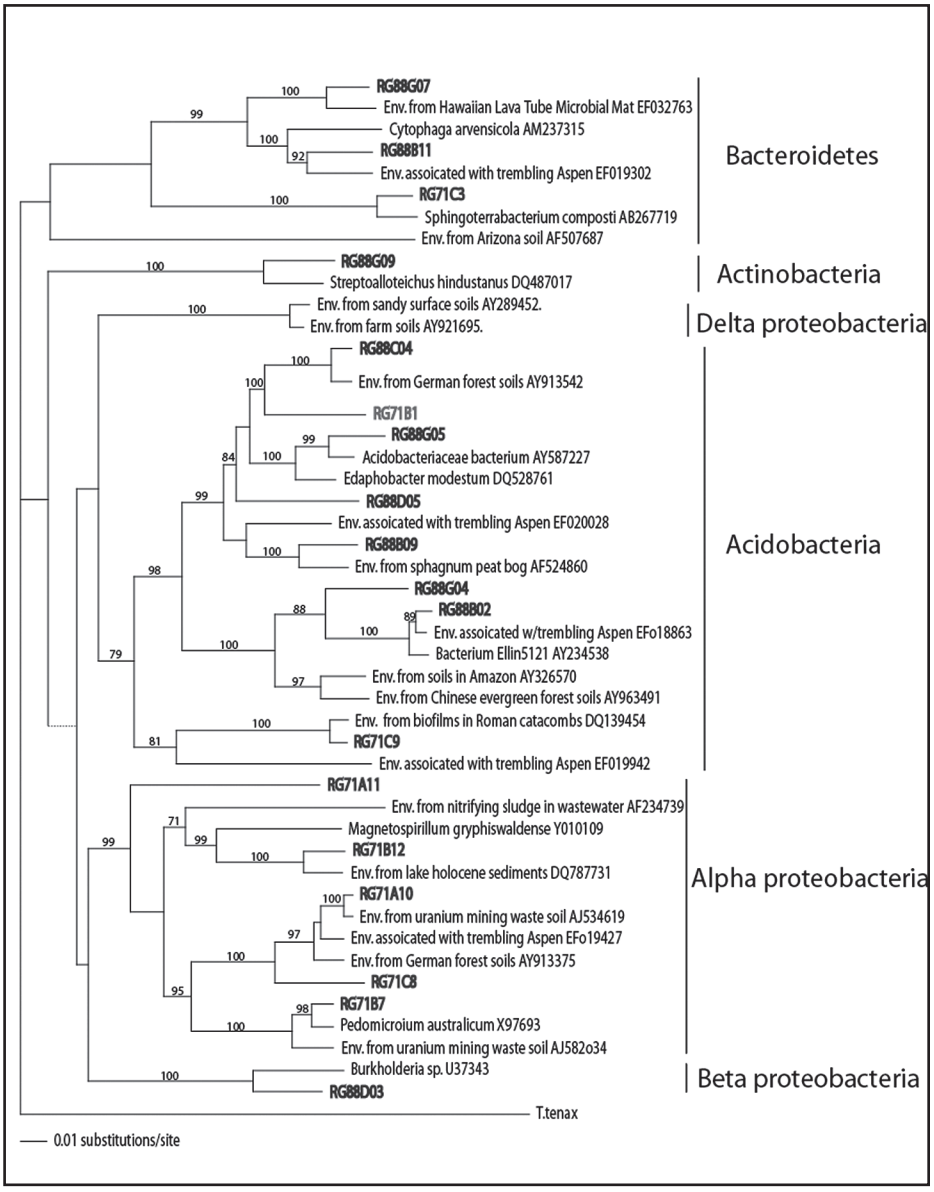

Figure 5: Neighbor joining tree of bacteria associated with roots in Roots Galore Cave. Note that while most of the clones have closest relatives found in soils, two of the clones have closest relatives that reside in other cave environments.

Phylum	NM cave roots	NM cave walls	Hawai`i cave roots	Hawai`i cave walls
Actinobacteria	X	X		X
Planctomyocetes	X			X
Firmicutes	X	X		X
Bacteroidetes	X			
Alphaproteobacteria	X	X	X	X
Betaproteobacteria	X		X	X
Deltaproteobacteria	X			X
Gammaproteobacteria	X	X		X
Acidobacteria	X	X		X
TM7	X			
Verrucomicrobia	X			X
Gemmatimonadetes	X			
Chloroflexi		X		
Cyanobacteria			X	
Nitrospira				X

Figure 6: Microbial populations by phyla from New Mexico and Hawaii cave roots and walls. The New Mexico cave roots and Hawai`i cave walls appear to have the most diverse communities of microorganisms.

with dolomite rocks, soils and Hawaiian volcanic deposits. Closest relatives of clones from the roots in Kula Kai Caverns in Hawai`i grouped in *Actinobacteria, Acidobacteria, Bacteriodetes* and *Gammaproteobacteria,* with 75% of the clones having closest relatives in the *Actinobacteria*. Most of the clones from Kula Kai Caverns have closest relatives that were associated with dolomite deposits in the Alps or with other soils. Figure 6 shows a chart of all phyla found in the roots and walls of New Mexico and Hawai`i lava tubes.

4. Conclusions

Comparisons of the phylogenetic trees from roots and walls in lava tubes show that while most of the bacterial sequences on the roots are typical root-associated bacteria, some bacteria more commonly found in bacterial mats on the walls of caves were found on the roots. In addition, evidence that some of the soil bacteria more commonly found associated with soil and plant roots have been also been found on the walls of the lava tubes. For example, RG88B11 and RG71C09 clones both group with bacteria mats found in Hawaiian lava tubes and Roman catacombs, respectively. Clones with these similar closest relatives have also been found on the walls of lava tubes in New Mexico. Such results may lend support to the suggestion that there are organisms that are indigenous to subsurface environments, such as caves and catacombs. This suggested that the roots could be picking up the bacteria as they grew through the ceiling of the cave, that the roots are introducing, or seeding, bacteria into the cave environment or that both the roots and the cave walls are acquiring bacteria from the soil overlaying the cave. These preliminary results suggest that the microbial communities on the roots and the walls are related and may be acquiring microbes from each other or another source. In addition, preliminary results of the nutrient analysis suggest that the roots represent an area of carbon enrichment in the cave and water dripping off of the roots is also carbon enriched. Our analyses suggest a diverse community of microorganisms inhabits both the root masses entering the lava tubes and the walls of the lava tubes.

Acknowledgements

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AS-SUWAYDA LAVA CAVES (SOUTHERN SYRIA): SPELEOLOGICAL STUDY COMBINING GEOLOGY AND HISTORY

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A very limited number of written documents and maps of Syrian volcanic caves is currently available. In January 2008, an expedition was organized by cavers from the Spéléo-Club du Liban to As-Suwayda Province in southern Syria in order to explore lava caves. The first target was set on the known Aariqa cave, which is in the center of the Aariqa town. In December 2008, another expedition took place to finalize the survey of Aariqa cave, which was extended to 562 m. Another cave was also explored and surveyed near Umm ar Rumman town. This cave resulted in 1615 m of underground tunnels, now the longest known development of lava tubes in Middle-East, passing Umm Jirsan in Saudi Arabia (total development: 1481 m). This paper discusses both Umm ar Rumman and Aariqa lava caves and provides speleological documentation combined to geologic and historical investigations.

Umm ar Rumman cave is south of As-Suwayda near the border with Jordan and about 20 km southeast of the city of Bosra. This lava tube formed in the earliest Quaternary lava sheets (the pahoehoe lavas of β1Q1). The cave entrance (14 m deep and 20 m wide), which is situated in a flat agricultural area, may have been formed by roof-collapse. Almost all features found in volcanic caves are also found in Umm ar Rumman cave; e.g.: levees and gutters, flow ledges, splash stalactites, lava columns and stalagmites, as well as rafts. In addition, beautiful calcite speleothems decorate this cave.

The Aariqa lava cave was also called Aahiré and it is within the Recent lava sheets (β5Q4; dated to 4000 years BP). The cave was used since the Nabatean period (64 B.C. / A.D. 106) until the Arab rebellion against the French mandate (1920–1924). The entrance is an impressive, open-collapse with constructed structures that function as facilities for operational personnel and visiting tourists. In addition to the famous basalt door (probably Nabatean in age), remains of stone walls, bones, and pottery were found. The cave, characterized by a flat floor, hosts remnants of human construction (housing). Some human activities are suggested by pottery, bones, fire places, and housing traces. A small fragment of pottery was dated to the Arab Period in southern Syria (A.D. 634–A.D. 643). Inscriptions are also seen on the passage walls. Near the end of the cave a narrow passage leads to a second entrance.

1. Introduction

As-Suwayda, Daraa and Hawran (Golan) provinces form the southwestern portion of the Syrian Arab Republic, bordering Jordan to the south and Palestine/Israel to the west (Fig. 1). In the center of this area lies Jabal Ad-Drouz volcanic range, which trends northwest-southeast and has a maximum elevation of 1785 m. This range has numerous volcanic cones, often organized in ridges whose slopes are covered with many lava flows (DUBERTRET, 1933). This volcanic terrain (called Al-Harra) stretches southwardly crossing Jordan and partly northern Saudi Arabia. In Jabal Ad-Drouz, the annual precipitation ranges between 200 and 350mm, while in the nearby Al-Harra plain it does not exceed 100 mm. The average annual temperature is between 15 and 19°C (PONIKAROV, 1967).

Although the geographic and geologic aspects of this volcanic region were properly studied previously during mapping surveys, no significant exploration and surveying of the lava caves have been published to date. This contribution discusses two major caves in As-Suwayda province: Umm ar Rumman and Aariqa (Fig. 1). The first one (Aariqa) has historical significance as it used to be apparently used for housing in historical and probably pre-historical times. Whereas Umm ar Rumman cave is a fantastic lava cave with beautiful speleothem decorations (volcanic and calcite) and features typical of lava tubes. Here, it must be mentioned that the whole area features historical Nabatean and Byzantine settlements before the Arabian period. A typical example of this rich historical area is the nearby town of Bosra, which hosts a huge amphitheater made-up almost exclusively of carved basalt stones.

Figure 1. Simplified map of the Syrian Arab Republic, showing the provinces and the locations of Umm ar Rumman and Aariqa caves in As-Suwayda Province.

2. Geologic Settings

Multiple, overlying, and overlapping volcanic sheets characterize the As-Suwayda region (Fig. 2). Neogene deposits, exposed in As-Suwayda, are mostly effusive basalt rocks of Pliocene or possibly Miocene age. Towards the west (in Hawran), these deposits pass into lacustrine, continental, and marine facies. PONIKAROV (1966) argued that Miocene undivided basalts (βN1) must underlie the thick sequence of Pliocene basalts in the central part of the Jabal Ad-Drouz Range (with an estimated thickness of ~750 m). The Miocene basalts do crop out south of Damascus (capital city of Syria) and consists of up to a 500 m thickness of dolerites, ankaramites, and plagio-dolerites. PONIKAROV (1967) subdivided the Pliocene sediments into two parts: a lower part composed of terrigenous rocks and an upper one consisting of basalts. The Pliocene basalts (βN2) are widespread in the As-Suwayda region, covering some 4000 km^2 and including many chains of volcanic bodies. The greatest thickness of the Pliocene effusives is observed in the massive of Jabal Ad-Drouz where it presumably reaches 700–800 m. βN2 comprises all the desert district of Al-Harra (the northern part of which is located in Syria while the southern part mainly in Jordan).

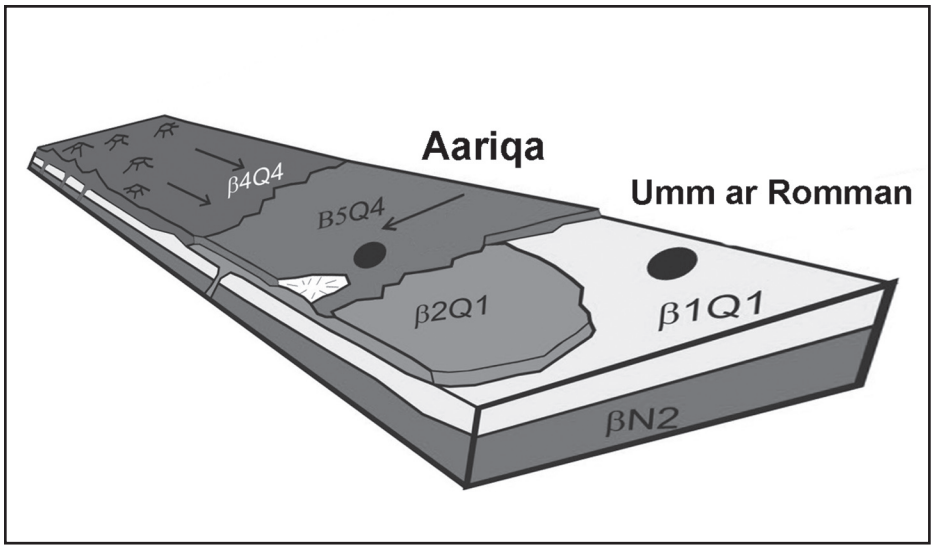

Figure 2. Schematic block-diagram showing the multiple Quaternary and Recent lava sheets in As-Suwayda region and the conceptual positions of Umm ar Rumman and Aariqa lava caves. The block diagram is modified from PONIKAROV (1966).

The Quaternary system, whose deposits are dominated by basalts in the study area, has been organized by Lower, Middle, Upper and recent series of deposits by PONIKAROV (1966). The lower series (βQ1) series of effusives is again classified into two age groups: 1) the sheet of "old pahoehoe lavas" (β1Q1), which occupies the foothills of Jabal Ad-Drouz Range, together with the vast distribution in the Hawran Province, the total area of this sheet reaches 3,600km^2; and 2) the overlying sheet of "dermolithic lavas" (β2Q1). The outcrops of β1Q1 are either arched parts of lava swells or blown up lava bubbles with a system of radials patterned fissures. The relative elevation of these positive surface elements does not exceed 8-10 m. The general orientation of lava flows is suggested to be westwards (to the Hawran valley). Probably the maximum thickness of separate lava sheets does not exceed 12-15 m. In these sheets, the Umm ar Rumman cave (about 1600 m) was found (see below).

The Middle Series (βQ2) of the Quaternary basalts is of limited distribution in the study area (total area is around 100 km^2). These consist mainly of a pahoehoe lava flow stretching in a narrow strip with a westward direction. In Jabal Ad-Drouz Range, the βQ2 effusives include scoria, scoriaeceous agglomerates, and incoherent pyroclastics (lapilli and volcanic bombs). The Upper Quaternary epoch (Q3) appears not to have witnessed volcanic activity.

PONIKAROV (1966) recognized seven alternating lava sheets of Recent age in Syria. The first and oldest basalt sheet (β1Q4) is limited in surface-extent (70 km^2) and located in the northeastern part of the As-Suwayda province. This sheet was formed by 2 or 3 eruptions, the thickness of the each erupted lava sheet reached some 10 m. These predate flows and sheets of basalts (β2Q4) of a more extensive nature occupying an area of 170 km^2 and underlying a third group of younger lavas (β3Q4). Another basalt sheet (β4Q4) consists of pahoehoe lavas and believed to be part of the volcanic plateau of Al-Laja. The sources of eruptions of these lavas are the volcanoes located in the region of the village Majadel (DUBERTRET, 1933). The average thickness of each sheet is considered to be 8 to 10 m.

Another distinctive group of basalt flows (β5Q4) is represented by lava flows from volcanoes of Tell Shihan and Ard El-Kra. Aariqa cave is found within these basalts (see below). The age of bone fragments of mammals, goats, and gazelles, was found to be 4,000 years (by carbon dating method; Ponikarov, 1966). The length of the pahoehoe lava flow from the eruption source (Tell Shihan) to the edge "tongues" reaches 45 km. Its width in the east, near the volcano, does not exceed 6 to 8 km, gradually increasing to the west reaching 10–12 km. The flow surface of the pahoehoe lavas features ropy lavas indicating a westward direction of lava flows. These basalt flows are overlain by the youngest recent effusives (β6Q4) observed in the study area; they are believed to have occurred in historic time – within the last 4000 years. They include block aa-lavas of the Shahba volcanoes and the southern portion of the Tell As-Safa Massif represented by pahoehoe lavas (PONIKAROV, 1966).

3. Lava Caves

Our speleological investigations led us to the discovery and exploration of two lava cave systems in different lava sheets (with respect to the age of the lavas).

3.2 Umm ar Rumman Cave (β1Q1)

Umm ar Rumman cave is located south of As-Suwayda near the border with Jordan, and about 20 km southeast of Bosra city. This lava tube is located within the earliest Quaternary

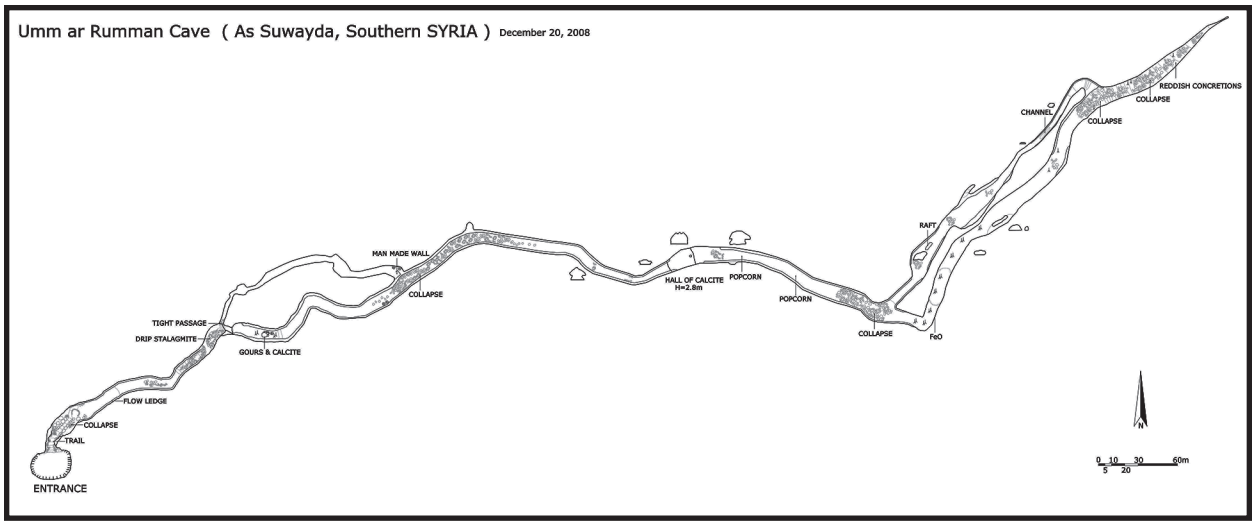

Figure 3. Map of Umm ar Rumman Cave (surveyed by members of the Spéléo-Club du Liban and drawn by Johnny Tawk).

sheets (the pahoehoe lavas of β1Q1, described above) in a flat agricultural area. It is characterized by an entrance (14 m deep and 20 m wide) that may have been formed by roof-collapse. The entrance is cluttered with fallen rocks, a big opening leads through an inclined gallery 10 m deep, to reach a linear gallery characterized by a well-traced trail. The total development of Umm ar Rumman cave is 1615 m (Fig. 3), and it contains braided galleries (Fig. 4). As the longest reported lava tube in Arabia was the Umm Jirsan cave in Saudi Arabia with a development reaching 1,481 m (PINT, 2008), Umm ar Rumman becomes now the longest surveyed lava tube development in the Middle East. Umm ar Rumman is a typical lava cave hosting almost all features found in volcanic caves: levees and gutters, flow ledges, splash stalactites, lava columns and stalagmites, as well as rafts. In addition, beautiful calcite speleothems decorate this cave.

Figure 4. Photo inside Umm ar Romman Cave, by Johnny Tawk.

The average diameter of the tube is 7.5 m with a height of 8 m. A huge collapse is 190 m from the entrance. A splash stalagmite is found, about 1 m high, near a molded tree. The collapse ended with a braided maize. After a small crawl, a second part continues. Calcite gours cover the floor where we found many fragments of pottery that, after examination, appeared to belong to the Islamic period (Ayyoubide or Mamlouk, ref. Dr. Leila Badr, conservator of AUB Museum, American University of Beirut). In this part of the cave, many collapses change the homogeneity of the cave profile (Figure 3). At some places, the roof reaches the height of 14 m.

At 800 m from the entrance, a second braided maze (Fig. 5) has calcite speleothems (i.e., popcorn, stalagmites, helictites, and others). At the end of the right sided tunnel, the cave's floor and walls are reddish with a large amount of fallen rocks. Umm ar Rumman cave ends with a narrow 10 m long tunnel.

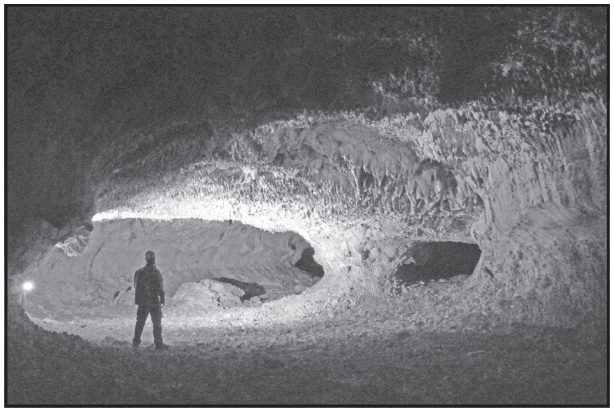

Figure 5. Photo of a Braided Maze inside Umm ar Romman Cave, by Johnny Tawk.

3.2 Aariqa Cave (β5Q4)

The Aariqa cave is situated in the center of the Aariqa

Figure 6. Entrance of Aariqa Cave, by Johnny Tawk.

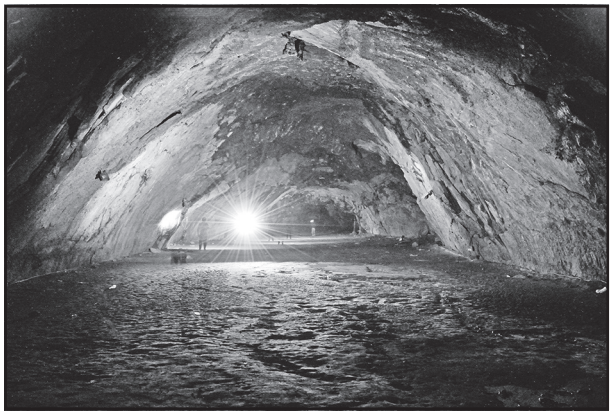

Figure 8. Photo of the touristic part inside Aariqa Cave.

village. It was also called Ahiré cave and was used during different historical periods in Syria. This cave is northward of the Umm ar Rumman and within the relatively younger β5Q4 recent pahoehoe lavas which have been dated at about 4,000 years (see above). At the end of the cave, the transition from pahoehoe basalt of the β5Q4 and aa of the overlying (younger) β6Q4 sheet has been observed. The entrance is an impressive open collapse seen from the main road with an average of 14 m wide and 16.2 m depth (Fig. 6). At -14 m from the road, and at the left side, a basaltic stair under two arches goes down 5 m towards Aariqa spring, which is used for domestic purpose in the city. The total development of the cave is 562 m (Fig. 7).

The entrance of the cave is protected by a carved monolithic basaltic door from Nabatean or Roman era (64 B.C. to A.D. 391) about 90 cm wide and 110 cm high, no inscriptions are observed. After three steps, you could reach the first part of the cave which is an east-west 165m long tube (Fig. 8). This part is developed as a show cave, electrical cables and projectors are seen on both sides. It is 16 m large and 9 m high with a flat muddy clay floor caused by dripping water from lateral sides. Scarce calcite stalactites are apparent. At the end of the tube, a large chunk of wall is fallen creating lining, the wall is glazed. Beyond this tube, the morphology of the cave takes different aspect followed with four smaller tubes linked by tight and low passages.

The first tube is distinguished by an important rock collapse, on which we could map seven enclosures separated by non-carved stone walls not more than 30 cm high. The interiors of these enclosures reveal a fireplace, animal bones and fragments of pottery (Arab period, after A.D. 634, pres. Communication Dr. Leila Badr, conservator of AUB Museum, American University of Beirut), documenting a past human occupation. Though some fragments are recent, a detailed study must be carried out *in situ*.

The second tube is 72 m long, 13 m wide, and 5 m high (Fig. 7). Here also, non-carved stone structures are located on both sides of the floor, animal bones and pottery. This tube is at -12 m from the touristic area. The third tube is 40 m long, 10 m wide, and 5 m high. This part represents the continuation of the second tube, which is separated by a ceiling collapse. At the end of the third tube, a side passage ascends 20 m high and reaches a second entrance to the cave in the garden of a private house. At the end of the cave, a rounded construction, bones, and pottery were observed. Also, dripping water is noted. Also, two cupolas are seen in the ceiling (Fig. 7). In general, the temperature of the cave is 18° C (December 2008) and some volcanic formations are spotted in this cave, including linings, splash stalactites, breakdown areas, and contraction cracks.

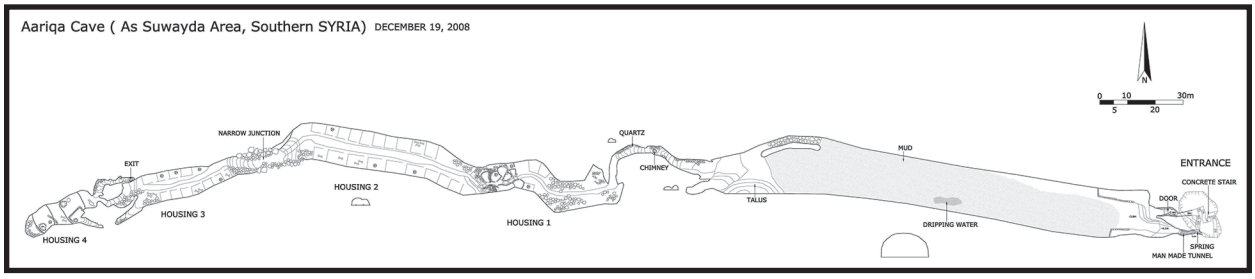

Figure 7. Map of Aariqa Cave (surveyed by members of the Spéléo-Club du Liban and drawn by Johnny Tawk).

4. Conclusions

Two expeditions led to the exploration and surveying of two significant lava caves in Syria and the Middle East. The first, Umm ar Rumman cave with 1,615 m of underground development can be considered the longest of its kind in Arabia and the Middle East. This cave, probably older than a million year (in the Quaternary lava sheet β1Q1) is also decorated with the full range of volcanic and breathtaking calcite speleothems. The second, Aariqa Cave, has a development reaching 562 m, still it holds an important historical aspect as housing remains were found in its galleries. Aariqa Cave must be younger than 4,000 years old as it is formed in the recent lava sheet β5Q4.

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Symposium 10

PROTECTION AND MANAGEMENT OF RARE AND ENDANGERED SUBTERRANEAN FAUNA

Arranged by:
Cyndee Watson
Oana Moldovan

GATING A CAVE PROTECTS A BAT COLONY ... EVENTUALLY

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The Guadalupe Mountains of New Mexico (USA) are best known for the highly decorated Carlsbad Caverns, which is home to a large maternity colony of Mexican free-tailed bats (*Tadarida brasiliensis*). The 'Guads' also have numerous smaller, less spectacular caves that are critical habitat for other bat species. Because cave resources can be damaged with unlimited human visitation, land managers often protect caves by installing cave gates. However, not all bat species readily accept gates and some bats have abandoned historic roosts once the sites are gated. Unfortunately these animals originally chose the caves because they had the appropriate species-specific temperature and humidity for their survival. We describe efforts to protect a maternity colony of cave myotis *(Myotis velifer)* in a Bureau of Land Management (BLM) cave near Carlsbad, New Mexico. A long-term (>15 yr.) monitoring program documents the near-demise of a significant bat colony, resulting both from human vandalism and the consequences of a cave gate. We describe how the size and placement of a gate, designed to protect the bats, resulted in cave myotis abandoning the cave. Fortunately BLM management appropriately addressed the problem and altered the gate design and placement so that bats have reoccupied the cave in historic numbers. We discuss possible consequences of gating caves without fully understanding how the bat species using the site might accept a gate. Because of 'before' and 'after' documentation of how this particular bat species responded to a gate, we strongly recommend long-term monitoring after installation of any cave gate designed to protect a bat colony.

1. Introduction

Carlsbad Caverns, Guadalupe Mountains, New Mexico (USA) is famous for its large, highly decorated chambers but also popular with visitors for the summer evening exodus of almost 500,000 Mexican free-tailed bats (BETKE et al., 2008). However, this region has numerous smaller, less spectacular caves that provide important resources for other cavernicolous bat species. These caves offer appropriate microclimate for roosting bats - species-specific temperatures and humidity, which insure reproductive success and survival (TUTTLE, 1979; GORE AND HOVIS, 1998). Because caves provide critical habitat for bats, exclusion from these sites can negatively impact populations. Unfortunately, bats are highly intolerant of human intrusion into their roosts (MANN et al., 2002; BUECHER, 2006; ELLIOTT, 2006) and will abandon important sites if disturbed too frequently (MOHR, 1972; TUTTLE, 1977; TUTTLE, 1979). Given that cave resources are fragile and bats need protection from human disturbance, land managers often install gates at popular caves to protect both biotic and abiotic cave resources.

Unfortunately, improperly designed cave gates intended to protect bats can often do more harm than good. TUTTLE (1977) discovered that at a number of caves, specifically gated to protect bats, the animals abandoned the sites within two years. This is due, in part, to alteration and reduction of the bats' flyway but can also result from changes in cave microclimate by modifying air exchange. Additionally, ill-conceived gates can provide a location for predators to grab bats when they are forced to fly slower to negotiate a gate (TUTTLE, 1977). Cave gates can also increase circling behavior by bats and cause bats to retreat more often into the cave prior to emerging from a site. This behavior is more pronounced in larger colonies whose gates are constructed in small passages (i.e. less available flight space per bat), impeding smooth emergence by the animals (SPANJER AND FENTON, 2005). Any bottleneck that gates create for bats emerging daily from a cave increases flight time and energy costs, which can reduce reproductive success and survival.

2. History of a Cave Gate

Yellow Jacket Cave overlooks Dark Canyon in the Guadalupe Mountains and is managed by Bureau of Land Management (BLM). The cave is approximately 10 miles from Carlsbad New Mexico and has over 1.5 miles of passage. In the spring of 1979, cavers from the Southwest Region (SWR) of the National Speleological Society (NSS) began mapping Yellow Jacket and discovered evidence of a major bat roost. In the spring of 1980 they reported to BLM *"... active bat roosts everywhere. It was suspected*

that the cave was used as a nursery. This was confirmed. Because of the nursery, we delayed further work." When SWR completed their map (BELSKI et al., 1986), they had documented 10 distinct areas in the cave where bats day-roost. Unfortunately, the proximity of Yellow Jacket to Carlsbad New Mexico resulted in its use as a "party cave" by locals and there was often evidence of vandalism, including fire rings, spent firecrackers, and graffiti. Because of these threats to the resource, BLM developed a cave management action plan in 1986 for the protection of Yellow Jacket Cave. Although the number of bats using the cave and the specific species was unknown, it was recommended that a cave gate be installed to protect the colony. Prior to the installation of this gate, BLM conducted 5 bat counts between June and August. These counts were conducted at the entrance of the cave as bats emerged to forage. During summer 1986 the average number of bats was 2,158 with the highest bat count at 2,742 in early July.

BLM and SWR installed a steel gate in December 1986 in a small passage (1 meter wide x 0.5 m high) approximately 25 m from the entrance. During summer 1987, BLM volunteers conducted 12 post-gate bat counts to monitor gate acceptance by the bats. The average number of bats emerging from the cave that summer was 1,145, with the largest number of bats at 3,246 in early August. Although the numbers looked reasonable, it was discovered that bats were often roosting in passages on the *outside* of the gate, avoiding the gate entirely and exposing the animals to continued harassment. In 1988 bats still avoided the gate and were still roosting in a side passage between the gate and the cave entrance. In an attempt to mitigate the situation, BLM left the gate open throughout the summer and continued to conduct evening emergence counts. Despite the open gate, bats still roosted outside the gate. Also during this year, garbage was repeatedly removed from the entrance area and BLM documented new fire rings and fresh graffiti. Due to budget cuts, no bat counts were conducted between 1988 and 1997, however cavers reported fewer bats using Yellow Jacket. Although the reduced flyway, created by the gate, no doubt impacted the bats, the low numbers were most likely due to harassment by humans. Evidence indicated that the cave continued to be used by local youths for parties, with beer bottles and fire rings often found in the entrance rooms. It was also reported that people harassed bats using tennis rackets and shotguns. This information confirmed the need to re-evaluate the situation and determine if a more bat-friendly cave gate might better protect the bats.

In 1997 BLM contracted a bat biologist to evaluate Yellow Jacket Cave, determine which bat species used the site and propose possible ways to protect the colony and restore the historic population. This study included seven emergence counts at the entrance and installation of a passive infrared bat counter to monitor bat activity throughout the night. It was determined that Yellow Jacket had a maternity colony of cave myotis (*Myotis velifer*). Cave myotis are the largest myotis species in North America with a wingspan of 28–33 cm and weighing 12–15 g. Compared to other myotis, they are recognized by a longer forearm (40–43 mm), lack of a keeled calcar and a sparsely furred area between the scapula (FITCH et al., 1981; ADAMS, 2003). During summer 1997 the cave myotis used the cave in low numbers (average = 290) but the population increased in the fall (799 in early September). This increase in bat numbers was observed each year and suggested that Yellow Jacket was important as a swarming site, where solitary bachelor males rejoin females to mate in the fall prior to entering hibernation (FENTON, 1969; SPANJER AND FENTON, 2005). At the end of the study, BUECHER et al. (1997) recommended that the existing gate be removed and a more bat-friendly gate be installed closer to the entrance in passage with a larger cross-section. This would offer an area for bats to circle on either side of the gate, provide more choices for flying through the bars and would reduce possible predation at the gate. In March 2000, the original gate was removed by SWR and a new steel bat-friendly gate (POWERS, 2004) was built in the large entrance passage. This location provided protection of all historic bat roost sites documented by SWR (BELSKI et al., 1986). Post-construction emergence counts at Yellow Jacket by BLM volunteers over foue years (2001–2004) documented dramatic increases in bat-use (Table 1) by cave myotis. The average number of bats now using Yellow Jacket Cave increased each year and the highest number of bats using the cave in 2004 was 6,155 bats. By all appearances, the bats definitely approve of the new gate design and its location in the larger cave passage.

Year	Average No.	Max. Number
2001	1663	4000
2002	2111	3845
2003	2175	4205
2004	3191	6155

Table 1: Average number and maximum number of bats documented in Yellow Jacket Cave each summer between 2001-2004.

3. Discussion

Pre-gate emergence counts indicated that the numbers of bats using Yellow Jacket were much higher before the cave was gated. In 1988 a gate was constructed in a small

cave passage because it was cheaper to build and easier to secure against vandals. Unfortunately, the placement of horizontal and vertical steel bars decreased the bats' flight window by almost half. The gate may also have provided a spot for predators to take bats from the air as they slowed to negotiate the gate. After installing the first gate (Fig. 1a), the fact that bats avoided it suggested that the gate was detrimental to the bat colony. Fortunately BLM management discovered this through post-gate emergence counts. They removed the original gate and restored the passage to historic dimensions. They then constructed a new gate in a larger passage using steel bars with wider horizontal spacing and eliminated many of the vertical bars (Fig. 1b). This bat-friendly design resulted in bats reoccupying the cave in historic numbers. This emphasizes the importance of conducting both *pre-* and *post-*gate emergence counts to fully understand how bats behave prior to a gate and, once a gate is installed, how well they accept the new 'obstacle' in their flyway.

In 1986 BLM attempted to protect the resources of Yellow Jacket Cave using the only method at their disposal, a cave gate. Although their efforts almost caused the demise of a maternity colony of cave myotis, it is important to understand that at the time, little was known regarding how bats responded to cave gates and why some bat species accepted cave gates, while others did not. It was, unfortunately, as a result of abandonment of known bat roosts across the U.S., due to a variety of ill-conceived gate designs, that we have learned which gates are best for bats (POWERS, 2004), which bat species may or may not accept gates (SHERWIN et al., 2004) and what gates do not negatively impact cave microclimate (RICHTER et al., 1993; KENNEDY, 2004). Gating caves has become a common management practice to protect fragile cave resources, both biotic and abiotic (TUTTLE AND TAYLOR, 1998; KERBO, 2004). Because of our 'before' and 'after' documentation of how this particular bat population responded to a gate, we strongly recommend long-term monitoring after installation of any cave gate designed to protect a bat colony. Evidence of additional circling at bat gates (SPANJER AND FENTON, 2005) requires more energy that can negatively impact bats. This may be more problematic at maternity roosts where pregnant females are less maneuverable and where newly volant young are less experienced flyers. Gating policies should consider all cavernicolous bat species in an area because caves are often used by multiple species (TUTTLE, 1977; LUDLOW AND GORE, 2000; SPANJER AND FENTON, 2005). Without fully understanding which bat species are using a site and whether they accept cave gates may result in negative consequences for populations. Given the sensitivity of bats to human disturbance but also the resistance of some species to cave gates, we must approach this issue with care in order that we do not exclude the very species we desire to protect.

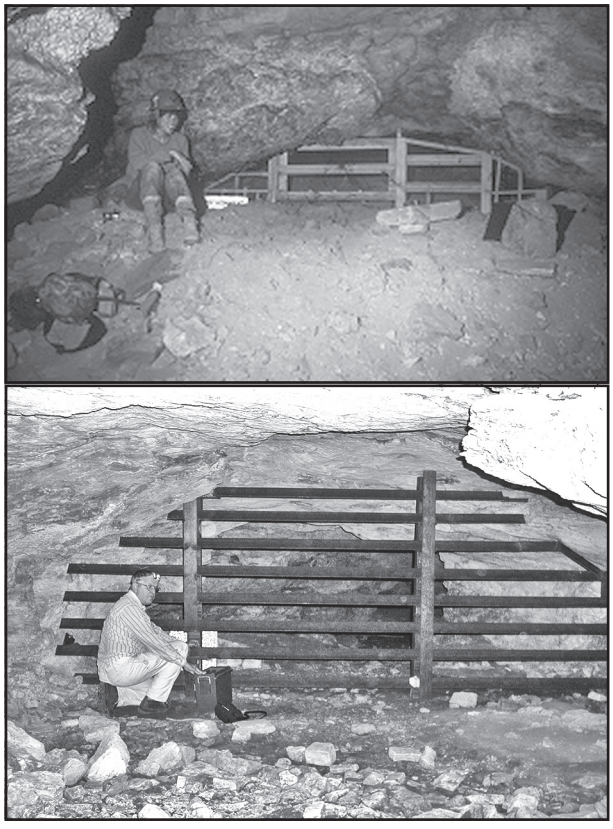

Figure 1: Top photo is of the 1986 cave gate. Note how much the bars of the gate reduce the flight window for bats. Bottom photo is the 2000 bat-friendly gate installed by BLM and SWR. Note the larger flight window and number of choices for bats exiting or entering the cave.

Acknowledgments

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REGIONAL HABITAT CONSERVATION PLANNING IN KARST TERRAIN, WILLIAMSON COUNTY, TEXAS, USA

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Abstract

Regional Habitat Conservation Plans (RHCPs) are an increasingly popular option for local governments to balance economic growth with conservation of habitat for rare and endangered species. For most of this decade, Williamson County, Texas has remained one of the fastest growing areas of the United States with much of that growth occurring on the Edwards aquifer karst. Nearly ten percent of the known caves in Texas lie within the path of growth west of the cities of Round Rock and Georgetown. Karst endemic species include three endangered karst invertebrates, more than a dozen other rare karst invertebrates, and several salamanders. Concerned community leaders, including several members of the Williamson County Commissioner's Court formed the Williamson County Conservation Foundation in 2002 to develop the County's regional planning approach. Approved by the U.S. Fish and Wildlife Service in October of 2008, the Williamson County RHCP provides expedited compliance with the Endangered Species Act while recovering two endangered species and precluding the need to list others. Mitigating species impacts on a regional scale allows high quality conservation areas to be selected on the basis of biological diversity and preserve integrity. A minimum of nine high quality karst preserves have been or will be established within the 100,000 acres of undeveloped karst by 2038.

INCITING PUBLIC INTEREST AND PROFESSIONAL PARTNERSHIPS IN THE INVENTORYING AND MONITORING OF CAVE INVERTEBRATES, KARTCHNER CAVERNS STATE PARK

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Abstract

Kartchner Caverns State Park (KCSP) is a commercial cave operated by Arizona State Parks. Opened in 1999 it was one of the most environmentally sensitive developments of a show cave anywhere in the world. When our visitors explore the large chambers and varied formations at Kartchner Caverns, they cannot fully realize or appreciate the myriad of tiny eyes, antennae and other sensory organs that our oligotrophic invertebrates are employing to detect their passage. Most of our invertebrates are associated with the seasonal influx of fresh bat guano. Some are parasites on the *Myotis velifer* bats, while others find a home in the cracks of the breakdown rock throughout the cave. Like the microorganisms that flourish in our cavern complex, cave invertebrates flourish in environments that are too small to be exploited by macroorganisms, and observed during cave tours. Before construction was begun in the cave a 4-year study of the undisturbed cave environment was undertaken. One study included an inventory of the invertebrates found in the cave. Thirty-eight species were documented, several of which are thought to be new species. One goal of the first study was to establish a baseline for future comparative studies. The Cave Science Unit at KCSP invites qualified invertebrate researchers to assist in ongoing habitat studies and inventory of known and different species.

In 2007 a graduate student from the Materials Science and Engineering Department at the University of Arizona performed high-resolution imaging and measurement of various invertebrate specimens that had been previously collected in the caves. Inspiring images of various specimens were produced by a scanning electron microscope (SEM) for the study. These were shared in presentations by staff and the researcher in a number of public forums. Preliminary findings from two species of beetles found after the predevelopment studies indicate they could also be new species. Both of these beetles were imaged by the SEM, which provided high-resolution details of their body morphologies for future study. SEM images of cave spiders showed no bacterial growth on their bodies, whereas other invertebrates where the spiders were found, exhibited bacterial components in abundance. Images like these pose intriguing questions about ecosystem dynamics. High-resolution imaging of our invertebrate world continues to inspire and awe park visitors. Through technology, shared goals, and partnerships, we hope to entice and develop a new generation of cave resource stewards. Future studies hope to address questions like, "Why is the surface of the spider's carapace so crenulated?" "Does it reflect or refract light, provide greater absorption of air born molecules, or help the spider sense subtle changes in air pressure that signal prey is near? How do our tiny springtails sense food sources like bacteria and fungi from great distances across the cave?" As a small part of the interpretive program at Kartchner, we found a very interested public fascinated by the SEM images and interested in protecting its invertebrate world. Cave invertebrates serve as important indices for measuring the balance of Kartchner's cave ecosystem. Thus, we look forward to partnering with others on a cost-effective and sustainable monitoring program that accurately assesses and conserve the invertebrates of Kartchner Caverns and other caves in the area.

THE ROLE OF KARST FAUNA AREAS IN THE ADVANCEMENT OF KARST CONSERVATION IN CENTRAL TEXAS

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Abstract

Urban development in central Texas is a threat to the integrity of natural habitats, especially caves and karst. Sixteen cave-restricted invertebrate species are protected by the U.S. Endangered Species Act (ESA) in Central Texas, while many others are considered species of concern. In order to prevent extinction of listed cave invertebrate species, to favor conservation, and ultimately to achieve species recovery, the U.S. Fish and Wildlife Service (USFWS) proposed guidelines to define areas that could be designated as units for conservation. The USFWS commissioned a study that defined and delineated Karst Fauna Regions (KFR) based on potential geologic and geographic barriers to karst invertebrate dispersal, and limits of species distribution. Since 1992, studies have shown that the boundaries proposed for the KFRs do not always correspond to the known species boundaries. In addition, some species previously thought to be restricted to one KFR have been collected over several contiguous KFRs.

The concept of a Karst Faunal Area (KFA) was first proposed in the *Recovery Plan for Endangered Karst Invertebrates in Travis and Williamson Counties, Texas*. Although titled as a recovery plan, the document objective is limited to downlisting the species, and recommends criteria and specific actions required to achieve that objective. These criteria include the following phrase: "three karst fauna areas within each karst fauna region in each species' range should be protected in perpetuity". In the Recovery Plan, a KFA was envisioned as a separate, protected unit of occupied habitat that would be officially designated and preserved for the benefit of listed troglobitic species recovery. Since the KFA concept was introduced, additional scientific knowledge of karst invertebrates has been gained, and many karst preserve areas have been established. However, only one of these preserves is considered a KFA by USFWS. This unit was established in November 2008, more than 14 years after the publication of the Recovery Plan.

Some of the criteria proposed to define KFAs are rather vague and subjective, particularly the requirement that caves within a given KFA must be independent from other caves. In the only currently designated KFA, the location on an isolated hilltop clearly suggests an isolated cluster of caves, but independence will be difficult (or impossible) to determine where the surface topography differs. In order to circumvent this problem and use a quantifiable scientific baseline to establish the independence among clusters of caves, we propose to use genetic data to assess the degree of connections between caves. We provide an example using mtDNA data of a troglobitic *Cicurina* to determine the structure of the genetic diversity of a small karst area and identify Significant Evolutionary Units (ESUs). ESUs are more appropriate units to guide conservation strategies because they are measurable, internationally recognized and scientifically sound.

SPELEOTHEMS AND LIVING ORGANISMS: WHAT KIND OF RELATIONSHIP?

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The idea that speleothems may be somehow influenced by living organisms is rather old, but specific studies have only started in the last few decades and presently there are only few systematic papers on this topic. The role of micro-organisms is perhaps the best investigated though not fully understood, while studies on upper organisms and speleothems are scarce and details on the involved genetic mechanisms are not always given. The aim of the present paper is to enhance the interest of the scientific community on this peculiar topic. In fact the complex biochemical reactions involved in the development of the different cave deposits clearly have an importance far exceeding the simple speleogenetic interest.

1-Introduction

The idea that the development of the secondary chemical deposits in caves may be somehow influenced by living organisms is rather old (SHAW, 1997): the shape and the internal structure of some speleothems (stalactites, stalagmites, coralloids...) suggested to the early visitors of caves (ALDROVANDI, 1648) the possibility that they grow as plants even though the current idea was that minerals (and therefore also the speleothems) were living organisms but at a lower level with respect to plants or animals until the second half of XVIIth century. In the second half of the XVIIth century a scientist put forth the idea that speleothems are true "rock plants" (BEAUMONT, 1676), this theory was later perfected by J. P. TOURNEFORD (1704) who wrote:

> *...That certain rocks nourish themselves in the same way as plants. Perhaps they reproduce also in the same way..... that there are seeds which gradually swell up and develop the regular structure which is perhaps hidden beneath their surface... Thus the congelations grow up from seeds.*

Thus, in the XVIIIth century, some of the most common types of speleothems were often represented just as part of a tree: with stalactites as roots, stalagmites and columns as trunks, helictites as leaves or flowers.

Since the second part of XVIIIth century the progress in chemical studies allowed the detection of the main mechanisms by which calcite and other minerals deposit in caves and consequently any possible biogenic interaction in speleothem evolution was rejected for over one century. But the increase of scientific observation inside caves which characterised the XXth century allowed the opportunity to reconsider the whole matter. Today the fact that living organisms may influence the external shape and/or the chemical composition of speleothems is generally accepted. Nevertheless systematic studies on this topic have never been done, except for a few dealing with microbiology (SASOWSKY AND PALMER, 1994; NORTHUP et al., 1997; FORTI, 2002). Research in this specific field started only fifty years ago, but their development progressively highlighted the role played by micro-organisms in the genesis and the evolution of secondary cave minerals. Therefore at present, some even doubt that caves may host speleothems developed without the active and/or passive control of living organisms. The role of micro-organisms is perhaps the best investigated, even if it is far from being fully understood. Studies on upper organisms and speleothems in caves are scarce and normally refer only to the occurrence of biologically controlled chemical deposits saying nothing on the involved genetic mechanisms.

2- The Role of Microorganisms

Presently, it is well established that microorganisms can directly cause biomineralization through enzymes, or can produce substances that lead to the precipitation of minerals (e.g. by changing the pH in their surrounding) or they may become the privileged support for nucleation. The microbial processes in caves often involve redox reactions. The microbial players are varied: aerobic (chemiolithotroph) microorganisms, which obtain energy directly from the oxidation of inorganic compounds, but also anaerobic (heterotroph) organisms which obtain energy from the oxidation of organic matter and reduce inorganic compounds.

2.1 The "sulfur cycle"

The microbial reactions of the "sulfur cycle" are perhaps the best studied and have been proved to cause the development of a lot of cave minerals: native sulfur, gypsum and iron oxides-hydroxides are the most common speleothems developed by them, but plenty of others have been reported in literature (HILL AND FORTI, 1997; SHOPOV,

2004; FORTI et al., 2009). Sometimes the large amount of organic matter produced in the "sulfur cycle" allow for the evolution of speleothems (pseudo-stalactites) consisting of single organic mat (mucus), which are normally called "mucolites." Apart from those related to the "sulfur cycle," many other kinds of biomineralization can occur in the cave environment: the most important of which are: 1- the salpeter evolution; 2- the phosphate deposition; and 3-the guano digestion.

2.2 The salpeter evolution

Actually it is well known that the deposition of saltpeter (nitrocalcite) and all the other cave nitrates is driven by nitrifying bacteria, but in the early times of cave science, there were several supposed origins for nitrates in caves. The most curious among them referred to the uplifting of nitric gas from deep inside the earth (ZIMMERMANN, 1788), or postulated the deposition by electric currents (GIOVENE, 1819). Only in 1839 the Danish LUND put forth the hypothesis that: *"... Salpeter earth (in caves) derives from surface organic matter..."* However, this theory took over 150 years to be demonstrated: in fact only in 1981 C. HILL established that: "... *nitrates leached from the surface soils, transported into caves by seeping waters, are deposited by the aid of the nitrogen bacteria* Nitrobacter..." Moreover, it is presently proved that the same mechanism may also leach nitrates from guano, rat droppings, and urine and deposit them into cave earth. Therefore it is only in very peculiar cave environments (like the volcanic caves) that salpeter may have an inorganic origin related to weathering of basaltic rock (HILL AND ELLER, 1977).

2.3 The phosphate deposition

The sources for PO_4^{-3} ions to produce minerals in caves are normally represented by bones and/or guano deposits inside the cave. The reaction between phosphoric acid, cave walls, clay and sand in the floor and/or other minerals dispersed in the hosting rock is absolutely an inorganic process, but the transformation of organic phosphorous into PO_4^{-3} ions seems to be always driven by the micro-organisms ruling the complex mineralization (mainly oxidation) processes of the organic mat inside a cave. Therefore probably almost all of the known cave phosphates are at least partially biogenic products. No specific study on this topic has been done until now.

2.4 The guano digestion

Mineralization of guano is a complex mix of different reactions, many of which are surely biologically driven. The previously described, related to the sulfur cycle, the saltpeter and phosphate evolution are among them and surely the most important, all of them occurring inside guano deposits. Micro-organisms may reasonably control many other processes, like those causing the deposition of halite, gypsum, iron and manganese oxides-hydroxides. Until present no specific study on the eventual biologically driven guano reactions has been done. Recently, in a different context (without guano), it was possible to demonstrate that the iron oxides-hydroxides depositing inside Odyssey Cave, Bugonia, Australia are surely a biogenic mineralization: here the bacteria *Lepothrics* spp and *Gallionella* sp were proved to precipitate ferrihydrite with characteristic morphologies (CONTOS, 2001; CONTOS et al., 2001).

2.5 Biogenic speleothems in silica-rich cave environments

The presence of high silica content in the cave wall and/or sediments may allow the development of peculiar micro-organisms which may in turn give rise to biogenic mineralizations. In some volcanic caves of Japan (KASHIMA et al., 1989) the development of several silica coralloids and helictites has been found to be strictly related to the presence of colonies of diatoms (genus *Melosira*). In fact these speleothems consist mainly of skeletons of such organisms that are cemented by small amount of silica. Their presence is strictly confined to the first part of the caves where a little of the external light can still reach the colonies of *Melosira*, because they need the energy supplied by the light to live. The light control is evident not only by the fact that these speleothems develop only in the threshold zone but also by their shape, which is always pointing towards the cave entrance. Beside this proven occurrence of biologically controlled speleothems in silica rich cave environment, there are several other cases in which a biogenic origin seems to be highly probable. Filamentous organic structures have been reported in opal coralloids from quartzite caves in Venezuela (ONAC et al., 2001) and in opal-sulfur speleothems in a gypsum cave of Sicily (FORTI AND ROSSI, 1987). Moreover in many of the lava tubes weathering of basaltic rock caused the evolution of a widespread amorphous silica moonmilk, extremely rich in organic matter (FORTI, 2002; CALAFORRA et al., 2008), thus suggesting that the weathering process is probably driven by micro-organisms. In Pico Island (Azores) there are gigantic opal flowstones (up to 5 or 6 meters (m) long and over 1 m thick) inside the Argar do Carbalo volcanic cave, which seem to derive from the diagenesis of the previously described silica moonmilk and, therefore, should be considered biogenic speleothems.

2.6 Biogenic carbonate speleothems

It is presently well accepted that by far the large majority of carbonate speleothems developing in a cave environment are

absolutely inorganic, however at least some of these deposits undergo biological control. Fungi, algae and bacteria have all been implicated in the precipitation of carbonate dripstones but until recently it was not proved if these micro-organisms helped actively (by driving the chemical process) or passively (serving as crystallization nucleus) in the deposition, or if they were just accidentally buried there, which seems rather to be the more common occurrence. Perhaps the best example of these processes are represented by the gigantic stromatolitic stalactites developing worldwide just at the entrance of many caves mainly in the tropical area. The algae colonies responsible for their development need strong light to survive and therefore such formations are present only up to the threshold zone. Over a score of several tens of years, an extensive documentation of the microbial precipitation of calcium carbonate exists in non-cave carbonate/travertine literature (EHRLICH, 1996), their direct involvement in cave carbonate deposition have only been demonstrated very recently (CONTOS et al., 2001; CONTOS, 2001). In her experiments CONTOS proved the active role played by bacteria in precipitating calcite crystals, and also experimentally evidenced that micro-organisms in Nullarbor caves (Australia) control also the shape of the generated calcite crystals, which are very different from those of the inorganic precipitated ones. Deposition of dolomite within cave environment was recently strictly related to the presence of bacteria (VASCONCELOS, 1995; VAN LITH, 2001; PANIERI et al., 2008). Fungal hyphae may act as nuclei for crystallization and a site for attachment for crystals. Algae can trigger the precipitation of calcium carbonate from solution, and may subsequently trap and bind the particles to carbonate speleothems. This may occur as the algae change the microclimate by respiring carbon dioxide (CO_2) and consequently causing the $CaCO_3$ to precipitate. Anyway due to their photosynthetic nature, except in show-cave environments, algae will only contribute to carbonate deposition at the entrance and twilight region of the caves, being responsible for the evolution of the previously cited stromatolithic stalactites, which may sometimes reach even gigantic dimension in the tropical areas. Finally bacteria which utilize CO_2 (like *Thothrix* in the sulfur cycle) have been proved to cause accelerated carbonate speleothem growth. Microbiological reactions seem to be frequently responsible for moonmilk deposition. In fact the two most common mechanisms for the evolution of moonmilk (HILL AND FORTI, 1997) are: 1- biochemical corrosion of the bedrock by organic acid produced by microorganisms (*Arthrobacter, Flavobacterium, Pseudomonas)*; and 2- active precipitation of moonmilk by bacteria (*Macromonas bipunctata*). Finally it is important to note that microorganisms should be fundamental also in the deposition of moonmilk made by different minerals: not only in the case of the amorphous silica already cited, but also when the moonmilk is made of gypsum, amorphous silica, etc. (FORTI, 2000) even if no specific studies have been done on this topic at present.

3- The Role of Plants and Animals in the Evolution of Speleothems

If the actual knowledge on the role played by microorganisms in speleothem evolution is surely not exhaustive but fairly good, the situation is far worse when considering the effect of plants and animals over the secondary chemical deposits in caves. In fact, in these two fields the research is extremely scarce and the available few papers always deal with spot observations without any attempt to consider the topic from a general point of view. Presently it's well accepted that plants (mainly roots) and remnants of animals (spider nets, bones, etc...) may passively improve the development of speleothems by enhancing capillary migration of waters to places where evaporation may occur. Further other cave formations exist, the genesis of which are directly related to plants and/or animal. Plants may induce the genesis of the low pulp density peat stalactites, which are generated by evaporation of suspensions coming from the surface through porous cap rock (BURKE, 1967). Animals with their dejections are directly responsible for the development of organic formations without any fixed chemical composition like amberat speleothems, related to the dung and urine of cave rats (SHOPOV, 2004), and mumijo, which is specific of the caves in the high mountains of central Asia where it is secreted from the excrements of animals like rabbits or mice which eat the peculiar grass and shrubs of these regions (HILL AND FORTI, 1997). Moreover animals, like bats, may deposit huge amounts of excreta in caves, which later undergo bio-mineralizations driven by micro-organisms. Anyway, in most cases, an active involvement of plants and animals in the evolution of speleothems is still speculative.

3.1 The influence of roots on speleothem growth

The root apparatus is the single portion of a tree which may somehow interact with speleothem evolution. The interaction may affect both the morphology of the speleothem (passive effect) and its chemical composition (active effect). However, plants normally cannot directly control the mechanisms of chemical deposition deep into the caves, because they need light to survive and their roots can hardly reach depths of several tens of meters. On the contrary in the show caves, where light is artificially supplied, plants often become not only an element of

disfigurement, but also may lead to a halt in the calcium carbonate deposition or even cause the corrosion of speleothems, due to the acid secretion of their roots. A peculiar lithogenetic effect induced by plants was described in the gypsum area of Bologna (FORTI, 1983): with the life activity of plants causing a concentrated local increase of CO_2 close to the root apparatus that allows the development of the incongruent dissolution of gypsum which leads to the evolution of carbonate speleothems to form layers inside gypsum flowers or even thin, pure calcite flowstones. The morphological (passive) effects induced by roots on speleothems are much more frequent and evident: in fact when roots enter cave voids their surface may become a preferential area for the flow of the seeping water and, if the suitable environmental conditions (diffusion of CO_2 and/or evaporation) exist, for calcium carbonate deposition. This mechanism causes the evolution of peculiar stalactites and columns, with a tilted often anastomized shape, over which several pseudo-helictites grow: these speleothems, growing over roots, have been observed with the same characteristics all over the world and are normally called "rootsicles" (HILL AND FORTI, 1997). Finally, in the wet tropical environment, the root apparatus of large trees may become the main driving factor for the evolution of peculiar speleothems, called "Showerhead," which were first described inside Brazilian caves (LINO, 1989) and then observed in many other tropical areas. Showerheads are cone-shaped, stalactitic speleothems from which a steady or intermittent shower of water can emerge: in many cases they develop along large fissures widened by the presence of roots which in turns are partially or totally transformed into rootsicles.

3.2 The influence of animals on speleothem growth

When considering the influence of animals on chemical cave deposits, it must be clear that lithogenetic phenomena like corals or others biogenic structures growing inside sea caves cannot be considered speleothems, because a cavern environment is normally not fundamental for their genesis and/or evolution. Therefore on the basis of the existing literature it should be stated that the influence of animals on speleothems is extremely scarce. In reality it is highly probable that upper living organisms should be able to influence specific speleothems inside peculiar cave environments, therefore the lack of papers on this topic would be the consequence of the scarcity of specific observations instead of the rarity of the event. Most of the existing papers deal with marine caves in which the underwater biogenic calcite overgrowth on pre-existing continental (inorganic) speleothems is induced by *serpulids* (ANTONIOLI et al., 2001). This kind of overgrowth rarely gives rise to specific new speleothems, normally just enlarging the pre-existing speleothem, the morphology of which remains reasonably unaffected. Sometimes, if the environmental conditions are suitable, the biogenic deposition induced by *serpulids* may allow for the development of single biogenic formations, the most characteristic of which are presently the "biogenic trays" observed inside the submerged Lu Lampiune cave in Apulia (ONORATO et al., 2003). The speleothems inside this cave consist of big (up to 2 m long and 40 centimeter (cm) in diameter) clearly deflected stalactites: in fact their tip always points towards the dominant water flow inside the cave: the resulting growth direction changes from sub horizontal close to the cave entrance to almost vertical in the cave bottom. The shape of these speleothems is not conical but flattened with the major axis being 3 to 4 times greater than the smaller one and with the tip larger than the base. The analysis of the internal structure evidenced the absence of even a small pre-existing continental stalactite, being totally developed due to a biogenic deposition in the marine environment. Morphologically they are extremely similar to the gypsum trays described inside the caves of New Mexico (CALAFORRA AND FORTI, 1994). In both these occurrences the deposition is controlled by the same agent (they develop against the flow direction), the fluid being the only difference (water in the Lu Lampiune cave and air in the New Mexico caves). Practically the direction of evolution of these biogenic stalactites is controlled by the *serpulids*, which must filter the water to obtain the necessary trophic support, and therefore tend to direct only upstream the water flow. The apical part is flattened and enlarged with respect to the basal section of the stalactites for the same reason: in fact the trophic support is highest at the apex rapidly decreasing toward the base, thus allowing the enlargement of the tip and avoiding the radial growth of the other part of the trays. Until now only one type of large biogenic flowstone made by upper living organisms has been described from a continental karst system in the southern part of Italy (POLUZZI AND MINGUZZI, 1998). The Vallone Cufalo gypsum cave (Verzino, Italy) is an active sinkhole with a river flowing inside. It hosts a large flowstone consisting of a gently terraced calcite crust up to 50 cm thick, 4 to 5 m wide, and some tens of meters long, covering the cave floor along the subterranean stream. Its complex genesis has been attributed to the large community of larvae of a troglobitic insect (*Tricoptera wormaldia*), living inside the cave over a large deposit of anthropogenic organic matter (olive oil factory waste discharged every year into the cave). Their life processes cause the production of large amounts of CO_2 which in turn react with the

water saturated in gypsum thus causing the deposition of calcite just around the worms. The final morphology of the flowstone was the result of a combined action of larvae living activities and kinetic energy of the flowing water: in fact while the larvae were alive the tubes were bent upstream to catch as much fresh water as possible, but after their death and/or evolution the further deposition of $CaCO_3$ was controlled by the kinetic energy of the water transforming the upper part in a normal flowstone evolving downstream. It is hard to believe that the Vallone Cufalo would be the only cave in the world in which the environmental conditions are suitable for an active upper living organism control over speleothems; therefore it seems reasonable that chemical deposits might develop due to the presence of animals in many other caves.

3.3 The influence of humans on speleothem growth

Normally humans are responsible for speleothem destruction and not the reverse: however, some examples exist of chemical cave deposits induced by the presence of humans. The early human frequentation of caves sometimes allowed for the development of peculiar speleothems: like those in the Romanelli cave (Apulia) where the organic compound mellite, originated by the reaction between coal, food remains and "terra rossa" within an ancient hearth, gave rise to euhedral honey shining large crystals and flowstones (GARAVELLA AND QUAGLIARELLA, 1974). In the second half of the XX century cavers were responsible of the development of a peculiar kind of speleothem in many natural cavities: the carbidimites (TUCKER, 1985). They are composed of vaterite self-transforming into aragonite and they developed over and/or close to huge deposits of exhausted carbide thanks to the reaction between the calcium hydroxide present in the deposits and the CO_2 of the cave atmosphere. They often gave rise to peculiar speleothems similar to small ice cream cones (IOWA GROTTO, 1959). Luckily these speleothems are no longer under development because cavers learned to take exhausted carbide out of the cave and more recently the light emitting diode (LED) technology solved definitively the problem.

4- Final Remarks

This short, and surely not exhaustive, overview on the biotic influence over the genesis and the evolution of speleothems clearly puts in evidence the very important role played by living organisms, mainly micro-organisms, over lithogenetic cave processes (speleothems and cave minerals evolution). The complex biochemical reactions involved in the development of the different deposits, though still not completely understood, clearly have greater interest and importance far exceeding simple speleogenesis. Normally these are low-enthalpy reactions (which involve low to very low quantity of energy) and their knowledge is fundamental to improve our understanding of the natural mechanisms by which even ore bodies of economic interest are formed and then mobilized. However the study of biologically driven speleothems is also fundamental to enhance the knowledge on peculiar environments like the chemioautotrophic ones, which are presently not well known despite their scientific interest. It is therefore reasonable to expect an increase in the cooperation between biologists and geochemists in the near future in order to obtain a fast improvement in the study of these phenomena. In conclusion it can now be stated that:

Speleothems definitely do not develop via vegetative growth ...

But without biogenic control caves would be very poorly decorated.

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CONSERVATION AND MANAGEMENT OF THE BRAZILIAN FREE-TAILED BAT: COLONY SIZE AND ACTIVITY PATTERNS USING THERMAL IMAGING

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Abstract

The Brazilian free-tailed bat (*Tadarida brasiliensis*) is one of the most abundant and conspicuous species in North America, where it provides one of the most important but underappreciated agroecosystem services to mankind. During peak lactation individual bats consume up to two-thirds of their body mass in insects each night. When multiplied by the hundreds of thousands of bats roosting in caves, bridges and other sites, enormous quantities of some of the most damaging pests to agriculture are consumed nightly. Historical records, however, indicate that there has been a severe decline in numbers during the last century. An accurate assessment of the agricultural and ecological value as well as the need for management and conservation of this species, require knowledge of nightly and seasonal patterns in colony size, and foraging activity. We present results from the application of a new method for censusing and quantifying the nightly and seasonal patterns of activity in Brazilian free-tailed bats using thermal infrared imaging and computer vision processing. Thermal infrared cameras were positioned both outside inside Carlsbad Cavern and the colony size and nightly activity of the colony was recorded in high temporal resolution. Automatic computer vision algorithms were used to analyze the thermal data producing graphical representations of the activity pattern for the entire colony. Results indicate high variation in the size and activity of the colony as a function of seasonal reproductive behavior and local weather conditions. Our results provide an accurate estimate of colony size and the first quantitative description of nightly and seasonal time budgets for this species. Such information is essential for modeling the impact of Brazilian free-tailed bats on agriculture and for understanding colony and population dynamics in response to changes in weather patterns and food availability.

BIOGEOGRAPHICAL DISTRIBUTION OF SUBTERRANEAN FAUNA IN APULIA (ITALY), IN THE CONTEXT OF THE PALEO-GEOGRAPHICAL EVOLUTION OF THE AREA

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Apulia (South-East Italy) is among the most remarkable areas as regards biospeleology in Italy, being the only continental region of the country where the biogeographical region coincides with the administrative one. Based upon analysis and distribution of the subterranean fauna, and the paleogeographic reconstruction of the Mediterranean Basin, Italy is subdivided into seven biogeographical regions, each one being characterized by a certain degree of fauna homogeneity. The largest biogeographical region is the Apenninic, which covers a large part of the Italian peninsula. Apulian troglobites represent a completely distinct set from the Apenninic subterranean fauna; the two regions have in common very few troglobites, whilst a total lack in Apulia of typical forms of the Apennines has to be registered. On the other hand, several troglophiles are present in Apulia, probably entered in the region during the Quaternary time. The first studies about Apulian subterranean fauna, which illustrated a distinction among the three karst sub-regions in Apulia (from North to South, Gargano, Murge, and Salento), are discussed in this contribution. Then, a quantitative analysis of troglobite presence and distribution in the Apulian caves is presented, aimed at highlighting the real differences between the three sub-regions, and the reasons for them as well. A particular focus is given to Salento, the southernmost portion of Apulia, that is the area where the highest number of troglobites and endemic species is recorded.

1. Introduction

The distribution of biota is controlled by a combination of factors, that include, but are not limited to, the geological history, the chemical characters of the aquifer, the connections between near regions, and so on. Central-southern Europe, with particular regard to the Mediterranean area, presents a taxonomic diversity and specie richness higher than other parts of Europe. This derives from a number of reasons, including the presence of extensive, temperate to Mediterranean climate, karst areas, extensive shallow embayments in the Tertiary, the occurrence of a salinity crisis in Miocene, the absence of Pleistocene glaciation, the common presence of anchihaline habitats in the coastal areas, and abundant freshwater subterranean habitats (HOLSINGER, 1993). The Mediterranean Sea had therefore a very complex history that includes the event of drying up about 6 million years ago, during the Messinian crisis. This event likely resulted in a greater invasion rate of the subterranean realm from marine waters, and probably contributed to the great subterranean diversity observed in many Mediterranean countries (GIBERT AND CULVER, 2005).

In Italy, a total of 265 stygobionts, 321 troglobionts, and an additional 317 troglobionts from the undergound shallow medium (MSS or *milieu souterrain superficiel*; JUBERTHIE et al., 1980) have been described (RUFFO AND STOCH, 2005). Based upon analysis and distribution of the subterranean fauna, and the paleogeographic reconstruction of the Mediterranean Basin, Italy is generally subdivided into seven biogeographical regions, each one being characterized by a certain degree of fauna homogeneity (Fig. 1). Most of them include different administrative regions, encompassing the legal boundaries. The largest biogeographical region is the Apenninic, which covers a large part of the Italian peninsula. There are only three exceptions where the biogeographical region coincides with the administrative one: two out of three are the major islands, Sardinia and Sicily. The third is Apulia, the heel of the Italian boot, located in the southeastern part of the country. This points out to the remarkable biogeographical importance of Apulia region, which in turn stems from its geological history. In addition, Apulia hosts a great variety of endemic species.

2. Paleogeography

In the last years, a large amount of works have been produced about the paleogeographical evolution of the central Mediterranean, mainly in the aftermath of discoveries of dinosaur footprints that pushed the geologists to "adapt" the previously established reconstructions in the new light provided by these additional data. The most

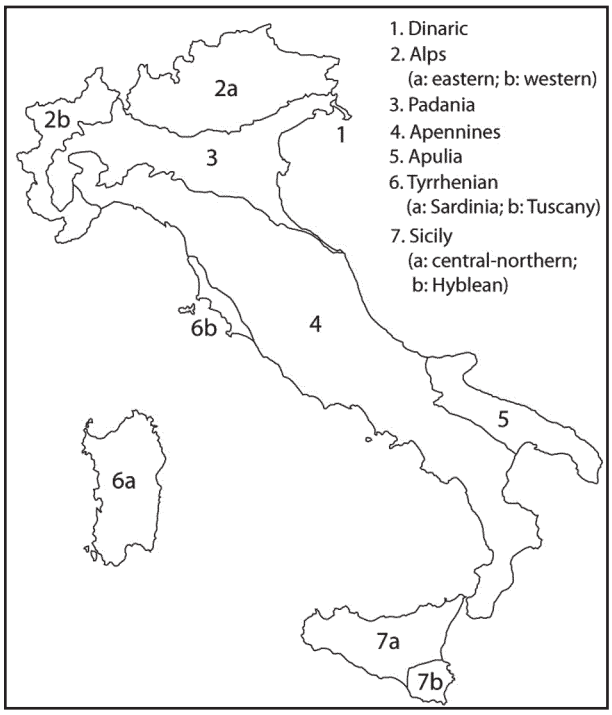

Figure 1: The Italian stygofaunistic provinces (after STOCH, 2008).

significant element of central Mediterranean is Adria, a structural element involving the crust and lithosphere, whether considered an independent microplate or a promontory of the African plate. From the paleogeographic point of view, a variety of environments including dry land, flat carbonate islands, tidal flats, marshes and shallow lagoons, deep sounds and basins may have coexisted on Adria. As pointed out by BOSELLINI (2002), many authors used the name Apulia for the same tectonic element, thereby generating considerable confusion. The easternmost platform of central-southern Italy, the Apulia Platform, is a Jurassic–Cretaceous shallow-water carbonate bank bounded by deep-water basins and one of the so-called peri-Adriatic carbonate platforms (D'ARGENIO, 1976; ZAPPATERRA, 1994; BOSELLINI, 2002). It belongs to Adria, like other Jurassic–Cretaceous platforms and deeper basins. The Apulia carbonate platform is essentially a Mesozoic paleogeographic element, which, in large part, acted as a rigid block during Alpine (Tertiary) orogenesis. During the Mesozoic, it was an isolated carbonate bank situated along the southern margin of the Mesozoic Tethys Ocean and was created during Early Jurassic rifting of the margin. Today, it is partly buried under the Apennine thrust sheets and partly constitutes the weakly deformed foreland of the Apennine and Dinaric chains (CHANNELL et al., 1979; UNDERHILL, 1989; BOSELLINI et al., 1999a, 1999b).

The dinosaur footprints and tracks recently found in the Apulia carbonate platform (GIANOLLA et al., 2000; NICOSIA et al., 2000) put strong constraints to plate tectonic and paleogeographic reconstructions of the eastern Mediterranean area: according to the new constraints, Adria was an African Promontory and the Apulia Platform was not an isolated "Bahamian" bank, but rather a sort of Florida Peninsula, a carbonate peninsula directly attached to the Cyrenaica spur of Africa during the Jurassic and Early Creatceous, thus subdividing the "Mesozoic Mediterranean" into a western Ionian basin and an eastern Levantine basin (BOSELLINI, 2002).

3. Distribution of hypogeous fauna in Apulia

Quantitative analysis carried out in caves and wells of Apulia in the last years showed the presence in the region of a total number of 42 troglobites (Table 1), 29 of which are aquatic, whilst the remaining 13 are terrestrial. In Table 2, the details of the distribution in the three karst sub-regions are given, also as regards the endemic species. These numbers indicate that the majority of Apulian troglobites (69%) consist of aquatic animals, as a likely consequence of the many trasgressive phases that the region experienced during its geological history, and that were one of the main reasons for the limited distribution of the terrestrial fauna. Colonization of subterranean waters may have occurred by adaptation of some organisms coming from surface, fresh or marine, waters through a passage in anchialine or interstitial waters, and eventually to subterranean waters.

Endemics in Apulia are 15 (9 aquatics and 6 terrestrials), thus representing 52% of the whole Apulian hypogeous fauna. Some of them are exclusive of this region, even as regards genus and family. Salento is the sub-region that presents the highest number of both troglobites and endemic organisms.

The presence in Apulia of a specialized fauna, together with numerous endemic organisms, has to be related to the widespread, multi-phase, karstic phases occurred in the region, as well as to the paleogeographic history of Apulia, above recalled. Apulian troglobites represent a completely distinct set from the Apenninic subterranean fauna; the two regions have in common very few troglobites, whilst a total lack in Apulia of typical forms of the Apennines has to be registered. On the other hand, several troglophiles are present in Apulia, probably entered in the region during the Quaternary time.

The first studies about Apulian subterranean fauna highlighted a distinction among the three karst sub-regions in Apulia: from North to South, Gargano, Murge, and

Order - Family	*Species*	*A/T*	*Distribution*	*Endemic*
Hachondrida Desmoxyidae	*Higginsia ciccaresei*	A	S	Y
Acarina Halacaridae	*Lohmannella stammeri*	A	S	Y
Acarina Ixodidae	*Ixodes vespirtilionis*	T	GM	N
Araneae Anapidae	*Zangherella apuliae*	T	S	N
Pseudoscorpiones Chthoniidae	*Chthonius ruffoi*	T	S	Y
Pseudoscorpiones Syarinidae	*Hadoblothrus gigas*	T	MS	Y
Cyclopoida Cyclopidae	*Diacyclops antricola*	A	GS	N
Cyclopoida Cyclopidae	*Diacyclops clandestinus*	A	G	N
Cyclopoida Cyclopidae	*Halicyclops troglodytes*	A	S	N
Cyclopoida Cyclopidae	*Metacyclops stammeri*	A	S	N
Cyclopoida Cyclopidae	*Metacyclops subdolus*	A	S	N
Harpacticoida Ameiridae	*Nitocrella stammeri*	A	GMS	N
Harpacticoida Ameiridae	*Parapseudoleptomesochra italica*	A	GMS	N
Harpacticoida Ameiridae	*Psyllocamptus monachus*	A	S	Y
Harpacticoida Parastenocarididae	*Parastenocaris proserpina*	A	G	N
Podocopida Loxoconchidae	*Pseudolimnocythere hypogea*	A	GMS	Y
Podocopida Candonidae	*Trapezicandona italica*	A	G	Y
Amphipoda bogidiellidae	*Bogidiella chappuisi*	A	S	N
Amphipoda Hadziidae	*Hadzia adriatica*	A	GM	Y
Amphipoda Hadziidae	*Hadzia minuta*	A	S	Y
Amphipoda Metaingolfiellidae	*Metaingolfiella mirabilis*	A	S	Y
Amphipoda Niphargidae	*Niphargus gr. orcinus*	A	GS	N
Amphipoda Niphargidae	*Niphargus longicaudatus*	A	GS	N
Amphipoda Niphargidae	*Niphargus parenzani*	A	S	N
Amphipoda Pseudoniphargidae	*Pseudoniphargus adriaticus*	A	GM	N
Amphipoda Niphargidae	*Niphargus aquilex*	A	GM	N
Amphipoda Salentinellidae	*Salentinella angelieri*	A	G	N
Amphipoda Salentinellidae	*Salentinella gracillima*	A	S	Y
Decapoda Palaemonidae	*Typhlocaris salentina*	A	GMS	Y
Isopoda Trichoniscidae	*Aegonethes cervinus*	T	G	N
Isopoda Trichoniscidae	*Castellanethes sanfilippoi*	T	M	Y
Isopoda Microparasellidae	*Microcharon arganoi*	A	G	Y
Isopoda Trichoniscidae	*Murgeoniscus anellii*	T	M	Y
Isopoda Trichoniscidae	*Trichoniscus ruffoi*	T	S	Y
Mysidacea Lepidomysidae	*Spelaeomysis bottazzii*	A	GMS	Y
Mysidacea Stygiomysidae	*Stygiomysis hydruntina*	A	S	Y
Thermosbaenacea Monodaellidae	*Monodella stygicola*	A	GMS	Y
Glomerida Glomeridae	*Glomeris stammeri*	T	S	Y
Collembola Hypogastruridae	*Bonetogastrura cavicola*	T	S	N
Collembola Paronellidae	*Troglopedetes ruffoi*	T	MS	N
Diplura Campodeidae	*Plusiocampa dolicophoda inguscioi*	T	G	Y
Coleoptera Carabidae	*Italodytes stammeri*	T	MS	Y

Table 1: Hypogeous species of Apulia. The third column (A/T) indicates whether the species is aquatic (A) or terrestrial (T). Key to the fourth column (Distribution): G = Gargano; M = Murge; S = Salento.

Salento. RUFFO (1955), for example, identifies among the Apulian troglobites: i) balcanic species, with trans-Adriatic distribution; ii) species with a southern paleogenic trans-Jonian distribution; iii) species with a paleo-mediterranean distribution. A clear distinction was, in particular, done between the hypogeous fauna in Gargano and that in Murge-Salento (RUFFO, 1955; ARIANI, 1982). According to these studies, Gargano was characterized by few evolved troglobites, a fact that was considered as due to the unfavourable ecological characters of the deep

	Troglobites			Troglobites present only in one sub-region			Endemic troglobites		
	aquatic	*terrestrial*	*total*	*aquatic*	*terrestrial*	*total*	*aquatic*	*terrestrial*	*total*
Gargano	16	3	19	5	2	7	2	1	3
Murge	8	6	14	1	2	3	-	2	2
Salento	21	8	29	11	6	17	7	3	10

Table 2: Troglobite distribution in the three Apulian karst sub-regions.

subterranean waters, and to isolation of the deep water table from that shallow. These considerations brought the above authors to conclude that there was no connection between Gargano and the rest of Apulia during Middle Miocene. Recent researches, however, have documented in coastal areas of Gargano the presence of troglobites of ancient origin, as *Spelaeomysis bottazzii* and *Typhlocaria salentina,* thus delineating a different paleogeographical framework (ROSSI AND INGUSCIO, 2001, 2003).

Figure 2 illustrates the distribution of 6 among the most significant hypogeous species in Apulia. *Hadoblothrus gigas* is the Apulian terrestrial troglobite which shows the most advanced adaptations. The genus *Italodytes* (Fig. 2B) is present in Apulia with two sub-species *(Italodytes stammeri stammeri* and *Italodytes stammeri antoniettae)*.

The genus *Monodella,* considered a Tethyan relict, has two species (Fig. 2C): one *(Monodella stygicola)* is in Apulia (RUFFO, 1949), whilst the other *(Monodella argentarii)* has been documented in Tuscany, and precisely in a cave in the Argentario Promontory. It has to be noted that about 50 million of years ago this Promontory, and part of Apulia were among the few emerged territories of the Italian peninsula.

As for the genus *Salentinella*, Apulia hosts two distinct species (Fig. 2D): *Salentinella angelieri*, and *Salentinella gracillima*. The first, highly euryhaline, lives almost exclusively in coastal areas. *Salentinella gracillima*, according to RUFFO (1982) has a paleo-mediterranean marine origin, and colonized subterranean waters during Middle Miocene; other authors, however, disagree with this hypothesis, retaining that the species followed the movements of the Mediterranean coastlines during Pliocene time (PESCE AND PAGLIANI, 1999).

Outside Apulia, the genus *Typhlocaris* (Fig. 2E) presents only two other species, respectively in Cyrenaica and in Palestine. It could represent species with paleo-mediterranean distribution that today are relict of a fauna which lived in subtropical climate, and later on survived to the post-Pliocene climatic changes only at a few sites.

Spelaeomysis bottazzii (Fig.23F) is the more widespread stygobiont (PESCE, 1975a, 1975b), and the only one for

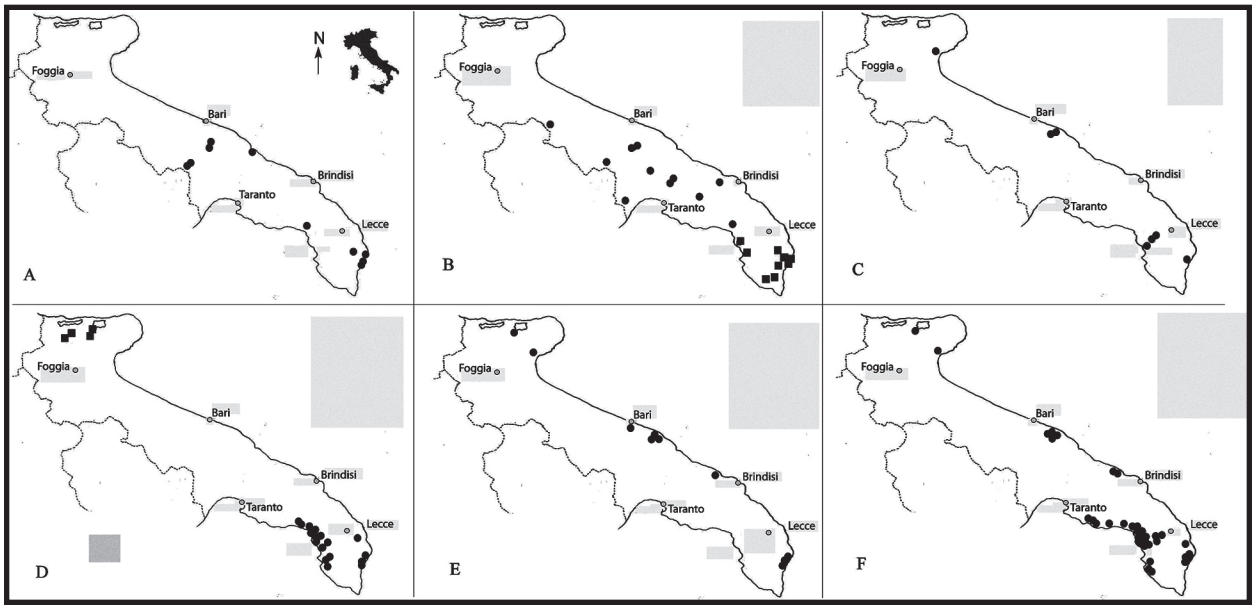

Figure 2: Distribution of the most significant species in Apulia: (A) Hadoblothrus gigas; (B) Italodytes stammeri stammeri (dots), and Italodytes stammeri antoniettae (squares); (C) Monodella stygicola; (D) Salentinella angelieri (squares), and Salentinella gracillima (dots); (E) Typhlocaris salentina; (F) Spelaeomysis bottazzii.

which data are available about its resistance to biological pollution. Worldwide distribution of the genus let suppose the past existence of correlations among the American, Mediterranean and Indopacific areas. This species feeds out of organic substances present in soft carbonate rocks; this characteristic may had contributed to colonization of subterranean waters, following the coastline movements during the Pliocene.

The species-area relationship can be considered as the most important factor in predicting species extinction (HOLT et al., 1999; HOLSINGER, 2005). Many hypogeous species are endangered by widespread urbanization, and the effects caused by a number of anthropogenic activities that cause pollution and environmental degradation to the karst (SKET, 1999; PARISE AND GUNN, 2007). THOMAS and co-workers (2004) predicted the extinction of 15-37% of total species (over 1 million) by year 2050.

The outcomes from a study in the Nardò district (Salento sub-region) showed that there is a possible trend number of species – resources relationship which could lead to the extinction of stygobionts in the near future (MASCIOPINTO et al., 2006), based upon the observed decline in hypogeous aquatic fauna biodiversity.

Aquatic hypogeous species, being highly sensitive to changes in the hydrological cycle and to habitat modifications caused by anthropogenic activities, have been proposed as indicators of environmental quality in Salento (MASCIOPINTO et al., 2006). To provide an example, *Spelaeomysis bottazzii* is a stygobiont omnivore that has largely increased in number and size in Salento with respect to other, smaller, species that are less resistant to water quality modifications. In fact, *Spelaeomysis bottazzii* is eurytherm and tolerant to a wide range of salinity.

4. Conclusion

The data presented here about distribution of the subterranean fauna in Apulia point out to the remarkable relevance of this southern Italian region. Among the main factors at the origin of such an importance, the geological history has to be considered. Until the Pleistocene, the three sub-karst regions (Gargano, Murge, and Salento) had insular character, hosting stygobionts of marine origin that are considered to be Tertiary relicts from Tethys, and show affinities with Caribbean and Indopacific species. The successive paleogeographical setting still needs further research in order to fully explain the observed specie distribution that does not appear simply to be distinct in Gargano and in Murge-Salento, as so far has been considered.

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DETECTION PROBABILITIES OF KARST INVERTEBRATES IN CENTRAL TEXAS

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Protection of federally listed endangered troglobites in central Texas focuses on caves that are occupied by the species. The determination of occupancy is based on presence/absence surveys for those taxa. Under current U.S. Fish and Wildlife Service recommendations, three surveys are used as a standard to determine presence or absence, and certain environmental and seasonal conditions must be met.

We used survey data from 23 caves on Camp Bullis Military Reservation, Bexar County, Texas to test the validity of the survey protocols. Presence/absence matrices were created for three cave species, two beetles *Batrisodes uncicornis* (Coleoptera: Pselaphidae), *Rhadine exilis* (Coleoptera: Carabidae), and a harvestman *Chinquipellobunus madlae* (Opiliones: Stygnopsidae). Eleven environmental and seasonal covariates that have been suggested to affect detection probability were tested for fit to the detection data. *B. uncicornis* and *R. exilis* were determined to have constant detection probabilities of 0.1226 and 0.1875. *C. madlae* was found to have a survey specific detection probability (average $p = 0.2424$), and in no case was detectability tied to any of the measured covariates. Parametric bootstrapping was used to simulate the number of surveys needed to have a 5% chance of not detecting the species if they were present at the site. The number of surveys needed ranged from 10 to 22.

These results indicate that more surveys should be performed before determining absence from a site. The results also indicate that most of the time cave species are not available to be surveyed, and we hypothesize that they retreat into humanly inaccessible cracks connected to the cave.

1. Introduction

Detection probability (p), or detectability, is the chance that a karst invertebrate will be observed if the cave is occupied by that species. In order for a species to be observed it must be both available (e.g. not hiding in a humanly inaccessible crack) and seen by the researcher. Occupancy (Ψ) is the proportion of sites that are occupied, or the proportion of areas where the species is present. Failure to take into account detection probabilities when using species counts can lead to underestimating cave occupancy, since non-detections in survey data do not necessarily mean that a species is absent unless the probability of detection is one (MACKENZIE et al., 2002; BAILEY et al., 2004). If the probability of detection is less than one, then surveys should be designed to account for imperfect detection.

Cave organisms are small and live in an environment that is difficult to sample because of constricted crawlways, vertical drops, low oxygen levels, and an abundance of mesocaverns, or tiny cracks and voids connected to the cave but inaccessible to humans. For the sixteen species of federally listed terrestrial karst invertebrates in central Texas, recovery is based on protecting habitat around caves known to contain the species, therefore estimating occupancy of caves is of paramount importance. Monitoring the populations in these caves and conducting surveys in new caves are listed as key components to the recovery strategy (USFWS 1994).

The U.S. Fish and Wildlife Service (2006) provides survey recommendations for these taxa and detail that permitted surveyors must have several years of experience with these or similar species under a permit holder. During the three surveys required to ascertain presence or absence of a species in a cave, certain environmental and seasonal conditions must be met. Thus far these conditions (number of visits, season, temperature, recent rain) have been determined based on non-quantified observations by researchers balanced with an estimation of observer impact on the environment (James Reddell and USFWS Bexar County Karst Invertebrate Recovery Team, pers. comm.).

Since newly found caves are rapidly being impacted by development, and the data from early counts of karst invertebrates are being relied upon for guidance of preserve designs, it is imminently important to estimate the utility of the recommended survey protocol with confidence. The focus

of this study is to determine the detection probabilities for several terrestrial karst invertebrates, to assess whether certain environmental parameters affect detectability, and to use detectability to determine the number of surveys required to be confident in a determination of absence from a site.

2. Methods

2.1 Study sites

Caves on Camp Bullis Military Reservation, Bexar County, Texas were used for this study, and the raw dataset along with detailed information about each site is reported in GEORGE VENI AND ASSOCIATES (2006). Cave sites were subdivided into zones, and these individual zones are the survey units. Surveys were conducted three times per year, during the spring (May), summer (July 15 – August 15), and fall (October). These started in the fall of 2003 and included spring 2007, for a total of eleven sample events. Prior studies have used this method (ELLIOTT, 1994) and it is consistent with U.S. Fish and Wildlife Service endangered species survey recommendations (2006).

2.2 Detection probabilities, occupancy, and number of surveys

The program PRESENCE (Proteus Wildlife Research Consultants, Dunedin, New Zealand) includes mark-recapture models modified by MACKENZIE et al. (2002) for use with presence-absence data. It was used to analyze the fit of several models to the dataset. The first test was to determine whether our dataset that included multiple years and seasons could be considered closed during the period of the surveys, fall 2003 to spring 2007. Closure means the cave zone did not experience a change in occupancy by the species during the time interval of surveys and is an assumption of the occupancy models (MACKENZIE et al,. 2002). To determine closure three models were compared. The first model considered the detection probability as specific to each survey event, the second as specific to each season, and the third as constant across all survey events. The models were compared using Akaike's Information Criterion (AIC) and AIC weights (BURNHAM AND ANDERSON, 2002). Once the assumption of closure was validated, detection probabilities were modeled as either constant among surveys, specific to individual surveys, or influenced by one of eleven covariates discussed below.

After model selection analysis, we determined the number of surveys needed to have a 5% chance of not detecting the species at sites where they are present, based on estimated probabilities of detection. For *Chinquipellobunus madlae*, we found that detectability varied with each survey. Therefore, we conducted a parametric bootstrapping simulation obtaining 1000 pseudo samples (MANLY, 1997). We used the formula

$$\prod_{i=1}^{s}(1-p)$$

where p is the detection probability on survey i and s is the number of surveys (JACKSON et al., 2006). For *Batrisodes uncicornis* and *Rhadine exilis*, whose detectability was constant across surveys, the calculations were based on the simpler formula

$$1-(1-p)^{s}$$

where p is the detection probability and s is the number of surveys performed (formula 6.1 in MACKENZIE et al., 2006). Simulations for each different number of surveys (2, 4, 6, etc.) were performed using the statistical software **R**, and consisted of 1,000 bootstrapped samples produced with a parametric and not a nonparametric bootstrapping algorithm. Then for each different number of surveys, the mean probability of failing to detect the species was calculated. For *Chinquipellobunus madlae*, the varying values of p allowed us to create 95% confidence intervals (Fig. 1).

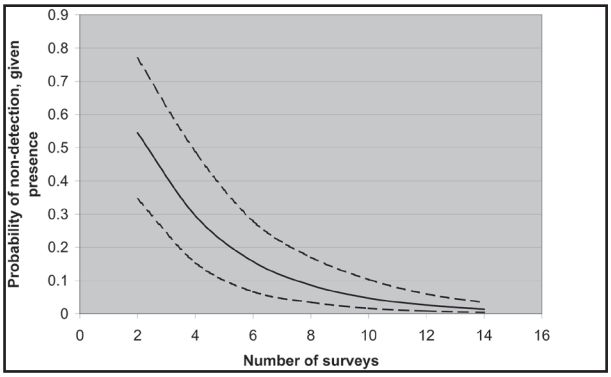

Figure 1: Simulations using the survey specific detection probabilties measured for Chinquipellobunus madlae show that more surveys decrease the probability that this species will not be detected at sites where they are present. Upper and lower 95% confidence intervals are shown as dashed lines. These findings suggest that 10-12 surveys are needed to be 95% confident that C. madlae are absent from a surveyed site.

2.3 Covariates

Detection probabilities were modeled as either constant among surveys, specific to individual surveys, or influenced by one of eleven covariates. Of these eleven covariates, four were unique to each cave site and seven were unique to each sample event. They were chosen based on personal observation, interviews with local cave biologists (James

Reddell, Peter Sprouse), USFWS recommendations (2006), and other research (SCHNEIDER AND CULVER, 2004). Site covariates included cave length, cave depth, size of floor search area, and size of wall search area. Seven sample covariates changed with each event and included four continuous variables: search time, in-cave temperature, in-cave relative humidity and surface air temperature. The remainder corresponded with USFWS survey recommendations and consisted of a yes/no determination for falling within the recommended surface temperature range, recommended sampling season, and a recent rain event.

2.4 Species

Batrisodes uncicornis is an eyed troglophilic (not restricted to caves, but can spend entire life cycle in a cave) pselaphid beetle (Fig. 2) that occurs in caves throughout central Texas. This species is not endangered, but it is closely related to endangered *Texamaurops reddelli* and *Batrisodes texanus*. It is known to occur in 9 caves containing 21 zones that were sampled 11 times.

Chinquipellobunus madlae is a troglobitic (restricted to caves) harvestman (Fig. 3) that occurs in caves throughout central Texas. This species is not endangered, but it is related to endangered *Texella cokendolpheri, Texella reyesi,* and *Texella reddelli* harvestmen. *Chinquipellobunus madlae* is known to occur in 22 caves containing 61 zones that were sampled 11 times.

Figure 2: Batrisodes uncicornis*, a tiny (2 mm) troglophilic beetle, from B-52 Cave, Bexar County, Texas.*

Rhadine exilis is a federally listed carabid beetle (Fig. 4) restricted to Bexar County, Texas. Survey results were used from 23 caves subdivided into 65 zones with 11 sample events.

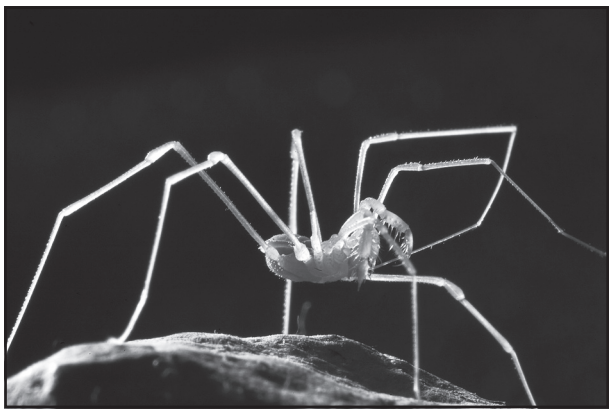

Figure 3: Chinquipellobunus madlae*, a troglobitic harvestman (2-3 cm), from Flying Buzzworm Cave, Bexar County, Texas.*

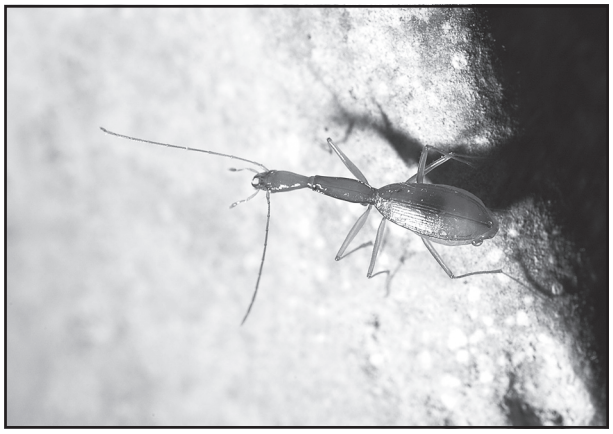

Figure 4: Rhadine exilis*, an endangered troglobitic ground beetle (1-1.5 cm), from Banzai Mud Dauber Cave, Bexar County, Texas.*

3. Results

The assumption of closure was met for all taxa, indicating that species do not colonize a site or become extinct from a site within the study period. Lower AIC values indicated the data for *Batrisodes uncicornis* were most consistent with constant detection probabilities and the data for the other two species varied by survey rather than being seasonal or constant. After closure was met, data from all years were used to test whether detection probabilities were either constant among surveys, specific to individual surveys, or influenced by one of eleven covariates. Of the three species,

Chinquipellobunus madlae was the only dataset found to have a clear best model, which was that the detectability was different for every survey. Detection probabilities ranged from 0.0595 to 0.3769, with a mean of 0.2424, standard error of 0.0943 and coefficient of variation of 0.3887. The proportion of sites occupied (Ψ) was 0.85 with a standard error of 0.06. The other two species had several models that rose above the rest but were not distinct enough to choose between, and in those cases the most parsimonious of the higher ranking models, constant probability of detection, was chosen. In the case of *Batrisodes uncicornis*, the constant detection probability was 0.1226, the proportion of sites occupied (Ψ) was 0.45 with a standard error of 0.16. In the case of *Rhadine exilis*, the constant detection probability was 0.1875 the proportion of sites occupied (Ψ) was 0.71 with a standard error of 0.07.

Parametric bootstrapping yielded the following recommended number of surveys for *Batrisodes uncicornis*, *Chinquipellobunus madlae*, and *Rhadine exilis*: 22, 10-12 and 14. These are the recommended number of surveys to conduct to reduce the probability of non-detection, given presence, to 5%.

4. Discussion

Many caves are surveyed to determine whether they are occupied by rare and endangered troglobites, and several researchers have examined accumulation curves and patterns of species richness in karst areas of West Virginia and Slovenia (CULVER et al., 2004; SCHNEIDER AND CULVER, 2004). These studies focused on determining the number of cave species in a region and how many caves would need to be sampled to obtain an accurate estimate of species richness for the area rather than for a single cave. Results included a lack of asymptotes or plateaus in species accumulation curves, with one explanation being that repeated visits are often necessary to collect all of the species found in a single cave (SCHNEIDER AND CULVER, 2004). CULVER et al. (2004) give an example of a new taxon being found after 6 visits, and two examples of new taxa being found after over a hundred visits to a cave. In the instance of Lakeline Cave, Williamson County, Texas, at least 45 biological surveys have been performed by experienced cave biologists of the entire cave (approximately 23 m long), and on approximately the 40th visit a new species of troglobitic pseudoscorpion was found. Clearly some species are commonly not available or not detected, however prior to this work no researchers have attempted to calculate detection probabilities or estimate the number of visits required to a single cave to find a troglobite.

The detection probabilities calculated herein suggest that modifications should be made to recommended survey techniques to confidently estimate occupancy. Even in taxa that are large and easy to see (*Chinquipellobunus madlae*, Figure 3), in our analysis of caves where they are known to occur, the proportion of sites occupied was 0.85 and the detection probability averaged only 0.24. With 10-12 visits recommended to confidently determining absence for this taxon, many more should be required of smaller, slower moving and more inconspicuous troglobites such as *Texella* species.

Suggestions about appropriate sampling conditions for cave fauna come from qualitative observations by cave biologists, and in Texas have generally included seasonal and weather conditions that are thought to make the interior of these shallow caves more favorable for finding cave species. In our lengthy list of possible covariates, however, none clearly demonstrated an association with detectability of these species. For one of three taxa, detectability definitively varied with each survey event, indifferent of all the covariates tested. For the other two taxa, the distinction was less clear and confounded by a small number of detections in the matrix of observation events. Patterns of species detections appear irregular, and more work needs to be done both on the environment and experimentally on the species to determine if the environmental variables we measure during these studies are actually related to detection probability. For example, dataloggers in caves can demonstrate if seasonal, temperature, or rainfall variation on the surface is reflected in the cave environment at different endangered species localities. The other critical component is to use experimental manipulation of the taxa to determine if they respond to the magnitude of changes that actually occur within the cave.

When the species analyzed herein are not available, the most obvious hypothesis is that they retreat into inaccessible cracks that are connected to the cave. These spaces, called mesocaverns (or sometimes called epikarst, voids, or unenterable caves), should then be considered a priority for conservation. Presently management focuses on caves and surface habitat immediately surrounding caves. Cave entrances and the surrounding surface area are important because they provide a nutrient source for cave ecosystems, but this suggests that a greater area of karst that is connected to caves may be where the species often reside. KNAPP AND FONG (1999) also concluded that the stygobites they studied occur primarily in a larger area of epikarst that is connected to the cave pools they could access, and considered the pools a small window into that habitat.

Acknowledgements

Jackie Schlatter (Chief of Natural and Cultural Resources, Ft. Sam Houston, Texas) provided permission to use the dataset

from Camp Bullis Military Reservation and coordination of the funding to collect the data. George Veni (George Veni & Associates) was the principal investigator and coordinator for all the research at Camp Bullis during the time these data were collected and always encouraged analyses to further the knowledge of these little studied systems. Cyndee Watson (USFWS) was involved in the project conception and provided many useful suggestions throughout the duration of the project. Rob Myers assisted with review and revisions of a draft version. James Reddell (Texas Memorial Museum) and Peter Sprouse (Zara Environmental LLC) provided suggestions of covariates to test. Kellie Cowan (Zara Environmental LLC) spent countless hours extracting and arranging the data for input into PRESENCE. Bill Elliott started monitoring cave species in central Texas and provided the framework for future research. Many people were involved in the in-cave data collection, including USFWS karst invertebrate permit holders Andy Gluesenkamp, Rob Myers, James Reddell, Marcelino Reyes, Peter Sprouse, Bev Shade and George Veni, and their observations and dedication created the large dataset used in this project and that will certainly be used for years to come. Funding for the analysis and this report was provided by Texas Parks and Wildlife through the Endangered Species Act Section 6 grant program of the U.S. Fish and Wildlife Service. In particular, Craig Farquhar (TPWD) did an outstanding job taking care of the administration of these funds. Matching funds and general support of the author were provided by Zara Environmental LLC and Texas State University.

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BATS: GOING . . . GOING . . . GONE WITH THE WIND

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Abstract

Throughout much of the world, wind energy has become an increasingly important sector of the renewable energy industry. Environmental benefits of wind energy accrue from the replacement of energy generated by fossil and nuclear fuels, thus reducing some adverse environmental effects from these industries. However, development of the utility-scale wind energy industry has led to some unexpected environmental costs. In particular, large numbers of bat and bird fatalities have been reported at utility-scale wind energy facilities in both forested and agricultural landscapes. Less is known about adverse effects of wind energy developments in arid regions and at offshore sites where wind energy capacity is often high. As the world demand for renewable energy increases, we are witnessing a near exponential growth of wind energy facilities. Given the current unregulated development of this industry in many parts of the world—including the United States—continued large numbers of bat and bird fatalities can be expected. To date, most of the bat fatalities have been reported from onshore localities in Europe and North America, where several local efforts are being made to monitor operational wind-energy facilities for turbine-related fatalities. Unfortunately, few if any assessments of bat or bird fatalities are being made in most other regions of the world. The wind energy industry is developing at such a rapid rate that the projected cumulative impacts of fatalities are staggering, affecting both cave-dwelling and tree-roosting species. Recent research has shown that adverse impacts of existing wind energy facilities on bats can be mitigated by operationally feathering turbine rotors at low wind speeds. The term "feathering" means that the turbine blades are pitched parallel to the wind and thus hardly move. This can be done at low wind speeds when bats are more often killed, and during high seasonal periods of bat activity (e.g., during fall migration).

Preliminary research suggests that this type of mitigation can reduce fatalities by up to 92%. Thus, the wind energy industry—to retain its "green" image—should be required to implement such measures during designated times of the year and at low wind speeds to reduce adverse impacts on bat populations. Such considerations should be part of the permitting process and required for the authorization of government-funded tax credits, Additional research is needed to identify geographic regions that are more appropriate for placement of new wind energy facilities, preferably where little or no bat activity has been documented. Finally, research is needed to assess the potential adverse impacts of community-scale wind energy developments on bats and birds, where such development could be "the next cat in the backyard."

CAVE ANIMALS IN SHOW CAVES IN SLOVENIA

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Abstract

Since the discovery of the cave salamander *Proteus anguinus* in Postojnska jama cave in 1796 and the first cave beetle *Leptodirus hohenwarti* in 1831, cave animals were important attraction for visitors in show caves in Slovenia. Proteus also became one of the symbols of the Postojnska jama. Animals were later, specially the proteus, on the display to visitors. At first they were displayed in pools or aquarium in the cave. Now a part of the cave, former speleobiological station with special entrance is arranged for visitors displaying proteuses and several other smaller cave animals like beetles and crustaceans in special aquariums or terrariums.

Visitors can see the proteus also in two other managed caves in Slovenia. Besides them black subspecies, *Proteus anguinus parkelj* can be seen in the natural environment in one karst spring.

In Postojnska jama cave tourism started in 1818 and there is less cave animals in some managed passages. In other parts of the cave impact of tourism is less pronounced. There is no impact of tourism on the proteus population which lives there. There is also no impact reported on proteus in other managed caves.

ON RARITY AND THE VULNERABILITY OF SUBTERRANEAN FAUNA

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Abstract

Rare species have small numbers of individuals or small ranges and are thus considered to be the most threatened. Many subterranean species can be considered rare, but little is known about how threatened they actually are. According to the IUCN there are three categories of threatened species: vulnerable, endangered, and critically endangered. We often declare subterranean species as vulnerable, if not endangered, but concise arguments for this axiom are rarely presented.

Our research over the past decade on terrestrial and aquatic invertebrate fauna in caves or other underground habitats, in both show caves and protected caves will be presented as either arguments or counter-arguments for the vulnerability of subterranean fauna. We also discuss the different human direct or indirect impacts and propose some management rules for protection of subterranean fauna.

CAVE MICROBIAL COMMUNITIES: IS PROTECTION NECESSARY AND POSSIBLE?

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Microbial communities in caves vary from the striking microbial mats observed in many lava tubes worldwide, to occasional colonies on the wall, to invisible biofilms on rock walls and ceilings of caves, to microbial end products, such as iron oxides. The investigations of the last decade, using culture-independent techniques in which we extract DNA from environmental samples and sequence clones to identify organisms present, have revealed a wealth of microbial species never described. Some of those organisms have been implicated in the dissolution and precipitation of cave rock and secondary minerals. Some may be critical in cycling nitrogen and carbon from the surface to the subsurface. Others have been shown to have the ability to kill cancer cells or produce antibiotics that might replace some of those antibiotics that are failing due to antibiotic resistance. Thus, we know that microorganisms found in caves are valuable, both for their intrinsic nature, and because they may prove useful to humans. Are they valuable enough to us to consider protecting them from we humans that explore their native cave habitat? To what degree do we, as cave visitors, impact these communities when we visit caves (Northup and Welbourn, 1995)?

The degree to which we impact cave microbial communities depends on the nature of the cave. Mammoth Cave in Kentucky, USA, and other caves like it, have rivers or streams running through major portions of the cave. Such caves are likely impacted by human visitation much less than arid-land caves, such as Lechuguilla Cave in New Mexico, USA. These drier and warmer caves contain significant microbial communities that can fall prey to a variety of impacts. When we explore caves, we leave behind pieces of ourselves: skin cells, bacteria and fungi from our hair and skin, hair, and occasionally worse things such as feces, urine, or mud and dirt from other caves, which carry their own microbial passengers. One of the major impacts that we can have on low-nutrient caves is the enrichment of the organic carbon present in those caves. We also compact any soil present and might leave other pollutants that affect microbial communities. How can we protect these microbial communities from such threats?

Several strategies can lower the impact that we have on cave microbial communities. Cleaning our gear, clothes, boots, and bodies between cave trips can limit the amount of cross-contamination that occurs among caves and lower the amount of organic carbon enrichment that occurs. Establish trails and camp areas (if camping is an issue) to confine human impact to a limited area of the cave. Encourage everyone to eat over bags to catch crumbs. A much more controversial strategy is the establishment of "microbial preserves" to preserve areas of unusually promising microbial potential by limiting the amount of human impact on the area.

Cave microbial communities can represent an extremely valuable resource that is worth protecting by modifying our behavior in visiting caves. The payoff may be an antibiotic that saves your life someday!

1. Introduction

Microorganisms in caves range from completely invisible to highly colorful microbial mats (Fig. 1) that line the walls of lava tubes to microbial waste products, such as iron oxides. It is hard to appreciate and value something that you cannot even see, but there are many compelling reasons to protect and conserve cave microorganisms and their habitat.

In the last two decades we have seen a major increase in research into the role that microorganisms play in the dissolution of bedrock and other surfaces and the precipitation of secondary mineral deposits (BARTON AND NORTHUP, 2007; NORTHUP AND LAVOIE, 2001). New discoveries of sulfur oxidizing bacteria in caves are revealing microbial roles in cycling sulfur in caves and enlargement of cave passages through sulfuric acid

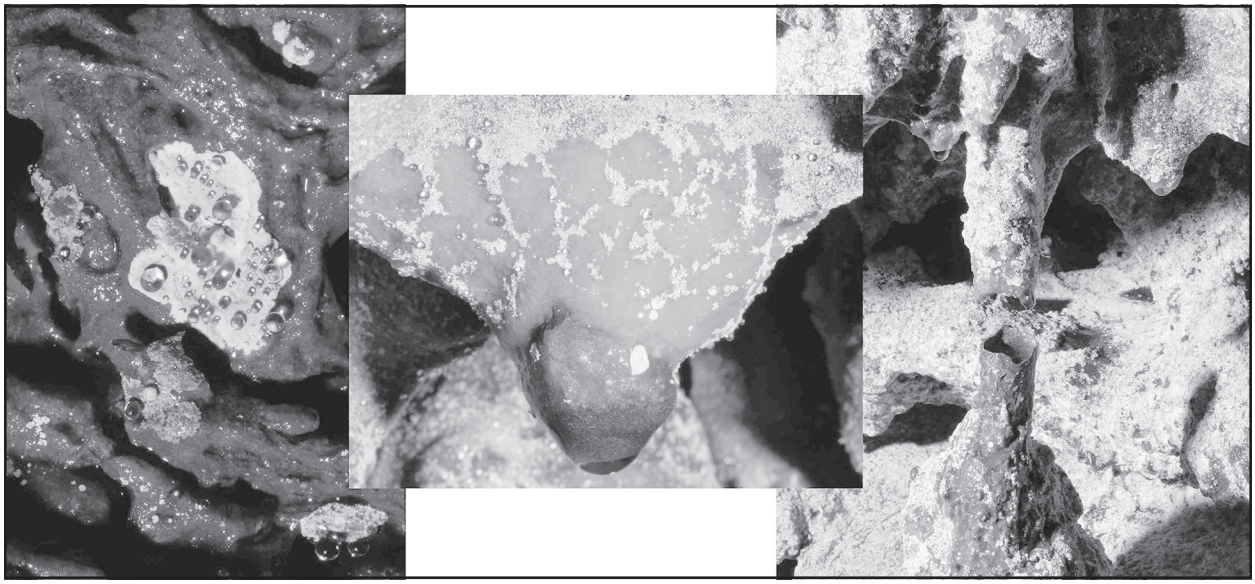

Figure 1: White, yellow, gold, and, pink microbial mats commonly line the walls and ceilings of moist lava tubes worldwide. Photos copyright 2008 Kenneth Ingham.

dissolution, as well as a possible role in sulfuric acid driven speleogenesis (ENGEL et al., 2004; HOSE et al., 2000). SPILDE et al. (2005) have shown a microbial role in the production of ferromanganese deposits in arid-land caves. These and other studies are showing key geomicrobiological roles for microorganisms in caves. Although much remains to be learned about the microbial role in energy transfer and elemental cycling, some evidence suggests that microorganisms facilitate the transfer of energy between cave life and organic carbon and serve as food for the cave life (SIMON et al., 2007). Perhaps most exciting is the amount of novel biodiversity that culture-independent molecular studies are revealing in caves (e.g. BARTON et al., 2004; GONZALEZ et al., 2006; NORTHUP et al., 2003). Some of these novel (and not so novel) species may produce chemical compounds that are very useful to humans, such as new antibiotics to replace those to which bacteria are now resistant (Dapkevicius, Terrazas and Northup, unpub. data). The geomicrobiological studies and those of novel microbial biodiversity also serve to aid our understanding of how to detect life on other planets, such as Mars, where life is likely to shelter from harsh surface conditions in the subsurface (BOSTON et al., 2001). Thus, our research is emphasizing the critical nature of cave microbial communities and suggests that their conservation is important.

2. Threats to Microbial Populations

Cave microorganisms are susceptible to a variety of threats, including human visitation, soil compaction, pollutant spills, cave restoration, and organic carbon enrichment. Whether microorganisms reside in arid-land caves, or those in areas with more rainfall, affects the degree to which these threats are an issue for microbial populations. Rivers and streams running through caves can carry away pollutants and dampen the effects of various threats; however, rivers and streams can also be the vehicle for introducing pollutants. Arid-land and caves with little inflow of moisture, in particular, are much more subject to the effects of organic carbon enrichment and other impacts that result from human visitation of caves. When we visit caves, we shed tens of thousands of skin cells, many of which are life rafts for our own microbial inhabitants, as well as hair and fibers and mud from our clothing (Fig. 2). If we are sick and vomit in the cave, we greatly enrich organic carbon in the habitat. Longer cave trips may bring the issues of urine and feces deposition (Fig. 3). While cricket and beetle feces are a natural part of the ecosystem, human feces are not. There is the matter of scale and the fact that human feces are almost 50% microorganisms. Urine can lead to the buildup of harmful compounds that change the microbial ecosystem (LAVOIE, 1995). As we walk through areas of the cave with soil or detrital material, we cause compaction of the soil, which decreases the available oxygen. Some visitors draw their names and dates in microbial mats (Fig. 4). Our studies (Lavoie and Northup, unpub. data.) suggest that human associated bacteria (e.g. *Staphylococcus aureus*) and fungi are preferentially found in areas with more human impact. If the cave is given time to "rest" (i.e. no human visitation) and we limit the amount of organic carbon buildup, these exotic populations generally die off. However, some exotic populations can persist and damage cultural artworks, such as those found in the caves of France and Spain (JURADO et al., 2008).

Figure 2: Humans leave detritus when they visit caves, such as hair, skin cells, food, and mud from other caves. Illustration by N. Robin Wilson, copyright 1993.

Figure 3: Long caving trips raise the issue of human feces disposal and possible impact as feces volatilize as they leave the body. Illustration by N. Robin Wilson, copyright 1993.

Also, our well intentioned efforts to restore and clean caves can lead to many problems for microbial communities as detailed in BOSTON et al. (2005). By trying to protect pristine pools in Lechuguilla Cave, we unintentionally enriched the amount of organic carbon in the pools from plasticizers in the tubing used to obtain drinking water. This led to a population explosion of a native bacterial population that appears to have then supported introduced *E. coli* in the pool (HUNTER et al., 2004). Through a variety of ways, we provide challenges to subterranean microbial populations. Where native microbial populations reside in oligotrophic habitats within caves, we will see the most profound effects. Oligotrophic microorganisms don't simply get "fatter" when you feed them more; they often die off, allowing more surface-adapted microorganisms to take their place (KOCH, 1997). Thus, human visitation can introduce new organic matter and exotic microorganisms into caves, which may harm native microbial populations.

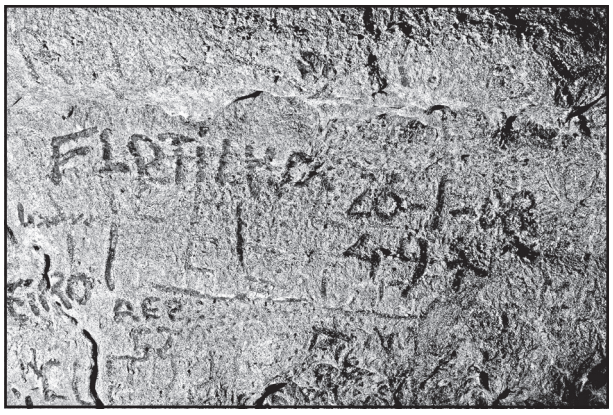

Figure 4: Cave visitors often draw their names in microbial mats that line the walls of lava tubes. Photo copyright 2008 Kenneth Ingham.

3. Is Protection Possible During Active Exploration and Scientific Investigation?

There are some relatively simple things that can be done to protect microbial communities in caves, but the success of these recommendations rests in the acceptance of the value of these microbial populations by cavers, scientists, and other visitors to caves. It is hard to think about and protect things that you cannot even see. If you believe that cave microorganisms are a key component of the cave ecosystem or that an effective treatment for cancer or a new antibiotic that could save your life someday could come from a cave microorganism, then you are likely to be willing to go the extra mile for the microbes. Getting people to this point will take more research into what harms and what protects microbial communities in caves and using that information to educate cave visitors about the problems and solutions. One of the payoffs is that educational programs about cave microorganisms often excite and engage cave visitors—the microbes have wonderful stories to tell.

4. Recommendations

To know how to protect something, you need to understand it. Our knowledge of cave microbial communities is rudimentary, limiting our ability to know precisely what efforts will protect microbial communities in caves. Several laboratories around the world are conducting outstanding culture-independent molecular studies of cave microbial communities to identify novel biodiversity, while others are culturing cave microorganisms to shed light on their

physiology and biochemistry, but we need more scientists involved. The first molecular study of microbial diversity was published in 1997, and while many others have followed it, much remains to be learned. Microbial inventories across gradients of depth, nutrient richness, distance from entrances, human impact, etc. are needed to compile a more complete picture of cave microbial communities. Many interesting ecological and evolutionary questions about cave microorganisms await researchers (e.g., SNIDER et al., 2009). Thus, research and inventory are key steps in the journey to protect cave microorganisms. The following recommendations are based on our preliminary investigations and insights, but their effectiveness remains to be tested.

As cavers and visitors to caves, we can take several actions to conserve microbial habitat and microorganisms:

- Establish trails for movement through the cave. When you establish trails, use inert markers that do not enrich organic carbon in the cave and do not degrade. If there are no marked trails, always walk where the "elephant tracks" are.
- For caves in which camping is necessary for exploration, establish camps to concentrate human impact.
- Eat over bags to catch all crumbs. What's a crumb to you is a supermarket to a microorganism.
- Clean your clothes and boots between cave trips to prevent cross contamination between caves.
- Brush your hair to remove loose hairs before going caving.
- Find ways around pristine pools and avoid dipping anything, including yourself, in the pool. Establish a clean pitcher for obtaining water.
- Educate new cavers in the ways to preserve and protect microbial communities.

Scientists, cavers, and cave managers who find unusual deposits that may be microbial should consider establishing a microbial preserve to allow investigation before visitation occurs to any extent. If you see something really intriguing, send a photo to one of the microbiologists around the world who studies these communities in caves. Scientists often study a few areas very intensively and may miss key discoveries. Cavers and scientists should collaborate on microbial discoveries for mutual benefit. Scientists can excite cavers and visitors by providing engaging information about their findings through public talks, articles, and other media that bring the science to the public.

5. Conclusions

Our knowledge of microbial diversity in caves is growing rapidly and revealing a wonderland of microorganisms (Fig. 5) that participate in precipitation and dissolution of cave mineral deposits that have roles in nutrient cycling within the cave ecosystem, that may produce chemical substances of great use to humans, and that serve as an analog for possible life on other planets. These important communities are, however, threatened by some of our actions when we visit or live and work above caves. By being conscious of the ways in which we may enrich organic carbon in caves, we can do much to protect microbial habitats and microorganisms in caves. Are cave microorganisms threatened? In 1997, Jim Staley wrote the following concerning microorganisms in general:

> "Our knowledge of microbial diversity, particularly bacterial diversity, is so meager that we do not yet know if and when most species are threatened."

This is particularly true of cave microorganisms and enhanced efforts to study and understand cave microbial communities are essential to our being able to truly answer the question of whether these populations are threatened.

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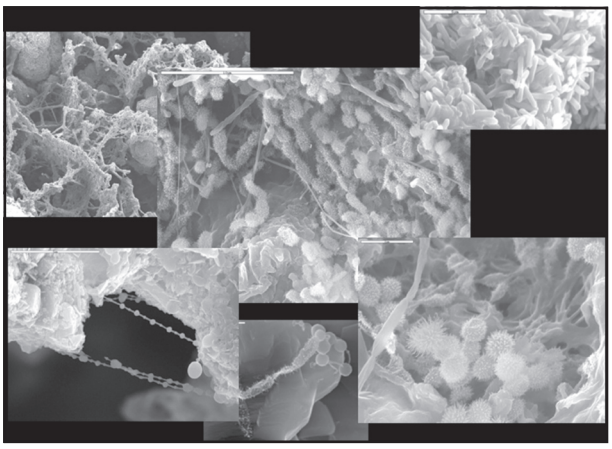

Figure 5: Cave microorganisms represent a wonderland of organisms as seen in these scanning electron micrographs from caves in New Mexico, Arizona, Mexico, and the Cape Verde Islands. Photomicrographs courtesy of Michael N. Spilde.

Val Hildreth-Werker and Jim Werker for photography, engineering, and lots of great research; Andi Hunter, for her invaluable research into the contamination of pools in Lechuguilla Cave; and Penny Boston and Mike Spilde, with whom I have had many stimulating conversations about microbes. The Charles A. and Anne Morrow Lindbergh Foundation, Mammoth Cave National Park, and T & E, Inc. provided financial support for the human impact studies that were carried out in collaboration with Kathy Lavoie who contributed substantially to the ideas on human impact. Thanks go to Leslie Melim and Kenneth Ingham for insightful comments on the manuscript.

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MANAGEMENT OF ENDANGERED KARST INVERTEBRATES ON THE BALCONES CANYONLANDS PRESERVE, AUSTIN, TEXAS

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Abstract

In 1996, the USFWS issued a 10(a)1b permit to Travis County and the City of Austin to mitigate for the loss of endangered species habitat due to urban development activities and to facilitate the recovery of eight federally listed endangered species, six of which are troglobitic invertebrates. A minimum of 30,428 acres in western Travis County, Texas will be set aside as preserve land to fulfill mitigation requirements. There are 62 karst features listed under the Balcones Canyonlands Preserve (BCP), including 35 caves containing at least one of the listed troglobitic species.

Currently, Travis County Natural Resources and City of Austin Wildland Division staff manages and protects 32 BCP karst features, including a cave cluster which supports one of the most diverse, terrestrial cave-adapted assemblages in the southwestern U. S. Management practices on the BCP include conducting annual faunal surveys within caves, seasonal cricket counts at cave entrances, and red imported fireant (*Solenopsis invicta*) control. Caves located near urbanized areas provide a unique challenge for karst managers but also provide an opportunity for public education.

In the spring of 2007, the City of Austin and Travis County began conducting quarterly surveys on eight selected caves in order to examine seasonal changes in species richness and abundance. Data from three seasons (spring, fall and summer) in both 2007 and 2008 was used for analyses. The relationships between the cave fauna community and three variables (site, year of sampling, and season of sampling) were tested using Mantel tests (Mantel 1967) between two similarity matrices calculated with two indices (S8: presence/absence and S17 which also accounts for abundances). No significant relationships were found between the fauna, year and season with both indices, but a highly significant relationship with the sites suggests that the fauna differs from cave to cave. A partial Mantel test (Smouse et al. 1986) found a significant relationship between *Texella reyesi* and season when controlling for the variability due to the sites. Although still preliminary, these results suggest that a given cave may not necessarily be a biological replicate of another cave despite geographical proximity, similar sampling intensity, and common geological history. Data collection in selected caves will continue seasonally for further subsequent analyses.

CONSERVATION OF SPECIES ON THE WRONG TRACK? IS CONSERVATION OF SPECIES LOSING ITS WAY?

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Abstract

To efficiently protect and conserve the subterranean fauna, knowledge of its composition, ecology, and the distribution of its taxa are necessary. Detailed investigations with new methods (mainly DNA analyses) show that the number of species is much greater, the distribution areas of species are much lower, and their endemicity higher than suspected. To complete the pictures of the real biotic richness of countries, intensive re-investigations are necessary. The researchers have to overtake the rapid destruction of the nature, destruction of access points and even rarefaction or extinction of subterranean species.

Therefore the first action of national agencies for environmental management, for nature conservation, departments for nature resources, and similar authorities, should be the legal protection of the subterranean environment which is in full accord also with more practical needs of the local population. It either results or even originates in protection of ground water resources. As the second, an obligation should be felt to encourage and support researchers to do the above mentioned investigations. Specialists are scarce and busy. They require support if they are at all available—globalization is necessary in this context. The additional training of local students and scientists, as well as registering guest scientists is useful, but it should not hamper their research. This is also in accord with the Convention on Biological Diversity (Article 7. Identification and Monitoring; Article 12. Research and Training), signed by presidents of many countries. Only as the third, a supplementary is development of 'protected species' lists that are forbid collecting. Such lists are useful only for the commercially interesting species.

Numerous cases illustrate how rapidly the access localities for subterranean fauna (including the type localities, of prime importance for science) are being destroyed. Calculations also show that collecting subterranean animals mostly can not endanger their populations. By means of fractal analysis we roughly estimated that less than 10% of the underground voids volume and less than 1‰ of the underground surface inhabitable by invertebrates is accessible to man. On the other hand, the whole system is accessible to pollution and other obstructions from the surface. Thus—with few exceptions—species protection policies 'protect' animals only from researchers; beside that, it can mask the absence of an effective habitat protection measure. Similarly counter-productive is the exaggeration of "provisions on access to genetic resources," triggered by a misleading interpretation of the Convention on Biological Diversity.

If these obstacles to the research are not soon removed, extinction will move forward much faster than research and protection of subterranean fauna. Both problems, threats to the subterranean environment, and administrative obstacles to investigations, are common to both the developed and the developing world.

KARST INVERTEBRATE HABITAT AND THE ROLE OF EXCAVATION

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Abstract

Two federally listed endangered troglobite species, the ground beetle *Rhadine persephone* and the harvestman *Texella reyesi*, were found in excavated karst features in Travis County, Texas within 2 m of the feature entrance during species surveys for placement of a water treatment plant. These may be the shallowest records for these cave species, with implications for the conceptual definition of habitat and practical determination of habitat and search effort.

In the case of *R. persephone* a feature was excavated to a depth of 2 m, where an artificially-enlarged space 1.5 m in diameter was bounded by a bedding plane of vuggy limestone with small voids extending in all directions in un-enterable mesocaverns. Un-baited sticky traps were placed and the feature was covered with plywood and black plastic sheeting to induce darkness, retain humidity, and buffer temperatures in the near surface zone, all with the goal of increasing the probability of detecting karst invertebrates that may occupy adjacent mesocavernous voids. Biologists were surprised to find 10 *R. persephone* on these traps. In two other features of similar depth extensive bedrock excavation revealed specimens of *T. reyes* during digging, but were not caught in traps or during visual searches following the covering of features with plastic sheeting and plywood.

KARST LANDSCAPE EVOLUTION: IMPACTS ON SPECIATION, BIOGEOGRAPHY, AND PROTECTION OF RARE AND ENDANGERED SPECIES

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Karst areas provide habitat to a diverse array of species, often adapted to spending their entire lives underground. Many of these species are rare and some are endangered. The evolution and biogeography of cave-dwelling species is strongly influenced by the evolution of karst landscapes relative to the following factors: lithology, geologic structure, burial, hydrology, and climate. The resulting karst provides potential habitat for cave-dwelling species, connectivity between populations, and restrictions and barriers to gene flow. Speciation often results when populations become isolated. Genetic isolation can be complete, a "barrier," or partial, a "restriction" to a species' distribution. In the case of a restriction, gene flow occurs through a relatively small area and/or an area that is traversable only for relatively short periods of time. The ecological and genetic effect of species moving through restrictions thus is often limited or diluted. Rare karst species most commonly occur where barriers and restrictions produce small habitats, and are more easily endangered where unsustainably impacted by human activities.

Evaluating the origin and evolution of karst landscapes and caves also provides a valuable means of protecting and managing cave ecosystems. Key management tools include delineation and establishment of:

- **Karst Fauna Regions**, defined by hydrogeological barriers and/or restrictions to the migration of troglobites over evolutionary time, which result in speciation between regions and the creation of similar groups of troglobites within the caves of a particular region;
- **Karst Fauna Areas**, locations, protected in perpetuity, known to support one or more sites of rare or endangered species and are distinct by acting as individual systems separated from other karst fauna areas by geologic and hydrologic features and/or processes that create barriers to the movement of water, contaminants, and troglobitic fauna;
- **Rare and Endangered Karst Species Zones**, which use biological and geological factors to estimate the likely boundaries of habitat for such species and areas of probable and improbable habitat;
- **Karst Preserves**, locales protected from non-natural activities to sustain the surface and subsurface components of rare karst ecosystems known to occur within certain caves.

Examples are provided from caves with rare and endangered species in central Texas, U.S.A.

1. Introduction

The origin and evolution of cave-dwelling animals is dependent on the occurrence and evolution of caves and conditions that would cause surface-dwelling creatures to retreat underground. Speciation occurs as cave habitat becomes available or attractive, and as incipient cave dwellers begin to diverge genetically from their epigean ancestors. As species become increasingly cave-adapted, their ability to survive on the surface decreases until they evolve into obligatory cave dwellers, troglobites. Speciation continues as caves and karst areas become fragmented by geologic processes and cavernicole populations become isolated, unable to cross the intervening non-cavernous areas. Several such isolated (endemic) species have been listed as endangered in the United States (U.S.). A clear understanding of these species' origin, distribution, threats, and management requires an analysis of their cavernous habitat and its geologic evolution.

The primary factors that determine the presence, size, shape and extent of karst caves are

- predominantly soluble rock;
- fractures or other permeable zones within the rock;
- water that is chemically undersaturated with respect to the primary soluble minerals present;
- sufficient hydraulic gradient to promote efficient groundwater circulation; and
- time.

Generally, caves become larger, longer, deeper, and more interconnected when any of the above variables increase, up to the point where karst denudation results in a net decrease in cave size. These and related variables can therefore be examined to delineate areas where caves, and related humanly inaccessible mesocavernous voids, occur to provide potential habitat to cavernicolous species. Cavernicoles generally evolve as a result of past climatic changes resulting in at least the local extinction of ancestor populations, prompting them to enter caves for shelter, moisture, or other needs. If the cave environment is sufficiently favorable, adaptation continues until the species become obligate cave dwellers, troglobites. Variations in geological and environmental conditions are key factors affecting the distribution, diversity, and conservation of cavernicoles and especially troglobites, the focus of this paper. Examples below are from the Austin and San Antonio areas of central Texas, which has some of the highest subterranean biodiversity in the United States (e.g. Hobbs, 2005).

2. Troglobite Biogeography and Karst Landscape Evolution

Speciation on islands, where a single ancestor may give rise to different species isolated on different islands, is similar in some respects to troglobite speciation in karst. By definition, troglobites are restricted to cave environments and thus to the geologic outcrops in which caves occur. A common surface ancestor can have several troglobite descendant species within separate karstified outcrops, assuming environmental and ecological conditions within the outcrops vary enough to promote different specialized adaptations. As karst landscapes evolve, such as by dissection into separate karstified areas and changing of groundwater levels, troglobite populations may become further isolated and speciated. As an example, the following discussion presents an abbreviated hydrogeologic history of karst development in the Austin and San Antonio areas (primarily summarized from Veni and Associates, 1992, 1994).

Karst development in the Austin and San Antonio regions of Texas began with the deposition of the Edwards and associated formations during Cretaceous time (for brevity, only the Edwards Limestone will be discussed in this paper; similar processes and histories occurred for the other associated units). The first episode of karstification occurred during the late Early Cretaceous when the San Marcos Platform was uplifted and subaerially exposed. By the Late Cretaceous, sea levels rose to bury the Edwards under a thick sequence of carbonate and fine-grained clastic sediments. During the very Late Cretaceous or Early Tertiary, the Edwards Plateau and Edwards Limestone were lifted above sea level. Balcones faulting in the Early Miocene accelerated stream incision. By the Middle Miocene, enough of the limestone was exposed to create a sufficient hydraulic gradient to initiate groundwater flow and conduit development, which accelerated with continued down-cutting and establishment of springs at lower elevations.

Erosion of the southern and eastern margins of the Edwards Plateau exposed the Edwards Limestone in bands, isolated from the limestone on the plateau in downthrown blocks of the Balcones Fault Zone. The absolute ages of their caves have not been precisely determined but some have been roughly estimated based on stream incision rates. Caves northwest of San Antonio are estimated as old as 3.58 to 6 Ma, while some in the Jollyville Plateau of the Austin area are potentially as old as 12.5 Ma. Troglobites, and/or their ancestral species, likely began to occupy caves in the sequence that caves developed and became habitable. White (2006) described how relay ramps (sloping fault blocks) sequentially exposed limestone sections to karst development, determining the timing of occupation. Continued stream incision has divided some of the fault blocks into segments connected by only narrow sections of cavernous limestone, further restricting the distribution of their troglobites.

Fine-scale distribution of species through the karst was determined by localized zones of preferential cave development and the creation of suitable conditions for troglobites. Veni (2005) identified distinct preferential modes of conduit development within the eight stratigraphic members of the Edwards Limestone and used them to evaluate troglobite habitat and management strategies. Such interpretation is crucial to predicting the extent and locations of mesocaverns, small, humanly impassable, solutionally enlarged voids that provide potential habitat for cave-dwelling species in the areas between caves.

Mesocaverns include solutionally widened bedding planes and fractures, anastomosed bedding planes and fractures, honeycomb solution zones, non-cemented collapse or fault-brecciated areas, porous cave sediments, and caves that have been near-completely filled with sediment. Mesocaverns may not hydrologically connect certain caves, but could provide avenues of movement between those caves for troglobites. The minimum width of mesocaverns for a significant troglobite fauna is probably 5-10 mm; this width corresponds to the threshold of turbulent groundwater flow that could carry particles of organic nutrients to the species. Although some species can traverse smaller openings, the lack of food probably restricts their migration. This hypothesis is supported by the

absence of troglobites in the Georgetown Limestone, which overlies the Edwards Limestone and is reported with fracture and bedding plane widths of generally <1 mm (Collins, 1989) and studies in Europe which show cave fauna generally inhabit voids greater >1 mm in width (Juberthei and Delay, 1981).

3. Troglobite Biogeography and Conservation

In 1988, five invertebrate troglobites in the Austin, Texas, area were federally listed as endangered by the U.S. Fish and Wildlife Service (USFWS) and another seven troglobites were listed as endangered in 2000 in the San Antonio area, about 100 km to the southeast (USFWS, 1988, 2000). Listing was in response to the threats and adverse impacts posed by urban growth into the species' geographically small habitat. Those threats include, but are not limited to, the destruction and adverse modification of habitat, degradation of water quality, introduction of non-native species, especially predatory red imported fire ants (*Solenopsis invicta*), and the inadequacy of existing regulations to protect the species. To establish effective protection and management strategies for the listed species, USFWS funded studies and programs (e.g. Veni and Associates, 1992) that biogeographically classified the species into four categories: Karst Fauna Regions, Karst Fauna Areas, Karst Zones, and karst preserves.

3.1 Karst fauna regions (KFR)

KFRs are the largest biogeographic unit. Their conservation purpose is to identify distinctive biographic regions, which is crucial to understanding and maintaining genetic diversity in the ecosystems that support rare and endangered species. They are defined by hydrogeological barriers and/or restrictions to the migration of troglobites over evolutionary time, which result in speciation between regions and the creation of similar groups of troglobites within the karst of a particular KFR. Geologic barriers are stratigraphic, structural, or hydrologic. The primary stratigraphic barrier is the simple lack of cavernous rock, but others include impermeable layers within an otherwise cavernous sequence. Structural barriers are usually coupled with stratigraphic barriers through fault juxtaposition of cavernous and noncavernous units. Hydrologic barriers vary according to the needs of the species in question; terrestrial species have a downward limit at the water table, which serves as the upper limit for aquatic species. Conditions that decrease the input of moisture or nutrients into a cave or mesocavernous voids beyond the organisms' ability to survive are also barriers.

KFRs are initially developed *a priori*, by defining the geologic features and conditions that may isolate or restrict species, and comparing those regions to the distribution of advanced troglobites. Tentative KFRs that do not contain a distinctive troglobite fauna are combined with one or more adjacent KFRs that possess the same suite of species to create biologically distinctive KFRs (e.g. combining of the initially proposed McNeil and Round Rock KFRs in the Austin area; Veni and Martinez, 2006). Distinctiveness does not mean all troglobites are endemic to each KFR. Recently adapted troglobite species are widely distributed and less likely found in only one KFR, while advanced troglobites are more likely to be sufficiently speciated and restricted to certain regions. Additionally, KFRs which are not completely separated geologically, or only recently separated, will share species due to insufficient time for speciation or sufficient gene flow through the restricted but connecting area.

KFR barriers and restrictions may not necessarily be from absent or narrow cavernous outcrops but locations where the outcrops extend under valleys with flowing streams and are thus below the water table. In such areas, restrictions occur where the water table periodically drops sufficiently below the stream bed and for sufficiently long periods to allow potential occupation of caves and mesocavernous voids by troglobites from each side of the valley (this paper only addresses terrestrial troglobites, not aquatic troglobites, stygobites, although many of the same principles can be applied to stygobite biogeography and management). The best example occurs in the Austin area. Ten troglobites were assessed in KFRs south side of the Colorado River and 28 in KFRs to north, only but two species were found common to KFRs on both sides of the river (Veni and Associates, 1992).

Species distribution among KFRs is not simply controlled by hydrogeological factors. Species which spend much of their time actively searching for prey or forage tend to be more widely distributed. In the San Antonio area, the carabid beetle *Rhadine exilis* occurs in four of the area's six KFRs, absent only from the Alamo Heights and Culebra Anticline KFRs which are geologically separated from the others (USFWS, 2000). In contrast, *Cicurina* spiders, with 57 recognized troglobites in Texas alone (Paquin and Dupérré, 2009), generally do not move far from their webs and are thus more likely to speciate.

Considerable biological information on troglobite diversity and distribution has been collected since the KFRs of central Texas were first proposed based on statistical analyses in the mid-1990s. A statistical reevaluation of the KFRs geological, topographical, and biological factors is needed, including results of DNA research that provides insight into the biogeography and evolution of the species. Such analyses should include the distribution of rare, non-listed troglobites for insight into region boundaries not

evident by data from the listed species alone, and for use in management to potentially preclude the need to list those species (Veni and Martinez, 2006).

3.2 Karst fauna areas (KFA)

The USFWS defined a KFA as "an area known to support one or more locations of a listed species and is distinct in that it acts as a system that is separated from other karst fauna areas by geologic and hydrologic features and/or processes that create barriers to the movement of water, contaminants, and troglobitic fauna. Karst fauna areas should be far enough apart so that if a catastrophic event (for example, contamination of the water supply, flooding, disease) were to destroy one of the areas and/or the species in it, that event would not likely destroy any other area occupied by that species" (O'Donnell et al., 1994). Conservation and recovery of endangered troglobites is accomplished by preserving a sufficient number of KFAs for each listed species, based on the number of KFRs in which a species occurs (e.g. O'Donnell et al., 1994). KFAs that contain more than one of the listed species, as well as non-listed troglobites, are especially sought to preserve maximum biodiversity. Key factors used to determine the configuration of a KFA includes, but are not limited to KFA and cave size and shape, location of the cave entrance, drainage into the cave, vegetative buffer, connectivity with other KFAs or preserved natural areas, and environmental quality. For a KFA to meet recovery criteria, the USFWS must concur that the area has accomplished all of the above criteria and criteria in O'Donnell, 1994, and that it is protected in perpetuity. Additionally, while not directly mentioned to avoid confusion in nomenclature, critical habitats designated for the endangered troglobites in the San Antonio area were largely based on the principles that define KFAs (U.S. Fish and Wildlife Service, 2003).

3.3 Karst Zones

Karst Zones identify the potential occurrence of endangered karst troglobites within KRFs and adjacent areas. Like KFRs, they are based on biological and geological factors. Four zones are generally established:
Zone 1: areas known to contain endangered cave fauna;
Zone 2: areas having a high probability of suitable habitat for endangered cave fauna;
Zone 3: areas that probably do not contain endangered cave fauna; and
Zone 4: areas which do not contain endangered cave fauna.

Similar zones could also be defined for rare, common, and specific species. Based on the definition of KFRs, it could be assumed that if listed troglobites occur in one cave of a KFR, they occur throughout the KFR, as strongly indicated by revision of Karst Zone mapping as new localities for the endangered species are discovered (e.g. Veni and Martinez, 2006). However, that cannot be used as the basis for effective management of human activities that may adversely impact the species. The USFWS has used Karst Zones in several ways, but primarily as management zones, determining what level of action and research is needed in the protection and study of areas within these zones (e.g. USFWS, 2001). Karst Zones are also used by businesses seeking to avoid environmentally sensitive areas, which would likely be more expensive to develop, leaving them more available for possible purchase for protection. The City of San Antonio incorporated Karst Zones into its geographic information system model for identifying environmentally valuable land for acquisition and conservation (Stone and Schindel, 2002).

Zone 1 is the most critical Karst Zone. It answers the question "How far can I be from a cave with endangered species before I am reasonably certain that the species may not be present?" Contacts between geologic units where caves are common versus units where caves are rare or absent are the most reliable factors in delimiting Zone 1 boundaries, but many Zone 1 boundaries are not that simple to define. Where no known discontinuity occurs in the cavernous limestone and for lack of other possible options, Zone 1 boundaries might be drawn along creek beds and the locally narrowest or lowest drainage divide. These locations are where the limestone is thinnest and may pose some restrictions on species distribution. Faults with cavernous rock on either side do not seem to restrict species distribution, but they may be selected as a Zone 1 boundary if other possibilities are exhausted. While some caves form along faults, fault planes filled with calcite or gouge are unlikely sites for cave development. Other factors considered in the delineation of Zone 1 boundaries include:

- Comparing the lowest known cave elevation with the lowest topographic elevation to be sure at least the known cavernous zone in the rock is encompassed.
- Examining the distribution of troglobites in different caves. If the same troglobites, and especially the same endangered troglobites, occur in different caves, those caves may warrant grouping as a single Zone 1 area. The quality of the collections should also be weighed. Collections conducted only once, under poor conditions, cursorily, and/or by non-specialists in the collection of cave species, should be given greater

weight for similarity of species, since more detailed studies would likely yield more similarities.
- Evaluating the type and extent of cave development in the area will help determine how realistic it may be for cavernous voids to occur in locations considered as zone boundaries.
- Assessing other caves in the area, especially if they occur between caves with listed species. This demonstrates the presence of potential habitat for the species, unless those caves have been carefully biologically surveyed and the species were not found.

These factors are not always consistent. For example, the geology may suggest a restriction, but the biology may indicate the opposite. All available factors and information should be considered to determine which features and locations are the mostly likely potential boundaries.

Zone 2 is often a potential Zone 1, where no reason is known to preclude the presence of the listed species, but where the listed species have not been found. This is primarily true where Zone 2 is adjacent to Zone 1. In most such cases, Zone 2 areas are where caves have not yet been discovered and/or biological surveys in the caves have not been conducted. Major exceptions to these types of Zone 2 are:

- Nearby but hydrogeologically isolated areas where troglobite populations may not have yet diverged.
- Karst that extends contiguously to where a different suite of species fills the listed species' ecological niche and the interface between the groups has not been delineated.
- Areas that would generally be considered Zone 1, except for being buried under thick alluvium or poorly permeable strata that limit nutrient and possibly moisture input to the underlying rocks, making any underlying voids less suitable habitat.

Zone 3 is typically poorly karsted limestone near or adjacent to Zone 1 or 2, where troglobites are rare or not known. Zone 4 is either a non-karst area, or a biologically well-studied karst area proven to have a different suite of species.

3.4 Karst preserves

Karst preserves are locales protected from non-natural activities to sustain the surface and subsurface components of rare karst ecosystems known to occur within certain caves. While often called "cave preserves," their effectiveness depends on protecting not just the known portions of caves but the parts of the surrounding karst that biologically and hydrologically affects the caves. Key considerations include maintaining for caves and their mesocaverns areas: a high quality of water entering a preserve by surface or subsurface routes, natural water quantity, stable microclimatic conditions, natural quantities and quality of nutrients entering the subsurface, healthy surface and subsurface ecological communities, and a minimum of contaminants, non-native plants and animals, and non-natural disturbance.

The intent of the karst preserves is to provide refuges that insure the survival of the endangered troglobites, including worst case scenarios where all surrounding land would be fully impacted by urban or other land use detrimental to the species. Karst preserves are developed in a similar manner to KFAs and could rise to the level of a KFA if they are protected in perpetuity and the USFWS concurs that the preserve meets recovery criteria. The USFWS (2006) provides the most current and comprehensive discussion of effective karst preserve design and maintenance, even though the report is in draft form for public comment (the final draft should be completed by the end of 2009).

4. Conclusions

The study, conservation, and recovery of rare and endangered karst troglobites is complex and vexed with uncertainties, since the species can only be observed for short periods and most of the habitat is physically inaccessible to humans. While many strictly biological and environmental factors dramatically affect the species, understanding the karst landscape's hydrogeological evolution is critically important in evaluating their biogeography and establishing effective management practices.

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PRESERVE DESIGN FOR ENDANGERED KARST INVERTEBRATES IN BEXAR COUNTY, TEXAS

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Nine federally endangered karst invertebrates inhabit caves and mesocaverns in Bexar County, Texas. These animals depend on high humidity, stable temperatures, and nutrients derived from the surface. Threats to these species include habitat loss and degradation associated with development. The recovery strategy (Service 2008) to protect these species includes the perpetual preservation and management of an adequate quantity and quality of habitat that spans each species' range. Multiple preserves (quantity) across each species' range are desirable to 1) reduce the risk that a catastrophic event would extirpate the species 2) to protect the genetic diversity and 3) allow possible migration or population dynamics necessary for long-term viability. Quality of habitat refers to the condition and orientation of preserve land with respect to the known localities for the species. Preserving habitat, being conservative in terms of allowing enough acreage for adaptive management, monitoring, and conducting research to refine our understanding of the species are key components of recovery and ensuring the establishment of karst preserves that will protect these species in perpetuity.

The reasoning and scientific support behind the recommended quantity and quality of habitat necessary to protect these species will be presented in a poster presentation at the International Congress on Speleology.

1. Introduction

On 26 December 2000, nine karst invertebrates were listed as endangered species in Bexar County, Texas. These species are troglobites and are restricted to the subterranean environment. They have pale coloration and small or absent eyes. Their habitat includes caves and mesocavernous voids in karst (terrain characterized by sinkholes and caves, produced by solution of bedrock). These animals depend on high humidity, stable temperatures, and nutrients derived from the surface. Examples of nutrient sources include leaf litter fallen or washed in, animal droppings, and animal carcasses. It is imperative to consider that while these species spend their entire lives underground; their ecosystem is dependent on the epigean (surface) habitat. Herein, information from Appendix B, titled "Preserve Design" of the draft Bexar County Karst Invertebrate Recovery Plan, is presented explaining the reasoning and scientific support for the recommended quantity (size) and quality of karst preserves necessary to recovery these species.

2. Preserve Design Principles

The objective of designing a karst preserve is to protect the surface and subsurface drainage basins of an occupied karst feature and adequate surface habitat to maintain native plant and animal communities around the feature. Details of the area needed to protect the feature are difficult to define due to limited information on the dynamics of the species and ecosystem processes. Furthermore, population trends of all the listed invertebrates are difficult to obtain due to small sample sizes. This means that the only way to determine with certainty that a preserve is inadequate to support karst invertebrates is to document the extinction of a population by observing no specimens for many years. Because it is unknown if these species can be reintroduced or migrate (except over evolutionary time) into habitat, this is not acceptable. In addition, if a preserve is later found to be inadequate to support the species due to developments being too close or dense, the potential for preserving that land or for adaptive management is lost. Because these species have relatively long life-spans and low requirements for food, a decline in population size or even the complete extinction of the population may take decades. Observations of a listed species over many years on a preserve that is too small for species preservation may not reveal declines. If these observations are used as evidence that a preserve size was adequate, then the potential for long-term preservation of that species may become lost due to irreversible development surrounding the preserve. So, due to the unique considerations of population viability and habitat requirements for these species, preserve design should be based on estimates and assumptions that favor a high probability for species conservation.

The concept of "how much is enough" should be answered in the context of the surrounding conditions (Harris l984). Three critical elements identified for maintaining habitat islands are the actual habitat size, the distance from similar habitat, and the degree of difference in the intervening matrix. Lord and Norton (1990) also cite ecosystem vulnerability to extrinsic disturbances. Because karst ecosystems cannot be recreated once destroyed, preserves should be designed and configured conservatively and incorporate the suite of biotic and abiotic factors needed to promote the integrity of fully-functioning ecosystems. To promote long-term, conservation of karst species and ecosystems, preserves should be designed to rely on minimal management to control threats.

Size and Shape of Preserves - Based on existing literature on habitat patch size, fragmentation, isolation, edge effects, corridors, and other factors considered in minimizing threats to ecosystem stability, a karst preserve should be at least 28 to 40 hectare (ha), including a core and buffer area, to protect the integrity of the biotic communities that support the karst ecosystem. In determining the actual size and configuration of a karst preserve, all of the factors listed below should be incorporated in preserve designs.

Protection of Water Quality and Quantity – Karst hydrology is more difficult to predict than that of surface water or of porous media groundwater movements. A detailed hydrogeologic investigation should be conducted to determine these drainage basins, local recharge areas, and direction of groundwater movement. It is often challenging to map these basins. For example, Flint Ridge Cave in Travis County, Texas was initially mapped as having a 0.30 ha drainage basin (State Department of Highways and Transportation 1989), later mapped as 15.8 ha (Veni 2000), and most recently found to be 22 ha (Hauwert et al. 2005). For information on how to determine subsurface drainage basins see Veni 2003, Veni 2004, and Veni and Associates 2002.

3. Protection of Habitat Area Needed to Sustain Viable Native Plant Communities

A minimum of 28 to 40 ha is likely needed to support a self-sustaining woodland-grassland mosaic community (Service 2003). This includes a core area of 24 to 36 ha and a minimum 20 m buffer to protect this core plant community from detrimental edge effects. These figures are the minimum size needed for an isolated preserve. Preserves that are adjacent to and share a large perimeter with another large preserve, or that are surrounded by low levels of development and native vegetation, in perpetuity, may be smaller. A preserve should be larger the more isolated it is from similar plant communities, or where it may become isolated in the future due to development. Long, narrow corridors that have some advantages to the vertebrate community are not likely to be effective in maintaining the native plant community because this configuration may be more vulnerable to edge effects and exotic species invasion (Saunders et al. 1990, Kotanen et al. 1998, Suarez et al. 1998, Meiners and Steward 1999).

4. Protection of Habitat Area Needed to Sustain Viable Native Animal Communities

Cave Crickets - The native animal community important for sustaining and providing nutrient input for karst ecosystems includes cave crickets (*Ceuthophilus* spp.) as well as other surface fauna. The cave cricket is a particularly important nutrient component (Barr 1968, Reddell 1993) and found in most Texas caves (Reddell 1966). Cave crickets forage on the surface at night up to 105 m from a cave entrance (Taylor et al. 2005). Also, Taylor et al. (2007), compared caves in urban areas to those in natural areas, and found significant differences in isotope ratios of cavernicoles between these two levels of impact demonstrating that nutrient flows are different in urban and rural areas. They also found the number of cave crickets is strongly correlated to the number of other cave taxa. Therefore, the foraging area of cave crickets and a protective buffer should be encompassed in the boundaries of the preserve.

Terrestrial Vertebrates - Species that occasionally use caves such as raccoons (*Procyon lotor*), white throated salamander (*Plethodon albagula*), cliff frog (*Eleutherodactylus marnocki*), and snakes and mice, may play an important role in the ecology of cave systems. Mammals may use caves for shelter from surface temperature extremes and aridity. Though we know of no studies delineating the exact role of mammals in central Texas cave ecology, the presence of a large amount of mammal-derived energy indicates their importance. This energy is in the form of scat, nesting material, and carcasses. Cave collembolan or springtails (a food source for endangered karst invertebrate predators), are frequently seen feeding on the scat (and associated fungus and microorganisms) and mammal carcasses.

5. Continuity of Habitat and Edge Effects

"Edge effects" are changes to the floral and faunal communities where different habitats meet. Preferably, preserves will be in an approximately circular or square configuration, to minimize edge effects. The more edge a habitat fragment or patch has, the larger the patch or fragment size should be to protect the core area from the

deleterious edge effects (Ranny et al. 1981, Lovejoy et al. 1986, Yahner 1988, Laurance 1991, Laurance and Yensen 1991, Kelly and Rotenberry 1993, Holmes et al. 1994, Reed et al. 1996, Turner 1996, Suarez et al. 1998). Minimizing edge effects in a preserve design means keeping the edge-to-area ratio low through increasing the patch size (Holmes et al. 1994) and/or using optimal preserve shapes.

The length and width of the edge, as well as the contrast between the vegetational communities, all contribute to the amount of impacts (Smith 1990, Harris 1984). Some types of edge effects include increases in solar radiation, changes in soil moisture due to elevated levels of evapotranspiration, wind buffeting (Ranny et al. 1981), changes in nutrient cycling and the hydrological cycle (Saunders et al. 1990), and changes in the rate of leaf litter decomposition (Didham 1998). These edge effects alter plant communities, which in turn impact the associated animal species. Edge effects can also affect animal species directly. Vegetation 2 m from an edge can be visibly affected within days (Lovejoy et al. 1986).

Hard edges can act as a barrier to distribution and dispersal patterns of birds and mammals (Hansson 1998, Yahner 1988). Invertebrate species are also affected by edges. Mader et al. (1990) found that carabid beetles and lycosid spiders avoided crossing unpaved roads that were less than 3 m wide. Roads can also constitute a hindrance to movement in forest-inhabiting mice and other small mammals (Mader et al. 1990). Increases in predation (Andren 1995, Bowers et al. 1996, Suarez et al. 1998) and competition for food sources (Hanski 1995) and den sites (Rosatte et al. 1991) also occur near edges. Saunders et al. (1990) suggest that as little as 100 m of agricultural fields may be a complete barrier to dispersal for small organisms such as invertebrates.

Edges often allow just enough disruption for invasive or exotic species to gain a foothold where the native vegetation had previously prevented their spread (Saunders et al. 1990, Kotanen et al. 1998, Suarez et al. 1998, Meiners and Steward 1999). The invasion of red-imported fire ant (*Solenopsis invicta*) (RIFA), an aggressive predator and threat to the karst invertebrates (Elliott 1994, Service 1994), is known to be aided by "any disturbance that clears a site of heavy vegetation and disrupts the native ant community" (Porter et al. 1988, Taylor et al, 2007). In southern California, Suarez et al. (1998) found that densities of another exotic ant species, the Argentine ant (*Linepithema humile*), (similar to RIFA), are highest within 100 m and rare or absent less than 200 m of an urban edge. Native ant communities tended to be more abundant in native vegetation and less abundant in areas with exotic vegetation. Edge effects on various habitats and taxa vary from as little as 15 m to as much as 5 km (Laurance and Yensen 1991). The effects of edge on fauna generally exceed the effects on vegetation.

A rule of thumb for the protection of a forest from a clear-cut edge is the "three tree height" rule (Harris 1984). Tree heights for the Edwards woodland association in Texas are 3 to 9 m (Van Auken et al. 1979). An average tree height of 6.6 m was used, and therefore an edge effect of approximately 20 m is estimated. The "three tree height" approach described by Harris (1984) was based on the distance that effects of storm events ("wind-throw") from a surrounding clear-cut "edge" will penetrate into an old-growth forest stand. Since the effects of edge on woodland/grass land mosaic communities have not been well studied, the "three tree height" recommendation is considered to be the best available peer-reviewed science to protect woodland areas from edge effects (Dr. Kathryn Kennedy, Center for Plant Conservation, pers. comm. 2003). Other studies, found that invasive species were within 16 to 137 m and 20 to 30 m from an edge; hence, we may be underestimating the area needed to buffer against invasive species.

For animal communities, reported edge effects are typically 50 to 100 m or greater (Lovejoy et al. 1986, Wilcove et al. 1986, Laurance 1991, Laurance and Yensen 1991, Kapos et al. 1993, Andren 1995, Reed et al. 1996, Burke and Nol 1998, Didham 1998, Suarez et al. 1998

Avoiding Internal Roads and Habitat Fragmentation - Because roads may hinder movement of fauna, no internal roads or other permanent habitat fragmentation should occur within a karst preserve. Where human access is critical, a bridge could be installed in lieu of a road, provided it does not alter a critical component of the karst ecosystem, such as the quality and quantity of water entering the subsurface. Internal clearing activities and other disturbances of soil and native vegetation should also be avoided to help minimize RIFA infestations. Urban runoff should be diverted away from the karst ecosystem to avoid contamination and increased RIFA activity.

Preserve Non-cave Karst Areas Between Known Cave Localities - Good connectivity with mesocaverns for population dynamics of troglobites should be maintained. Restrictions on impervious cover and the use of Best Management Practices in the karst areas extending to the entire range of the listed species would provide some landscape scale consideration to the species that may

otherwise be susceptible to problems caused by isolation. These conservation actions will not only help maintain mesocaverns, they will also potentially supply corridors for migration of troglobites, provide surface corridors for trogloxenes, provide genetic diversity for maintaining native flora and fauna, and buffer water quality and quantity entering the subsurface.

6. Discussion

To summarize, it is important to design karst preserve that 1) are 28 to 40 ha; 2) in an approximately circular or square configuration to reduce edge effects; 3) protect the surface and subsurface drainage basins; 4) protect the native animal community including the cave cricket foraging area and a buffer; 5) protect the native plant community; and 6) protect mesocavernous areas between occupied caves. The current science indicates that the information above should protect an adequate quantity and quality of habitat to ensure that the endangered karst invertebrates of central Texas can survive in perpetuity; however, further research is needed to refine our understanding of these species. For a comprehensive discussion on preserve design see the draft Bexar County Karst Invertebrate Recovery Plan (Service 2008) – Appendix B, titled "Preserve Design."

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PHYLOGEOGRAPHIC MODELING OF THE EDWARDS AQUIFER KARST AS A MANAGEMENT TOOL FOR RARE AND ENDANGERED SPECIES IN CENTRAL TEXAS; A CASE STUDY USING TROGLOBITIC *CICURINA* SPIDERS

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Abstract

Four species of troglobitic *Cicurina* cave spiders known from the Balcones Escarpment in and around San Antonio, Texas are listed as endangered under the Federal Endangered Species Act (ESA). Many other troglobitic *Cicurina* from central Texas are petitioned for listing. A compelling argument for listing is that economic development is degrading and fragmenting habitat faster than it can be surveyed for biota. Among thousands of known caves in central Texas, only a small percentage have been surveyed due to the limited number of researchers and restrictions on access to private land. Based on mtDNA data, diversity among troglobitic *Cicurina* spiders is the product of the progressive availability of vadose zone habitat as discrete recharge areas developed within the broader Edwards aquifer system. Older genetic lineages occur in structurally high, mature karst terrains while the younger lineages occur in structurally low, emergent karst terrains. Since these areas are geographically concordant, non-overlapping and strongly correlated with geologic structure, genetic mapping of the vadose zone provides the first phylogeographic model for predicting the distribution of listed species and for predicting which un-sampled areas are likely to be rich in genetically distinct populations or species. As a short cut to traditional biota survey strategies, phylogenetic modeling provides a robust basis for regional conservation planning and more efficient allocation of limited karst management resources.

Symposium #11

SPELEOGENESIS IN REGIONAL GEOLOGICAL EVOLUTION AND ITS ROLE IN KARST HYDROGEOLOGY AND GEOMORPHOLOGY

Arranved by:
John Mylroie
Angel Ginés

ORIGIN AND DEVELOPMENT OF THE DAM-VALLEY LAKES AND RELATED KARST HYDROGEOLOGIC SYSTEMS: AMTKELI RIVER (WESTERN CAUCASUS)

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Abstract

Dammed lakes in river valleys of mountain karst regions can be formed by rockslides. Ancient relict cave systems, which had already been abandoned by their flow, can have their hydrologic function reactivated as a result. Interest in their study is due to the fact that they represent a natural model of an engineering situation that arises during dam construction in karst.

The Amtkel karst area is situated on the south slope of the Abkhazsky mountain range, in the western Caucasus, where the River Amtkel crosses the belt of Cretaceous limestone. After an earthquake-induced rockslide in 1891, a dammed lake was formed in the river. Relict caves in the slopes of the valley were flooded and began to function as water intakes. The valley downstream from the rockslide dam was drained, which made former intakes at the river bed open and accessible.

In order to study cave hydrogeologic systems of the area, topographic, geologic, bathymetric, hydrochemical, thermal, and speleological investigations have been conducted. The large karst hydrogeologic system has been revealed, where ancient components received intense recharge from lake waters. Areas of recharge, transit, and discharge have been identified in the system, with discharge occurring to a karst spring located 9 km away from the dammed lake. Three hydrochemical facies were identified in waters of the area: non-karstic groundwaters in the Paleogene sediments, Amtkeli Lake waters with two temperature sub-facies (shallow and bottom), and river waters. Chemical processes in the system have been modeled through the use of mixing equations for both low-flow and high-flow regimes. In this way the speleogenetic evolution of the karst system of the Amtkeli Lake and river during the Pliocene-Quaternary has been reconstructed.

BASE LEVEL RISE AND *PER ASCENSUM* MODEL OF SPELEOGENESIS (PAMS). INTERPRETATION OF DEEP PHREATIC KARSTS, VAUCLUSIAN SPRINGS AND CHIMNEY-SHAFTS.

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In Mediterranean karsts, the Messinian Salinity Crisis induced first a deepening of the karst systems, then a flooding after the Pliocene transgression, and finally a reorganization of the drains after this base level rise. This reorganization mainly corresponds to the development of phreatic lifts: the chimney-shafts and the vauclusian springs. Such a *per ascensum* speleogenesis appears with a base level rise, which is caused by eustatism, by fluvial aggradation or valley infilling, or by continental subsidence. Consequently, we explain the origin of most of the deep phreatic cave systems (which are not hypogenic) by a base level rise which flooded the deep karst, producing phreatic lifts connected to vauclusian springs.

1. Introduction

Where no impervious aquiclude is present, cave levels can be correlated to base level (Granger et al. 2001; Anthony & Granger 2004; Häuselmann et al. 2007). Authors generally explain them as the result of descending base level caused by valley incision. Cave levels are implicitly associated with a *per descensum* evolution. Since the ages of cave levels are correlated to successive stages of valley entrenchment, the lowest levels are considered the youngest, and conversely (Palmer 1987). And when a base-level rise is taken into account, its role is generally limited to the flooding and filling of cave systems, without noticeable speleogenesis.

Studies of speleogenesis associated with the Messinian-Pliocene eustatic cycle, i.e., the succession of Messinian Salinity Crisis (MSC) and Pliocene High Stand (PHS), demonstrate the speleogenetic role of base-level rise as a *per ascensum* process, by the formation of phreatic lifts, or "chimney-shafts" (Mocochain et al. 2006). By extension, other contexts of base level rise, mainly caused by fluvial aggradation, produce a similar speleogenesis, making it possible to extend the *Per Ascensum* Model of Speleogenesis (PAMS).

This paper presents our results, carried out first in the French Mediterranean area and associated with the impacts of the MSC. Second, we extrapolate to other contexts of base-level rise that also show a PAMS. Their origin could be eustatic, climatic (transgression or fluvial aggradation), or tectonic (regional subsidence).

2. The PAMS Associated with the Messino-Pliocene Cycle in the Mediterranean

The French Mediterranean periphery displays a cluster of deep phreatic cave systems (Fig. 1). Many authors once interpreted it by the Four State Model (Ford 1977), assigning a bathyphreatic origin with a speleogenesis not influenced by the base-level position. From the 1980s onward, according to concepts developed by Clauzon et al. (1997), the origin of such a deep-phreatic speleogenesis gradually shifted to the MSC. This revision provides conceptual tools based on the influence of large-scale base level changes on deep phreatic cave systems.

Recent studies have identified several types of flooded cave systems (Mocochain 2007; Audra 2007). This typology is built not only on morphological criteria, but also on the elevation of the caves according to the current base-level position. It is possible to distinguish flooded cave systems located mainly below the base level (marine or fluvial), from those currently in the vadose zone but having a phreatic origin.

2.1 Flooded coastal karst, the Port-Miou submarine spring

The Port-Miou submarine spring, near Marseille, is fed by part of the Provence karst (Fig. 1). It has been explored for more than 2 km and down to 179 m depth (Fig. 2). The offshore bathymetry reveals submerged karst features (dolines, poljes, and canyons) (Blanc & Monteau 1988; Collina-Girard 1996). The Cassidaigne Canyon is interpreted as an old pocket valley developed during the Messinian low

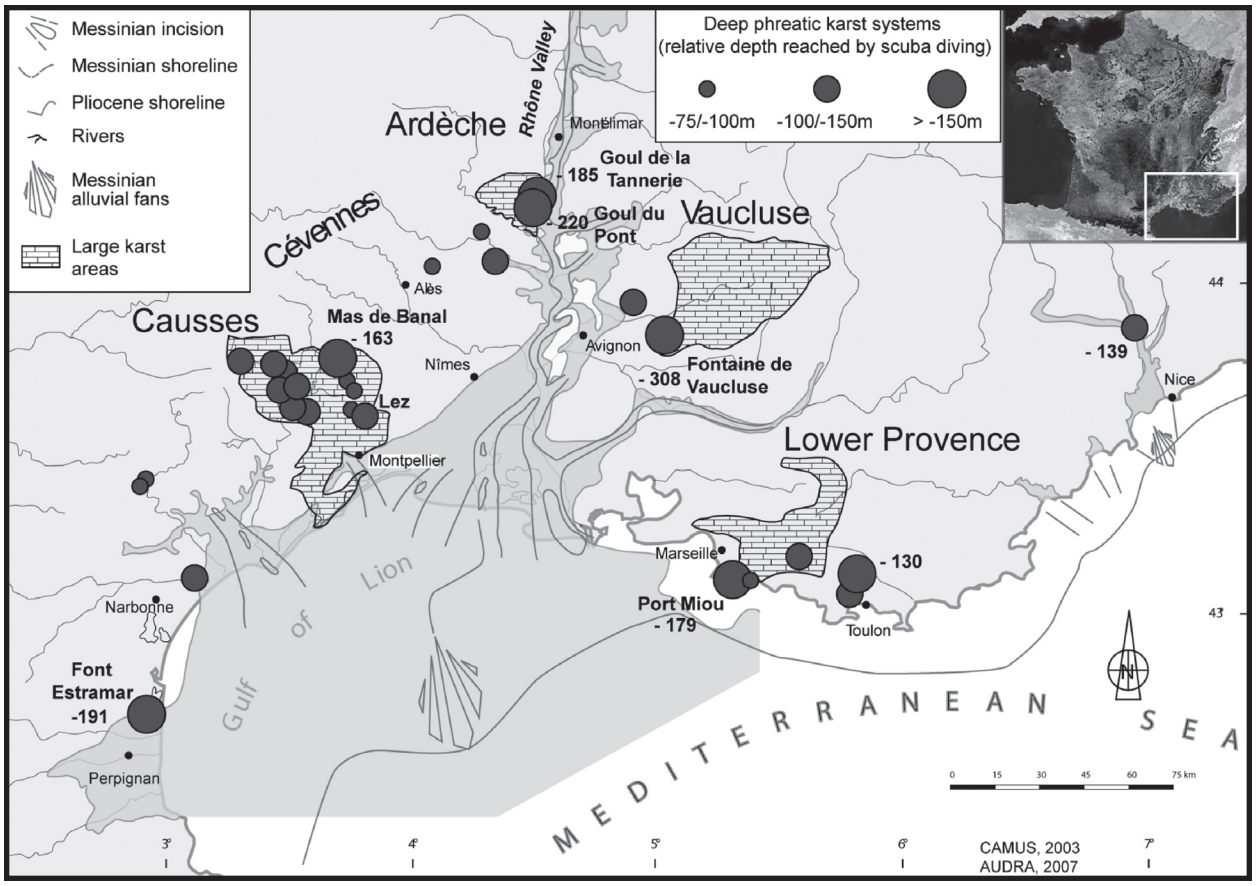

Figure 1: Deep-phreatic cave systems in Mediterranean France. All cave systems are connected to the Mediterranean or to the Pliocene rias ("flooded valley") (map after Clauzon et al. 1997; Camus 2003; caves updated from Audra 1997).

sea level. Since the Pliocene transgression, the deep karst has been flooded. Sea water enters several kilometers into the aquifers through the old Messinian drains. This intrusion is responsible for the salinity of the spring (Gilli 2001; Blavoux et al. 2004; Cavalera 2007).

2.2 Flooded continental karst: the Fontaine de Vaucluse

The Fontaine de Vaucluse drains the largest karst area of France (1130 km^2, Q = 23 m^3/s; Fig. 1). It is famous for its considerable depth of 308 m, i.e., 224 m below current sea level (Bayle & Graillot 1987). Wall karren are developing down to 170m below sea level. They testify to past epiphreatic conditions by successive flooding and draining. The Fontaine de Vaucluse appeared during the MSC (Gilli & Audra 2004). Seismic investigations reveal

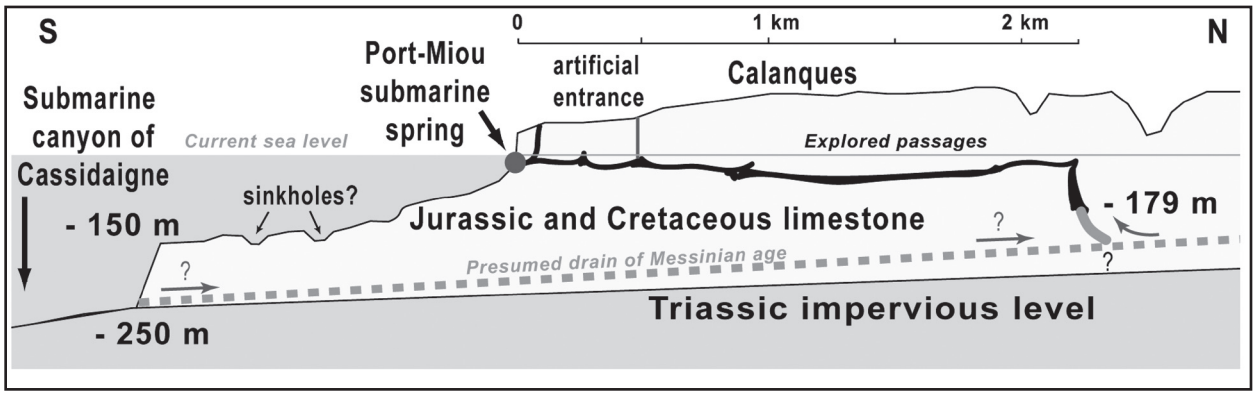

Figure 2: Port-Miou submarine spring. In the Messinian drain, opening offshore at the head of the Cassidaigne Canyon, the water is blocked by the density of the salt water. The underground flow follows a phreatic lift connected to the submarine spring (Blavoux et al. 2004; survey after Douchet & Fage 1993).

a Messinian canyon filled with sediments, located 20 km to the west and originating from the Fontaine de Vaucluse (Schlupp et al. 1997). This pocket valley has been filled during the Pliocene (Fig. 3). The fill blocked the canyon at depth and forced the flow upward and to use the past overflow route as a perennial spring. The lowest part of the karst is flooded to a great depth. A similar evolution occurred in Ardèche, where the Goul du Pont and Goul de la Tannerie springs have been explored by scuba divers down to -220 m (Fig. 1).

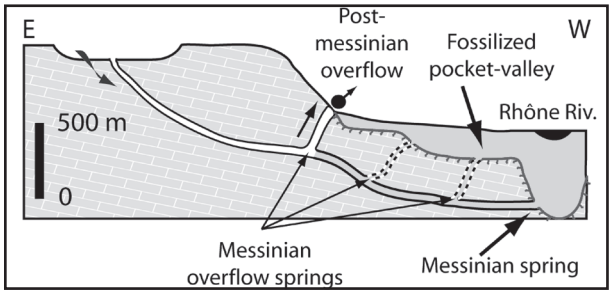

Figure 3: Speleogenetic model of the Vaucluse karst. The Messinian canyon of the Rhône River is filled with Pliocene deposits. Its bottom is at 900 m below current sea level. The Messinian cave system, which was probably connected to this canyon, has been flooded and filled with sediment during the Pliocene. Since that time, the underground flow has used a chimney-shaft opening to the current base level at the Fontaine de Vaucluse.

2.3 Drained karst: the Ardèche

The canyons were deeply entrenched during the Messinian and then filled with sediments during the Pliocene, causing a base-level rise of similar amplitude. This rise first occurred by flooding of the valleys during the Pliocene transgression, then by fluvial aggradation through to the end of the Pliocene (Fig. 4). Cave levels are correlated with the successive positions of the base level during the Messinian-Pliocene cycle.

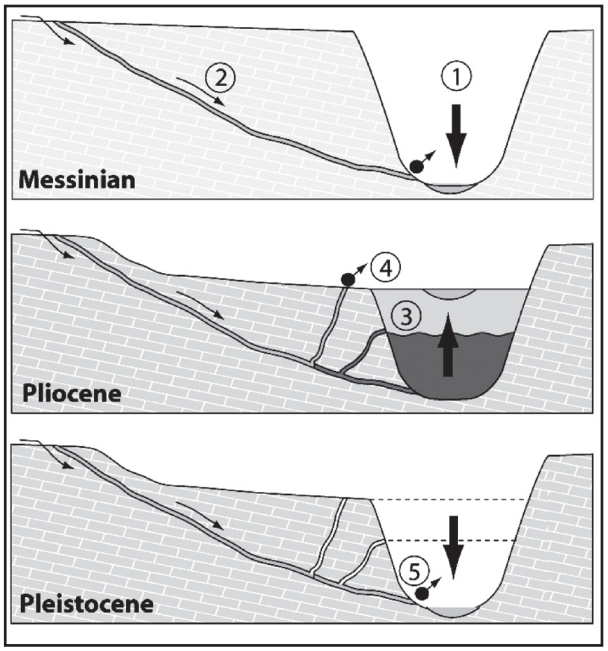

Figure 4: PAMS during the Messinian-Pliocene cycle. Left: Messinian canyon entrenchment caused the deepening of karst drainage. Center: Pliocene base level rise occurred in two steps – by marine ingression as ria (dark gray), then by fluvial aggradation (light gray). Deep drainage uses phreatic lifts to emerge as vauclusian springs, recording successive positions of the base level. If the Messinian canyon is located below the current base level, it remains fossil; the karst remains flooded and discharges by a vauclusian spring (fontaine de Vaucluse type). Right: if the Messinian canyon is located above the current base level, the canyon is exhumed and the karst is drained. The current drainage uses the deep Messinian drain; the Pliocene phreatic lifts are abandoned as fossil "chimney-shafts".

Foussoubie is a 25-km long cave system with a main drain displaying a regular gradient (2.5%) between the sinkhole and the resurgence in the Ardèche Gorge (Fig. 5). Above the resurgence are vertical series with phreatic features that

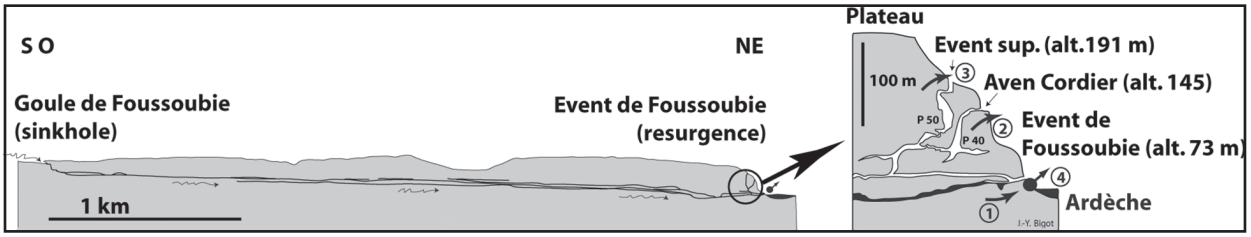

Figure 5: PAMS in the Foussoubie Cave System, Ardèche. The phreatic lifts resurge at vauclusian springs connected to the higher base-level positions corresponding to the Pliocene filling. During the Pleistocene, the Messinian canyon was exhumed and cleared of its Pliocene fill down to its bottom. Current drainage reuses the deep Messinian drain. The Pliocene phreatic lifts are abandoned as fossil "chimney-shafts" (Bigot 2002; Mocochain 2007; Mocochain et al. 2006, 2008).

clearly show a rising flow. The rectilinear long profile shows that the main drain developed during the Messinian, at a base level at the bottom of the Ardèche Canyon (Bigot 2002; Mocochain 2007). Filling of the canyon causes the development of resurgences as phreatic lifts, or "chimney-shafts". The elevations of resurgences record the stages of base-level rise due to Pliocene fluvial aggradation. During the Pleistocene, the Messinian canyon of the Ardèche was exhumed by clearing away of the Pliocene filling: Foussoubie chimney-shafts became fossil, and the Messinian drain returned to a vadose flow (Figs. 4, 5).

In partly exhumed canyons, the lower part of the karst has remained flooded since the beginning of the Pliocene, and they discharge as vauclusian springs (Fontaine de Vaucluse type). In the entirely exhumed canyons, the karst is drained and the chimney-shafts are fossil (Foussoubie type). In turn, the chimney-shafts, which are systematically associated with paragenesis, are interpreted as a **record of the PAMS**, which originates from a base-level rise. Consequently, a base-level rise is interpreted to be a founder speleogenetic event. Besides the Messinian-Pliocene cycle, other causes of base-level rise also produce *per ascensum* speleogenesis and the development of chimney-shafts.

3. Extrapolation of the PAMS to Other Causes of Base-Level Rise

The speleogenetic role of the Messinian-Pliocene cycle could be attributed to a dramatic base-level drop that allowed a deepening of karst drainage, followed by a base-level rise of similar magnitude. This base-level rise flooded the deep drainage and developed chimney-shafts, sometimes associated with new horizontal cave levels, as in Saint-Marcel Cave, Ardèche (Mocochain et al. 2006). The occurrence of deep phreatic karsts, vauclusian springs, and chimney shafts all around the Mediterranean is a consequence of speleogenesis during the Messinian-Pliocene cycle (Figs. 1, 7).

Besides the Messino-Pliocene cycle, the PAMS applies to every kind of base-level rise (following a low base-level position). A base-level rise is shown by filling of the lowest parts of valleys by water, ice, or sediment. The driving force could be eustatic (transgression), tectonic (subsidence), climatic (clearing of slopes soils, glacial advance), or even anthropic (e.g., man-made dams).

3.1 The Miocene eustatic cycles

In the Rhodanian-Provence foreland basin between the Fontaine de Vaucluse and the Rhône, the marine molasse records several eustatic cycles during the Miocene (Aquitanian, Burdigalian). The regression, which is linked with tectonic uplift, follows valley entrenchment up to 100m-deep, with eventual flooding and filling with sediments by transgressions (Besson et al. 2005a, 2005b; Parize et al. 1997). Near the Fontaine de Vaucluse, a fossil pocket-valley ends exactly at the Valescure Shaft, which displays characteristic chimney-shaft features. The Valescure Shaft used to be a vauclusian spring during the Burdigalian, following the filling of the pocket-valley with the molasse. An earlier outflow should exist, buried beneath the molasse sediments.

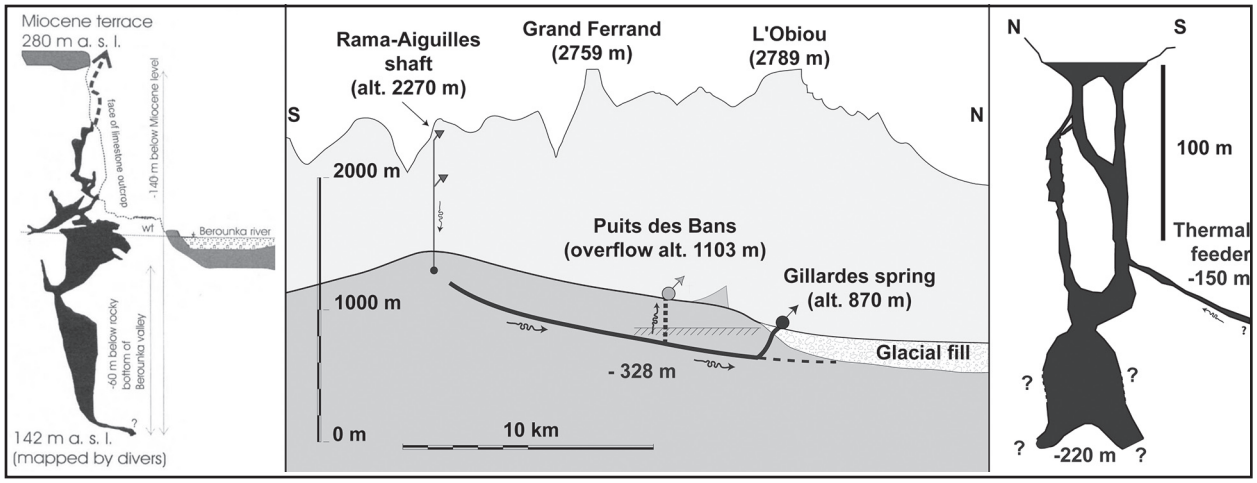

Figure 6: Left: Podtraťová jeskyně, Moravian karst, Czech Republic, a 140-m high chimney-shaft, the lowest part of which is flooded below the Beroukna valley (Bruthans & Zeman 2003). It could show a record of the base-level rise of the hydrologic network after pre-Badenian entrenchment. Center: the Puits des Bans and the Gillardes Spring (French Alps). The basin fill (glacial, lacustrine, and fluvio-glacial) has blocked the Gillardes Spring. In high water, the Puits des Bans, a 300m-high chimney-shaft, floods and overflows. Right: Lagoa Misteriosa (Brazil), a 200-m deep phreatic shaft, a window in a karst aquifer flooded after the continent subsidence (survey by G. Menezes).

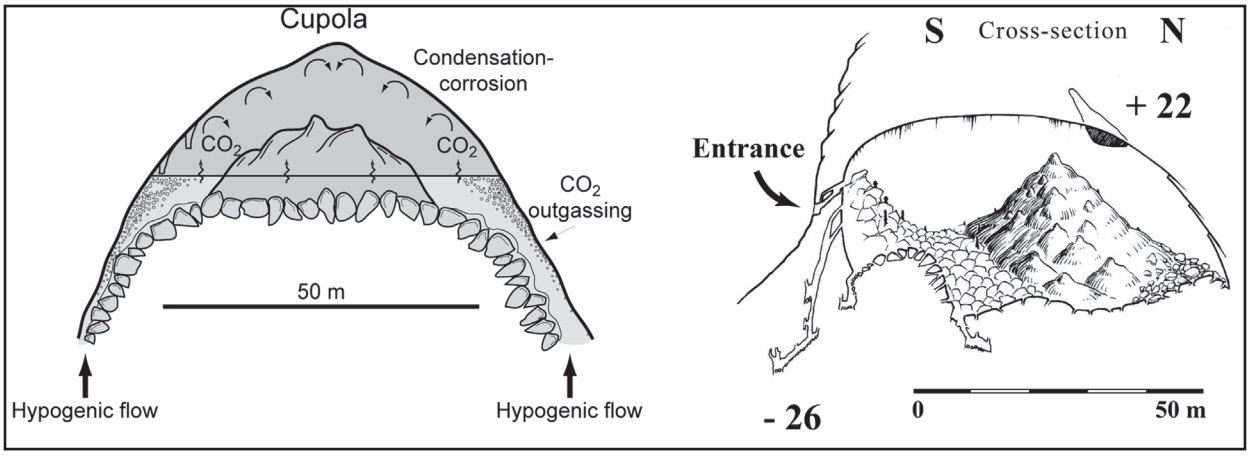

Figure 7: Distribution and origin of the deepest phreatic cave systems in the world.

In the Rhodanian-Provence basin, the speleogenetic influence of the Miocene eustatic cycles is partly hidden by the imprint of the younger Messinian-Pliocene eustatic cycle. On the contrary, the Paratethys molassic basin of central Europe, at least in its northern part (Czech Republic, Slovakia, Poland, etc.), has not been affected by Messinian entrenchment. Consequently, the oldest eustatic cycles are better recorded. The transgressions of the Carpathian (i.e., Burdigalian) and especially of the Middle-Badenian (i.e., Langhian-Serravalian) follow continental erosional phases, which deepened valleys as much as 150-200 m, and which were later fossilized. Pre-Badenian karsts are well-known: tower karst in Zbrasov (Czech Republic) partly exhumed from the molasse; caves filled with molasse in Bohemian; caves and fluviokarst morphologies in the Moravian karst (Kadlek et al., 2001). In the Bohemian karst, the Podtraťová jeskyně (cave) is a chimney-shaft partly drained and more than 100 m deep (Fig. 6). It is developed below the Beroukna Valley, which was entrenched before the Burdigalian and then exhumed during the Pleistocene (Bruthans & Zeman 2003, Fig. 6). If some caves in this area have a hypogenic origin, its chimney-shaft features would have recorded the Miocene base-level rise by *per ascensum* speleogenesis.

3.2 Glacio-eustatic transgression

Post-glacial sea-level rises have flooded the coastal karsts (Fig. 7), including the cave systems developed during previous low sea levels. It is evidenced by submerged speleothems, which have been observed down to -120m, around the Gulf of Mexico: Yucatan Peninsula, Bahamian blue holes, Wakula Spring in Florida, etc. Such types of karst discharge through vauclusian springs at the mouths of phreatic lifts. In French Normandy, Pleistocene sea-level changes are well recorded in cave systems developed in chalk. The high conductivity of the chalk allows cave systems to adapt precisely to the slightest base-level changes, with chimney-shafts less than 10 m high (Rodet 1991; Rodet et al. 2001).

3.3 Fluvio-glacial flooding

Glacial retreat leaves moraine dams across valleys. Behind them, lacustrine and fluvio-glacial sedimentation occurs, sometimes up to several hundred meters high. Cave outlets connected to the valley bottom become plugged. Some chimney-shafts are still developing, allowing phreatic lifts from deep passages up to the uplifted base level. The height of the chimney-shafts corresponds to the height of the base level rise. The Puits des Bans (French Alps), is a 300-m high chimney-shaft (Fig. 6).

3.4 Base-level rise after continental subsidence

In Brazil, the Lagoa Misteriosa is a deep-phreatic shaft explored to -220 m by scuba divers (Fig. 6). Regional subsidence (communication from A. Auler) can be considered a relative base-level rise that has flooded the karst.

4. Conclusion

Studies of the Messinian-Pliocene eustatic cycle in the Mediterranean allow us to design a model of karst adaptation to major oscillations of base level. Pliocene base-level rise has flooded the karst and systematically produced phreatic lifts – chimney shafts – which feed vauclusian springs. Some cave systems remain flooded, and others have been partly or entirely drained after Pleistocene re-entrenchment of the valleys. Other causes of base-level rise (eustacy, fluvial aggradation, continental subsidence), less significant in amplitude, have the same effect on PAMS. Consequently, there should be a global genetic model for most deep-phreatic systems (Fig. 7). Some of them have a hypogenic origin (e.g., in South Africa, North America, etc.)

(Audra 2007). However, most of them could correspond to a base-level rise inducing the PAMS, which first flooded the karst and then allowed the development of phreatic lifts, chimney-shafts, and of vauclusian springs,

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THE PATTERN OF HYPOGENIC CAVES

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The hypogenic cave pattern reflects the speleogenetical processes. Processes vary according to the depth in the aquifer, involving mixing corrosion by convergent flux and with meteoric water, cooling, sulfur oxidation, carbon dioxide degassing, and condensation-corrosion. Cave patterns are: isolated geodes, 2D and 3D multistorey following joints and bedding planes, giant phreatic shaft, water table mazes, isolated chambers, upwardly dendritic spheres, water table cave, and smoking shafts.

1. Indroduction

The development of caves by hypogenic processes (i.e. "hypogenic speleogenesis") corresponds to *the formation of caves by water that recharges the soluble formation from below, driven by hydrostatic pressure or other sources of energy, independent of recharge from the overlying or immediately adjacent surface* (Ford 2006). Hypogenic caves - often referred to as "thermal caves" or "sulfuric acid caves" – were often considered as an "exotic" side of the "normal" (i.e. meteoric) caves. Palmer (1991) estimated that about 10% caves have hypogenic origin. Recent studies (overview in Klimchouk 2007) have emphasized the specific hydrogeological background and shown that hypogenic caves are much more common than previously thought. The extreme diversity of settings (carbonic, sulfuric, thermal, cold, deep phreatic, shallow phreatic, vadose...) in different geological or geomorphological contexts produces a puzzling impression: each hypogenic cave seems to be unique, with few characteristics in common with the other hypogenic caves regarding their pattern.

2. Method

A data base of more than 350 hypogenic caves was constructed from the literature, comparing geological structure, hydrology, morphology of caves at different scales (wall features, passages morphology, and cave pattern), mineralogy, deposits... Field study of the most representative hypogenic caves, combined with the information in the literature, show that the apparent dissimilarity in shape can be overcome. Taking into account the diverse settings (hydrologic, geologic) and the speleogenetic processes, we obtain a conceptual model of a cave pattern, integrating all kinds of hypogenic caves (Fig. 1) (Audra 2007). Patterns are subdivided into two main types: deep phreatic systems generally developed in a confined aquifer by transverse speleogenesis (*sensu* Klimchouk 2000), and cave systems developed above the water table, where condensation-corrosion plays a paramount role.

3. Hypogenic Cave Patterns in Phreatic Condition

3.1 Isolated geodes

At depth, mixing allows complex dissolution and deposition processes. Large crystals (calcite, gypsum...) are deposited in slightly saturated water, together with diverse minerals (mainly metallic sulfides) (Fig. 2).

3.2 3D Multistorey maze caves

The rising hypogenic flow uses alternatively joints and bedding planes, producing a 3D maze cave, in a staircase pattern. Generally, the cave has a main trunk where hypogenic flow was rising, surrounded by 3D mazes, smaller in size (Fig. 3). In Monte Cucco Cave system (Italy), the sulfuric water was rising toward the top of the anticline, where impervious covers are breached, allowing the discharge of the karst aquifer. Contiguous vertical passages correspond to discrete hypogenic trunks, inclined galleries follow dip, horizontal passages and some cave entrances record past base level positions (Galdenzi & Menichetti 1995). In the Black Hills (South Dakota), Jewel and Wind Caves range among the largest maze cave of the world. There genesis is complex, involving several early phases (Palmer 2006). However, the pattern resulting from the main speleogenetical phase is simply a dense network of enlarged discontinuities, similar to the previous examples.

3.3 2D maze caves

If an aquitard is present, the cave develops below this impervious ceiling, as a 2D maze cave (Fig. 4). The passages are horizontal or inclined, according to the dip. The Denis Parisis system in the central part of Paris basin is horizontal.

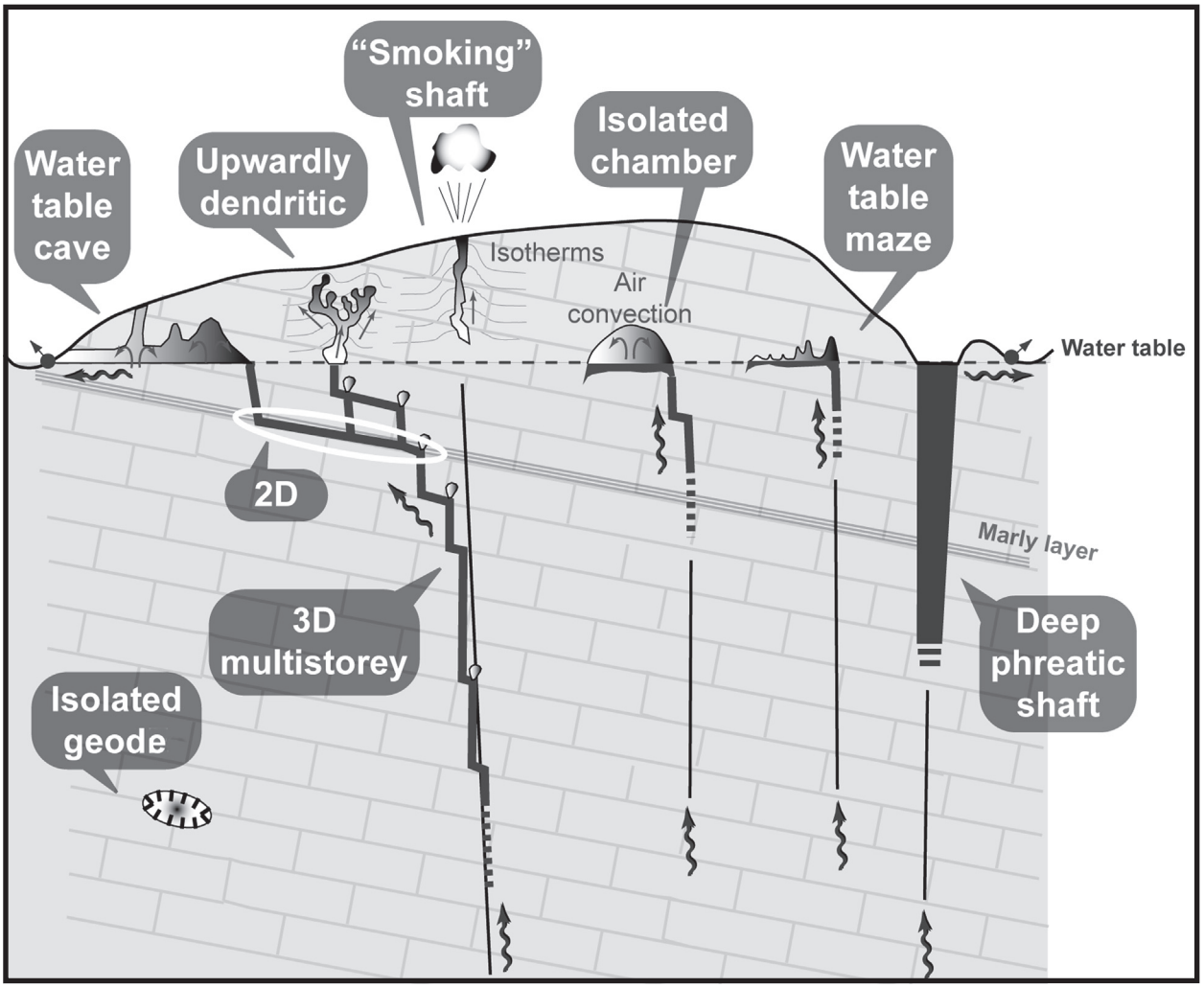

Figure 1: Conceptual model of the hypogenic cave patterns, according to the geological structure, the groundwater recharge, and the speleogenetic processes.

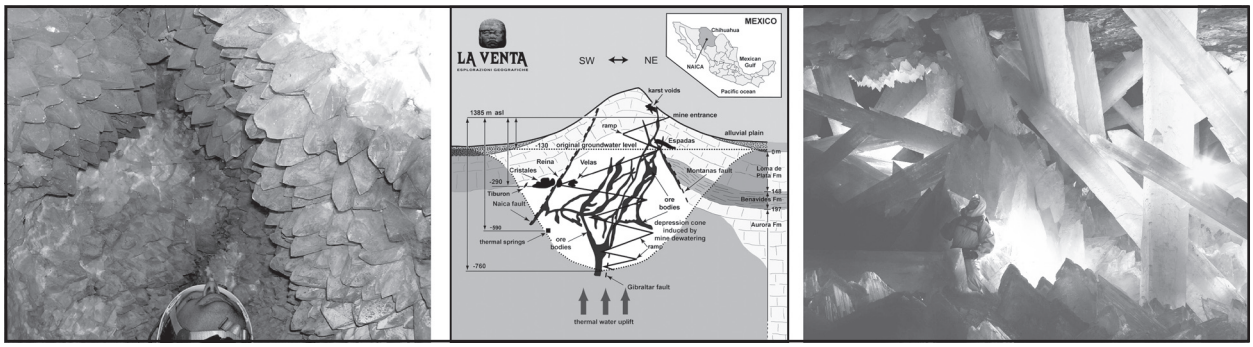

Figure 2: Isolated geodes. Left: geode lined with calcite spar, France. Center-right: cueva de los Cristales (Chihuahua, Mexico) was intersected and drained by the Naica mine (Bernabei et al. 2007). The gypsum swords in this cave are the largest crystals of the world.

In Monte Cucco, the Faggeto Tondo develops below the inclined marly cover (cave indicated as no. 2 in Fig. 3, right). The 2D maze cave is a subtype of 3D maze cave; some parts of 3D mazes locally develop as 2D mazes, when a less permeable stratum is present.

3.4 Deep phreatic shafts

In active tectonic areas, the combination of rising warm

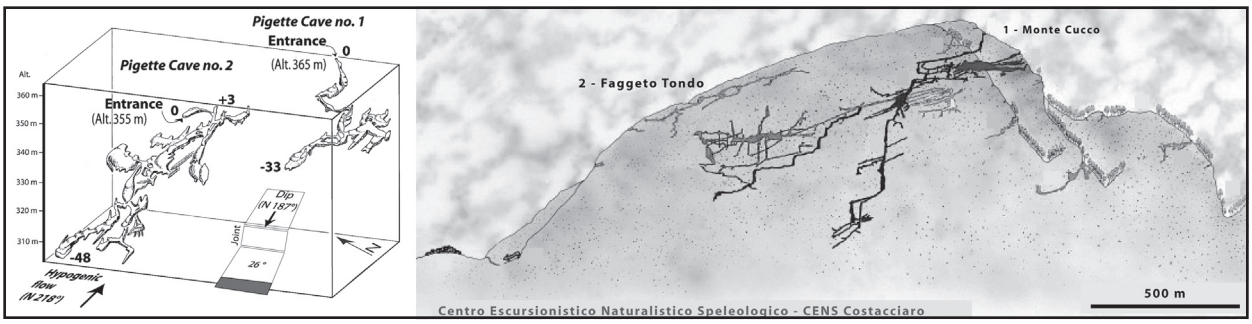

Figure 3: Left: perspective view of the Pigette Caves (France), a 3D multistorey maze cave originating in the phreatic zone by hypogenic upwelling, following structural weaknesses (inclined dip and vertical joints) (sketch by J.Y. Bigot). Right: Monte Cucco system (Italy), probably the deepest hypogene cave system of the world (- 923 m / 31 km), with large shafts of several hundred meters of depth and ramps inclined along the dip of the anticline (Cairoli et al. 1991).

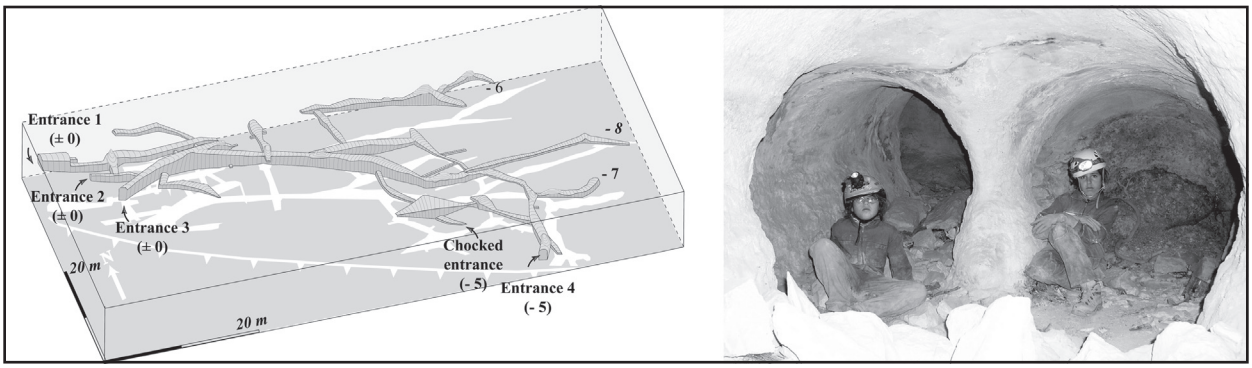

Figure 4: A sub-type of the 3D maze, the 2D maze confined under an inclined impervious roof. Grotte de Saint-Sébastien (France). The dip is towards the SE, water used to well up towards the left.

water, with CO_2 and H_2S outgassing concentrates speleogenetic processes along major fault lines, producing the deepest phreatic shafts of the world: pozzo del Merro, Italy (-392 m); El Zacaton, Mexico (-329 m, Fig. 5); Hranica propast, Czech republic (-267 m).

4. Hypogenic Cave Pattern Along or Above the Water Table

4.1 Upwardly dendritic caves

Above thermal water, condensation occurs at the ceiling

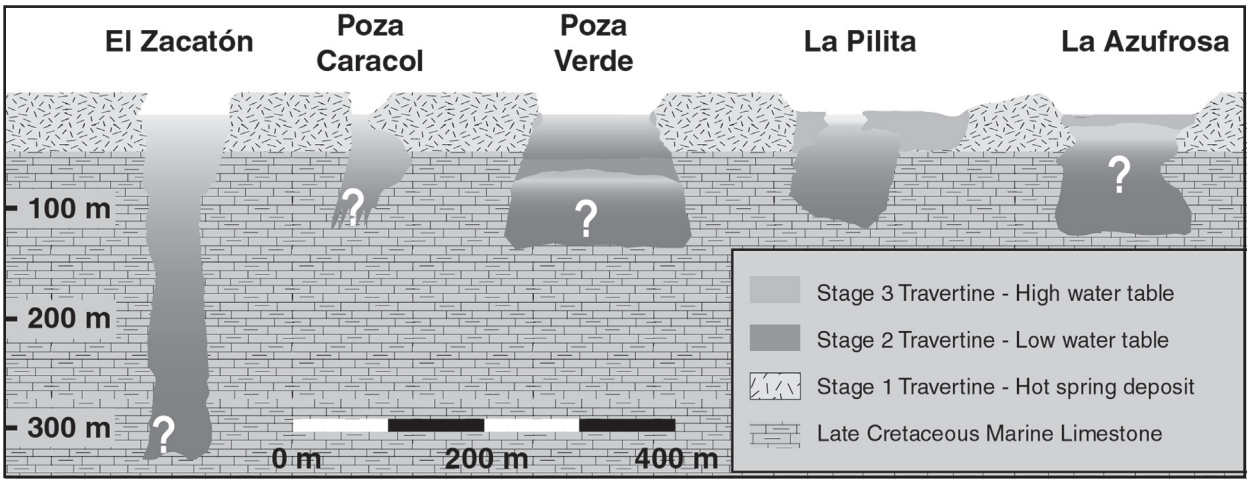

Figure 5: Deep phreatic shafts. Zacaton shaft is one of the numerous windows in the karst aquifer of Tamolipas area (Mexico), reaching a depth of 329 m. Investigation showed nearby volcanoes were the source of H2S. Microbial activity based on sulfur oxidation is present (Gary & Sharp 2006).

which is cooler. CO_2 and H_2S outgassing enhance aggressivity. By condensation-corrosion, cupolas develop upward as a dendritic pattern of stacked spheres (Audra et al. 2007). The development of two neighboring spheres will be divergent, toward the greatest potential heat transfer, because the rock in between the two spheres has less transfer potential and remains warm (Szunyogh 1990), giving the bush-like structure, as found in the Sátorkö-puszta Cave, Hungary (Fig. 6).

4.2 Isolated chambers

When strong degassing occurs, upwardly dendritic spheres enlarge and join together, eventually producing large isolated chambers (Fig. 7) (Audra et al. 2002). With a moderate thermal gradient and pCO_2, modeling shows that such volume can develop in a rather short time span, about 10 000 years (Lismonde 2003). From Israel occurrences, Frumkin & Fischhendler (2005) assign the origin of isolated chambers to phreatic convections.

4.3 Water table sulfuric acid caves

Above the water table, sulfuric vapors and thermal convections produce strong condensation-corrosion and replacement gypsum crusts (Egemeier 1981). The main drain develops headwards from springs (Fig. 8). Due to the sulfuric corrosion the cave has a low gradient (Fig. 9). Minor changes in base level cause the flow to migrate laterally making incipient mazes (fig. 9) (Audra 2007).

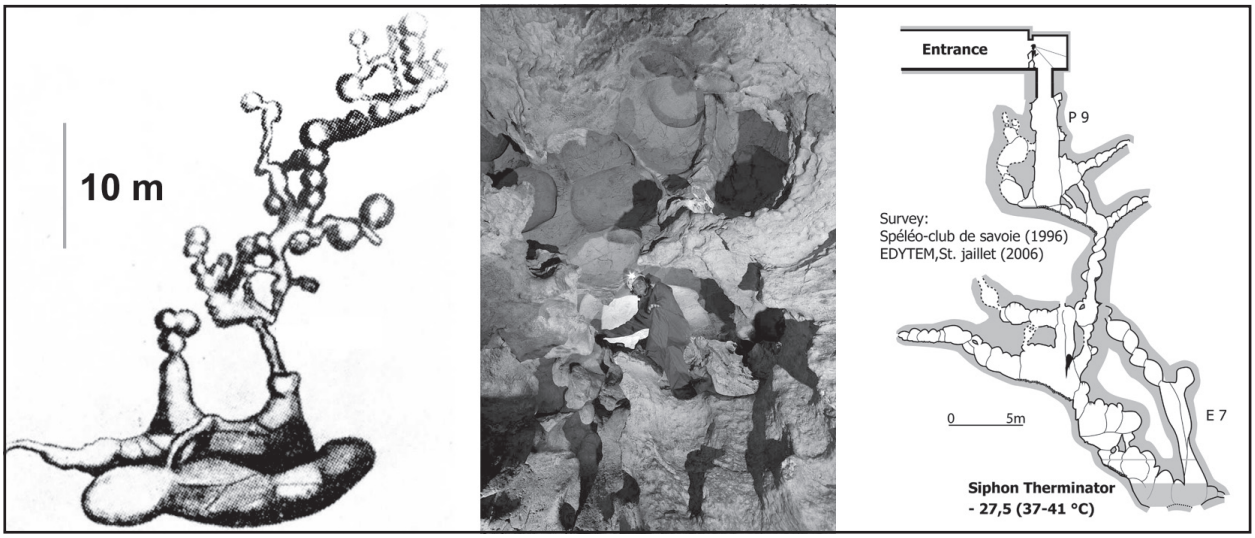

Figure 6: Upwardly dendritic caves. Left: Sátorkö-puszta Cave, Hungary, has been used to represent thermal speleogenesis. Upwardly dendritic spheres develop above a basal chamber (survey in Ford & Williams 1989). Center: stacked up spheres in Serpents Cave, France, which is close to Chevalley. Right: Chevalley shaft, France (Audra et al. 2007).

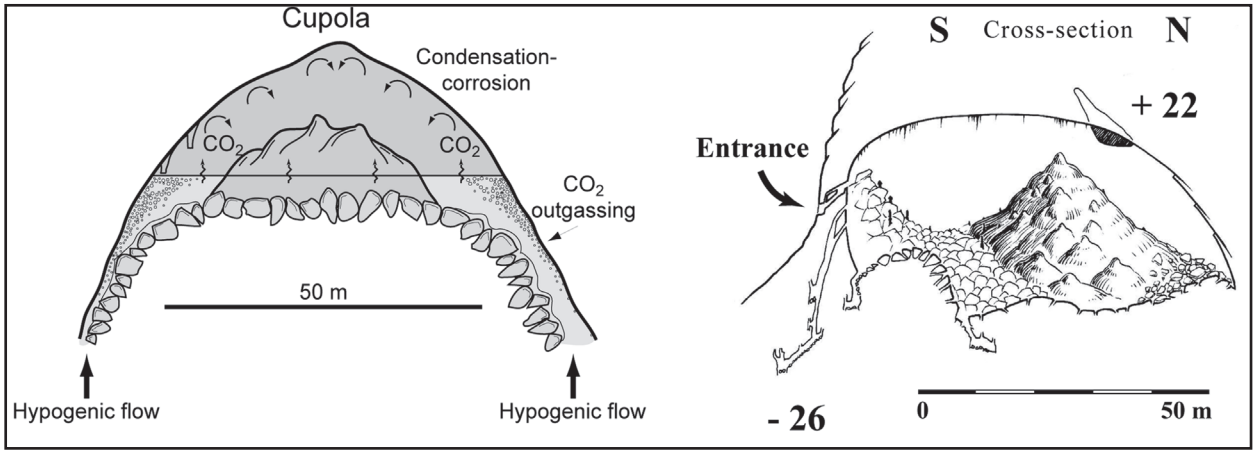

Figure 7: Isolated chambers. Thermal hypogene flow degasses at shallow depth, the thermal convections with CO2 (or H2S) gas enhance strong condensation-corrosion and the development of large isolated chambers. They tend toward a hemispherical shape. Simultaneously, a massive calcite deposit occurs in the lake, oversaturated after CO2 degassing; Champignons, France (sketches J.-Y. Bigot).

Condensation domes develop upward and may breach to the surface (Fig. 8). The most demonstrative water table sulfuric caves are Cueva de Villa Luz (Mexico), Chat Cave (France), Kane Caves (USA). Because of major base level lowering, successive horizontal cave levels develop: Frasassi Cave (Italy).

4.4 "Smoking" shafts in the vadose zone

Above thermal aquifers, the rock is significantly heated by the geothermal gradient. In winter the atmosphere of open shafts is unstable: the cold air sinks inside the shaft and expels the warm air out of the shaft which condenses, giving the impression that the shaft is smoking. The air flow follows ceiling channels where condensation-corrosion focuses. Eventually, it produces condensation ceiling cupolas and channels, which could lead to misinterpreting them as phreatic in origin (Vapeur Shaft, France; Nasser Schacht, Austria; Fumarollas and Vapor Shafts, Spain). The origin of the shaft is generally a mechanical fracture; the hypogenic role of the thermal gradient is indirect and limited to the etching of the wall features.

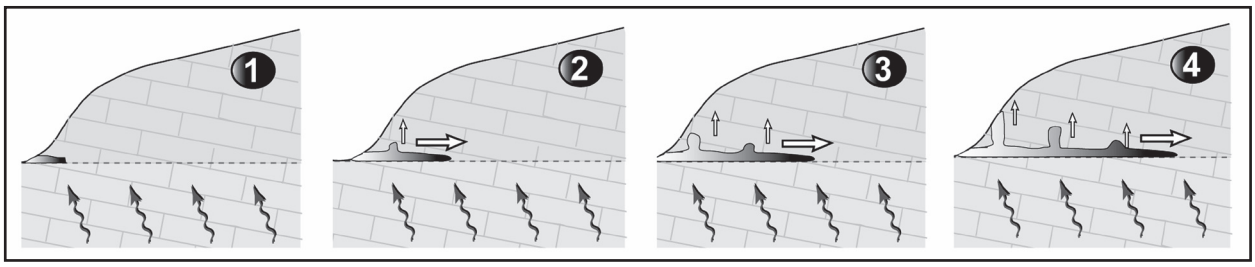

Figure 8: Water table Sulfuric cave. Headwards evolution by condensation-corrosion along the water table, supplied with major sulfuric upwelling along a fracture. Simultaneously, hydrothermalism lifts the hot air, condensation-corrosion occurs, bells and chimneys develop, some finally break through to the surface. The white arrows indicate the direction of cave development (inspired from Cueva de Villa Luz, Mexico).

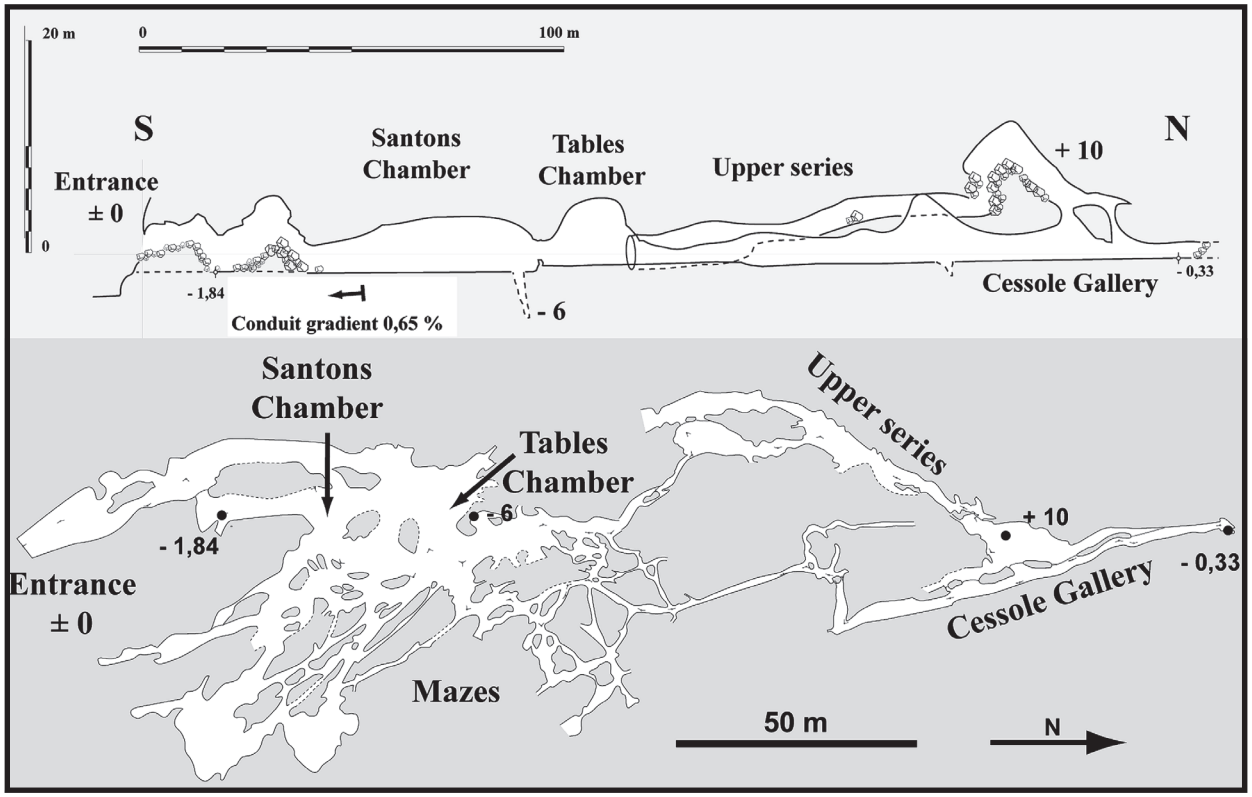

Figure 9: Chat Cave, France. The long profile with very low gradient (0.7%) results from the sulfuric flows. Incipient mazes beside the main drain result from lateral migration of the flow due to minor changes in base level (plan from M. Rousseau, profile Ph. Audra).

5. Conclusion

The diversity of hypogenic caves is now placed in a global model, explaining all kinds of patterns, depending on the geological structure, the groundwater recharge, and the speleogenetic processes. Beyond hypogenic caves developed at depth by mixing corrosion and rising flow, some hypogenic caves are developing in the atmosphere at -or above- the water table, mainly by condensation-corrosion, due to the combination of thermal convection, sulfuric and carbonic corrosion.

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MORPHOLOGY AND GENESIS OF CAVES IN IRON-RICH ROCKS

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Abstract

Caves in iron-rich rocks, although mentioned in the Brazilian geological literature since the 19th Century, have been subject to very few detailed studies. At present, nearly 2000 caves have been identified in the two major Brazilian mineral provinces, i.e., the "Iron Quadrangle" area of southeastern Brazil and the Carajás plateau in eastern Amazonia. The large majority of known occurrences in Brazil are developed either in iron ore or in canga, a surficial iron-rich rock composed of varying quantities of detrital fragments cemented by a ferruginous matrix. Caves in iron-rich rocks are usually small, the longest surveyed cave being only 350 m long. Cave patterns comprise a number of irregular chambers connected by smaller passages. Entrances are also small, suggesting that these caves evolved initially as isolated entranceless chambers, with a later connection to the surface and between chambers.

Speleogenesis involves the generation of porosity through the leaching of more soluble constituents, such as silica, creating a low-density zone that can slowly be enlarged through the colloidal removal of iron constituents. Following the opening of an entrance, the sloping nature of these caves tends to favor the removal of clastic material through piping processes. In iron-rich rocks the cave-forming process is unequivocally linked to the genesis of the high-grade ore. The management of these caves thus involves a delicate balance between cave preservation and iron mining.

THE ALKALI SPELEOGENESIS OF RORAIMA SUR CAVE, VENEZUELA

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It has been known for almost two decades that microbial species can contribute to the formation of caves, although such activities generally occur through the production of acids within carbonate rock. Other processes of biogenic speleogenesis are less easy to explain, such of the formation of Roraima Sur Cave, Roraima Tepui, Venezuela. This 16.4 km long cave, formed within generally insoluble orthoquartzite contains a noticeable microbial population and unusual opal formations. While no current conditions within the cave suggest extreme acidity, we believe that microbial activity is leading to an increase in pH and silica dissolution. Empirical evidence suggests that ammonia is accumulating within the silica rock at sites of primary dissolution, which correlate with high levels of microbial activity within the cave. Numerous bacterial species isolated from the cave have demonstrated nitrogen fixation abilities, with a concurrent accumulation of ammonia within the media, suggesting that this is the source of possible alkaline conditions. Although nitrogen fixation is an energetically expensive process, we believe that microbial hydrogen oxidation and methanogenesis are generating the energy necessary to drive this process. Together these data suggest a microbially-driven alkaline-speleogenesis in the formation of Roraima Sur Cave.

1. Introduction

The Tepui Mountains of Venezuela are a spectacular range of isolated table mountains formed within the Matauí Formation (Briceno et al. 1990). The age of the Matauí Formation is still under debate, primarily due to the lack of zircon and other minerals that can be used for radiometric age determination. Nonetheless, it is known that it formed from arenitic sandstones of the Trans-Amazonian Mountains, which were deposited via braided fluvial, tidal and wave action into the same ancient basin that formed the Roraima Supergroup. Santos et al. (2003) noted that the Matauí Formation is separated from the Roraima Supergroup by a regional unconformity (the Capas de Abarén unit), that may represent the later development of a secondary basin. As a result, Santos et al. (2003) have estimated the age of the Matauí to be similar to the Serra Surucucus Formation, at 1552 ± 6 Ma. Subsequent metamorphosis led to the formation of the orthoquartzite massifs that currently represent the Matauí Formation, which varies from 200 – 850 m in thickness.

The orthoquartzite nature of the Matauí Formation makes it particularly resistant to dissolution, which is evident by the dramatic table mountains such as Auyan-tepui, Chimantá and Roraima Tepui, which often rise over 1000 m above the surrounding eroded terrain (Fig. 1). Yet these mountains are known for the large number of cave systems they contain, with 12 caves exceeding 1 km in length and 16 caves exceeding 200 m in depth (Auler 2003). Recently a cave was discovered in Roraima Tepui, a 32 km^2 massif of the Matauí Formation, located between the borders of Venezuela, Brazil and Guyana. This cave, originally named Sistema Roraima Sur by Venezuelan speleologists (also known as Sistema Ojos de Cristal), exceeds 16 km in length. During a recent reconnaissance expedition (2005), a high level of microbial activity was found within the cave, much higher than observed in other cave systems, despite the nutrient limitation and lack of soil on Roraima Tepui. We therefore decided to investigate whether there was a link between the high amount of microbial activity and the extreme length of this quartzite cave.

Figure 1: The Kukenan Tepui rises 1000 m above the Gran Sabana plain in Venezuela.

2. Materials and Methods

Small rock samples were collected from the ceiling of the cave in three locations, 30 m, 120 m and 500 m into the cave: Cricket Pool, Red River and Largo Grande, respectively. Water samples were also collected from the stream flowing through the cave near each sample location. These samples were analyzed in the field for pH, dissolved silica, ammonia and nitrate. Rock samples were analyzed for silica by adding 2 volumes of distilled water (pH 6.9; dissolved silica 0.0 ppm) to 1 volume of crushed rock (vol/vol). The sample was then shaken and the amount of dissolved silica (SiO_2) was assayed using a pocket colorimetric assay (Hach Company, Loveland, CO). Samples were also preserved in 4% paraformaldehyde for scanning electron microscopy (SEM). As a control, water and rock samples were collected from outside the cave.

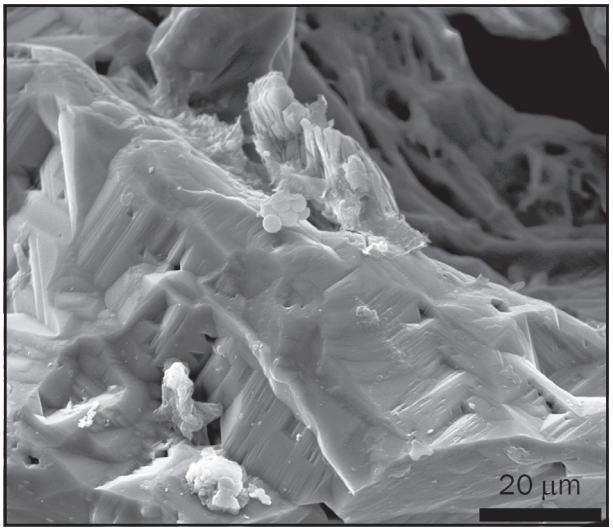

Figure 2: An SEM image of quartz sand grains taken from Roraima Sur Cave. The triangular-shaped pits are indicative of chemical weathering. A cluster of what appear to be bacterial cells is present in the upper-middle.

3. Results

For a long time speleologists have argued whether caves in the tepui mountains of Venezuela represent karst or psuedokarst; an argument based on the relative contributions of dissolution and erosion to the speleogenesis of this system (Wray 2003). To determine whether silica in the cave was being dissolved by chemical or physical weathering we used SEM analysis of quartz grains. The results (Fig. 2) clearly demonstrate the classic etch pits that are indicative of chemical weathering of quartz grains (physical weathering leads polishing of the grains) (Bennett and Siegel 1987). These data favor the role of dissolution in speleogenesis of Roraima Sur Cave.

Due to the stability of the Si-O bond, acidic silica dissolution only occurs under highly acidic conditions (pH 2), yet this same bond is susceptible to nucleophilic attack, allowing dissolution under more moderate alkaline conditions (pH 8.5). Within Roraima Sur Cave we did not find any geochemistry that could justify the presence of strongly acidic conditions. However, microbial activity can potentially raise local conditions above pH 8.5, by the production of ammonia (NH_3) or amines (NH_2). Given the large amount of microbial activity in the cave, we wondered if these species were able to locally alter the pH conditions, leading to quartz dissolution. To test this hypothesis, we examined the pH and dissolved silica concentration at each sample site within the cave, as well as control samples from the surface of the tepui (Table 1). As a control, the pH of the stream flowing along the floor of the cave near each sample site was also recorded.

While the surface stream pH was measured at pH 6.5 on the plateau, before this entered the cave system it flowed through a large amount of decaying plant material. This process causes the stream to pick up humic acids and become more acidic (pH 5.5), similar to its pH in Cricket Pool 30 m inside the cave. As this stream continued to flow through the cave, it became more acidic (to a pH 5.0), which also coincides with an increase in dissolved silica content (the saturation index of silica is ~15 ppm under these conditions (Wray 2003)). Nonetheless the pH remains well above the pH necessary for acidic dissolution of silica. No evidence of recent flooding (within the last 100+ years) was seen in the system, primarily through the decomposition state of dead animals in the cave (a near complete quadamundi skeleton was seen ~1 m above base level suggesting that flooding events within the cave are rare).

	Stream			**Rock**	
Sample	pH	Dissolved silica		pH	Dissolved silica
Surface	6.50	2 ppm		6.87	5 ppm
Cricket Pool	5.56	4 ppm		7.01	72 ppm
Red River	5.10	6 ppm		7.16	88 ppm
Largo Grande	4.97	15 ppm		7.68	64 ppm

Table 1: pH and dissolved silica present in surface samples and at each sampling site within Roraima Sur Cave

	Stream			Rock	
Sample	Ammonia	Nitrate		Ammonia	Nitrate
Surface	0.00 ppm	0.00 ppm		0.00 ppm	0.00 ppm
Cricket Pool	0.00 ppm	0.00 ppm		~ 0.25 ppm	~ 0.25 ppm
Red River	0.00 ppm	0.00 ppm		~ 0.25 ppm	~ 0.25 ppm
Largo Grande	0.00 ppm	0.00 ppm		~ 0.25 ppm	~ 0.25 ppm

Table 2: Ammonia and nitrate from surface samples and at each sampling site within Roraima Sur Cave

While dissolved silica increased slowly in the stream (to 15 ppm), there was a remarkable amount of mobilized silica in the rock (Table 1), especially when compared to surface rocks (5 ppm) and exceeding the SI of silica. Our rudimentary pH measurement also indicates that as the sample sites become further from the entrance, the pH of these samples increases. While this number again does not reach the basic conditions necessary for dissolution, they are within 0.82 pH units of reaching the solubility threshold for silica. To determine if microbial activity was responsible for this dissolution, we cultivated ~500 bacterial species on low nitrogen (5 mM) media containing silica from the three sites. Of these isolates, a large number (83%) belonged to genera known to be either involved in nitrogen fixation or nitrogen cycling within the environment (ammonia oxidation, nitrate reduction, etc). When a selection of these species were grown in a media containing amino acids, an *Arthrobacter sp.* isolate demonstrated hyper-ammonia production, significantly increasing the pH of the surrounding media. Therefore, to determine whether ammonia and nitrate played a role in the geochemistry, we measured the ammonia and nitrate levels at each sample site (Table 2). Although the field measurement techniques were crude, ammonia and nitrate were only found in the cave locations where dissolved silica levels were also high. Due to the nitrogen starved nature of the tepui environment, the ammonia detected is derived from microbial nitrogen fixation.

4. Discussion

Current theories on the development of caves within silicate rocks are based on arenization, wherein dissolution plays a critical role in the process of speleogenesis by removing the cements between quartz grains (Martini 1979). Erosion of this loosened material by surface streams then leads to the formation of cavities and enlargement to produce the cave systems, although the relative contribution of each to speleogenesis in silicate rocks remains controversial (Aubrecht et al. 2008; Wray 2003). Our results suggest that microbial activity may be involved in the initial dissolution of these silica cements in the orthoquartzites of the Matauí Formation.

While nitrogen fixation by bacteria leads to the generation of ammonia, the high energetic cost of acquiring this substrate means that it would be tightly regulated by the cell. Nonetheless, some nitrogen fixing bacteria produce amino acids to balance oxidative stress (González-López, et al. 2005) on aromatic carbon sources. The consumption of these amino acids by other bacteria (such as the *Arthrobacter* isolate we obtained) will also cause ammonia to be excreted into the environment, further increasing pH. A more detailed molecular phylogenetic analysis of the microbial community found at each site confirms both the presence of nitrogen fixing bacteria and an active nitrogen cycle that includes ammonia oxidizing bacteria and archaea (see Giarrizzo, these Proceedings).

The decrease in pH of the stream as it flows through the system is also of interest. The water on the surface of the tepui has a slightly acidic pH (6.5), which decreases as the water flows through decaying plant matter. This material contains an excess of soluble humic acids produced by the microbial degradation, which are normally removed by the

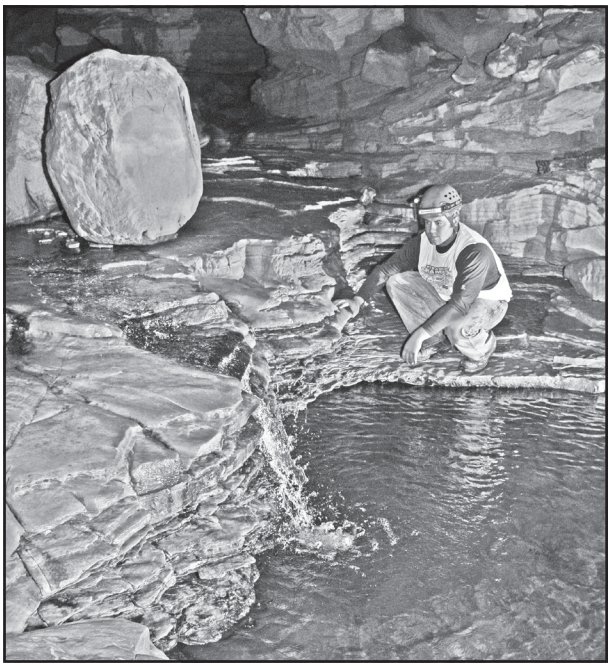

Figure 3: In areas of active stream flow, smoothing of the rock demonstrates the humic-acid dissolution process.

absorptive properties of soil (Kirk 2004). In the absence of soil these humic acids remain in solution and give the water of the tepuis their distinctive amber-brown coloration. Humic acid, due to its multifunctional organic structure, has been shown to chemically erode quartz in groundwater (Bennett and Siegel 1987). Our results suggest that as this humic acid-rich water travels through the cave, it mobilizes silica from the streambed, deprotonating the humic acid and increasing the amount of dissolved silica (Vandevivere et al. 1994). An important role for dissolution by the stream is seen by the smoothing and rounding of the streambed throughout the cave (Fig. 3). In areas of more turbulent flow, an aerosol of these silica-rich organic material is created, which is presumably the source of the opal and chalcedony formations seen in the cave.

While the organic etching of these caves by humic acids likely plays a significant role once speleogenesis has begun, it does not account for the breakdown of the orthoquartzite to the much more friable sands seen throughout Roraima Sur Cave. This breakdown is particularly prominent in areas with active microbial activity (Fig. 4), where it is possible to push a pencil many cm into the rock. These loose areas still overlay orthoquartzite, with a gradual transition to the harder rock. Due to the instability of the Si-O bond to nucleophilic attack, especially by amines, subaerial microbial weathering can be proceeding at a rate many times greater than humic dissolution (Bennett and Siegel 1987; Hiebert and Bennett 1992; Icenhower and Dove, 2000). While the effect we observed is only sufficient to raise the pH of the rock by <1 pH value, microbial species can induce local or ion effects that dramatically increase the microenvironment surrounding the cell (Bennett and Siegel 1987; Hiebert and Bennett 1992; Vandevivere et al. 1994).

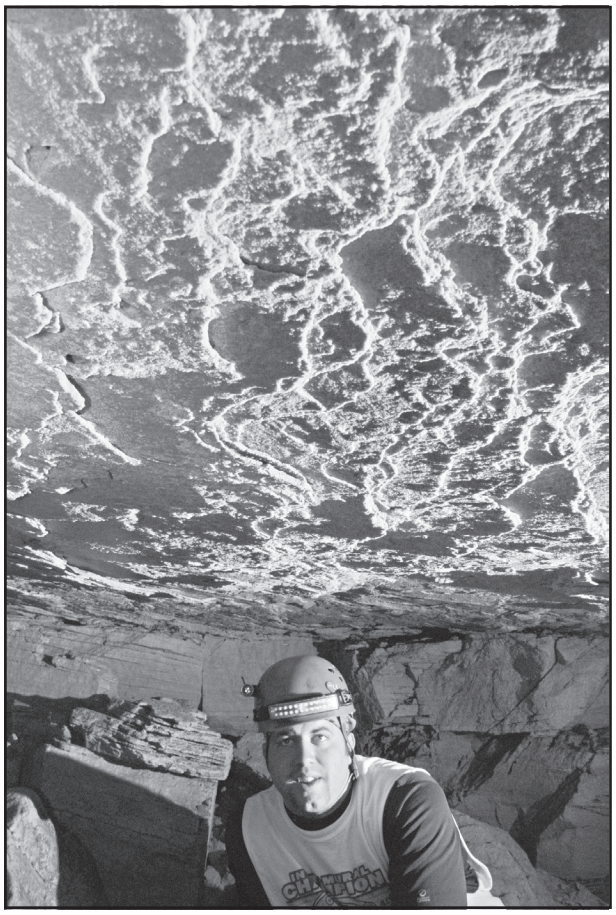

Figure 4: In areas of active microbial activity, the orthoquartzite is continually degraded to a loose sand-like consistency.

Given these findings, we therefore propose an adaption to the arenitization model by (Martini 1979) for the speleogenesis for the tepui caves of Venezuela. In this model (Fig. 5), microbial activity in orthoquartzite beds leads to the production of ammonia and amines. This leads to a local change in pH and dissolution of the silica cements between the quartz grains, increasing the porosity of the deposit. Eventually meteoric water, rich in humic acids, can enter and lead to the formation of an open conduit. Microbial activity continues to degrade the silica cements of the orthoquartzite, weakening the integrity of the rock on the walls and ceiling. Flood events or stoping may then erode these layers, dramatically increasing the size of the cavity. Eventually the cavity becomes large enough that only down-cutting by humic-rich water continues speleogenesis. Whether this hypothesis is correct requires additional examination of the geology, microbial activity and geochemistry of these remarkable cave environments.

Acknowledgments

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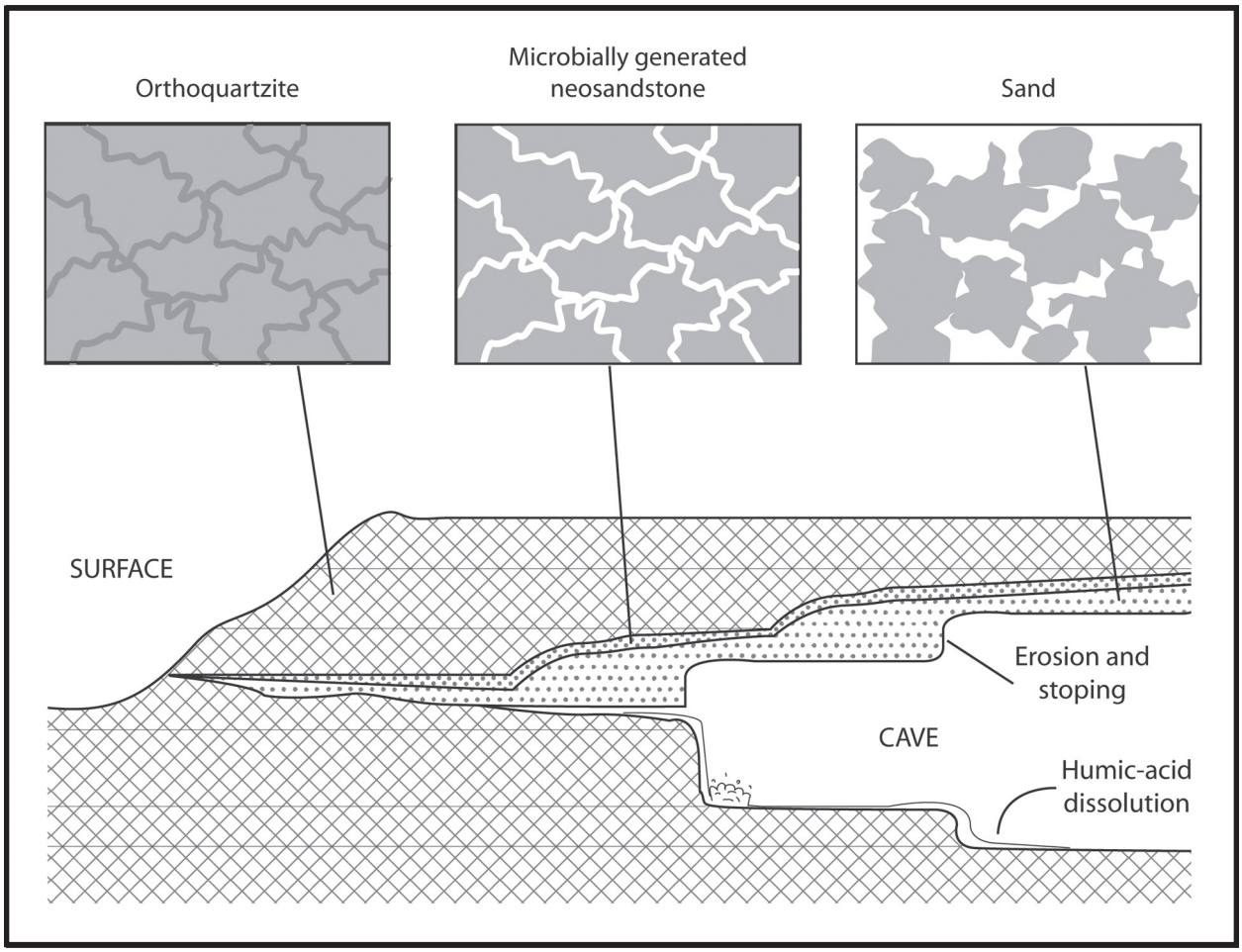

Figure 5: Model for the microbially influenced speleogenesis of Venezuelan tepui caves. Microbial metabolic activity leads to the dissolution of the silica cements of the orthoquartzite. This dissolution leads to a loss of structural integrity of the orthoquartzite and the production of neosandstones and sand. The increase in porosity allows the entry of humic acid-rich surface waters, which chelate silica and lead to cavern enlargement through dissolution. The cave continues to increase in size as the loose material is removed by erosion and stoping events. In very large systems, humic acid dissolution becomes the primary mechanism of cavern enlargement (adapted from Martini 2003).

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RELATIONS BETWEEN SPELEOGENESIS AND SURFACE MORPHOGENESIS OF AN EXHUMED KARST PLAIN (THE SLUNJ KARST PLAIN, DINARIC KARST, CROATIA)

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The Slunj karst plain is developed in Mesozoic carbonate rocks. In some places they are covered with Neogene clastic lacustrine sediments, usually occurring as denudational remnants. Initially, Neogene sediments covered most of the plain and a well developed drainage system formed. After erosion of the Neogene sediments, the Mesozoic carbonate rocks were exhumed and karstification led to disorganization of the surface drainage. In such conditions many ponors and associated caves developed. At first cave genesis was mainly lateral, as phreatic tubes and/or as vadose canyons. Change of the stress direction in the neotectonic phase led to the genesis of pull-apart basins and hills with a pop-up structure. Because of the neotectonic uplift of pop-up structures, some lateral cave channels were abandoned and new vertical shafts started to develop. These shafts represent the youngest speleogenesis phase. This paper compares the development of the underground and surface features.

1. Introduction, Geologic and Geomorphologic Settings

The research area is situated in the framework of the Dinaric mountain system next to the Pannonian Basin. It has an area of 336 km^2, and is a part of a larger area called the Karlovac karst plain, which extends to Slovenia in the south-west and to Bosnia and Herzegovina in the south-east (Fig. 1). The largest part of the area is made of more or less permeable, karstified, carbonate deposits of Mesozoic age (from Middle Triassic dolomites to Upper Cretaceous limestone). Only a small part of the research area is made of the oldest rocks, Permian sandstones (Korolija et al. 1979, 1981; Polšak et al. 1976 1981). Miocene lacustrine deposits are preserved only in tectonic downwarps or as smaller denudation remnants on the plain. In a structural sense the area represents a series of structures and faults of mainly Dinaric direction, but with a marked bending of fault lines caused by a change in stress orientation. The result is that there are sequences of pop-up and pull-apart structures in the plain. The lowest height above sea-level is 196 m, and the highest is 658 m. The average altitude of the area is 353 m. A change in the stress direction has caused a prominent right horizontal component of the fault movement, as well as the development of most of the secondary morphostructures, because of the change to a new tectonic regime. Recent active faults have a significant effect on the landscape forming steep steps and escarpments, elbow-like valley bends and linear sections of active and dry valleys. Karst and fluviokarst morphogenetic types are the most represented exogenous processes and forms. The most significant surface karst forms are dolines, grikes, residual hills and shallow uvalas. Areal and contact fluviokarst processes and forms have been found. Dry ponor valleys and active canyon sections of the Korana and Slunjčica River valleys are especially prominent among them. The karst plain is the most spacious and probably oldest relief form of this area. Fluvial and fluvio-denudational processes highly influenced the karstification processes of the Slunj Plain, because the Korana River represents the erosion base-level for a large part of this area.

Many scientists have written about the relief development in the Dinaric karst plains: e.g., Cvijić 1921; Roglić 1951, 1957; Gams 1986, 2001; Herak 1986; Bahun (1990); Mihevc (2007) and others. Garašić (1984, 1991a) worked out the speleogenetic problems of this area several times; Bočić (2003a, 2003b), Bočić et al.. (2003), Bočić and Baćurin (2004) and Bočić (2009) researched the relation between speleomorphology and the surface landscape. Data about caves are collected from field explorations and the published and unpublished results of many speleological explorations of this area (e.g., Poljak 1914; SDH 1965; Čepelak, R. 1965; Čepelak, M. 1983; Božić 1973; Garašić 1984, 1987; Jelinić 1998; Kuhta 2001; Baćurin et al. 2004; Bočić & Baćurin 2006;

2. Speleomorphologic Characteristics

Data from about 103 caves of the Slunj Plain have been used in this study. Out of 101 caves (data are not available for two of them), 75 are horizontal and 26 are pits. A great part of the horizontal caves (almost 75%) support the fact that lateral circulation of the underground water played a dominant role in the speleogenesis of the known caves, while gravitational recharge through the vadose zone had

Figure 1: *Location of the research area.*

a dominant role for a smaller number of caves (pits, about 25%).

In the Slunj Plain most caves are simple (69 %), while branchwork caves (20%) are also significant. Only 2% are caves with distinct levels, 7% are "knee-shaped" with alternating horizontal and vertical sections, and 2% are cave systems composed of two or more connected caves. Consequently, in the Slunj Plain simple caves dominate, most probably they are parts of larger active and fossil underground karst conduits (White and White 2003). A preponderance of one morphologic type points to relatively homogenous speleogenetic conditions, which is different from the representation of morphologic types in the whole karst area of Croatia (Garašić 1991), where heterogeneity of speleogenetic conditions is more prominent, as well as a greater representation of the knee-like type connected chiefly with pits. The cave system Panjkov ponor–Varićakova, 12,385 m long, is the longest in the study area. At the same time it is the second longest cave in Croatia (after the cave system Đulin ponor-Medvedica, 16,396 m long). Except for this system, there are two more caves longer than 2,000 m in the study area, then two caves longer than 1,000 m, six longer than 500 m, 17 caves longer than 100 m, while other caves are shorter than 100 m (51 caves). By considering of length of 79 caves (there are no information for other caves) the total length of all known caves of the Slunj Plain is 28,906.5 m. The average length of a particular cave is 365.9 m, consequently, the density of the cave passages is 85.9 m/km^2. If we take into consideration only the area of developed karst and fluviokarst relief (278.4 km^2), the density of the known cave passages is

103.8 m/km^2. The average length of a single cave, calculated without the length of the Panjkov ponor-Varićakova cave (because its length significantly stands out from the other caves' length) is 211.8 m, which points to a high degree of speleogenesis. In the continuation of the Slunj Plain in Bosnia and Herzegovina, at the edge of the study area, there are some more caves. They are: the cave Runica, 1,052 m long, then the cave Gatica (1,195 m), and the cave Šarićeva, 1,378 m long (Garašić 1991b). Data about those caves were not considered in this analysis. The deepest caves in the study area are: Volovska jama (129 m deep), Kojina jama (109 m) and Kunina jama (103 m), then Barićeva špilja (102 m). They are, at the same time, the only caves in the Slunj Plain deeper than 100 m. Out of the available data about the depth of 29 caves in this area (mainly pits) the average depth of 38 m was calculated. These data point to the fact that the depth of the caves in the Slunj Plain is relatively small in relation to the depths in other parts of the Croatian karst (the deepest is the pit system Lukina jama-Trojama, 1,392 m deep). However, compared with the other parts of the shallow, so called Kordun karst, the Slunj Plain has somewhat deeper caves, so the Volovska jama is the deepest known cave in the Kordun karst. The entrances of the caves range in altitude from 210 to 550 m high (Fig. 2). The relationship between the individual caves and their heights above sea level is fairly linear, except for a somewhat smaller number of caves between 400 and 450 m. More significant differences are observed when their depths are plotted (i.e., the heights above sea-level of the deepest points). It appears that greater depths are characteristic of the caves at higher elevations, and the elevations of the deep points increase with the heights of entrances.

Certain conclusions about this area's speleogenesis can be made on the basis of morphologic data and field studies. Speleogenesis developed at several stages. At the first stage it was conditioned by lateral movement of the underground water. Channels developed in phreatic tubes and shallow vadose canyon passages, and speleogenesis developed mostly in length. Neotectonic uplift played a very important role. It

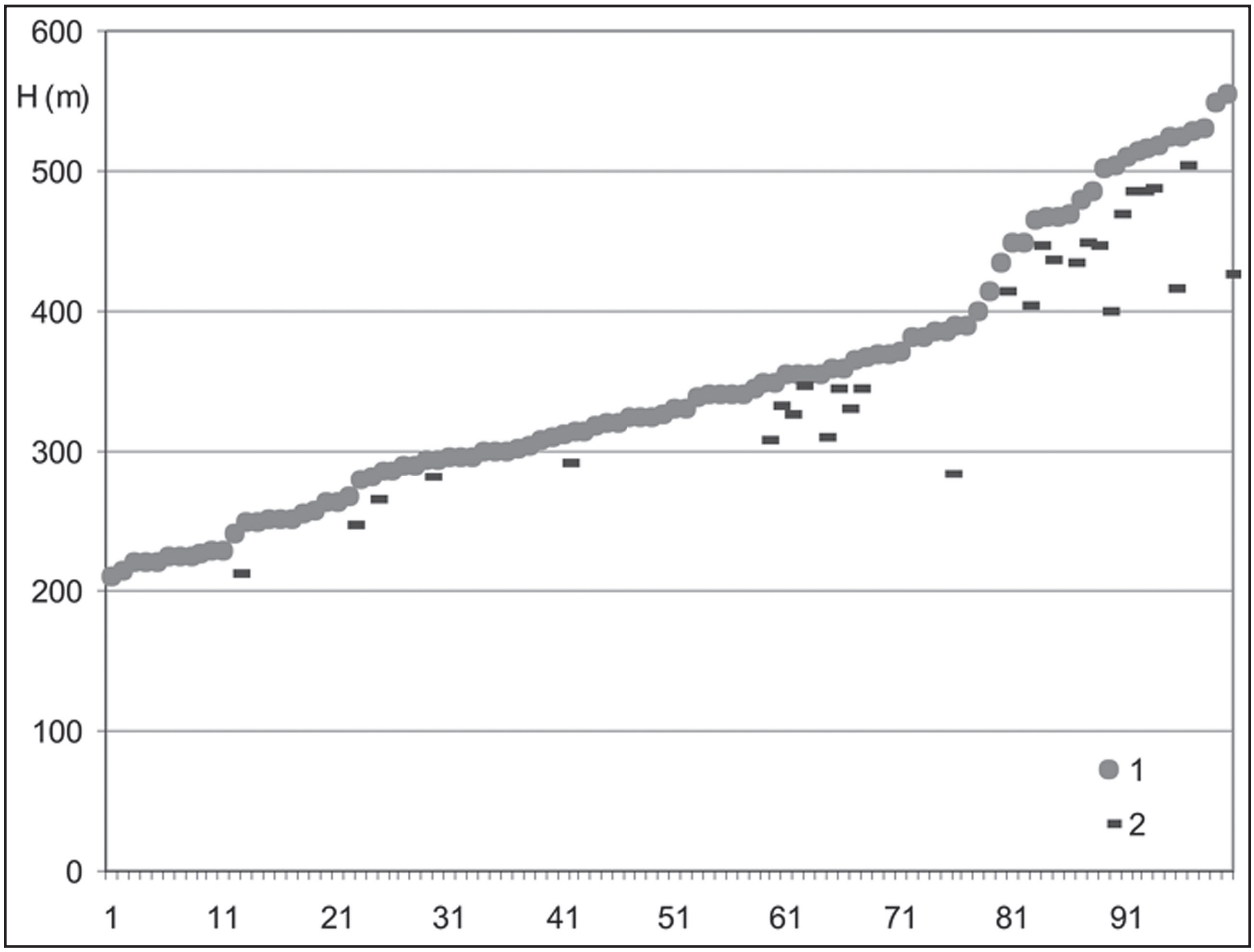

Figure 2: *Plot of cave entrance elevations (1) sorted by elevation above sea level (dots), and (2) elevations of lowest points in caves (rectangles), plotted directly beneath their corresponding entrance points. Most caves are too shallow for their deep points to be distinguished on the graph.*

caused the emergence of increasingly low and young levels, so the phreatic channels, which had found themselves in the vadose zone, cut keyhole-shaped cross sections. In the uplifted zones lateral circulation was changed by vertical circulation of the underground water, which created relatively younger vertical vadose channels.

3. Discussion – Relations Between Speleogenesis and Surface Morphogenesis

In the Mesozoic, carbonate platform sedimentation dominated in this area. At the end of the Cretaceous, this sedimentation ceased, and the area was eroded to a plain. By the end of the Cretaceous and at the beginning of the Palaeogene, tectonic movement occurred during the Laramian orogenetic phase. Under its influence particular parts of the carbonate platform were uplifted exposing them to exogenous processes. Those processes could have lasted until the Middle Eocene. During the Pyrenean orogenic stage (Upper Eocene – Lower Oligocene), Cretaceous carbonate rocks were thrust over Eocene flysch deposits. Those processes probably caused a partial destruction of the past exogenous activity, but they also caused new strong exogenous processes, which probably lasted until the Middle Miocene. In that period of approximately 20 million years there was intense karst denudation. The karst plain could have developed in that period. The occurrence of Neogene bauxites in other parts of the plain also point to karst denudation (Šinkovec et al. 1985). One can presume that it was one of the final stages of the karst plain formation, which was afterward, according to Bahun (1990), for the most part covered by the Middle Miocene lacustrine clastics. Middle Miocene clastics were deposited during a transgression over the karsted bedrock (Kranjec and Prelogović 1974). During Middle Miocene lacustrine sedimentation, exogenous processes were interrupted. After repeated uplift, a dense fluvial network was developed on the lacustrine clastics. That network determined fluvio-denudation and fluvial characteristics of that period landscape. Primarily erosion and slope processes dominated in that area, and they led to thinning, and partially to complete denudation of the Middle Miocene clastics. That exposed the carbonate bedrock, so karstification could be activated again. During that process a network of valleys also developed on the carbonate bedrock. Gradually, the valleys on carbonates lost their flow to caves. In that way the post-Miocene speleogenetic processes were activated. Emergence of underground space was probably connected with earlier karstification stages, but such traces have not been discovered yet. The border between karst and non-karst areas migrated retroactively because of denudation, so the karst area grew with time. During the Pliocene there was again a shorter lacustrine stage. Until the end of the Pliocene, speleogenesis developed mainly in the phreatic zone (because of its high position near the land surface). Cave channels most probably started to develop laterally, along the privileged directions of the underground flowing. Input of water into the underground was primarily determined by the position of the carbonate-caprock contact. Channels developed in phreatic and shallow vadose conditions (canyon channels) and speleogenesis proceeded mostly longitudinally. The underground waters, as well as speleogenesis, were directed toward the intermediate layer and tectonic fractures, especially faults. The cave Kojina jama is among the most prominent examples. Its position and interior morphology point to the dominant impact of faults on cave genesis.

Neotectonic movements were intensively revived by the end of the Pliocene (Prelogović 1975; Velić et al.. 1982), and they were accompanied by the stress orientation change from the direction northwest–southeasst to the north–south. There was the activation of older faults of the Dinaric orientation, but with a prevailing right horizontal shift component. The stress orientation change caused bending of the fault routes and emergence of local compression and extension regimes. They led to the creation of pop-up and pull-apart structures, i. e., forming positive and negative morphostructures in the framework of the plain. Besides the bending of the longitudinal fault lines, there was also activation of diagonal faults and structure rotation. Neotectonic uplift caused an intensified denudation of positive morphostructures, and neotectonic lowering protected the basin bottoms from denudation, so there are now well-preserved remnants of the Miocene clastics with a developed surface drainage network (e. g. Kršlja basin). Tectonic lowering also caused cutting of favorable underground water flows, so springs developed (Bahun and Fritz 1987), and ponors could develop in basins (e. g., Panjkova and Varićakova caves in the Kršlja basin). Because of exhumation, more and more plain area was exposed to karstification, with sinking streams and the emergence of more dry inactive valleys, which were transformed into relict valleys owing to karstification. Uplift of particular blocks caused development of more cave levels. Except in the phreatic and subphreatic zones, more vadose cave development occurred, leading to canyons and keyhole-shaped cross sections. Neotectonic uplift of the whole plain, probably during the Pleistocene, caused the Korana River flow to downcut 50 m below the surrounding plain. In that way the relief of the Slunj Plain was finally formed. It is primarily characterized by a planated surface with dolines and a fragmented network of dry and relict valleys with

residual hills. Streams and fluvial erosion were preserved on the down-dropped morphostructures (e.g., Kršljanska basin).On the uplifted morphostructures, karst denudation intensified, and the underground flow was gravitationally directed into the vadose zone. As a consequence, the development of the youngest underground channels are vertical. They cut the older phreatic channels, which became uplifted and inactive. New channels developed, mainly along younger fissure zones, which had developed as the consequence of the stress change, i. e., adaptation of geologic structures to a new stress orientation. The old passages were filled with speleothems and undissolved residual material (e. g., at Kunina jama). In the Mašvina region many relatively deep pits formed.. Several generations of huge collapsed dripstones in the Kojina jama are the result of tectonic movement. Lowering of the erosional base-level produced dolines and shallow pits in the plain. The terrain, lowering under the influence of karst denudation, cut into caves, which created secondary entrances (e. g., Kojina jama, Jama Davorinka) and partially or completely destroyed others. The final destruction of some caves has been noticed in the Mašvina region (e. g. the caves RI-M2, RI-M3). In the Slunj Plain there has recently been neotectonic uplift and intensive karst denudation, which causes seasonal sinking of the main river in this area, the Korana River, in its upper reaches. Parallel with karst denudation on the surface, complex speleogenetic processes are occurring underground.

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HOW CAN GHOST ROCKS HELP IN KARST DEVELOPMENT?

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For several years, numerous examples of ghost rocks have been described in Belgium and in France. They correspond to decalcified pockets but also include big weathered networks of soft alterite. This phenomenon is present in several different geological and geomorphic contexts. These features illustrate one step in the geological history of the area, and their genesis implies certain geological, hydrological and morphological conditions. Exploration of mines allows us to study many examples of ghost rocks, linked or not with mineralization. At the top of the alterite we have found a thick level of laminated sediments that shows the existence of previous water circulation in the gap between the ghost rock and the vaulted roof. In some places the alterite has been progressively removed by seepage, to form little rooms. In one mine, large karstic galleries have reused old weathered sections and eroded the initial ghost rocks. These examples show how the formation of ghost rocks prepares some carbonate plateaus for more "classical" karstification by forming gaps that can be used by underground water flow. Hydrogeological systems can expand quickly and extend their catchment areas by utilizing these discontinuities.

1. Introduction

Researches of Belgian geologists have shown the existence of a special karstification: the ghost rock (Vergari and Quinif 1997; Vergari 1998). Many examples are now well known all around the world (Schmidt 1974; Häuselmann and Tognini 2005; Martini 1985; Tognini 2001; Willems 2002), in different rocks, carbonates or not, and in several geological and geomorphic contexts. We have also found and studied some of them in France (Bruxelles 2004). In this paper, we want to describe different examples and to show some links between ghost rocks and classical karstification.

2. Ghost Rock Formation

Ghost rocks consist of soft and clayey materials situated within the rock. They can appear in different ways. Sometimes they involve large surfaces, like those in the Hainaut Province (Belgium), but they can occupy pockets, big and small, or in corridors between two walls of competent rock. At first glance they look like classical karstic fillings with allochthonous sediments. But if we take a closer look, we note that we can follow the original stratification of the rock from one wall to the other, through the soft material (Fig. 1). Lithologic features, such as fossils, joints, and sylolites, can be recognized inside this material.

Figure 1: Ghost rock cut by a quarry in Belgium. Horizontal stylolites can be followed from the safe limestone trough the alterite.

Ghost rock is an isovolumic alteration that occurs by disappearance of soluble components and conservation *in situ* of less-soluble materials (sparitic calcite, siliceous framework, dolomite, etc.). In addition, some clays have formed *in situ* by neogenesis. Contrary to "classic karst," the volume initially created by dissolution is distributed as pores in the whole of the alterite (Quinif 1999). It is formed by very slow percolation of water, which penetrates into the rock by fractures and carries the aggressiveness to depth. As the drainage is very slow, there is no possibility of exporting the residual material. This change takes place from the surface, *per descendum*, in a context of weak hydraulic gradient and extensive fracturing. In this case, ghost

rocks are formed in a context of low relief and low erosive energy. Recently, ghost rocks have also been discovered in association with mineralizations in southern France (Bruxelles and Wienin, in press) and undoubtedly have a hypogenic origin.

The weathered parts are organized into a network of corridors from tens to several hundred meters long. They can coalesce and, in the case of big ghosts, form some huge volumes of alterite that can reach more than one hundred meters below the surface. At further depth, this type of structure extends into pseudo-endokarst, with features that look like filled galleries beneath a competent calcareous roof (Fig. 2). Nevertheless, this conduit was never empty and the filling consists of the alterite (Vergari 1998). The origin and development of the pseudo-endokarsts are still poorly understood. They imply reactions of oxidation-reduction (sulfides, organic matter), migration of silica and carbonates, and also maybe bacterial action. The pseudo-endokarst may achieve complex forms, often labyrinthine, guided over large distances by faults and joints.

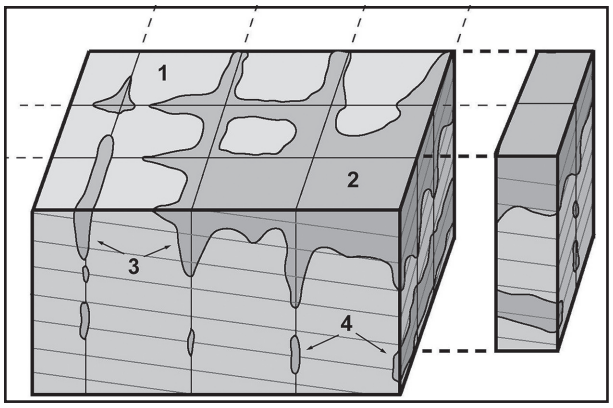

Figure 2: Schematic diagram showing the different types of ghost rocks. 1 – competent rock; 2 – large area of ghost rocks, with overlying voids formed by compaction of the alterite; 3 – pockets and corridors developed along discontinuities and fractures; 4 – ghost rocks under a secure roof : the pseudo-endokarst.

Therefore, we can distinguish several different kinds of ghost rock (Fig. 2): (a) large areas of ghost rocks, above which depressions are formed by compaction of the alterite; (b) farther down, many pockets along discontinuities and fractures; and (c) in some places, ghost rocks beneath a competent roof: the pseudo-endokarst..

3. Some Examples of Underground Ghost Rocks

One of the well known examples of pseudo-endokarst, the "Pic à Glace," was described in Belgium by Anne Vergari (1998). This example is surprising because it looks like a classic cave section, some kind of meander, with various levels of detrital fill. We can even recognize the wall features, with projecting shelves that could represent different stages of excavation by an underground stream. But study reveals that, in fact, the filling is not allochtonous sediment. The best demonstration is that we can follow several chert beds from one wall to the other across the soft material. This is an example of ghost rock formed under a limestone roof. This cave had never been empty, and there was never an underground river in this cave. The wall features correspond to differential weathering of the limestone. The geometry of the alterite is also interesting. The different levels show a concavity more and more pronounced from the bottom toward the roof of the section. It is due to the removal of part of the limestone by weathering, which provoked the compaction of the alterite.

In France, we also have many examples of ghost rocks (Rodet 1996; Courrèges 1997 and Bruxelles 2004). Some of them in the Grands Causse are spectacular. They are developed in limestone with chert, but also in dolomite. This weathering has produced clays with flint or dolomitic sand that cover part of the plateau and contribute to crypto-corrosion (Fig. 3). In the Cévennes (south of the French Massif Central), there are many mines in lead, zinc, and iron ores. They are excavated in dolomite and limestone but, in many areas, they have intersected what was once thought to be karstic fillings (Fig. 4). But we can recognize the stratigraphy of the initial rocks by the presence of sandy levels with chert fragments from the dolomite, and clayey zones from the limestone. We can even see some mineralized veins, initially formed in the limestone, and now preserved in the alterite (Fig. 4A).

Figure 3: Section in the Bajocian cherty limestone in the Grands Causses (France). We can recognize pockets of clay with chert (dark grey formation), but also pseudo-endokarst under a roof of competent limestone.

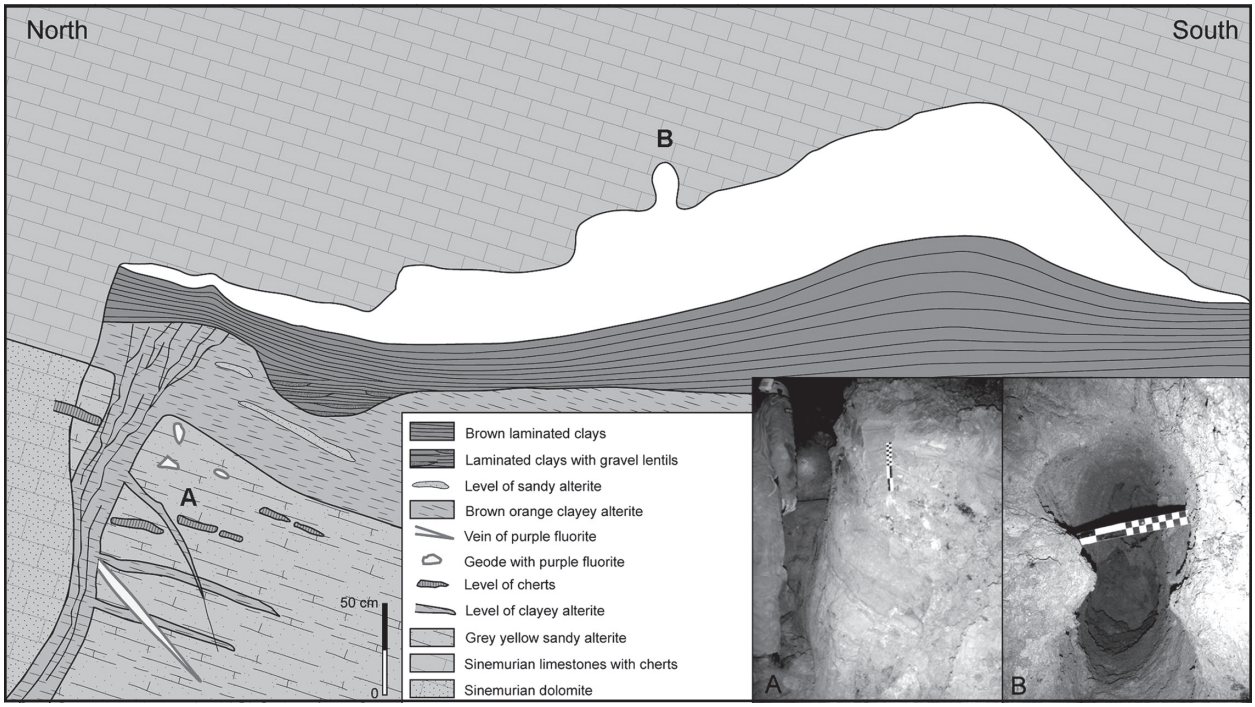

Figure 4: Section of the East gallery of the mine of La Grande Vernissière (South of France) showing the link between weathering and classic karstification. A: Fluorite mineralization in the ghost rock; B: Classic karst feature.

4. Links Between Ghost Rocks and Karstification

We have seen before that the different levels of alterite within the pseudo-endokarst show an increasing concavity from the bottom toward the roof of the section. This is a very important point because this process creates a space between the ghost rock and the roof that can be used later by a stream of water. This is the case in the pseudo-endokarst of the "Pic à Glace" in Belgium, and also in the mine we have studied in the Cévennes (La Grande Vernissière, Fressac; Bruxelles and Wienin, in press).

In the eastern gallery of this mine, between the ghost rock and the roof, we have identified 10-30 cm of laminated clays (Fig. 4). There is an erosional unconformity between the alterite and the laminated clays, and we can clearly see sedimentary features that indicate the circulation of water. The void between the alterite and the roof was used by an underground stream. The top of the ghost rocks was first eroded before deposition of the clayey layers. At the roof, we notice some karstic features that can be linked to this process (Fig. 4B). So, by this example, we can see that compaction creates a discontinuity which can be used by "classic" karstification.

In the same mine, in several places, the artificial gallery has cut the bottom of a pseudo-endokarst. This opening permits removal of the alterite by creating an exit for dripping water (Fig. 5). Since the excavation of the mine about 20 years ago, a void nearly 5 m high has formed and continues to grow each year. Soft alterite is very susceptible to erosion, and the appearance of a new hydraulic gradient, different from the one that led the weathering, provoked the hollowing-out of the pseudo-endokarst.

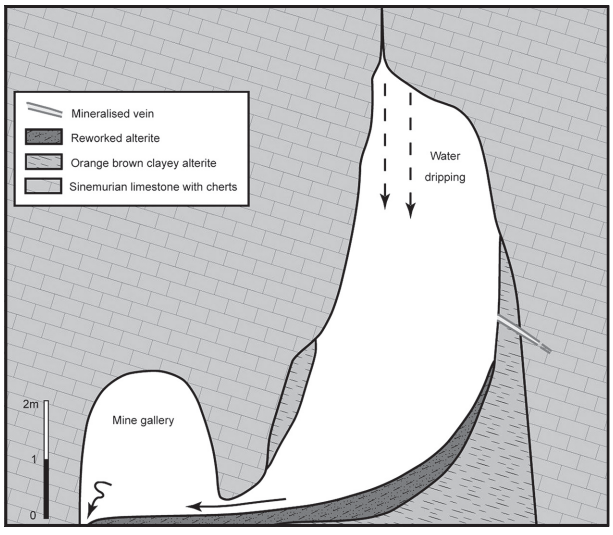

Figure 5: Schematic section of a vertical pocket. Ghost rock has partially eroded since the opening of the mine.

In Belgian quarries we can observe the same phenomenon on another scale. During excavation of the limestone, much pseudo-endokarst has been intersected. As the quarries are situated below base level, many springs have appeared on top of the alterite. With time, these springs became larger and began to erode the ghost rocks. Caves could form within a few weeks, some of them of explorable size. They look like big meanders and become larger each day because of the erosion of the alterite by the new underground streams.

Another important point is that if we draw a map of the pseudo-endokarst, we can see that they constitute a real network with several ghost rocks interconnected. In fact, all the tensional fractures present during the weathering were affected (generally in two directions). As in the examples of Belgian quarries, during the uplift of a region or the entrenchment of a valley, the hydraulic gradient becomes steeper. The presence of pseudo-endokarsts introduces an important discontinuity that is exploited preferentially by underground streams. From the spring, headward erosion permits the emptying of the alterite and the quick extent of the catchment area inside the plateau (Fig. 6). It can be responsible of the formation of some labyrinthine caves, with a high density of big galleries, like the Trabuc Cave (Cévennes, France).

On the French Grands Causses Plateau, entrenchment of canyons has permitted the appearance of some powerful karst springs. In the weathered dolomite, headward erosion removes the dolomitic sand and empties the highest joints. By this way, the catchment areas of springs can grow quickly throughout the plateau. On the surface, many pits appear and lead to the removal of the alterite by underground streams (Fig. 5). At this time, many sinkholes open regularly. The catchment area of the Durzon spring, for example, is capturing the catchment area of other springs that have drained this part of the plateau for a long time (Bruxelles 2004). This process is leading to destruction of old horizontal morphologies and development of the most typical landscape of the Grands Causses: the tower-like mega-lapiaz.

5. Conclusion

Ghost rocks are a special case of karstification formed *per descendum*, but also *per ascensum* in association with hypogenic circulation. Instead of forming a single void, they consist of porous alterite that retains the original shape and volume of the original rock. Pseudo-endokarsts can form an interconnected network that promotes the development of the future karst. When a new hydraulic gradient appears, springs are formed and permit the erosion of the alterite. Parts of the weathered networks are progressively emptied. Benefiting from the existence of these discontinuities, the catchment areas of these springs can expand quickly. Re-use of pseudo-endokarst by underground streams result in classic karst morphologies, provokes drainage reorganization, and introduces, for the first time, allochtonous sediment.

This process of cave genesis should make us have another look at some of our classical cavities. It can also provide new interpretations concerning karstic morphologies and the functioning of underground streams. Furthermore, the

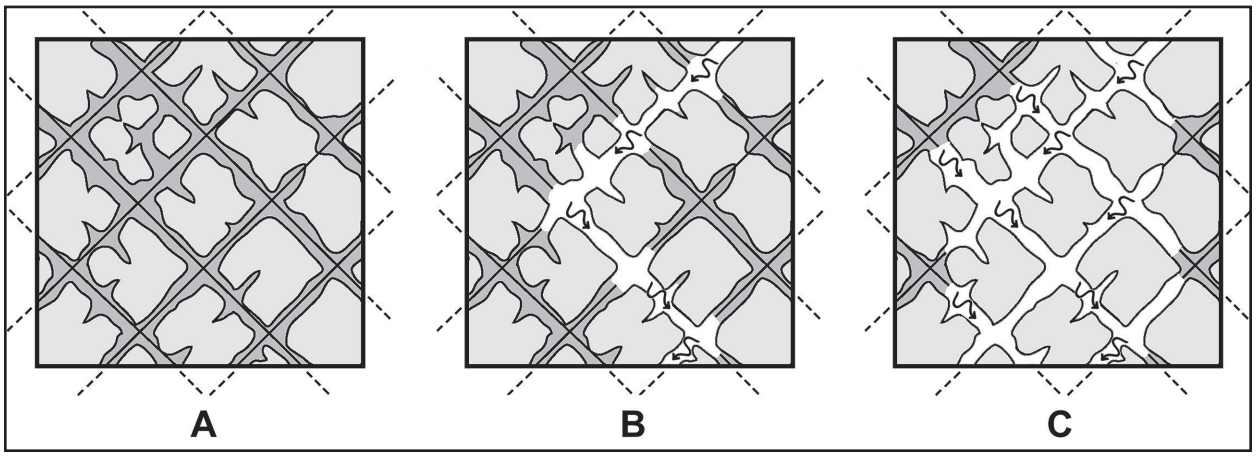

Figure 6: Schematic diagram of evolution from a pseudo-endokarst to a "classic" karst. A - Pseudo-endokarsts are interconnected along the tectonic network exploited by the weathering. There is not enough energy to evacuate the alterite; B - Uplift or valley entrenchment increases the hydraulic gradient. The underground drainage exploits the ghosts and removes the alterite by headward erosion; C – The catchment area of the spring spreads quickly and allows a network of galleries to appear.

discovery of ghost rocks in a karstic area can help assess the risk of collapse and protect groundwater resources.

Acknowledgments

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EVOLUTION OF PORTUGUESE KARST REGIONS IN A BASIN-INVERSION SETTING: IMPORTANCE OF FAULTING AND CONFINEMENT ON CAVE DEVELOPMENT AND SPRING LOCATIONS

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The Mesozoic extensional break-up of the Iberian Variscan belt produced the Lusitanian basin, which was inverted during the Cenozoic. Late Variscan faults were then reactivated as frontal or lateral ramps in a transpressional regime. The resulting uplift produced the Estremenho Massif, in which Jurassic limestone forms three elevated areas separated by grabens with the structural trends NW-SE and NNE-SSW. On the south, the plateaus and sierras are bounded by a NE-SW thrust. This is the Portuguese main karstic area, which includes the most important caves, karst springs and poljes. Extensive speleogenesis is associated with poljes and border faults, where caves reach lengths on the order of one to ten kilometers.

Early speleogenesis is revealed by shallow isolated conduits with a close relation to bedding. They are relics that preserve coeval underground deposits. Extensional faults were reactivated as strike-slip faults during basin inversion. These were the first to furnish preferred paths for concentrated infiltration and therefore promoted the origin of cave networks. Then, as fault movement continued, there was persistent displacement of broken conduits, although with non-uniform horizontal and vertical shifting.

The rate of fault displacement was greater than that of karstification and completely disrupted the earlier networks and isolated segments both upstream and downstream. In the inner parts of rotated fault-bounded blocks some fractures have increased permeability as a result of secondary traction and have enhanced karstification along these directions. Finally, maze caves developed at the contact of Mesozoic karst rocks with confining impervious Cenozoic sediments. There the karstification exploited multiple fractures along thrust surfaces, creating an isotropic matrix where oblique strike-slip faults determined the direction of trunk conduits and therefore the origin of main karst springs.

1. Introduction

The Portuguese mainland is composed of a Variscan massif bordered by western and southern Mesozoic basins, respectively the Lusitanian basin and Algarve basin. After about 135 Ma of extension (Wilson et al. 1990, 1996), with minor early transient inversions (Terrinha et al. 2002), the basins were subjected to Cenozoic compression as a result of convergence between the African plate and the Iberian microplate (Ribeiro et al. 1990).

The Lusitanian basin was formed as a consequence of North Atlantic opening during the Mesozoic, following Pangaea fragmentation. It resulted from the breakup of the Iberian massif, which is part of the western arc of the Variscan orogen. Late Variscan northwest-to-southeast main fractures (Ribeiro et al. 1979; Ribeiro 2002) were subject to four rifting episodes (Kullberg et al. 2006) taking place as follows: (i) Triassic – Sinemurian (ca. 220-190 Ma), (ii) Pliensbachian – Oxfordian (ca. 190-156 Ma), (iii) Kimmeridgian – Lower Berriasian (ca. 156-145 Ma), and (iv) Upper Berriasian – Upper Aptian (ca. 140-112 Ma). The first rift deposits are a Triassic siliciclastic red-bed formation followed by Hettangian evaporites deposited in grabens or half-grabens (Rasmussen et al. 1998), of great importance in the tectonic evolution of the basin. The Sinemurian is represented by dolomites. The second rifting event produced carbonate rocks, mainly marly limestones in the Lower Jurassic, and oolitic to bioclastic limestones in the middle and upper Jurassic. The deposits of the last rifting events became in general more siliciclastic. The total thickness of the deposits in the center of the basin is about 5,000 m.

The basin developed in an almost north-south direction, along which several faults delimited horsts and grabens. It can be subdivided further in the northern, central, and

southern parts, which are separated by ENE transverse faults. The central part is limited by the Nazaré fault on the north and the Arrife fault (or, accordingly to other authors, Arrife, Lower Tagus, Tagus neck faults). During Mesozoic extension these strike-slip late Variscan faults behaved as normal or listric faults associated with rollovers, with the vector of maximum extension changing from northeast-southwest to an almost east-west trend (Crispim 1993; Kullberg et al. 2006).

Tectonic inversion during Cenozoic times has generated two alpine chains along the borders of the Iberia microplate: the Cantabrian-Pyrenean on the north, and the Betic on the south. Intraplate and distant reflexes of these compressions were the reactivation of Variscan basement faults, namely along the Central Cordillera, and detachment of Mesozoic cover where the basal evaporitic complex was thick enough, as in the Lusitanian basin (Fig. 1). Africa-Eurasia Paleogene convergence was NNE-SSW, while Neogene convergence was NNW-SSE. Former NNE-SSW extensional normal faults reactivated as lateral ramps, whereas ENE-WSW faults behaved as frontal ramps, and NNW-SSE faults formed dextral dominos compatible with slight NW-SE shortening. Inversion also caused renewal of motion of Lower Jurassic evaporite layers along thrust faults, forming salt walls or diapiric anticlinal structures (Ribeiro et al. 1990; Crispim 1993; Pinheiro et al. 1996; Kullberg et al. 2000; Ribeiro 2002).

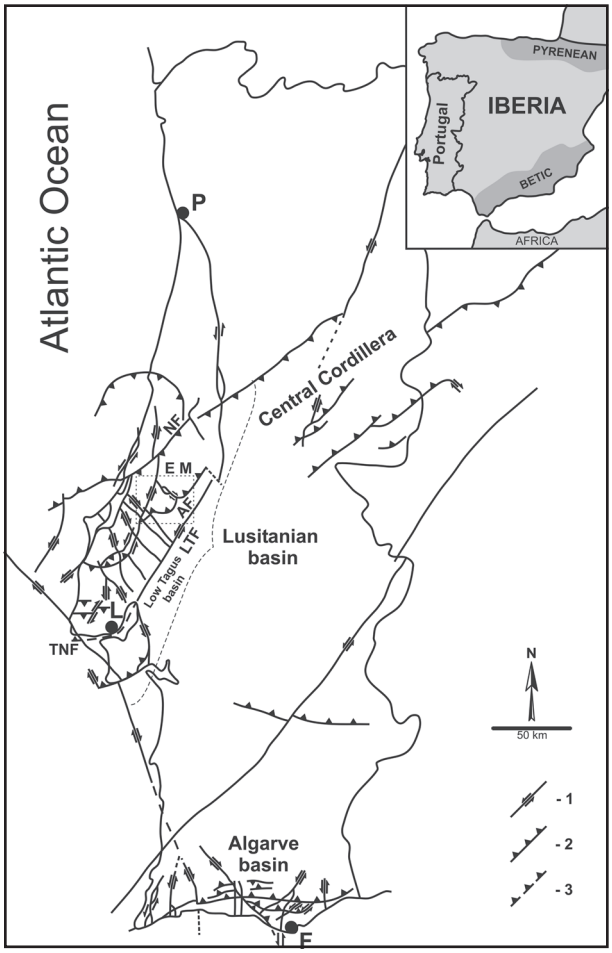

Figure 1: *Map of structures active in Portugal during the Alpine collision (with minor modifications, from Ribeiro et al, 1990). 1 - Strike-slip faults; 2 - thrust faults; 3 - Probable thrust faults. NF - Nazaré fault; AF - Arrife fault; LTF - Lower Tagus fault; TNF - Tagus neck fault; E M - Estremenho massif. P - Oporto; L - Lisbon; F - Faro. Dashed square = area represented in Fig. 2.*

2. Tectonic Inversion in a Selected Karst Region

The Estremenho limestone massif is the main Portuguese karst area (Martins 1949; Crispim 1992). It constitutes the southern part of an inversion area on the Lusitanian basin, bounded by the Arrife fault, which is oriented NE-SW. Two convergent sets of faults partition the massif and compose the boundaries of two graben stripes, one NNE-SSW and the other NW-SE, along which the poljes of Alvados and Minde fomed. The westernmost geomorphologic unit of the massif is the Candeeiros sierra, structurally the flank of a NNE-SSW anticline, while the easternmost unit is the São

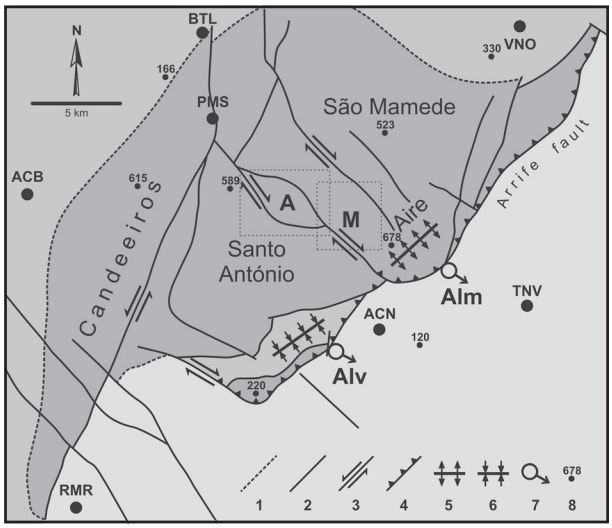

Figure 2*: Sketch of Estremenho limestone massif. 1 - Topographic limit; 2 - Fault; 3 - Strike-slip fault; 4 - Arrife thrust fault; 5 - Aire anticlinal; 6 - Monsanto syncline; 7 - Karst spring; 8 - Altitude asl (m); Dashed square A: Alvados polje (represented in Fig. 4); Dashed square M: Minde polje (represented in Fig. 3); Dark grey texture: Jurassic limestone of Estremenho massif; Medium grey texture: mainly Mesozoic detrital rocks; Light grey texture: Tagus basin Cenozoic formations. ACB - Alcobaça; ACN - Alcanena; BTL - Batalha; PMS - Porto de Mós; RMR - Rio Maior; TNV - Torres Novas; VNO - Ourém. Alm - Almonda spring; Alv - Alviela spring.*

Mamede plateau. Between the two sets of faults is the Santo António plateau, whose triangular shape points northward (Fig. 2).

The NW-SE set of faults, the Costa de Alvados fault on the northwest and Costa de Minde fault on the southeast, consists of two almost parallel side-stepping braided faults with an overlapping zone of about five kilometers. This overlap zone defined a lazy S-shaped basin (Mann et al. 1983) that delineates the Alvados polje. It can be considered a pull-apart basin in a sinistral strike-slip regime, chiefly extensional. During inversion a north-south compression induced a dextral strike-slip regime. The north and south borders of Alvados polje were then transformed, each in a push-up situated on its respective restraining bend (Fig. 3). The center of the polje is a graben in which the Upper Jurassic outcrops are surrounded by Middle Jurassic push-up structures (Crispim 1993).

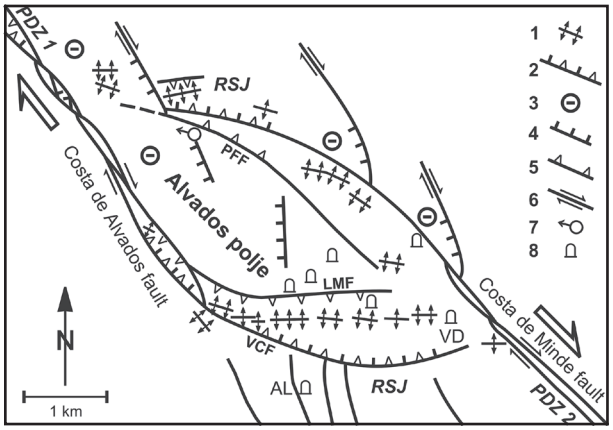

Figure 3: *Main fractures on the east slope of Minde polje, interpreted according to a theoretical simple shear zone (adapted from Crispim 1993). R - Synthetic shear ("Riedel"); R' - Antithetic shear (conjugate "Riedel"); P - Secundary synthetic shear ("P" shear); E - Extension fracture (or tension fracture, "T"). APCF - Algar do Portal da Covadinha cave fault; MVF - Moinhos Velhos cave fault; RF - Regatinho cave fault; ALF - Algar da Lomba cave fault. The springs represented are Pena, on the left, and Regatinho.*

Minde polje is situated on the east block of Costa de Minde fault. This one, like Costa de Alvados fault, dips to northeast and is the footwall of a broad extensional roll-over whose axis is in S. Mamede plateau (Manuppella et al. 2000). However, this roll-over is sliced by NW-SE faults parallel to Costa de Minde fault. The slices near Minde polje constitute its bottom and eastern flank. So, this flank is limited by two strike-slip faults, which moved dextrally during inversion (Fig. 4). Analysis of secondary fractures on this NW-SE block reveals the typical directions associated with a simple dextral shear system, such as synthetic and antithetic Riedl faults, as well as symmetrical to Riedl (Riedl 1929; Tchalenko and Ambraseys 1970; Wilcox et al. 1973; Bartlett et al. 1981).

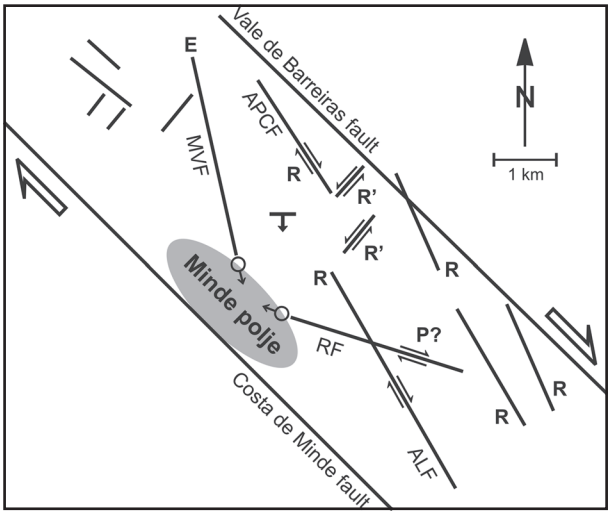

Figure 4: *Simplified sketch of strike-slip tectonics and karst features around restraining bend of Alvados polje (modified from Crispim 1993). 1 - Anticlinal fold; 2 - Normal reverted fault; 3 - Depressed block; 4 - Normal separation; 5 - Reverse separation; 6 - Dextral slip, 7 - Karst spring (Falsa); 8 - Other caves. RSJ - Restraining junction; PDZ - Principal displacement zone (1 - associated to Costa de Alvados fault; 2 - associated to Costa de Minde fault). PFF - Pena da Falsa fault; LMF - Lapa dos Morcegos fault; VCF - Vale da Canada fault. VD - Ventas do Diabo cave; AL - Algar do Ladoeiro cave.*

Both the Costa de Alvados and Costa de Minde faults behave as dextral lateral ramps on the inversion regime. Their movement is blocked against the Arrife fault, the abovementioned south-bounding fault of the main inversion area on the Lusitanian basin. So, the main Arrife fault was a frontal ramp during inversion, causing the Estremenho limestone massif to thrust over the Cenozoic formations of the Tagus basin. Situated respectively north and south of the lateral ramp, the Aire anticline and Monsanto syncline, both with NE-SW axes, are the main folds parallel to the thrust trend. The contact is very irregular because of the low-angle dip of the fault plane. The thrust zone exhibits secondary folds and is cut by faults with strikes near or oblique to the thrust trend. The broad movement also has a sinistral component.

In conclusion, the initial setting for speleogenesis must first take into consideration the former extensional regime with extension direction from northeast-southwest to east-west, which provided uplift along the roll-over axis, eventually with exposure of soluble rocks. Second, compression on the

north quadrant during inversion established transpressive regimes with dextral sense in the northwest-southeast lateral ramps and compressive to transpressive with a sinistral component in the northeast-southwest frontal ramp, while, in the inner parts of the domino blocks, related faults with simple shear were dominant.

3. Speleogenesis Associated with Extensional Structures

Speleogenesis associated with the former extensional regime must be searched for, first of all at higher levels of the massif surface, and secondly on fractures related to the extension. Two types of features must be considered: (i) sediments, and (ii) speleological features. Sediments may be masses of sand or flowstone, while the most significant speleological features are horizontal or sub-horizontal passages. They may be primitive isolated karst features, or they may evolve into integrated caves. Some represent ancient, in general weakly developed cave passages, later perched and truncated by massif uplift and slope retreat. In other cases they continue performing a hydrologic role by themselves or by complementing successor cave systems.

Examples of fossil infillings are spread widely over the study area. In general they do not allow depicting their structural origin, as they are limited remnants. Its distribution in altitude, when coupled with regional geomorphologic features and their correlative sediments, may be valuable in deciphering past phreatic levels. Examples in the study area are not related neither to the extensional phase nor to the Miocene main inversion regime, but instead with a Plio-Pleistocene littoral to which can be related a fringe of sands and dispersed flowstones bordering some south-facing slopes. A few more extensive features, including roofless caves, are in contrast good indicators of ancient flow trends. Collapsed roofs are better identified in aerial photographs, since their surface morphology is in general made uniform by later slope evolution and vegetal cover. Several asymmetric open dolines settled on steep slopes at different heights are the result of roof collapse of phreatic trunk passages.

Unfilled penetrable caves are in general of modest diameter and extend for short distances. They seem to be remnants of vadose or tributary passages, with no coeval sediments but thin layers of calcified clays and silts on the floor. Some are dip-oriented.

Exceptional and controversial are presently active caves that formed along extensional faults. This is the case of Cova da Velha cave, which is located on a northwest-seoutheast fault parallel to the Costa de Alvados main extensional fault. It is a 1 km single passage with a linear pattern, which was intercepted by slope retreat in a pocket valley. In winter, water collected along the fault plane rises up through the entrance. This hanging spring is suspended about 250 m above the regional base level and is partially explained by fault confinement of overhanging aquifer horizons defined by alternation of layers of different types of limestone. In neither the cave nor at the surface is there morphological evidence of recent displacement along the fault plane. So, it seems that the genesis of this cave has resulted directly from an extensional structure not reactivated by later inversion. However, two speleogenetic factors must be considered, which are first the decompression of the massif, and later the fault cross-cutting, which allowed the water to flow. The existence of a latent proto-cave dating from extensional times seems implausible and not verifiable.

Several inactive caves, at higher levels adjacent to currently active caves, can be interpreted as remnants of ancient cave networks related to extensional structures. Distinguishing between piracy and independent cave networks may be difficult, because the passage trends and their concordance with regional dip are more straightforward criteria. In some cases the currently active network cut unexpected and untraceable passages filled with anomalous sediments. They are surely signs of a former speleogenetic stage but are not exclusively attributable to extension.

4. Cave Networks Installed on Structures Related to or Reactivated on Inversion

Some important caves partially follow faults that are related to, or have been reactivated by, inversion. In the case of the Minde polje shear strip, the most important cave of the area, Moinhos Velhos cave, has a trunk passage with more than 1 km along an extension fracture; the direction of Pena cave is close to the trend of the main strike-slip fault; Algar do Portal da Covadinha and Algar da Lomba caves are partly guided by Riedel shears; and passages in Regatinho cave follow a direction close to a secondary synthetic P shear (Fig. 3).

Regatinho and Pena caves discharge at two springs at the foot of the east flank of the polje, and are less than 1 km long. They have, like Olho de Mira and Contenda, a maximum discharge of about 2 m^3/s and are intermittent. The largest springs of the Estremenho massif are Almonda and Alviela, which are situated at the points where oblique strike-slip faults cross the main thrust fault of Arrife. Here, maze caves have developed at the contact of Mesozoic karst rocks with confining impervious Cenozoic sediments. Cave development followed multiple fractures along the contact zones of thrust surfaces,

creating an isotropic matrix where oblique strike-slip faults determined the direction of trunk conduits, and therefore the emplacement of the main karst springs. Almonda cave is about 12 km long and the spring discharges about 15 m^3/s at its maximum, while Alviela spring discharges 17 m^3/s maximum. This cave has been dived to a depth of 130 m through a total of 1.5 km of passages.

5. Effects of Inversion on the Adaptation and Disruption of Cave Networks

As mentioned above, in the study area inversion took place along a lateral ramp in a regime of dextral strike-slip and along a frontal ramp in a thrust regime with a slight sinistral component (Fig. 4). Falsa is a temporary spring located on the northern push-up of the Alvados polje. The cave is composed of an initial part with narrow passages that in general follow the trend of the main strike-slip dextral transpressive fault. After about a 1-km straight line in the W-E direction, one suddenly reaches a trunk passage developed in the direction NE-SW. The southwestern extension of this passage is blocked against the strike-slip fault, and the water had to find its way along the fractured strip contiguous to the fault. Some sand deposits found at the surface may be related to possible abandoned fragments of the trunk passage. On the south flank of the Alvados polje, uplifted along the push-up structure related to the passage of the south strike-slip fault, other minor caves are also disrupted on both sides of the fault (e.g. Lapa dos Morcegos cave, Lapa do Necrial).

Algar do Ladoeiro cave, south of the southern push-up of Alvados, is in an area where parallel tension fractures predominate. The uplift in this compression zone and correlative erosion laid open several caves while relative slip on the faults break up old trunk passages and provide the path to new vertical speleogenesis.

In the Minde polje, another remarkable example of disruption of a big trunk passage occurs in Moinhos Velhos cave, where Galeria Gémea ends abruptly against an impressive block chaos. The link between this fossil trunk passage and the active collector is a very narrow passage 200 m long (Crispim 1987). Along the top of the scarp of the Costa de Minde fault, and also on its west slope, are several caves cut off by slope retreat. Some, like Lapa da Ovelha and Ventas do Diabo, are big enough to be considered trunk passages whose upstream continuation has disappeared as a consequence of differential uplift and erosion along the fault line. The plunge of passages is important and proves that the block west of the fault was tilted after the cave origin. This means that even if the extensional listric fault was the first to disrupt the cave networks with a vertical component, the west member would retain its original dip. The effect of the transpressional regime was to accentuate vertical displacement, increasing the plunge of passages and causing a horizontal shift between the western and eastern sections.

6. Conclusions

The study area of Estremenho limestone massif is perhaps the most outstanding karst region in the world in which to study speleogenesis in the context of transpression associated with side-stepped overlapping strike-slip faults. The clearness of the tectonic structures, and the number of caves available, allow the outlining of an evolutionary pattern dating from remote extensional phases to the Miocene, when the inversion achieved its maximum expression.

Even if somewhat misleading, relict caves and other karst features are valuable objects for the study of early speleogenesis. Several cases of truncated ancient collectors allow an interesting evaluation of the capacity of caves to keep up with tectonic evolution, and to investigate the modalities of hydrologic adaptation. They can also provide a measure for displacement or shortening along main fault zones.

It was shown that in the inner parts of the massif, i.e., in the area of poljes, the main strike-slip faults and their conjugates are very important not only to speleogenesis but also in the location of karst springs. The same is valid along the southern border of the massif. Here, the Cenozoic impervious rocks function as a confining layer in the syncline area or as a dam along the contact with the limestone massif. However the emplacement of the Alviela and Almonda springs is determined by oblique faults that also guide the development of associated caves.

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AGE OF CAVES IN THE CORDILLERA DE LA SAL (ATACAMA, CHILE)

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Although the Cordillera de la Sal, close to San Pedro de Atacama (Chile), is one of the driest places on Earth, it contains extensive cave systems that have developed in halite. A detailed morphological study of these caves, combined with 16 AMS radiocarbon ages on wood and bone fragments recovered from cave ceilings and diamictons, have allowed us to define when these systems formed and when sediments were emplaced. The sometimes huge cave passages appear to have formed in less than 2000 years by a succession of short-lived flash floods, probably after single extreme rain events.

1. Introduction

Rock salt or halite is at least three orders of magnitude more soluble than limestone. Because of this it rarely crops out extensively at the surface and where it does it is readily dissolved leaving insoluble residue (mainly clays and marls). Rock salt can only survive at the surface in an extremely arid climate and normally displays a large set of typical solution morphologies similar to those developed on limestone. Solution of rock salt also leads to the formation of true caves that can extend several km underground. Important salt karst areas with extensive cave systems include Mount Sedom in Israel (Donini et al., 1985; Frumkin, 1994, 1997, 1998; Frumkin and Ford, 1995), probably the best-studied example, Algeria (Sesiano, 1986) and the Zagros Mountains of Iran (Bosak et al., 1999; Bruthans et al., 2006).

Recently, interesting salt caves have also been discovered in one of the driest places on Earth, the Atacama Desert, where mean annual rainfall averages 20-50 mm y^{-1} and where there may be no rainfall at all for several years at a time (Houston and Hartley, 2003; Sesiano, 2006). Close to the village of San Pedro de Atacama, North of the Salar de Atacama basin, there is an important NNE-SSW trending elongated anticlinal ridge composed of Oligo-Miocene evaporitic rocks known under the name Cordillera de la Sal. The thick salt beds of this ridge, even in this hyperarid climate, have been karstified by occasional rains showing a well developed surface karst geomorphology with extremely sharp rillenkarren often isolating salt pinnacles of up to 15 m in height. In the past 15 years several cave expeditions have discovered and documented a subterranean karst drainage network with more than 4 km of caves and tunnels (Fryer, 2005; Maire and Salomon, 1994; Padovan, 2003; Salomon, 1995; Sesiano, 1998; 2006; Walek, 2005).

A detailed morphological study of this area has been carried out both at the surface and in the most important caves of the Cordillera de la Sal with the aim of understanding the mechanisms responsible for their formation and evolution.

2. The Caves

There have been cave expeditions to the Cordillera de la Sal since the early 1990s (Maire and Salomon, 1994) but only recently have American (Fryer, 2005; Walek, 2005), Italian (Padovan, 2003) and French caving teams (Sesiano, 2006) conducted detailed explorations. Mainly caves in the area close to San Pedro de Atacama have been surveyed, as the area south of the road leading to the Valle de la Luna is dangerous because of land-mines and as a result has largely been avoided. There are only three explored caves in this southern area (Cueva Zorro Andina or cave of the Andean fox (Fryer, 2005) and Cueva de l'Election (Sesiano, 2006) and Cueva à Eclipses (Sesiano, 1998). In the ridge between San Pedro and the Valle de la Luna there are about 15 surveyed caves, although several others are known but have not been mapped. Six of these caves have been studied on maps and/or in detail: these caves are the Zorro Andina, Cueva Mina de Chulacao (Chulacao Mine Cave), Cueva Lechuza de Campanario (Barn Owl Cave), Cueva Paisaje del Sal (Salt Landscape Cave), Cueva Palacio de Sal (Salt Palace Cave) and Cueva Paredes de Vidiros (Fryer, 2005). These caves were selected for study because of their extent and the presence of sometimes abundant speleothems. Cave locations are shown in Figure 1 and cave plans and profiles are in Fryer (2005)

2.1 Morphology

All six caves, which are the best developed cave systems of the Cordillera de la Sal, are "through caves", in that they can be followed from the stream input entrance to the outflow

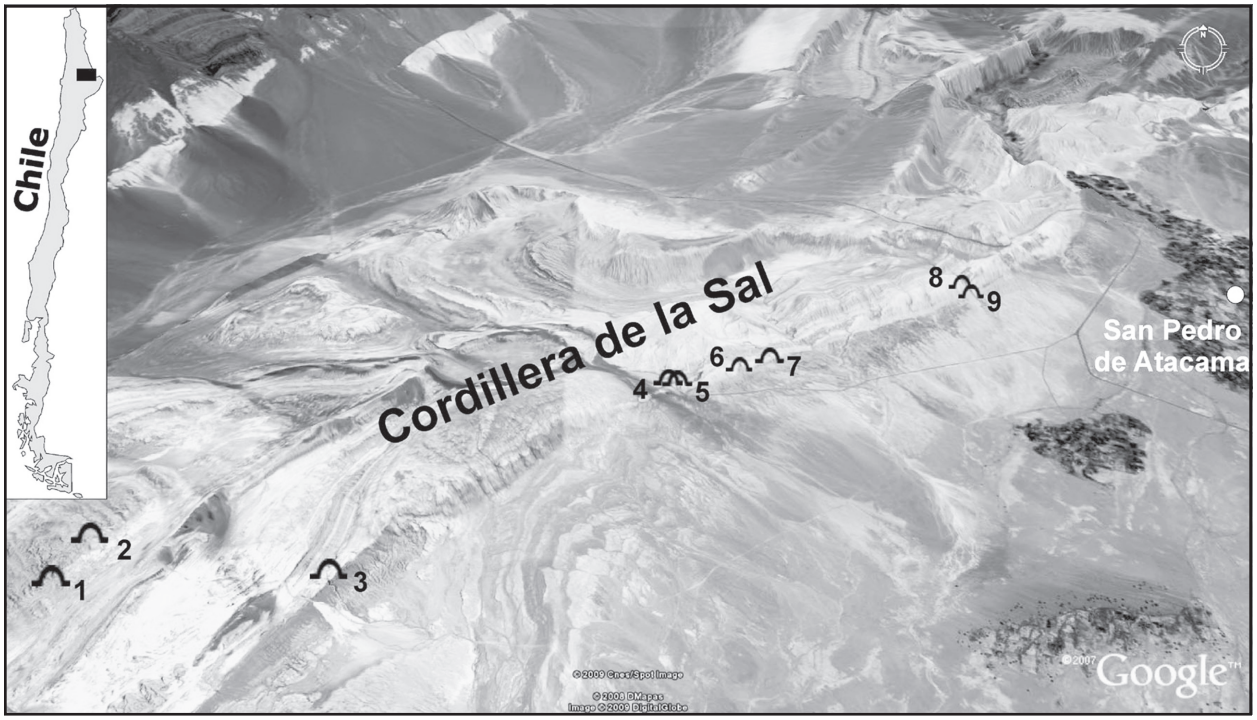

Figure 1: *The Cordillera de la Sal showing the locations of caves examined (modified from Google Earth). 1. Cueva de l'Election, 2. Cueva à Eclipses, 3. Cueva Zorro Andina, 4. Cueva Palacio de Sal, 5. Cueva Paredes de Vidiros, 6. Cueva Paisaje del Sal, 7. Cueva Lechuza de Campanario, 8. Cueva de Chulacao Fossil, 9. Cueva Mina de Chulacao.*

point. Upstream entrances are generally vertical (salt shafts or collapses) and soon connect with sub-horizontal rock salt passages that slope gently to the outlet. The salt is dissolved initially along fractures but solution continues underground regardless of structure, often cutting inclined to almost vertical salt layers. The sub-horizontal rock salt passages develop close to the local base level, at equilibrium gradients so that there is neither net erosion nor deposition. Zorro Andina and Lechuza del Campanario have a single elongated and often meandering cave passage, while the others are branchwork caves with multiple stream entrances and rock salt passages of 1st and 2nd (Paredes de Vidiros, Chulacao, Palacio del Sal) up to 3rd order (Paisaje del Sal). Passages in all of the caves tend to widen downstream, indicating a gradually increasing flow of water that is not saturated with respect to halite probably because of high flow velocities and resulting rapid flow-through times.

One of the most striking features of the caves is vadose canyons with laterally evolving meanders. These meanders are generally not related to bedrock features (e.g. gypsum interbeds, fractures) and evolve freely, increasing sinuosity while downcutting. The cross-sections change shape vertically following the meander entrenchment, but the passage width remains more or less constant. In some upper (older) levels the width of the channel seems to be greater, suggesting a climatic control (these might have developed in more rainy conditions).

2.2 Cave deposits

The halite caves of Atacama, like those in other halite karst areas (Donini et al., 1985; Bruthans et al., 2006), contain ephemeral speleothems that evolve relatively rapidly after short wet periods. Most are composed of salt and have grown in fossil passages or well above the present cave floor, since sporadic flooding readily dissolves them. In sheltered areas near entrances, there are large white halite flowstones probably deposited by evaporation of both infiltrating and condensation waters. Most of these are relict features evidenced by chisel marks made by salt miners who frequented these caves several hundred years ago. Stream passages that contain water only after rare major precipitation events have floors covered by a thin crust of halite.

The most interesting cave deposits, however, are massive diamictons up to 3-4 meters thick that in places almost completely fill the cave tunnels. These bedload deposits are the result of major flood events that occurred after long dry periods, when channel floors and slopes were covered with debris that was readily transported by the flood runoff. In Lechuza de Campanario cave two main diamictons have

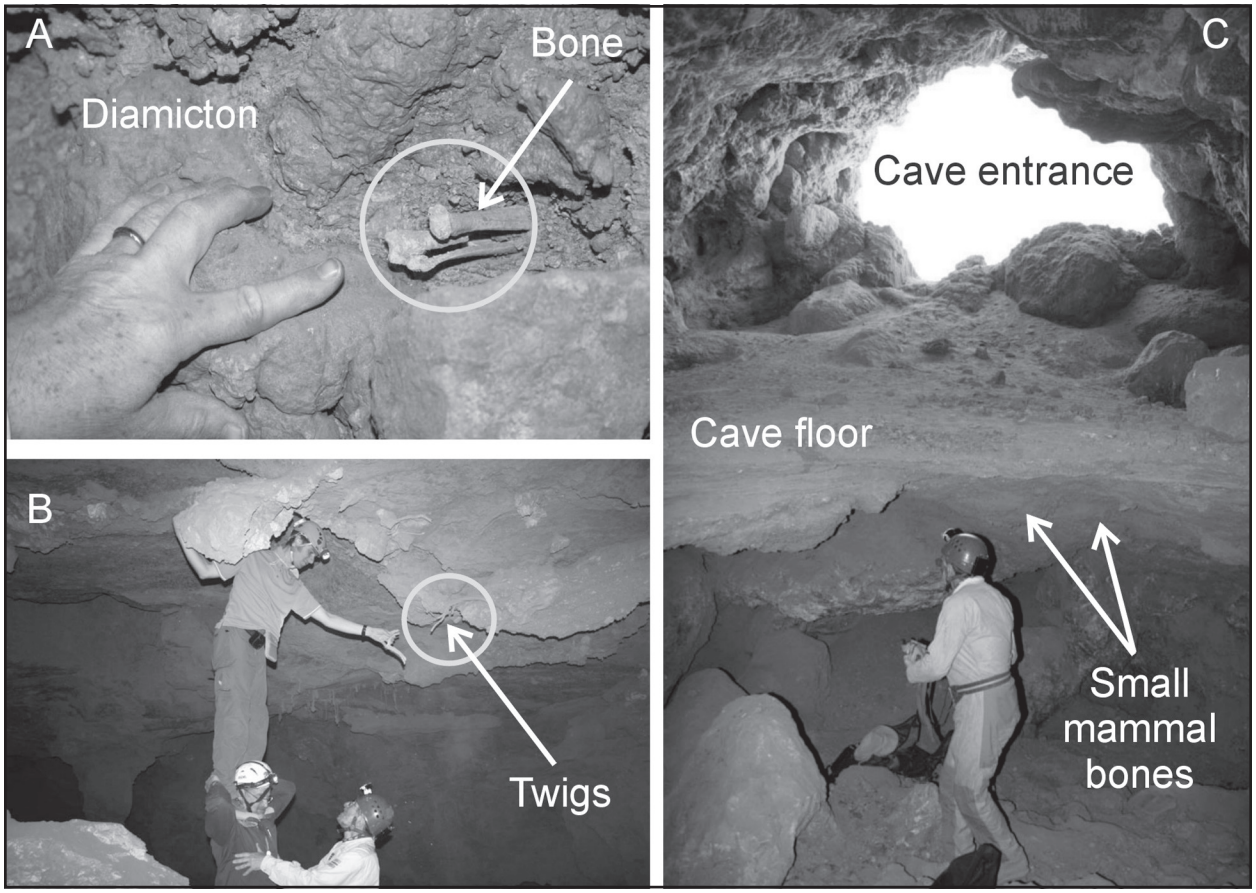

Figure 2: *Examples of sample locations: A: Cueva Lechuza de Campanario, bone in a diamicton; B: Cueva Palacio de Sal, sampling twigs stuck in the ceiling; C: Cueva Mina de Chulacao, small alcove just beyond the main collapse entrance, where small mammal bones were obtained from barn owl (?) pellets.*

been recognized, while in other caves, with bigger drainage basins, similar events are preserved only randomly. Due to the extreme aridity, wood fragments and bones are preserved remarkably well inside these diamictons or in alcoves and in slackwater deposits on fossil benches (Fig. 2).

3. Downcutting Rates

In order to determine how fast salt is dissolved in the Cordillera de la Sal area, a total of seven Micro Erosion Meter stations (MEM-stations) were installed in November 2007. These stations consist of 5 stainless steel nails allowing measurement of 3 spots/station. Six stations were placed in Lechuza de Campanario cave: two on exposed horizontal rock salt surfaces, two on vertical bare rock salt walls, one on the roof, and one on a lateral horizontal bench 2 meters above the floor. A seventh station was placed on a salt block along the canyon floor of Quebrada Lechuza (Table 1).

Measurements were made in November 2007, at the time of emplacement and a few days afterwards, and in the period March-April of 2008 (Table 2).

Based on the first set of measurements, the mean erosion rate on horizontal surfaces is 4.8 mm y^{-1}, on vertical walls 2.4 mm y^{-1} and in the cave generally around 1 mm y^{-1} (slightly greater on the floor than on the roof). A small flood between measurements had entrenched at least 2 cm into the salt block on the canyon floor of Quebrada Lechuza, pulling out the stainless steel nails but leaving the deeper parts of the drill holes as evidence of where the nails used to be. This observation suggests that floods are at least one order of magnitude more important in entrenchment than is downcutting due to films of condensation waters. A 5 meter high cave canyon passage might thus be developed in less than 1000 years. The mean downcutting rate of 5 mm y^{-1} is slightly lower than rates reported for the Mount Sedom area (Frumkin, 1995), which has a higher precipitation than the Atacama. It is useful to point out that entrenchment rates in caves can be exceptionally fast in the early stages of cave development, because the stream gradient, and therefore the cave profile, reaches equilibrium close to base level quite quickly, but down-cutting slows down once equilibrium is reached. Further entrenchment is possible only if boundary conditions change (e.g. base level lowering or uplift).

Station	Altitude (m asl)	Exposition	Description
1	2521	Vertical Southwards	500 m East of Valle de la Luna (VdL), under an abandoned salt quarry, +/- 100 m S of the road.
2	2519	Horizontal	Same as before, on salt block on the ground at 4 meters from Station 1.
3	2460	Horizontal	At the upper entrance (collapse doline) of Chulacao cave, at 50 m distance from ancient mine reservoirs.
4	2502	Vertical Southwards	400 m upstream of Chulacao main doline entrance, on the northern bank of the small valley.
5	2437	Horizontal	On salt block in the bed of the Quebrada Lechuza, at little more than 200 steps from the cave entrance.
6	2405	On cave roof	Cave roof in upper passage at 20 meter from the entrance (flowstone)
7	2405	On cave floor	Floor of upper abandoned meander, at 3 m height (left side) and at 60 m from the flowstone entrance climb.

Table 1: *Location and characteristics of the MEM stations.*

Station	Data + calibration (in mm)		Measure (in mm)		Surface lowering (in mm)	Average Lowering (in mm)	Days	Annual lowering (in mm)
	1st	2nd	1st	2nd				
1	24/11/07	29/03/08	10.37	9.66	0.99			
	8.84	9.12	8.26	7.36	1.18	1.03	126	3.00
			7.47	6.82	0.93			
2	24/11/07	29/03/08	9.43	8.03	1.68			
	8.84	9.12	6.42	5.53	1.17	1.41	126	4.10
			7.83	6.62	1.39			
3	30/11/07	30/03/08	4.27	2.74	1.85			
	8.80	9.12	12.43	11.94	0.81*	1.80	121	5.44
			7.71	6.29	1.74			
4	24/11/07	30/03/08	7.90	7.80	0.43			
	8.84	9.12	9.34	8.90	0.77	0.60	127	1.73
			8.52	8.25	0.60			
5[1]	25/11/07	01/04/08	12.84	Diss.	/			
	8.84	9.10	16.95	Diss.	/	> 20[1]	127	>20[1]
			12.28	Diss.	/			
6	26/11/07	01/04/08	11.26	11.26	0.31			
	8.79	9.10	9.55	9.56	0.30	0.30	126	0.88
			8.40	8.41	0.30			
7	25/11/07	01/04/08	8.25	8.20	0.36			
	8.79	9.10	10.10	10.03	0.38	0.36	126	1.04
			6.32	6.29	0.34			

* Salt surface of measuring point was overgrown with new halite crust. This measure was dis-

Table 2: *Lowering rates registered at the 7 MEM stations.*

4. Dating of Caves

To have a more precise idea of entrenchment rates and age of cave passages, a series of wood and bone fragments were recovered from diamictons and cave roofs for radiocarbon dating purposes. Ages of wood and bone fragments enclosed in diamictons date the sediment itself, while wood fragments left behind in alcoves or jammed in cracks in the roof represent the latest flood that passed through the passage and reached that height. In all cases the cave passage are older than the dated twigs and bones. Results are given in Table 3.

The oldest dated wood fragment was obtained from a diamicton in Lechuza de Campanario cave and gave a

Sample ID	Type	Number	pmC		1 σ	$d^{13}C$ corrected Libby Age		1 σ	$d^{13}C$
Palacio Del Sal Legn, +50-70 cm	twigs	R 03265	118,27	±	0,34	**-1277**	±	**23**	-16,23
Palacio Del Sal Legn, Roof, Alti +35	twigs	R 03266	76,65	±	0,22	**2142**	±	**23**	-24,25
Chulacao fossil 1	wood; small branch	R 03267	90,09	+	0,26	**852**	±	**22**	-23,4
Chulacao fossil 2	wood; branch	R 03268	81,60	+	0,23	**1651**	±	**22**	-22,88
Chulacao fossil 3	wood; small branch	R 03269	81,88	+	0,24	**1612**	±	**23**	-24,27
Chulacao fossil 4	wood; small branch	R 03270	86,105	+	0,256	**1197**	±	**23**	-25,56
Chulacao fossil 5	small bones	R 03271	89,769	+	0,245	**940**	±	**25**	-15,92
Chulacao fossil 6	small bones	R 03272	82,712	+	0,229	**1598**	±	**25**	-15,9
Chulacao 1	wood; small branch	R 03273	98,165	+	0,283	**159**	±	**23**	-23,73
Chulacao 2	wood	R 03274	89,646	+	0,249	**981**	±	**22**	-12,32
Chulacao 3	wood	R 03275	94,286	+	0,284	**483**	±	**24**	-23,66
Chulacao 4	wood	R 03276	91,652	+	0,27	**737**	±	**23**	-20,49
Chulacao 5	bone	R 03277	98,867	+	0,273	**143**	±	**25**	-18,56
Lechuza 1	splintered wood	R 03278	61,008	+	0,224	**3996**	±	**29**	-21,78
Lechuza 2	twigs	R 03279	83,605	+	0,269	**1464**	±	**25**	-21,84
Lechuza 3	bone	R 03280	83,754	+	0,24	**1482**	±	**23**	-17,78

Table 3: *Samples and their radiocarbon ages.*

corrected Libby age of 4025-3967 y B.P. (1 σ uncertainty). In the same cave a twig and a bone in a lower and younger diamicton gave ages of 1489-1439 and 1505-1459 y B.P., respectively. These debris flows seem to belong to two distinct flash flood events that occurred after long periods of drought, enabling surface runoff to carry large amounts of bedload.

Six wood and bone fragments from a small cave in another sector of the Cordillera gave ages of 1573-1673, 1220-1174 and 965-830 y B.P. A much larger cave in the same area but 15 m lower, provided five ages younger than 1000 y B.P. (around 980, 740, 480 and a bone and a twig around 150 y B.P.)

Finally, in another well-developed cave, with large underground stream passages, one wood fragment jammed in a crack in the ceiling 3.5 m above the floor and another in a wall crevice less than 1 m above the floor, gave corrected Libby ages of 2165-2119 and 1300-1254 y B.P., respectively.

5. Conclusions

Caves in the Cordillera de la Sal appear to have formed in the past few thousand years. The oldest cave passage (Lechuza de Campanario) must be slightly older than 4000 years B.P. Downcutting appears to occur during very localized heavy storms, when rainfall is able to create sufficient surface runoff to temporarily form a river with turbulent flow that can transport centimeter-sized cobbles. Exceptional, but probably very localized rainfall/runoff events (since they don't appear clearly in all caves), occurred around 4000, 2140, 1500 and 1280 y B.P. and deposited prominent diamictons and slackwater deposits. However, there is no evidence that similar-sized deposits were emplaced in recent times possibly suggesting that rainfall has been lower in the last millennium. All of the caves have sub-horizontal passages, adjusted to the present base level except for Lechuza del Campanario where the outlet of the cave is 3 meters above the canyon floor. There has been no important incision of this cave floor since the tectonic uplift (< 1500 years) that caused downcutting in the canyon. Due to their very rapid evolution, perfect preservation of sediments (diamictons, wood and bones), and peculiar morphologies (cave cross-sections, meanders, ecc.), salt caves are clearly important recorders of past climates and environments.

Acknowledgments

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KRAUSHÖHLE (AUSTRIA): MORPHOLOGY AND MINERALOGY OF AN ALPINE SULFURIC ACID CAVE

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Kraushöhle (Gams, Styria, Austria) is the only currently known sulfuric acid cave in the Eastern Alps. Cupolas, ceiling partings and portals, ceiling channels, replacement pockets, horizontal corrosion/convection notches, sulfuric acid karren, blind chimneys, incomplete dissolution walls, drip holes and cup shaped hollows in the floor are the most striking morphological features in this cave. Mineralogical analysis showed the presence, besides calcite, of gypsum, gibbsite, opaline, jarosite, metalunogene, hydroxylapatite, halloysite, and alunite. The timing of speleogenesis was preliminarily determined using $^{40}Ar/^{39}Ar$ dating of alunite, a product of acid limestone weathering, to 80 Ka +/- 80 (the cave is thus younger than 160 Ka). Preliminary U-Th dates of calcitic stalagmites indicate a minimum age of gypsum deposition of 52 Ka. Stable isotope data of these speleothem are consistent with an epigenic origin of the drip water at that time.

1. Introduction

Sulfuric acid corrosion in caves was first identified in France (Socquet, 1801), then in Austria and Italy (Hauer, 1885; Principi, 1931; Martel, 1935). Sulfuric speleogenesis was discussed later in the American literature (Morehouse, 1968). The remarkable publication on Kane Cave (USA) by Egemeier (1981) suggested a speleogenesis entirely dependent on the effect of sulfuric vapor, which caused the replacement of limestone by gypsum. This cave, at that time considered to be an "exotic" form of speleogenesis, became a reference work after the discovery of the famous Lechuguilla Cave in New Mexico (Hill, 1987; Hose et al., 2000; Engel et al., 2004). Considerable progress with regard to gypsum development and corrosion was made in Italy, mainly by the study of the Frasassi caves (Galdenzi and Menichetti, 1995). Following Egemeier, Audra et al. (2007) suggested that a major part of sulfuric speleogenesis may occur in the cave atmosphere (i.e., above the water table) by thermal convection and condensation-corrosion.

The sulfuric acid process of speleogenesis is based on the oxidation of sulfides to sulfuric acid (1), either directly, or by an intermediate reaction involving native sulfur (2). These reactions are facilitated by sulfo-oxidant microbes. Sulfuric acid then reacts by dissolving the calcareous host rock, creating replacement gypsum and releasing carbon dioxide (3), which dissolves even more limestone according to the reaction (4):

(1) $H_2S + 2O_2 <=> H_2SO_4$ ($SO_4^{--} + 2H^+$ in aqueous solution)

(2) $H_2S + O_2 => 2S° + H_2O$ and $2S° + 3O_2 + 2H_2O => 2\ SO_4^{--} + 2H^+$ (in aqueous solution)

(3) $CaCO_3 + SO_4^{--} + 2H^+ + 2H_2O => CaSO_4 \cdot 2H_2O$ (gypsum)$' + CO_2' + H_2O$

(4) $CaCO_3 + CO_2 + H_2O => Ca^{++} + 2HCO_3^-$

The general reaction of sulfide oxidation thus requires oxygen in gaseous or dissolved form. Limestone undergoes a double dissolution, part involving the replacement

by gypsum. Dissolved sulfate and alkalinity are carried away by the karst water. The reactive paths of the sulfuric replacement corrosion develop from the deeper, phreatic parts of the aquifer to the vadose zone near the emergence according to the following succession:

- At depth in the aquifer: microbial reduction of sulfates derived from evaporites into sulfites;

- in the aquifer body: possible addition of sulfate derived from the oxidation of pyrite, likely to be re-reduced thereafter;

- at shallow depth: dissolved sulfide of deep water partly becomes oxidized by mixing with oxygenated meteoric water, reacts with the limestone rock and produces sulfate in solution.

- In the confined atmosphere of the cave: H_2S degasses and oxidation continues, forming sulfuric acid on the walls and in the cave pools: sulfuric acid dissolves limestone, which is replaced by gypsum.

- Above the water table: condensation runoff along the walls dissolves gypsum. The detachment of the gypsum crusts makes them fall into the pools and adds to the washing out of sulfates;

- In the pools: the slowly flowing water gradually removes alkalinity and sulfate produced by the sulfuric dissolution of limestone.

In this paper the results of a multidisciplinary study on a remarkable sulfuric acid cave in the Eastern Alps, Kraushöhle near Gams in Styria (Austria) are reported.

2. Exploration History and Previous Works

Franz Kraus started exploration of a small and inconspicuous cave ("Annerlbauerloch") in 1881 and discovered most parts of Kraushöhle as it is known today. Due to rich speleothem decoration, but primarily because of massive gypsum deposits, he excavated a second entrance and opened "Kraus-Grotte" for visitors as early as 1882. In 1883 Kraushöhle became the first show cave in the world equipped with electric lights – one year before Postojnska Jama. Hauer (1885) already linked cave genesis to a nearby sulfide spring and suggested replacement of limestone by gypsum as a minor cave-forming process. Kraus (1891, 1894) supported this hypothesis ("cave genesis due to metamorphism") and gave a detailed description of the cave and its morphology. Trimmel (1964) interpreted the origin of the *Main Chamber* by dissolution of a gypsum body. Puchelt and Blum (1989) examined the sulphur isotopic composition and validated the hypothesis of Hauer (1885), but also concluded that this process had only limited impact on the development of the cave. No detailed morphological studies had been carried out on this cave prior to our study.

3. Study Site

Kraushöhle is situated in the easternmost section of the Hochschwab karst massif which is part of the Northern Calcareous Alps (NCA). The area shows a complex tectonic style and is affected by major strike-slip faults. Whereas the NCA are dominated by Triassic carbonates the cave formed in the Hirlatz Formation, a red Jurassic crinoidal limestone. The cave opens at 616 m asl, 90 m above the Gams brook that carved a narrow gorge in its upstream section. According to a complete resurvey in 2008 the total length of the cave is 767 m and the vertical range is ±53 m (+31, –22 m; Fig. 1). The cave consists of a *Main chamber* 50 m long, 6 to 15 m wide, and a volume of ca. 6000 m^3. It is connected with another chamber, the *Elysium* (25 x 10 m). Several conduits spread from these chambers that are partly parallel and interconnected. They are mainly subhorizontal but also show vertical steps of up to 10 m. Both cave entrances are incidental intersections of the cavern with the erosion surface. The section close to the upper entrance shows a 3D maze pattern (Fig. 1). Several blind chimneys up to 4 m in diameter reach upward; the highest of them terminates 30 m above the floor of the main chamber. A step of this chimney, which is not covered by gypsum or clastic sediments like most of the other parts of the cave floor, shows up to 1 m deep karren. The walls and the ceilings of almost all parts of the cave are formed by cupolas and mega-scallops. Larger cupolas have diameters of up to 3 m and often show portals that connect two of them. Notches with flat roofs and convection niches formed at several levels, in particular in the *Main chamber*. Condensation-corrosion channels are mainly present close to the lower entrance. Especially the lower parts of the cupolas are sculptured by gypsum replacement pockets. In the southernmost gallery several cup-shaped corrosion features are present below triple junctions of cupolas. Both chambers, the interconnected galleries east of them and adjacent chimneys contain gypsum. Massive gypsum on the floor is up to a few meters thick and is often perforated by drip holes. On the walls and ceilings gypsum crusts and crystals are present, which reach up to 30 cm in length in the main chimney where they cover several square meters. The cave also contains calcite speleothems including stalagmites, helictites, popcorn, a shield and locally extensive moonmilk.

During strong rain or snowmelt several small rivulets enter the cave. Water drains towards the deepest point of the cave which is blocked by breakdown material. Parts of the cave that are affected by this modern vadose water lack gypsum deposits. Locally this epigenic overprinting is documented by allochtonous pebbles that are typical for the geological units in the upstream part of Gams Brook. A lukewarm H_2S-rich spring (8.6 - 20.0°C) emerges at the level of the Gams Brook, 71 m below the deepest known point of the cave. Isotope data show that the water is a mixture of cold karstic and thermal waters (Zetinigg, 1993). Presently there is no thermal anomaly in Kraushöhle. The average annual temperature in the *Main chamber* is 7.6 (±0.2) °C which corresponds perfectly with the average outside air temperature.

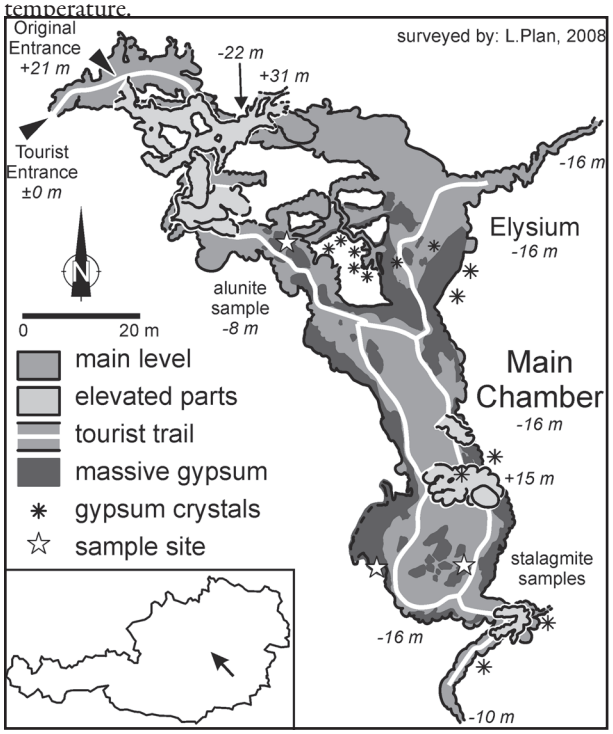

Figure 1: *Plan view of Kraushöhle with gypsum occurrences, sample sites and location in Austria.*

4. Morphologies and Their Genesis

The morphology of the cave is mainly due to its sulfuric origin by H_2S degassing of water rising from depth. H_2S oxidized to sulfuric acid either in shallow pools fed by both rising water and downflowing condensation runoff, or on walls and ceilings through condensation. These two types of environments (i.e. aqueous/gaseous) produced two families of corrosion features. The sulfuric water probably ascended along fractures, which are no longer visible due to later clay deposition. In the *Main chamber* and in some adjacent passages shallow pools were present. The aggressive water body caused lateral corrosion, which formed a notch with a flat roof, corresponding to the former pool level (Fig. 2A). The rising water was also probably thermal. At the rim of the "warm" pools, juxtaposed convection cells caused condensation-corrosion (Fig. 2B. Wall convection niches developed, which intersect in a blunted vertical edge (Fig. 2C). When deeply incised into the wall, their coalescence tends to form a notch with shallow embedded niches (Fig. 2B). The thermal gradient produced convection cells of bigger size, which carved the upper walls and the ceilings according to the airflow paths. Condensation-corrosion produced wall niches, ceiling cupolas (Fig. 2H), condensation-corrosion channels, and blind chimneys, whose walls are covered by megascallops (Fig. 2G). As a consequence, and in contrast to epigenic caves which develop along the entire conduit length, sulfuric caves developing mainly by condensation-corrosion, expand at discrete places (Osborne, 2007). Adjacent passages intersect, creating larger passages which evolve into condensation domes. Remnants of wall partings form ceiling partings, portals (Fig. 2H), protruding corners, blades, etc. Condensation prevailed in the "cool" upper parts, causing diffuse and differential corrosion and giving rise to boxwork-like structures. On the contrary, the lowest parts of the walls were warmer and prone to evaporation. Sulfate precipitated as gypsum crusts, giving rise to corrosion below the gypsum deposits. At half-height of the wall, where condensation and evaporation competed, gypsum is restricted to replacement pockets (Galdenzi and Maruoka, 2003) (Fig. 2D). Downwards, gypsum crusts thickened as a result of increasing evaporation. These crusts commonly detached from the walls and piled up as gypsum floors, locally in excess of 1 m (Fig. 2E). Primary formation of gypsum occurred as microcrystalline gypsum, and later recrystallization through condensation and evaporation produced large crystals (Fig. 2F). Calcite speleothems did not form during the hypogean phase, and are most likely entirely related to the epigene phase. After the cessation of the sulfuric phase, morphological changes due to meteoric infiltrations also resulted in the deposition of clay. Consequently, diagnostic features of hypogenic speleogenesis such as the "morphologic suite of rising flow" (Klimchouk, 2007) are not clearly visible, being masked by sediments and speleothems.

5. Mineralogy

Thirty samples were taken at different locations inside Kraushöhle. Mineralogical analyses were carried out using a Philips PW 1050/25 X-ray diffractometer, and, if only small amounts of sample were available, using a Gandolfi chamber (diameter 114.6 mm). In both cases the

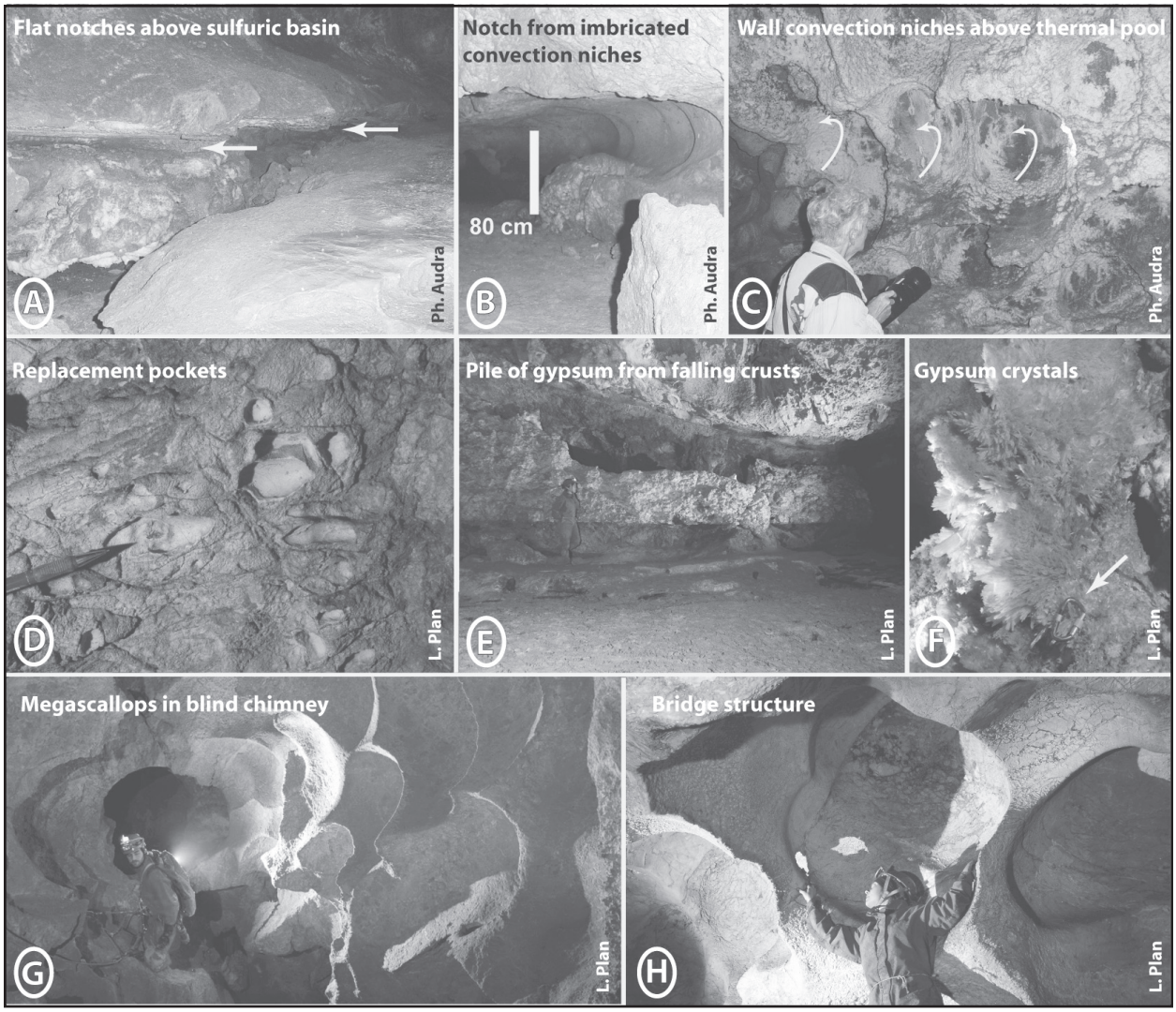

Figure 2: *Cave morphologies: A) Notches with flat roofs carved by lateral corrosion of a sulfuric acid pool; B) Notch formed by imbricated wall convection niches above the level of the thermal basin; C) Wall convection niches above the thermal pool; D) Replacement pockets; E) Pile of gypsum from detaching crusts; F) Gypsum crystals; G) Megascallops in a blind chimney; H) Portal between two adjacent cupola.*

experimental conditions included 40 kV and 20 mA, CuKα radiation, and a Ni filter. In addition to calcite (derived from the host limestone) and gypsum, seven additional minerals were identified: opaline ($SiO_2 \cdot xH_2O$), jarosite ($KFe_3(SO_4)_2(OH)_6$), gibbsite ($Al(OH)_3$), metalunogene ($Al_2(SO_4)_3 \cdot 12H_2O$), halloysite ($Al_2Si_2O_5(OH)_4 \cdot 2H_2O$), alunite ($KAl_3(SO_4)_3(OH)_6$), and hydroxylapatite ($Ca_5(PO_4)_3(OH)$). Gypsum is abundant in Kraushöhle and forms large deposits or replacement pockets along the walls and on the roofs. Many of the replacement pockets still host the pseudomorph gypsum which preserved structures of the original limestone such as calcite veins and fossils. Opaline is a rather common mineral in lava caves, but is rare in limestone caves (Hill and Forti, 1997). Its presence indicates rather acid conditions, compatible with sulfuric acid speleogenesis. The three sulfate minerals (jarosite, metalunogene and alunite) and the silicate halloysite are also typical of such low-pH conditions and this mineral association has been reported from Frasassi Cave (Bertolani et al., 1973) and from Guadalupe Mountain caves, New Mexico (Polyak and Güven, 1996). These minerals, together with the alluminium hydroxide gibbsite, are the products of alteration of clay deposits under acidic conditions (Polyak and Güven, 1996; De Waele et al., 2008). Hydroxylapatite was found in one single sample only and appears as transparent vitrous inclusions together with minor quartz, illite and gibbsite in a amorphous brown matrix. Its presence might be related to the alteration of organic material (bone?).

6. Alunite

Alunite was reported as a speleogenetic mineral in caves of the Guadalupe Mountains by Polyak et al. (1998) who successfully dated this mineral to yield the timing of speleogenesis of sulfuric acid caves in that area. The raw alunite-bearing Kraushöhle sample was treated with 25% HF for one hour. Approximately half of the raw sample dissolved. XRD results showed the presence of gibbsite in the raw sample, but probably not enough to make up half of the sample. EDS showed the presence of Al, S and K (Fig. 3A). It is likely that amorphous materials make up some of the raw sample. The Kraushöhle alunite crystals are similar in size and appearance to alunite from Carlsbad Cavern and Lechuguilla Caves (Polyak et al., 1998; Polyak and Provencio, 2000). They are pseudo-cubic rhombs ranging in size from 1-10 μm (Fig. 3B). After HF treatment, XRD results showed pure alunite (Fig. 3C). Refined unit-cell dimensions of A = 6.962 Å and C = 17.260 Å indicate that the sample consists of K-rich, near-end-member alunite.

The speleogenetic Kraushöhle alunite has an exceptionally young $^{40}Ar/^{39}Ar$ plateau age (≤160 ka), suggesting that the timing of formation of the cave is recent (Fig. 4). This is the first dated cave alunite outside of the Guadalupe Mountains.

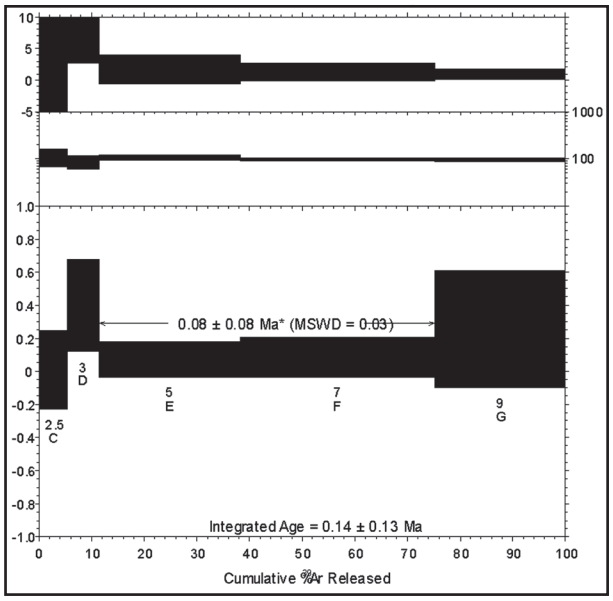

Figure 4: *$^{40}Ar/^{39}Ar$ age spectrum for a sample of fine-grained alunite from Kraushöhle, Austria.*

7. Calcite Speleothems

Kraushöhle contains abundant stalagmites, many of which were removed by vandalism. Preliminary investigations suggest that these speleothems are low-Mg calcite and

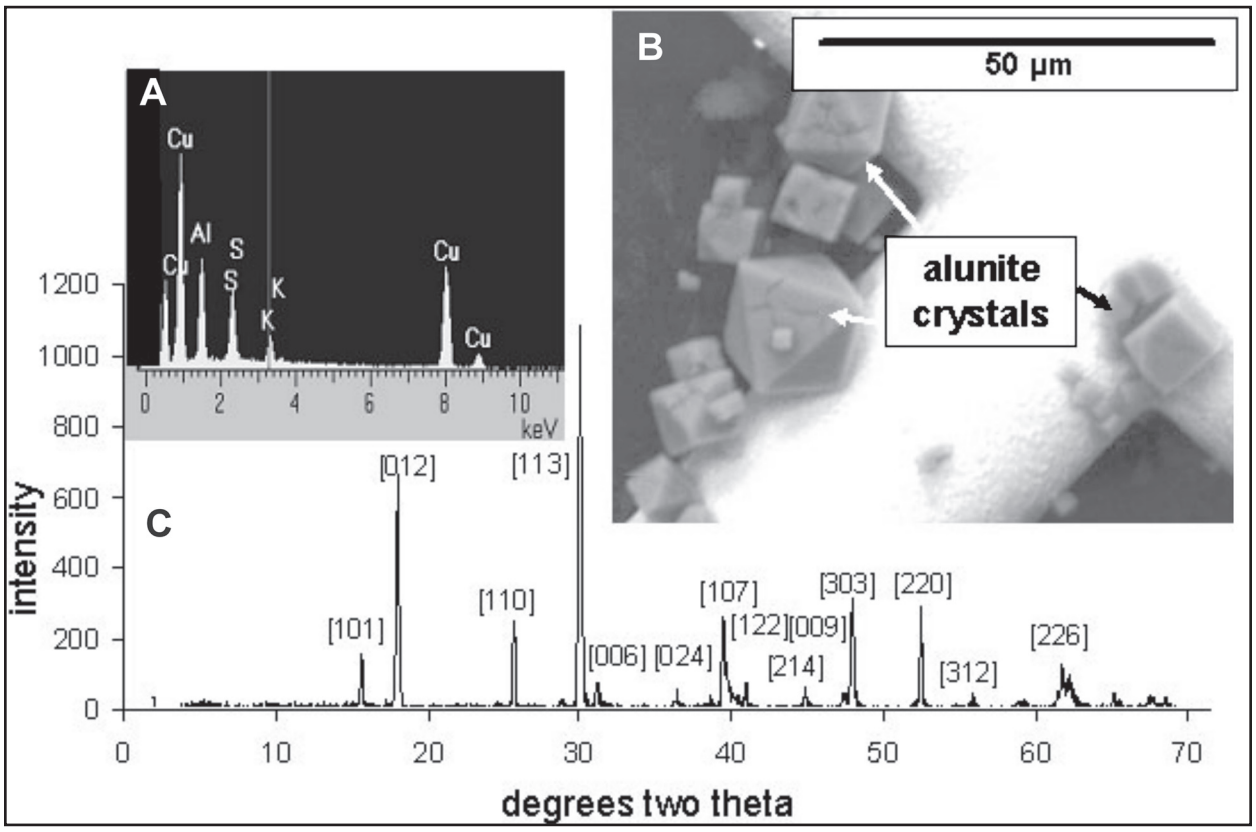

Figure 3: *The Kraushöhle alunite is the K-rich endmember. A) the three detectable elements using EDS are Al, S, and K; B) crystals are micron-sized rhombs; C) the XRD pattern of the HF-treated aliquot indicates that alunite is the only crystalline phase.*

are composed of a dense, transparent fabric. Speleothem deposition clearly postdated formation and local subsequent dissolution of massive gypsum as shown by the location of stalagmites in depressions surrounded by remnants of thick gypsum. Active soda straws and flowstone crusts on roots (close to the upper entrance) give evidence of rapid modern speleothem and moonmilk formation.

Fragments of two inactive stalagmites were dated using U-Th methods and yielded ages of 52 and 36 ka, thus providing a minimum age constraint for the cessation of gypsum deposition and subsequent local removal. $\delta^{13}C$ values range from -7.9 to -6.9‰ and from -2.4 to +0.4‰ VPDB suggesting variable amount of biogenic (soil-derived) C input into the seepage waters during this early stage of epigenic speleogenesis. $\delta^{18}O$ values range from -8.6 to -8.2‰ and from -10.3 to -8.5‰ VPDB. Modern drip water samples are required to relate these values to past environmental conditions, but it is likely that the large range in O isotope values of the second sample represents a paleoclimatic signal, consistent with the known high-amplitude climate variability during the time interval of the last glacial.

8. Conclusions

Kraushöhle is a remarkably young sulfuric acid cave with a minor epigene overprinting. The suite of morphologies such as cupolas, ceiling partings and portals, ceiling channels, replacement pockets, horizontal corrosion/convection notches, sulfuric acid karren, blind chimneys, incomplete dissolution walls, drip holes and cup-shaped hollows in the floor are diagnostic features of hypogenic speleogenesis due to sulfuric acid. Also mineralogy displays a distinctive set of sulfates and hydroxides typical of acid weathering. Alunite, in particular, has been dated using the $^{40}Ar/^{39}Ar$ method and has shown that the acid corrosion, responsible for the cave development, is younger than 160 ka. Two U/Th dated stalagmites yielded ages of 52 and 36 ka and confirm the extremely young epigenic phase that followed the sulfuric acid speleogenesis.

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THE AGE OF CAVE SYSTEMS IN CENTRAL-EAST SARDINIA: PRELIMINARY DATA

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The island of Sardinia has some of the most extensive cave systems in Italy, such as Codula Ilune (more than 42 km), Bue Marino cave (more than 17 km) and several others. Many caves seem to have developed over a long time span, and probably started forming during the Tertiary. A minimum age of these cave systems could previously be obtained indirectly because in certain areas Pliocene basalts sometimes fill karst conduits. To attempt to date some of the oldest cave branches quartz sediments were carefully mapped and nine samples for cosmogenic nuclide burial dating with ^{26}Al and ^{10}Be were taken in the summer of 2005 in two karst areas in Central-East Sardinia. The cosmogenic results indicate that all of the cave levels have similar ages, and are probably of Upper Pliocene age or maybe older.

1. Introduction

Caves are important geomorphic features for studying past environments, because they can preserve sediments that are otherwise difficult to find in surface deposits. Many caves are believed to have formed during Quaternary, when climate and changing base levels (sea level, glacial erosion, etc.) were ideal for the development of karst systems. There is, however, increasing evidence that many important accessible and still-active cave systems developed before the onset of the Quaternary (e.g., Anthony and Granger, 2004; Häuselmann and Granger, 2005). This includes several active cave systems in Central-East Sardinia (Insular Italy), which are known to have started forming during Tertiary, since well-developed conduits are filled with Pliocene basalts (De Waele, 2004). Dating caves is often difficult and minimum ages can be obtained using isotopic methods on chemical (speleothems) and physical (sediments) deposits in caves. In this research the sediments of four inactive caves in the Taquisara valley and a fossil conduit in the Codula Ilune cave system have been studied and were dated using cosmogenic nuclides. This research allows some preliminary conclusions to be drawn on the geomorphic evolution of this part of Sardinia.

2. Study Area

In Central-East Sardinia large Mesozoic carbonate mountains rest unconformably on a Palaeozoic basement complex composed of metasediments, metavolcanics and intrusive bodies. Surface and subsurface karst landforms are well developed in the largest of these carbonate areas: Supramonte, the Gulf of Orosei and several table mountains called Tacchi. The evolution of this interesting landscape, with the karstic areas towering above the basement complex and separated in different units by structurally controlled deep valleys and gorges, is believed to have occurred in the past 5 million years. With the aim of carrying out cosmogenic burial dating of cave sediments, two cave areas have been selected based on the abundance of quartz in well-documented cave sediments and the importance of underground karst in the framework of local landscape evolution.

The first area, the karstic Taquisara valley, is situated south of the Gennargentu mountains in the central-eastern part of Sardinia. It flows from NE to SW and is developed between the altitudes of 780–700 m asl. The valley dissects the Jurassic carbonate table mountains Tacco of Ulàssai and Taccu Isara and almost reaches the Palaeozoic basement. The evolution of this valley and of the deeply incised Riu Su Pardu and Rio San Girolamo valleys, which separate the Tacco of Ulassai and Arba from the other table mountains, is reported to have occurred during Plio-Quaternary (De Waele et al., 2005) based on geomorphic observations, but there are no exact time constraints relying on precise dating methods. Many caves are known along the borders of the valley, mainly characterized by sub-horizontal passages often partially occupied by stream sediments. These water table caves are situated at different heights along the valley borders, especially at elevations of 775 m, 815–830 m , 850–870 m and 930–950 m asl on the SE side and 900 m and 950–955 m asl on the northwestern side (Fig. 1).

The second area is located in the Codula Ilune river, which extends its drainage basin on granite rocks before cutting

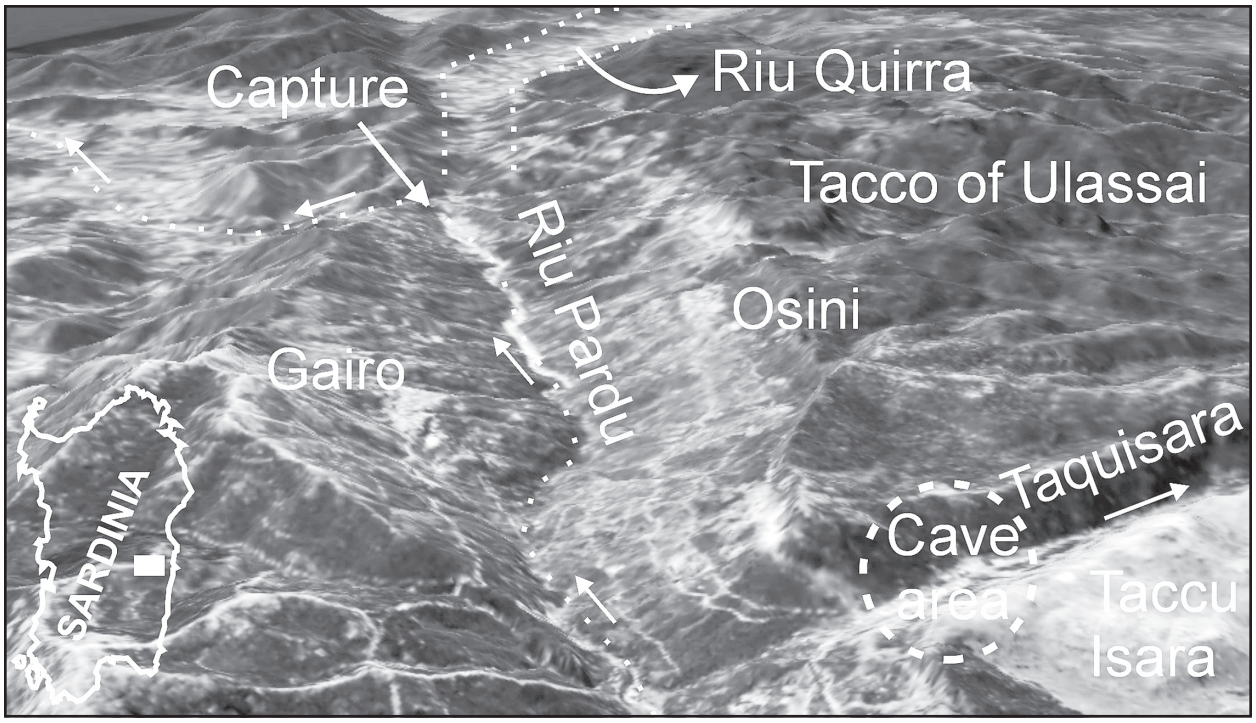

Figure 1: *3D view of Riu Pardu valley looking SSE (from Google Earth). The Taquisara valley cave area (bottom right), the capture of Rio Pardu (top left) and the abandoned Riu Quirra (top middle) are indicated.*

its canyon through the Gulf of Orosei Mesozoic carbonate rocks, reaching the Tyrrhenian at Cala Luna beach. This area hosts the most important cave systems of the island, with more than 42 km of mapped passages in the Codula Ilune cave system and 17 at Bue Marino cave. Pliocene basalts (2-3 My) fill ancient karst conduits cut by more recent cave branches, and the canyon has cut a more than 100 m deep gorge in the past 2 My as shown by the basalt plateau dissected by the canyon (De Waele, 2004) (Fig. 2).

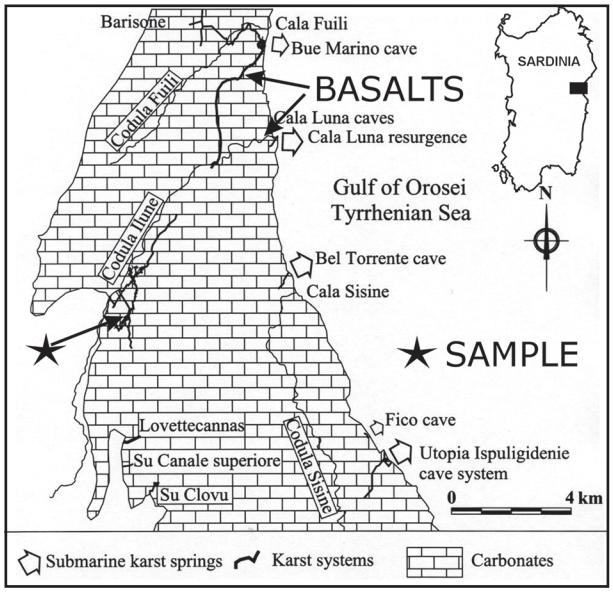

Figure 2: *Karst area of the Gulf of Orosei (bricks) and major cave systems (black lines). The sample location is indicated by the star.*

3. Caves and Their Sediments

Taquisara valley is one of the richest cave areas of Ogliastra (Bartolo et al., 1999). Six caves have been studied in detail and a total of eight quartzite pebble samples have been taken in four of these (two in each cave) (Fig. 3). In Genna 'e Ua cave (952 m asl), on the northwestern flank of the valley, the impressive main passage has a length of 60 m and is characterised by the presence of two underground collapse sinkholes that give access to an underlying cave level. The walls of these sinkholes reveal a >4 m thick section of quartzite conglomerates intercalated with flowstone levels and overlying a 1 m thick sequence of clayey sands (Fig. 4A-B). This sedimentary sequence is capped by an important flowstone (Fig. 4C). In two places this flowstone shows a thickness of more than 2 m and is extremely corroded. Samples were taken at the top and at the bottom of the conglomerate.

At Taquisara cave (954 m asl), 500 m southwest of Genna 'e Ua, the underground river passage shows important cave sediments and a complex geomorphic history with an active cave level 70 meters below. Cave sediments are represented by quartz conglomerates with minor phyllite fragments sometimes occupying entire rooms, successively eroded

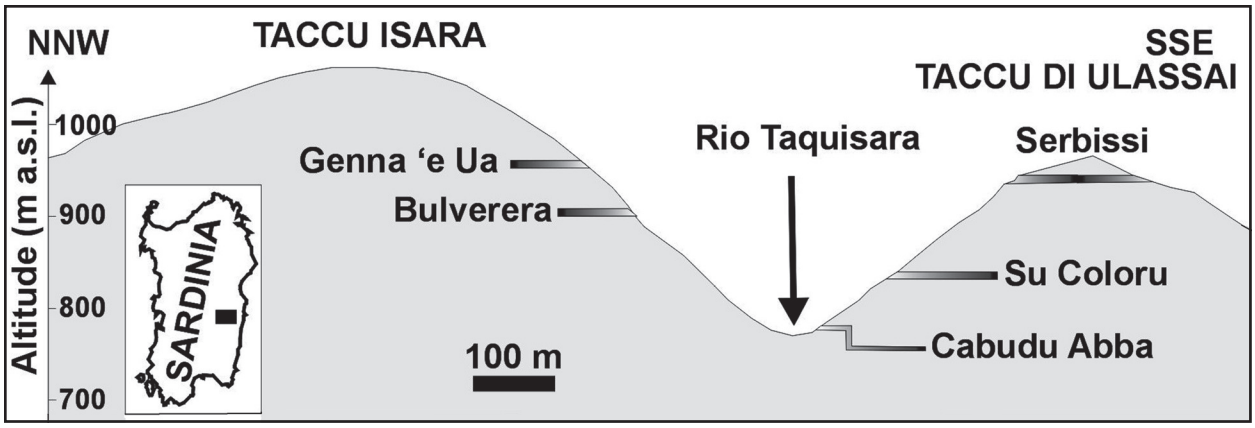

Figure 3: *NNW-SSE profile of Taquisara valley at the height of Genna 'e Ua-Serbissi caves: only sampled caves are shown (except for Cabudu Abba Spring).*

and transported to lower levels. No samples were taken in this cave. On the opposite side of the valley the big Serbissi cave (938 m asl) represents another underground river passage, most probably related to the same karstic cycle that generated the Genna 'e Ua and Taquisara caves. Although the passage is close to the surface (rock thickness above the cave might be less than 20 m, thus sediments might not be completely shielded from cosmic rays), two samples have been taken at different heights in the most internal part of the cave.

In the underground stream passage of the Sa Bulverera cave (901 m asl), located 50 m below Genna' e Ua, concretions are corroded and sediment relics occur along the walls at heights of almost 2 m, testifying that the passage was almost entirely filled with quartz conglomerates, successively removed during a re-activation period. The dimensions of this cave are less important and probably reflect a shorter period of formation than the one that was responsible for the huge passages of Genna 'e Ua, Taquisara and Serbissi. Samples were taken at 2 m and 0.5 m above cave floor in the final part of the cave.

In the meandering Su Coloru cave (816 m asl), on the opposite side of the valley, the sedimentary sequence is more articulated, with alternating quartz conglomerates and flowstones demonstrating cyclic erosion and depositional events (Fig. 4D). Dimensions are similar to those of Sa Bulverera, suggesting a comparable time span of formation. Also here two samples were taken, one at 0.5 m above cave floor, the second 3 m higher. At the same altitude several other interesting caves are known close by, documenting a stable base level.

Twenty meters lower, the active Cabudu Abba resurgence (800 m asl) descends very rapidly and hosts several sumps located 15 m below the present Taquisara valley floor, containing sediments characterised by quartzite-carbonate sands deriving from the Genna Selole Formation. No samples were taken here since the cave is believed to be of very recent origin. An analysis of valley morphology did not reveal distinct river terraces, but the cave floors testify to different base level still stands.

The Codula Ilune cave system is, with more than 42 km of total surveyed passages, the biggest cave system of Sardinia. It is composed of three main confluent underground rivers that form a principal drain that has its ultimate outlet at the Cala Luna resurgence, an underwater spring in the Tyrrhenian Sea. The upstream part of this cave system, Su Palu cave, is characterised by at least 5 levels of conduits, the highest of which is located 180 m above the present active river level (Fig. 3). It is here that quartz pebbles have been sampled on the floor of a fossil phreatic conduit. Sediments were characterised by sands (deriving from granite and carbonate rocks) containing quartz pebbles of some cm in diameter.

4. Methods and Results

Burial dating of cave sediments with ^{26}Al and ^{10}Be is one of the few radiometric methods that date lower Quaternary and Pliocene deposits ranging in age from about 100,000 years up to 5 Ma. Burial ages indicate the time sediment has been underground, often corresponding to the time in which the passage has developed or, in some cases, giving a minimum age of the passage. More details on the method are reported in Granger et al., 2001 and Granger and Muzikar, 2001. Cave sediments have been carefully mapped and samples were taken in the summer of 2005.

All of the cosmogenic nuclide concentrations in the sediments were very low, indicating relatively high erosion

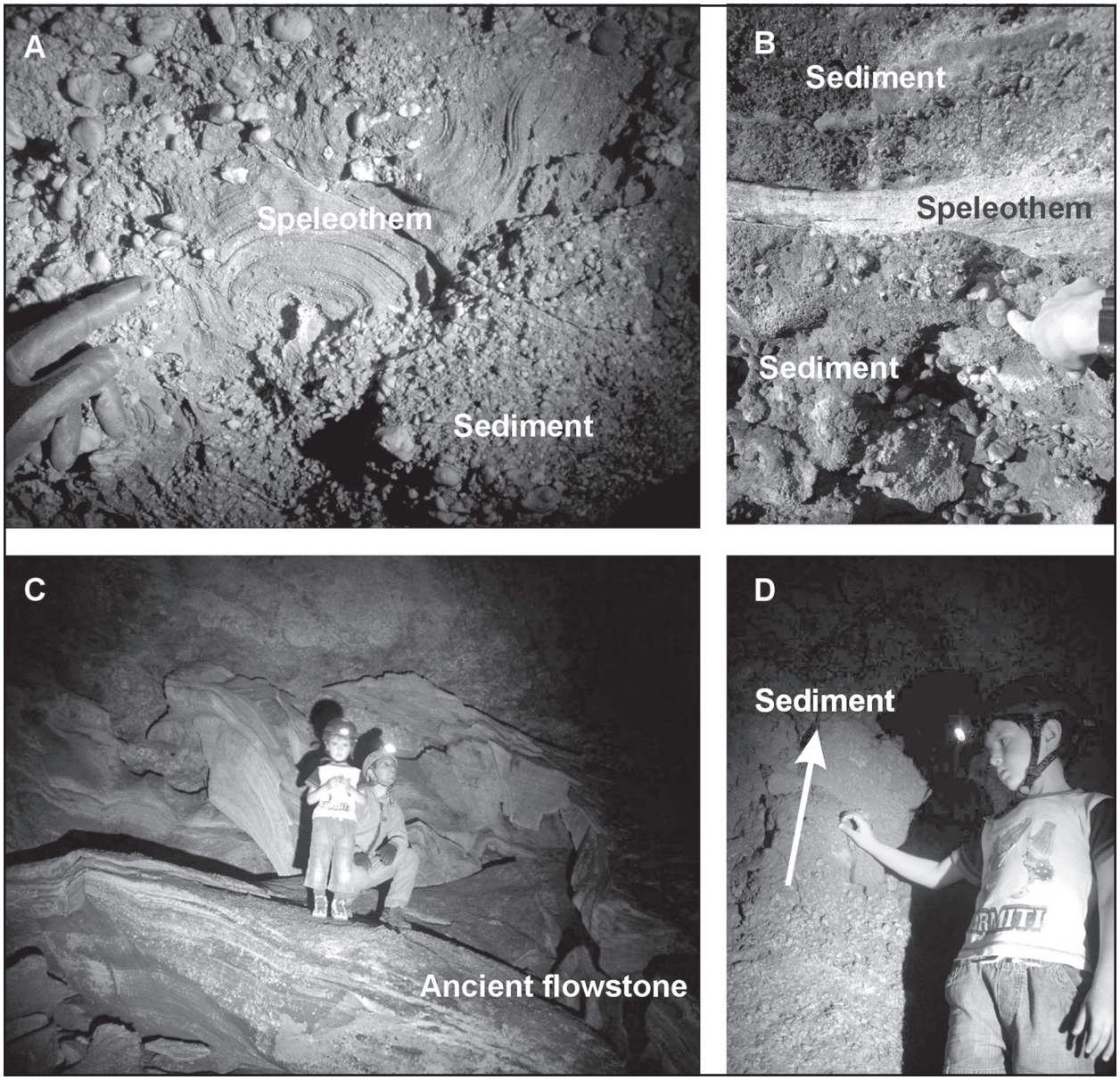

Figure 4: *Samples: Genna 'e Ua cave, A) quartz sediment with old speleothem layers exposed on a cave roof; B) detail of the thick sediment showing a flowstone floor in between quartz deposits; C) The large ancient flowstone that covers the entire quartz sediment sequence; D) quartz pebble sediments in carbonate cement attached to the wall of the river passage in Su Coloru cave. All photographs by Laura Sanna.*

Cave	Burial date (My)
Genna 'e Ua (2 samples)	2.82 ± 0.50
Serbissi (2 samples)	undatable
Sa Bulverera (2 samples)	2.46 ± 0.53
Su Coloru (2 samples)	2.76 ± 1.17
Codula Ilune (upper level)	2.37 ± 0.47

Table 1: *Cosmogenic $^{26}Al/^{10}Be$ burial ages of cave sediment.*

rates in the sediment source area. Uncertainties in the burial ages are thus quite large. Of the five caves of Taquisara, the sediments at Serbissi proved undatable due to insufficient burial depth below the surface. Resulting ages are shown in Table 1. The cosmogenic results indicate that all of the cave levels have similar ages, and date at least to the Upper Pliocene. The horizontal cave passages of the Taquisara caves have formed during relative stable periods during which the Taquisara river slowed its incision, but the cosmogenic nuclide dating did not achieve sufficient precision to distinguish these various still stands. The fossil Su Palu conduit has a similar age, and is thus also of Pliocene age or older.

5. Conclusions

The Taquisara valley, according to these (few) dates, appears to have already achieved its present shape in the Pliocene (2-3 Ma). Its drainage basin almost certainly extended far beyond the actual outcrop of Jurassic limestones. The deep valleys such as Rio San Girolamo and Riu Pardu, instead, are younger than the Taquisara incision, and have presumably formed in the last 2 million years.

The fossil levels of the Codula Ilune cave system (based on one cosmogenic date) also appear to be of Pliocene age and could be older. Karst conduits filled with Pliocene basalt are in agreement with this cosmogenic burial age. The deepening of the canyon, and thus also of the cave system, appears to have occurred after the emplacement of the basalts, thus during Quaternary.

From these preliminary data the present landscape of Central-East Sardinia, with its isolated table mountains (*Tacchi*) or the rough mountains of *Supramontes*, resting on the Palaeozoic basement, seems to have started forming during Late Tertiary, with a major incision rate during the last 2 My. Further research is needed to confirm these dates and to relate these events to the incision of other main rivers of the region, that according to these preliminary data appear to be less than 2 My old.

Acknowledgments

The first surveys and geomorphic investigations in the Taquisara area have been carried out with the help of Roberto Follesa. This work has benefited from the collaboration of Salvatore Cabras, Barbara Ibba, Alberto Muntoni and Laura Sanna. Many thanks to Laura Sanna for sharing her cave pictures. Cosmogenic dating has been carried out at the Department of Earth and Atmospheric Sciences, Purdue University.

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PRELIMINARY DEVELOPMENT OF A STATISTICALLY-BASED KARST CLASSIFICATIO SYSTEM, PHORMS

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A karst classification system is necessary in order to identify common processes of karstification in disparate regions. A robust classification scheme for karst terrains and aquifers should be grounded in 1) a well-constructed geologic framework and 2) the hydrogeologic processes of karst development taking place within that framework. Prior classifications of karst have been largely descriptive, lacking a foundation in quantifiable parameters. A classification of karst should avoid being based solely upon morphologic descriptions of the numerous geomorphic features recognized within karst terrains, and instead be linked to the processes and geologic attributes that give rise to karst features. Ranking such processes and attributes according to their importance for karstification allows for a statistical comparison of different karst regions, and ultimately a more quantitative classification of karst terrains.

Here, we introduce the PHORMS karst classification method. PHORMS is an acronym for the six factors considered in the classification: Physiography and climate, Hydrology, Other conditioning attributes, Rock properties, Morphology of karst features, and geologic Structure. The method is designed to be as quantitative as possible. Each factor comprises several attributes that are numerically scaled with regard to their relative importance for karstification processes then summed. A 6 x *n* matrix results: 6 numerical PHORMS factor values for each of the *n* karst regions being compared. The karst regions are then classified through the statistical techniques of Hierarchical Cluster Analysis (HCA), and the importance of each of the PHORMS factors within the classification is assessed through Principal Components Analysis (PCA).

The approach presented here is preliminary and subject to refinement. Our goal is to provide a classification system based upon quantitative parameters that can be used to efficiently compare karst terrains around the world. The PHORMS classification method is sufficiently flexible to be used as an exploratory tool as well as a means of comparison among factors responsible for karstification in a wide range of environments.

1. Introduction

Attempts to classify karst extend as far back as the history of karst science. Early work by Cvijić and Grund classified karst terrain according to the degree of development of morphometric and hydrologic features, resulting in the broad classifications of *holokarst* (complete or true karst), *merokarst* (partial karst) and *transitional karst* (SWEETING, 1973). QUINLAN (1967) and SWEETING (1973) expanded upon this approach and attempted to classify karst based upon a range of geomorphologic factors. More terms were added to the list of karst types, including designations such as fluviokarst, glacio-karst (also known as nival-karst or cryo-karst), cone and cockpit karst (*kegelkarst*), tower karst, interstratal karst, naked karst (*nacktkarst*), denuded karst, exhumed karst, covered karst (including variants within), relict or fossil karst, paleokarst, syngenetic karst, thermal karst and pseudokarst. In spite of these various designations of karst types, several universal criteria were recognized to be important for karst development: rock properties, geologic structure, climate, type of unconsolidated cover, physiography, and past and present hydrologic conditions.

Recently, greater focus has been placed upon the processes of karstification as a means of classifying karst. Debate has turned from questions such as "what is epikarst?", "what is paleokarst?", or "what is pseudokarst?" to "what are the criteria for epigenic and hypogenic karst development?" The three former questions arise when comparing karst terrains on the basis of their geomorphic features;however, due to varying interpretations of processes that give rise to observable morphologic features, clear consensus is

hardly possible. The latter question, on the other hand, grounds the discussion in the processes of karstification and landscape evolution that give rise to the features we observe, many of which are common in seemingly disparate regions.

Quantitative approaches to classification of karst have been based largely upon aquifer characteristics (see, for example, BAKALOWICZ AND MANGIN, 1980; SMART AND HOBBS, 1986; EL-HAKIM AND BAKALOWICZ, 2007). In spite of the potential success of such an approach, its application thus far has been largely conceptual rather than practical. A more comprehensive approach would incorporate the geologic and geomorphologic aspects of karst development (WHITE, 1999), but this, too, has yet to be formulated in a practical manner.

2. The PHORMS Classification System

Here, we present a preliminary classification system designed to include both the geomorphologic and hydrologic aspects of karst in a quantifiable manner that can be applied globally to any karst region where the requisite data exist. We call this the PHORMS classification. PHORMS is an acronym for the six

ATTRIBUTES OF KARST		KARST						REGIONS COMPARED								
Values listed from none, low, med, high (0,1,2,3) to indicate relative importance to karstification	WEIGHT	Mammoth Cave, Kentucky	Ozarks, Missouri	Edwards Plateau, Texas	Shenandoah Valley, Virginia	Classical Karst, Slovenia	Libburn Cave, California	Omega System, Virginia	Burnsville Cove, Virginia	Sistema Zacatón, Mexico	Bahama Flank Margin Karst	Alpine Karst	Idealized Carbonate Island	English Chalk	Biscayne Aquifer, Florida	Basin and Range, Nevada	Puerto Rico Cockpit Karst	Tropical Mts., Mexico
P - Physiography & Climate		5	4	5	6	8	6	8	7	7	7	8	7	4	7	6	8	8
Relief of soluble terrain (<50m=1, 50-300m=2, >300m=3) *(degree of gradient)*	1	1	1	2	2	3	3	3	2	1	1	3	1	1	1	3	2	3
Unconsolidated overburden thickness (>10m=1, 3-10m=2, <3m=3) *(degree of mantling)*	1	2	1	2	2	3	2	3	3	3	3	3	3	1	3	3	3	2
Climate (Arid=0, Semi-arid=1, Temperate=2, Tropical=3)	1	2	2	1	2	2	1	2	2	3	3	2	3	2	3	0	3	3
H - Hydrology		9	8	7	5	6	9	9	9	4	4	9	3	3	3	3	9	9
Q freq. dist. (unimodal=1, bimodal=2, multi-modal=3) *(degree of discharge variation)*	1	3	3	3	2	2	3	3	3	2	1	3	1	1	1	1	3	3
% Allogenic recharge (none=0, <10%=1, 10-30%=2, >30%=3)	1	3	3	2	1	2	3	3	3	1	2	3	1	1	1	1	3	3
Baseflow depletion coeff. a (<0.01=1, 0.01-0.02=2, >0.02=3) *(degree of aquifer storage)*	1	3	2	2	2	2	3	3	3	1	1	3	1	1	1	1	3	3
O - Other Conditioning Factors		0	4	4	7	0	2	1	1	7	3	0	3	0	0	7	0	2
Pre-existing karst (none=0, low=1, med=2, high=3) *(degree of invasion/overprinting)*	1	0	1	2	3	0	0	0	0	1	0	0	0	0	0	2	0	0
Hydrothermal influence (none=0, low=1, med=2, high=3)	1	0	2	0	2	0	2	1	1	3	0	0	0	0	0	3	0	1
Enhanced geochemical corrosion (none=0, low=1, med=2, high=3)	1	0	1	2	2	0	0	0	0	3	3	0	3	0	0	2	0	1
R - Rock Properties		7	7	8	6	9	7	6	6	6	7	8	5	5	6	7	8	9
Primary Porosity (>15%=1, 5-15%=2, <5%=3) *(higher porosity = less karstification)*	1	3	3	2	3	3	3	3	3	1	2	3	1	1	1	3	2	3
Impurities (>50%=1, 10-50%=2, <10%=3)	1	2	2	3	2	3	3	2	2	2	3	2	3	3	3	2	3	3
Bedding thickness (<1m=1, 1-3m=2, >3m=3)	1	2	2	3	1	3	1	1	1	3	2	3	1	1	2	2	3	3
M - Morphology		8	6	3	6	8	7	7	6	6	5	8	5	4	5	5	6	9
Median cave length (<300m=1, 300-1000m=2, >1000m=3) *(degree of flow integration)*	1	3	2	1	1	2	3	3	2	2	2	3	1	1	1	1	2	3
Dolines per sq. km (none=0, low=1, med=2, high=3) *(degree of surficial karstification)*	1	3	2	1	2	3	2	1	2	1	2	2	3	2	3	1	3	3
Cave depth (<30m=1, 30-100m=2, >100m=3) *(degree of deep karstification)*	1	2	2	1	3	3	2	3	2	3	1	3	1	1	1	3	1	3
S - Structure		3	3	6	9	9	8	6	9	3	1	9	1	2	3	9	2	9
Inclination of strata (<5°=1, 5-30°=2, >30°=3)	1	1	1	1	3	3	3	2	3	2	1	3	1	1	1	3	1	3
Sub-vertical fracture frequency (low=1, med=2, high=3) *(degree of vertical permeability)*	1	1	1	3	3	3	2	2	3	1	0	3	0	1	1	3	1	3
Faulting and folding (none=0, low=1, med=2, high=3) *(degree of rock deformation)*	1	1	1	2	3	3	3	2	3	0	0	3	0	0	1	3	0	3

Table 1. *Attributes included in the PHORMS classification and the values assigned to the karst regions being compared. Values include relative scales for some attributes and quantitative scales for others.*

factors considered in the classification: Physiography and climate, Hydrology, Other conditioning attributes, Rock properties, karst Morphology, and geologic Structure. Each factor comprises several attributes that are ranked with regard to their relative importance for karstification processes (Table 1). The physiography and climate (P) factor includes topographic relief, prevailing climate, and thickness of insoluble, unconsolidated overburden. The hydrology (H) factor includes the modality of discharge frequency distribution for an index spring, the percentage of allogenic recharge, and the baseflow depletion coefficient of the spring as a measure of storage within the aquifer of interest. A factor termed other conditioning factors (O) accounts for hydrogeologic processes that may influence current karstification processes, such as paleokarst, hydrothermal flow, or strong geochemical drivers toward karstification such as mixing corrosion or the influence of sulfuric acid on speleogenesis. The factor that describes morphology of karst features (M) includes estimates on the spatial density of dolines, length of caves, and depth of caves. Rock properties (R) include matrix porosity, purity, and thickness of bedding. Finally, the geologic structure (S) factor includes inclination of strata, fracture frequency, and degree of deformation as expressed by faults and folds. This preliminary classification system only considers karst in carbonate rocks; classification for karst within other rock types and for pseudokarst will be developed separately.

This system is designed to be as quantitative as possible, but necessitates some degree of subjectivity and simplification to include as many relevant factors as required to generate a useful classification. We have followed a method of attribute ranking and weighting as is done in karst groundwater and fractured aquifer vulnerability assessments (DOERFLIGER ET AL, 1999; DENNY ET AL, 2003). The approach ranks each factor attribute in terms of its perceived significance to karst development, as well as permits relative weighting (integer multipliers) of the attributes of each factor. The weighted ranks of the attributes within a factor are then summed, and the resulting values of a particular factor are normalized among all karst regions being compared for statistical and graphical purposes.

For example, doline density is an attribute of the Morphology factor. As with all attributes, we use a simple tiered ranking, with 0=none, 1=low, 2=medium, 3=high. A more quantitative ranking could be based on an actual value of dolines per square kilometer where data are available. The higher rank indicates a higher significance for karstification. The other Morphology factor attributes are mean cave depth and mean cave length. The attributes values are then summed to provide a single numerical value for the factor. This factor value is then standardized by subtracting the mean and dividing by the standard deviation among all of the other M values assigned to the karst regions being compared. Standardization is necessary to place all of the factor values within the same numerical scale. The standardized values of all PHORMS factors are a matrix of $6 \mathbf{x} n$, with n being the number of karst regions compared.

Two multivariate statistical methods (DAVIS, 2002) were employed to explore the data: Hierarchical Cluster Analysis (HCA) and Principal Components Analysis (PCA). HCA classifies the different karst regions according to hierarchical correlations among the values in the PHORMS matrix. PCA identifies the components of the matrix that account for the greatest amount of variance in the dataset. Although PCA is not a technique that can be directly used for classification, it permits an examination of those aspects of the dataset that are most likely exerting strong control over the classification borne out by the HCA.

3. Results

The example data shown in Table 1 are preliminary and are used to demonstrate "proof of concept" only. For this example, we chose to weight all of the attributes equally. Addition or modification of attributes, including weighting, within each of the six PHORMS factors is expected as the method is refined.

The HCA was performed twice: first using only the values of the six PHORMS factors as variables, and a second time using all of the attributes included in the classification as variables (Fig. 1). This served to test the method of summing the attribute values into single PHORMS factors. The HCA results of the PHORMS factors (Fig. 1A) fall into two major groupings separated to the first-order on the basis of hydrologic condition: those having deep or significant phreatic storage, and those generally lacking such storage. To a second-order, the classification seems to further divide the first-order groups on the basis of structural deformation or lack thereof. At the third-order, differentiation among karst regions occurs more rapidly as other conditioning attributes, such as pre-existing paleokarst, strong acids, or hydrothermal activity come into play. In contrast, the results of the HCA performed on a matrix of all attributes as individual variables showed a different discrimination within the first-order, placing those regions having high structural deformation as well as significant phreatic storage into the same grouping as those with little phreatic storage (Fig. 1B). As before, the first-order discrimination among the three groups appears to be largely based on the degree of

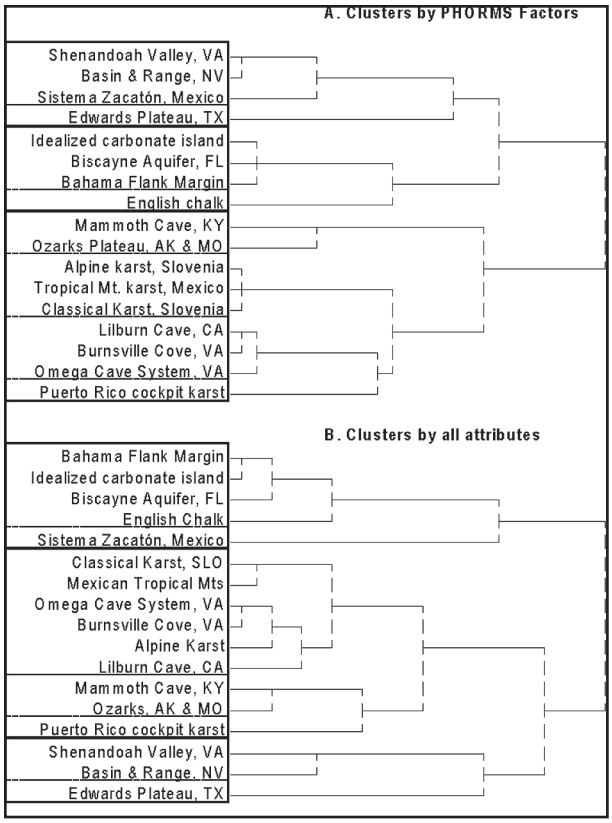

Figure 1. Hierarchical Cluster Analysis (HCA) results. A) HCA results using the six PHORMS factors (summed attribute values) as variables. B) HCA results when all of the attributes were used as individual variables in the HCA classification.

phreatic storage; however, the discrimination is stronger.

Although there is some similarity between the two HCA results, the discrepancies are interesting. For example, the Shenandoah Valley, Basin and Range, and Edwards Plateau regions were shifted out of the first-order grouping reflective of high phreatic storage when the analysis was performed on all attributes. In order to explain this, the results of the Principal Components Analysis (PCA) can be used to provide additional insight into the HCA classification. In the case of the Shenandoah Valley and Basin and Range, the shift in categorization might be explained by the lack of primary porosity in the indurated Paleozoic carbonate rocks of these regions, since this attribute has the highest factor loading within the first component of the PCA (Table 2). For the Edwards Plateau, the explanation is likely a more complex combination of attributes.

As with the HCA, the PCA was performed first using only the six PHORMS factors. The first two components account for 66% of the variance of the data. The projection of the 6-dimensional data cloud into 2-dimensional space may be visually misleading due to the collapse of some points near to one another that may, in fact, be separated in a space of greater dimensions (Fig. 2). For example, the vectors for physiography (P), hydrology (H), rock type (R), and morphology (M) all fall within a cluster. These four factors would be more separated in a space of greater dimension, as indicated by the factor loadings provided in the full component matrix (Table 2A). The first component accounts for 47% of the variance of the data, and the factor loadings show that the greatest influence on this component is exerted by the morphology (M=0.85) hydrology (H=0.78) and rock type (R=0.75) factors. The second component accounts for an additional 19% of the variance in the data matrix, and its loading factors are most strongly weighted on other conditioning attributes (O = 0.82) and geologic structure (S = 0.65). The third component is most weighted on the physiography factor (P=0.77).

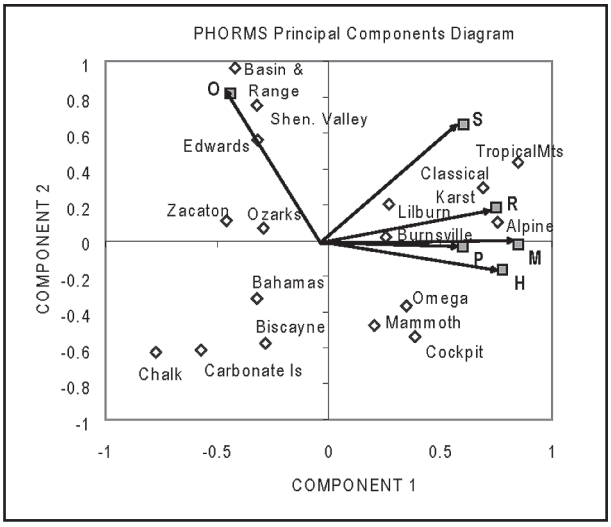

Figure 2. Principal Components Analysis results of the PHORMS factors. The arrows are vectors of the factor loadings, indicating relative importance for position of points within the 2-component space.

The PCA using all of the karst attributes as variables required three principal components to explain the same amount of variance (69%) that two components explained using only the six PHORMS factors as variables. High factor loadings (>0.70) within the first component were on structural attributes (dip of strata, fracture frequency, and degree of faulting and folding) and hydrologic attributes (discharge frequency distribution and baseflow storage); however, the highest loading (0.89) was on rock porosity (Table 2B). Other attributes with high loadings within the first component (in decreasing order) were topographic relief (0.83) and cave depth (0.75). Attributes of the first principal component with moderate loadings (between 0.70

and 0.50) were the percentage of allogenic recharge and cave length. The second principal component was most heavily weighted on other conditioning factors such as the presence of paleokarst (-0.82) and hydrothermal activity (-0.69). The negative loadings on these attributes indicate an inverse relation between these attributes and others with moderate loadings within the second component such as allogenic recharge (0.68) and doline density (0.66), possibly reflecting the different expressions of deep and shallow karstification.

A. PHORMS Factors	COMPONENT FACTOR LOADINGS					
	1	2	3	4	5	6
P	**0.60**	-0.04	**0.77**	0.02	0.00	0.21
H	**0.78**	-0.16	-0.45	-0.14	0.14	0.35
O	-0.44	**0.82**	0.03	0.01	0.35	0.11
R	**0.75**	0.18	-0.14	**0.62**	0.01	-0.08
M	**0.85**	-0.02	0.06	-0.26	0.32	-0.32
S	**0.60**	**0.65**	-0.08	-0.23	-0.40	-0.03
Cumulative % Variance Explained:	47%	66%	80%	88%	95%	100%
B. All attributes	**COMPONENT FACTOR LOADINGS**					
	1	2	3	4	5	6
Relief	**0.83**	-0.05	0.40	-0.13	0.01	-0.18
Cover	0.02	-0.01	**0.65**	0.49	-0.17	-0.43
Climate	-0.49	**0.50**	0.17	0.48	-0.04	0.34
Q-freq. dist.	**0.70**	0.44	-0.36	0.09	0.31	-0.03
Allogenic rech.	**0.61**	**0.68**	-0.28	0.08	0.10	-0.13
Baseflow Storage (α)	**0.76**	**0.56**	-0.17	-0.02	0.04	-0.02
Paleokarst	0.11	**-0.82**	-0.18	-0.12	0.35	0.17
Hydrothermal	0.32	**-0.69**	-0.27	0.31	-0.12	0.13
Enhanced Acidity	-0.43	**-0.58**	0.03	0.38	0.22	0.03
Porosity	**0.89**	0.04	-0.13	-0.07	-0.04	0.10
Rock purity	-0.45	0.36	0.45	-0.43	0.21	-0.02
Bedding	0.11	0.17	0.35	0.34	**0.79**	0.06
Cave length	**0.61**	**0.58**	-0.14	0.38	-0.10	-0.04
Doline density	-0.20	**0.66**	0.33	-0.15	-0.12	**0.54**
Cave depth	**0.75**	-0.34	0.13	0.39	-0.12	0.25
Dip	**0.79**	-0.30	0.38	0.04	-0.23	0.16
Fracture freq.	**0.81**	-0.29	0.28	-0.26	0.20	0.04
Faults and folds	**0.87**	-0.22	0.26	-0.27	-0.05	0.08
Cumulative % Variance Explained:	37%	59%	69%	77%	84%	88%

***Table 2**. Component matrices of the PCA results. Higher absolute value of a factor loading indicates a greater contribution of that variable to the overall component. Factor loading values with absolute value greater than 0.70 are highlighted in gray; absolute values greater than 0.50 are in bold. A) PCA results using only the values of the six PHORMS factors as variables. B) PCA results using rank values of each individual karst attribute as variables; only the first six principal components are shown for clarity.*

4. Discussion

There are several advantages to the PHORMS classification system. The first is that quantifiable information common among many karst regions is used in order to provide as objective a classification as possible. Databases on karst are growing rapidly in different regions; however, these databases lack a standard structure or guidance as to the key parameters needed for karst classification. The PHORMS system may serve as a guide to summarizing data collected within a particular karst setting in order to place the karst region within the classification. Admittedly, the values shown in Table 1 are based partly on objective data from the literature and partly upon "educated guesses" of the authors; thus, the analysis presented here should only be considered as preliminary. Nevertheless, the exercise provides a framework for further refinement.

The second advantage is that it permits direct comparison of different karst regions as well as a structure for statistically exploring the empirical connections among index parameters. Finally, the matrix structure also allows one to explore 'predictions' of karst attributes. For example, one might create a multiple regression model in which doline density is set as the dependent variable in order to assess the relative importance of the other attributes on the surface expression of karst. Although empirical, the exercise may provide useful insight and help steer new research directions concerning the underlying processes and controls on karstification.

5. Conclusion

The preliminary PHORMS classification system reflects an initial step toward a comprehensive classification of karst. Whatever classification scheme is applied to karst, it should enable theoretical models of karst processes to be placed within the classification alongside well-characterized regions. The ability to compile quantifiable aspects of karst regions around the world is increasing with increasing research. The PHORMS classification system attempts to take advantage of these data for practical application in karst research and possible inclusion into developing databases such as the Karst Information Portal (KIP) or other future and existing systems of karst information organization.

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TECTONIC INFLUENCES ON SPELEOGENESIS IN THE GUADALUPE MOUNTAINS, NEW MEXICO AND TEXAS, USA

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Sulfuric acid speleogenesis in the Guadalupe Mountains of New Mexico and Texas is a consequence of the rise of the Alvarado Ridge and subsequent opening of the Rio Grande Rift during Cenozoic time. Uplands of the late Laramide (~38-35 Ma) Alvarado Ridge provided an immense recharge area that supplied water to aquifers draining eastward into the Permian basin. Prior to, or during the early stages of the opening of the Rio Grande Rift, hydrostatic head in the Capitan aquifer caused strong water flow that displaced oil in traps in the southeastern corner of New Mexico. At this time, water also flowed upward along fractures to artesian springs in the aquifer within the ancestral Guadalupe Mountains. This resulted in solution enlargement of fractures and development of early-stage caves that may not have involved H_2S. Extensional faulting since 29 Ma fragmented the east flank of the ridge, progressively reducing the size of the upland recharge area and reducing hydrostatic head. Fresh water influx also introduced microbes into Artesia Group (Permian, Guadalupian) oil reservoirs, causing biodegradation of petroleum and generating copious H_2S. The water table within the Guadalupe Mountains began to fall 14-12 Ma in response to erosion and tectonism. During this time, oxygen-rich meteoric water mixed with H_2S water to form sulfuric acid, which enlarged passages and galleries at the water table. Tectonic spasms related to the opening of the Rio Grande Rift caused abrupt drops in the water table, shifting the locus of sulfuric acid dissolution eastward and downward. Cave levels formed by sulfuric acid record the position of the water table at a given time, and the elevation difference between levels may correlate with episodes of Rio Grande Rift tectonism since 12 Ma.

1. Introduction

The Guadalupe Mountains of southeastern New Mexico and west Texas lie on the north margin of the Permian Delaware basin (Fig. 1). Within these mountains, Tertiary uplift and erosion exposed Permian (Guadalupian) strata that contain caves formed by sulfuric acid. The current model for the speleogenesis of these caves is a combination of ideas first proposed by Davis (1980) and Egemeier (1981 1987), where H_2S derived from petroleum deposits was oxidized to sulfuric acid that dissolved limestone. Hill (1987 1990) confirmed a petroleum source and modified Davis' conjectures by suggesting that speleogenesis was dependent on migration of H_2S from the basin to the reef. Palmer and Palmer (2000) showed that initial stages of cave development resulted from rising water that reached the surface through springs, emphasizing the need for oxygen to convert H_2S to H_2SO_4. Once primary conduits were formed, episodic lowering of the water table resulted in enlargement of passages and galleries at the water table where oxygenated meteoric water was available to mix with sulfidic water and form sulfuric acid. Polyak et al. (1998) used radiometric dating to show that Guadalupe caves were formed 12 – 4 Ma, with the oldest caves found at the highest elevations. The decrease in age with elevation reflects the progressive lowering of the water table over a span of 8 Ma (Polyak et al. 1998; Palmer and Palmer 2000).

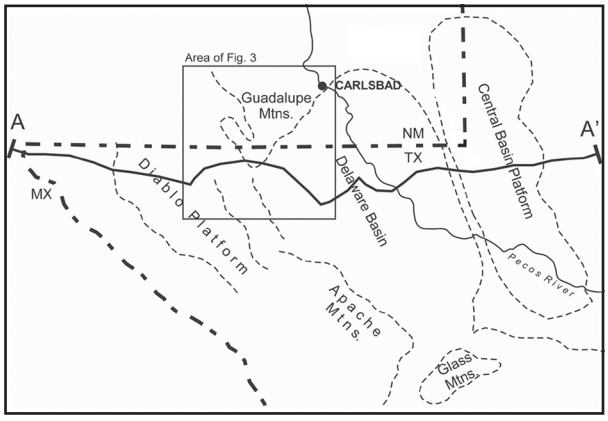

Figure 1: Index Map of the Guadalupe Mountains and vicinity. A – A' is the cross section shown in Figure 4.

2. Tectonic Setting

The Guadalupe Mountains are located on the eastern flank of the Rio Grande Rift, an intermontane and intracratonic extensional feature superimposed on the Cenozoic Alvarado

Ridge (Fig. 2) in southern New Mexico and west Texas (Eaton 1986 and 1987; Chapin and Cather 1994). These mountains lie between the Salt Basin graben and the Pecos River valley, and rise southwestwardly from beneath Ochoan evaporites and Pecos valley Quaternary fill to an elevation of 2767 m at Guadalupe Peak in Texas (Fig. 3). The western margin is the Border Fault zone of King (1948). The upland surface of the Guadalupes slopes 1.2 degrees northeast (DuChene and Martinez 2000) and is continuous with the extensive upland of the Llano Estacado (Bretz and Horberg 1949), a late Eocene surface capped by Ogallala gravels (Fig. 2). The Pecos River valley is incised into the Ochoan evaporite sequence between the Llano Estacado and the Guadalupe Mountains where it breached the Capitan Reef Complex (Fig. 2)(Bretz and Horberg 1949; Motts 1968; Hiss 1980; Bachman 1980).

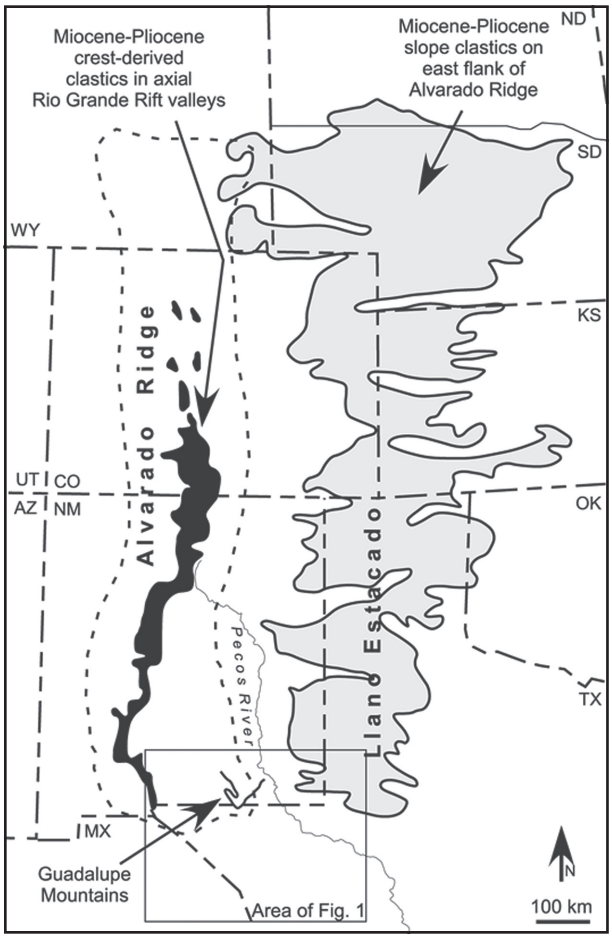

Figure 2: Distribution of Ogallala-age sedimentary cover. Modified from Eaton, (1987, fig. 4).

The Alvarado Ridge (Fig. 2) is a regional topographic feature extending from southern Wyoming to westernmost Texas and northeastern Mexico (Eaton 1986, 1987). The feature was caused by distributed subcrustal thinning and related extensional strain, a mechanism similar to the cause of known marine and continental rift zones. The ridge is characterized by youthful mountains enclosing axial rift valleys, and by eastward and westward concave-upward slopes where elevation decreases asymptotically away from mountain crests. Sedimentary cover on the slope is composed of Miocene and Pliocene fluvial sediments interbedded with rhyolitic tuffs, with the youngest undisturbed lithologies belonging mostly to the Ogallala Formation (Fig. 2). These sediments were derived from upland areas of the Alvarado Ridge (Eaton 1987) and transported downslope to sites of deposition on a regional Eocene planation surface (Gregory and Chase 1992). The distribution of Miocene-Pliocene sediments is a consequence of the tectonic history of the Alvarado Ridge, a feature that has persisted against supracrustal and subcrustal degradation for at least 38-35Ma (Gregory and Chase 1992). The age of sediments derived from the crest of the ridge correlates with periods of tectonic maxima in the southern Rocky Mountains with rift initiation at 29-27 Ma, a maximum phase of extension between 17-14 Ma, and rift culmination at 7-4 Ma (Seager and Morgan 1979; Eaton 1987; Chapin and Cather 1994).

3. Hydrogen Sulfide and Sulfur

Hydrogen sulfide (H_2S) is common in subsurface formations in southeastern New Mexico (Bjorkland and Motts 1959; Hinds and Cunningham 1970). This H_2S is a byproduct of microbially assisted degradation of hydrocarbons associated with alteration of anhydrite to calcite (Kirkland and Evans 1976; Wiggins et al. 1993). Oil and gas accumulations in Permian Artesia Group strata east of the Pecos River become progressively more degraded to the west (DuChene and McLean 1989), and are rare west of the Pecos River.

The most common occurrences of native sulfur are diagenetic deposits derived from reduction of H_2S (Machel 1992). Diagenetic sulfur and H_2S are common in the subsurface on the north flank of the Guadalupe Mountains (Hinds and Cunningham 1970). Diagenetic sulfur also occurs in the Gypsum Passage of Cottonwood Cave, in the Big Room of Carlsbad Cavern, and four sites in Lechuguilla Cave (Davis 1973; Spirakis and Cunningham 1992). In these deposits, and in associated cave gypsum deposits, sulfur is isotopically light compared to the Canyon Diablo Troilite (CDT) standard (Hill 1987). Limited fluid inclusion data and modeling of the water chemistry in Lechuguilla Cave suggest that some sulfur formed subaqueously at a geochemical interface that was probably controlled by the availability of dissolved oxygen. Water composition was a complex mixture of fresh water,

salty water, and various gases including CO_2, CH_4, H_2S and light (C1 – C6) aliphatic hydrocarbons (Spirakis and Cunningham 1992).

4. Cave Elevations and Water Table

There are numerous caves in the western part of the Guadalupe Mountains with entrances at high elevations. A typical example is Hell Below Cave, located 8.9 km from the western escarpment (Fig. 3). Hell Below is about 150 m deep and has morphologic and mineralogic characteristics typical of sulfuric acid caves (Palmer and Palmer 2000). The entrance is at 2043 m, near the top of the Seven Rivers Formation and lies 945 m above the salt pan near Dell City, Texas (Fig. 3). Veldhuis and Keller, (1980) estimate 500 m of bolson fill in the Salt Basin, so the contact between the Yates and Seven Rivers formations is at least 1400 m lower in the Salt Basin than at Hell Below Cave.

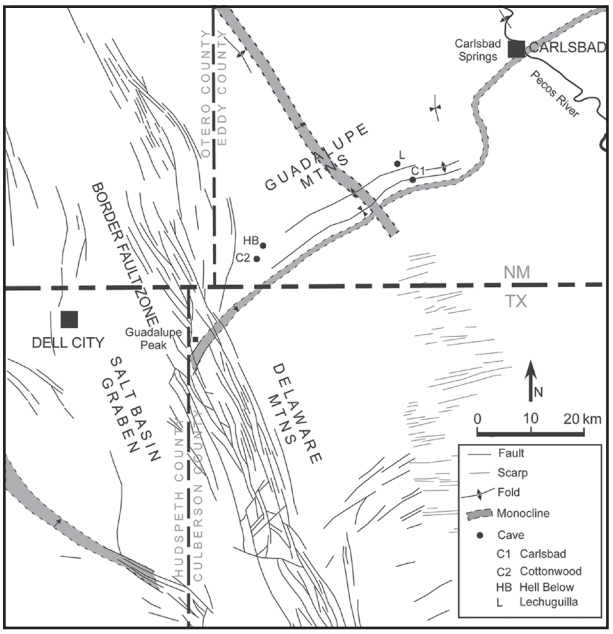

Figure 3: Tectonic map of the Guadalupe Mountains and vicinity with key landmarks and caves. Modified from Hayes, (1964, fig. 24).

Most of the stratigraphic units that comprise the Capitan aquifer of Hiss (1980) crop out on the western escarpment of the Guadalupes (King 1948) and are above the modern water table. Today, the water table is at an elevation of 945 m at Carlsbad Springs (Fig. 3), and is estimated at 963 m at deep points within Lechuguilla Cave (Jagnow 1989). Extrapolating the gradient westward to Hell Below Cave gives an estimated potentiometric surface of 991 m, which is 1052 m below the entrance. This estimate compares favorably with Polyak's estimate of an 1100 m decline in the water table since 12 Ma (Polyak et al. 1998; Polyak and Provencio 2000).

If Hell Below Cave was the site of a flowing spring early in its development, then the entrance had to be at or below the water table at that time. The present structural position and topography of the Guadalupe Mountains precludes a water table at the level of the entrance to Hell Below. There had to be aquifer continuity and sufficient elevation gain to the west to support the hydrostatic head required for a flowing spring. This means that the Salt Basin graben had not yet subsided when speleogenesis was active at Hell Below Cave. Polyak et al. (1998) did not report an age for Hell Below Cave, but did report that nearby Cottonwood Cave, which has an entrance at 2073 m, formed 12.3 Ma.

5. Discussion

Sulfuric acid enlargement of caves occurred 12-4 Ma in the Guadalupe Mountains. However, the caves that were modified by sulfuric acid speleogenesis formed earlier (Palmer and Palmer 2000). These caves formed by solution enlargement of fractures below the water table, a process that may not have involved H_2S. Age dates reported by Polyak et al. (1998) record the time of sulfuric acid dissolution at the water table, not the onset of cave development, so the absolute ages of Guadalupe caves are unknown (Palmer 2006).

The Cenozoic tectonic history of the region provides some constraints on timing of speleogenetic events. The Alvarado Ridge began to rise in early Tertiary time, and by 38-35 Ma, an elevated regional erosion surface extending across New Mexico had developed (Gregory and Chase 1992). Prior to opening of the Rio Grande Rift, the ridge was an immense upland recharge area for aquifers where groundwater flowed to the east. As pointed out by Lindsay (1998), there was strong hydrodynamic flow in the mid-Tertiary that swept oil from Central Basin Platform fields. To move oil from these reservoirs requires a stronger hydrodynamic flow than exists today, so the aquifer system must have extended farther west than the Border Fault Zone (Fig. 3). The presence of sulfuric acid caves in the high western part of the Guadalupes also indicates that the aquifer had to extend farther west.

As the Rio Grande Rift developed, the immense recharge on the east flank of the Alvarado Ridge was progressively reduced in area by extensional faulting (Fig. 4). Evidence of early rift tectonism is not recognized in Guadalupe caves. However, the interval from 14-4 Ma fits well with the 12-4 Ma cave age dates reported by Polyak et al. (1998). During this time, the elevation of the water table in the Capitan aquifer fell at least 1100 m between the westernmost caves in the Guadalupe Mountains and the deepest points in Lechuguilla Cave. The locations of cave passages and

galleries mark the position of the water table at each pulse of sulfuric acid speleogenesis. Progressively lower levels of sulfuric acid enlarged passages from west to east record the times when the water table was stable, but the vertical difference between levels reflects times when either there was no speleogenetic activity, or the water table dropped more rapidly.

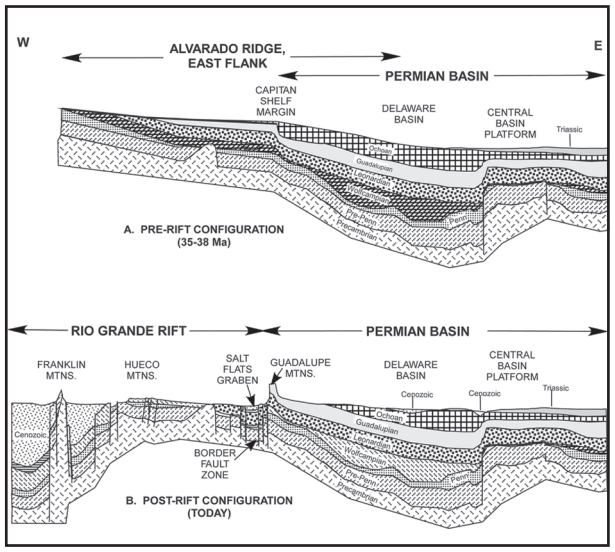

Figure 4: Cross section A shows the Guadalupe Mountains region prior to development of the Rio Grande Rift. Cross section B shows today's structural configuration. Modified from Matchus and Jones, (1984), and Lindsay, (1998, fig. 3).

Subsidence of the Salt Basin graben on the western margin of the Guadalupes began sometime between 12-4 Ma and probably contributed to the lowering of the water table in the Guadalupes. Once the graben subsided below the elevation of the lowest major passages in Carlsbad Cavern, active sulfuric acid speleogenesis in the Guadalupes ceased. This implies that the Salt Basin graben reached essentially its present configuration 3.8 Ma, the youngest age date for Carlsbad Cavern (Polyak et al. 1998), and this event brought the era of sulfuric acid speleogenesis in the Guadalupe Mountains to an end (DuChene and Cunningham 2006).

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SPELEOGENESIS OF THE NEW ENGLAND MARBLE CAVES

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The structural geology of the northern Appalachians in New England, USA, comprises a collage of some ten Caledonide terranes that have over-thrust older, Grenville-age, rocks of the Canadian Shield. Some of these terranes contain karstic metacarbonates (marbles) of Precambrian to Middle Ordovician age that are commonly highly dismembered into lenses and merokarsts, and which contain >150 known caves with >9km of passages. Because the geological inheritance is rather similar to that of the previously-studied region of Central Scandinavia, it is instructive to compare the caves from the two areas and to consider variations in their speleogenesis. In Central Scandinavia, it has been reported that cave development proceeds as a four-stage process that is governed by the repeated Quaternary cycle of glaciation, deglaciation and inter-glaciation. New England has a similar glacial history and the area provides evidence both of the deglacial seismicity that is probably necessary to create tectonic inception fractures within the marbles and of the deglacial ice-dammed lakes that enable the fractures to enlarge into phreatic conduits and cave passages by dissolution. The low angles of foliation of many New England marbles give their cave surveys a relatively planar appearance, and their mean lengths, cross-sections and volumes are rather smaller. However, the mean vertical range is comparable and subsurface cave distances are also consistently less than one-eighth of the depth of local glacial valleys, as in Central Scandinavia, suggesting that inception fractures were produced by similar processes. There are proportionately less "mainly vadose" caves, but those that exist have larger mean cross-sections, probably arising from a longer period of interglacial conditions. The New England marble caves comply with the principles of the Top-Down, Middle-Outwards model of cave development that applies in Central Scandinavia, although they commonly have less vertical complexity. It is concluded that were produced by similar processes, but that there are few "multi-cycle" caves that pre-date the Wisconsin glaciation. The relict (phreatic) caves and most "combination" caves that contain both relict phreatic and mainly vadose passages are "single-cycle" caves that started to form during deglaciation after the Last Glacial Maximum. The few mainly vadose caves are "half-cycle" caves, which enlarged to present dimensions primarily during the Holocene. Similar processes also appear to apply to the caves in the Grenville-age marbles of the Adirondack Mountains of New York state.

1. Introduction

The New England (NE) marble caves lie in the northern Appalachian part of the Laurentian Caledonides, along the western side of Vermont, Massachusetts and Connecticut. The Caledonide mountain chain was formed during the Silurian closure of the Iapetus Ocean, when sedimentary rocks were subducted to depths of tens of kilometres, metamorphosed, and then overthrust on to older basements (Gee and Sturt, 1985). The limestones, whose ages vary from Precambrian to Middle Ordovician, were converted into marble and lost their original structures. Later rifting created the Atlantic, when the original Caledonides separated into various terranes on both sides of the ocean. Subsequently, the whole north Atlantic region has undergone repeated glaciations, probably since the late Miocene, and some marbles have been karstified. The purpose of this paper is to compare the speleogenesis of these marble caves with that of marble caves in the four Caledonide allochthons of Central Scandinavia (CS), which was studied by Faulkner (2005a; 2006a; 2006b; 2007a; 2007b; 2008). He concluded that those caves commonly experience a four-stage, top-down, middle-outwards (TDMO) cycle of cave development that is driven by the glacial cycle:

1: Rapid deglacial isostatic rebound causes seismicity and forms inception fractures to a maximum distance from the surface equal to one-eighth the depth of the local glacial valley (tectonic inception)

2: Phreatic passages enlarge beneath flowing deglacial ice-dammed lakes (IDLs) over periods up to 2000 calendar years at relatively high wall-retreat rates, despite low

temperatures and low P_{CO2} (deglacial speleogenesis)

3: Mainly vadose passages entrench during interglacials (interglacial speleogenesis)

4: Glacial erosion removes whole caves or their upper and outer parts during the next glaciation (glacial removal)

2. New England Carbonate Geology

The structural geology of NE is more complex than that of CS, because the area comprises a collage of some ten Caledonide allochthons that have over-thrust older, Grenville-age, rocks of the Canadian Shield. The thrust slices culminate in the Taconic Allochthons along their western extremity (Keppie, 1985). Where they occur, the karstic metacarbonates are commonly highly dismembered into lenses and merokarsts with low angles of dip, rather than into the long north–aligned steeply-foliated stripe karsts that dominate much of CS. Faulting, jointing and thrusting at a local scale also occur. Individual metacarbonate blocks were sporadically transported across more competent rocks, and unconformities between rock types are sharply delineated. For example, it is sporadically possible to insert a hand between the upper surface of a marble outcrop and an overlying phyllite. Metamorphism varies from high to low grade, in a south–north direction, and intrusions are common at higher grades. Some (short) caves are recorded in Winooski and Dunham "Dolomites" (Quick, 1994), although these probably refer to dolomitic limestones rather than to pure dolomite. The area is characterised by north–south aligned valleys extending from altitudes below c. 200m up to vegetated ridges and peaks, some being above 1,000m.

3. New England Glacial History

The glacial history of NE is rather similar to that of CS. As with its counterpart in Europe, the Wisconsin glaciation also appears to have had less magnitude than the two previous glaciations (Andersen and Borns, 1994, p40). According to Dyke et al. (2002) and Marshall et al. (2002), the icesheet thickness at the Last Glacial Maximum (LGM) increased from zero off the coast at Boston, via 1500–2500m across the Caledonides, to >3000m above Hudson Bay (when it may have extended over many basins of warm-based glaciation with subglacial lakes). Northern America apparently experienced several subsequent deglaciation / reglaciation phases (Dyke and Prest, 1987; Johnson and Lauritzen, 1995), with north–south flow-switching as the Great Lakes region alternately melted and froze between the LGM and the Holocene (Clark et al., 2001). This may explain why a few caves contain five or six cycles of rhythmic deposition of clay sediments and larger material (R. Pingree, pers. comm., 2002). Wisconsin deglaciation was probably complete in NE by c. 13000^{14}Ca BP (Dyke and Prest, 1987; Andersen and Borns, 1994), c. 4000^{14}Ca earlier than in CS, and the impact of Younger Dryas cooling was much attenuated inland (Cwynar and Spear, 2001). Depositional evidence for the later stages of IDL evolution adjacent to retreating ice margins that moved from SE–NW (Stone and Borns, 1986, Fig. 1) has been reported by (e.g.) Clark and Karrow (1984: glacial Lake Iroquois at 329m altitude); Bierman and Dethier (1986: Lake Bascom, at >317m initially); Parent and Occhietti (1999: Lake Candona, which coalesced with the 125km-long Glacial Lake Vermont); Ridge and Larsen (1990) and Ridge et al. (1999): Lake Hitchcock; Rayburn et al. (2007); and Thieler et al. (2007). Prior to this stage, only LaRocque et al. (2003) appear to have discussed the top-down melting of ice from mountain ridges that created static nunatak IDLs (when there was little sediment to be deposited), which later evolved into active IDLs as the ice sheet lowered. The author is unaware of any local models of early deglaciation with high-level IDLs that equate to the work of Grønlie (1975), who studied geomorphological features to calculate the rate of ice sheet lowering in CS, or to the thesis of Faulkner (2005a), who showed that all parts of inland CS were submerged beneath lowering IDLs for periods up to 2000 calendar years during deglaciation, with outlet flows into englacial Röthlisberger and / or subglacial Nye channels. However, it is assumed in this paper that similar processes applied in NE, so that local IDL flow regimes could also integrate with any underlying karst hydrology.

The Holocene uplift for the area varies south to north from c. 60–180m (Andersen and Borns, 1994, p18). The Atlantic coast contains many non-carbonate sea caves at and above the present sea level, where Rubin et al. (2002) discussed evidence of raised sea levels (including elevated sea caves, sea stacks and boulder beaches) on Mount Desert Island, Maine. However, the sea caves all have entrances that are only a few metres high, with a complete absence of *very tall* entrances (Rubin, pers. comm., 2002). This may indicate that the sea froze here before there was significant isostatic depression at the onset of the Wisconsin glaciation, suggesting that there was no *glaciation* marine limit equivalent to one in CS suggested by Faulkner (2005b). However, as the karst areas are c. 180km from the coast at elevations >200m, probably none of the caves could have been inundated by the sea during either glaciation or deglaciation events, and the construction of local isobase maps is less relevant in NE to an understanding of cave development. The well-documented existence of many 'tectonic fissure', 'fracture',

and 'talus' caves in a variety of metamorphic rock types provides evidence that this area also experienced many severe seismic shocks following rapid deglaciation and uplift, perhaps comparable to those experienced in eastern Sweden (e.g. Mörner, 2003). The seismicity in *northern* NE was probably greater than that in CS, because, being nearer to the centre of the icesheet (in a position more comparable to eastern Sweden) the thickness of ice removed was even greater. However, the majority of the karst caves are located in the southern part of NE, where deglacial seismicity was probably less severe.

4. New England Karst Caves

A desk-based study of 153 marble caves was completed in 2004 by extracting information from Quick (1994) and from the *NE Caver* magazine into a North American Caledonides cave database, which is based on MS Excel. The database is incomplete, because location and altitude information is commonly suppressed in northern America (to protect the interests of property owners). However, the recording of karst type, cave type, cave hydrological class, main dimensions, entrances and hydrology was achieved to the definitions used by Faulkner (2005a) in CS, mainly from the well-presented cave surveys and descriptions. It is anticipated that these data are representative of the state of knowledge prior to 2004. About 9 km of passages are known, and the completeness of exploration may be higher than in CS, because groups of active cave explorers live locally in NE, although many karst outcrops and potential cave entrances are covered by extensive vegetation and glacial till. The author also made brief field trips to NE in November 1996 and June 2002, visiting five of the caves.

The NE cave surveys do not have the same "feel" as those in the steep stripe-karst outcrops of the Helgeland Nappe Complex in CS. The reason is apparent from Table 1, which shows that 52% of the NE caves occur in *low angle karst* (L, commonly monoclinal, with dip ≤30°). Some 12% are in *angled stripe karst* (A, ≤80°), and *none* occur in *vertical stripe karst* (V). The karst type for 37% of the caves is unknown (X), but many of these (shorter) caves are probably also in low angle karst. Consequently, NE cave surveys are commonly less linear than in CS, and, with the strong faulting and jointing, some caves display "fissure network" patterns (Palmer, 1991). With a mean length of only 59m, the caves are commonly shorter than those in CS: the longest (**Aeolus Bat Cave**, VT) is only 900m long. The mean cave cross-section (XS, 2.9m^2) and volume (234m^3) are correspondingly smaller. However, at 9.3m, the *mean* vertical range (VR) is remarkably similar, and slightly deeper caves probably occur in karsts with lower dip angles, as in CS. The deepest (**Purgatory System**, VT) has a VR of 82m and a maximum subsurface cave distance of c. 40m. The passage with the greatest distance to the surface (68m) is in a deep sump in **Morris Cave** (VT). This is situated in a glaciated valley whose floor is at about 210m between peaks above 1,000m. Thus, the known distance of its deepest passage from the surface is well-within the one-eighth constraint that was proposed for the deglacial creation of inception fractures in CS during early fast uplift. The caves also commonly contain large amounts of breakdown on chamber floors away from entrance areas and there are few chambers with smooth floors, suggesting that the caves were subjected to large seismic shocks. The author's 2002 visit to **Nickwackett Cave** and **Chaffee Mountain No. 2 Cave** (VT) revealed evidence of internal tectonic movements of up to 15cm. The breakdown there is commonly covered by clay, suggesting phreatic deposition after the last deglacial earthquake to modify an existing passage. Cave passages sporadically occur at junctions of two marble lithologies,

	New England						Central Scandinavia					
Karst Type (See text)	**V**	**A**	**L**	**C**	**X**	**ALL**	**V**	**A**	**L**	**C**	**X**	**ALL**
Count		18	79		56	153	235	480	127	3	39	884
% of caves		11.8	51.6		36.6	100.0	26.6	54.3	14.4	0.3	4.4	100.0
Total cave length (km)		1.37	6.33		1.39	9.09	20.25	37.79	12.64	2.91	1.30	74.88
% of total cave length		15.2	69.7		15.2	100.0	27.0	50.5	16.9	3.9	1.7	100.0
Mean cave length (m)		76	80		25	59	86	79	100	968	33	85
Mean cave VR (m)		9.7	11.2		6.4	9.3	8.6	9.0	9.5	17.3	5.5	8.8
Mean cave XS (m^2)		1.6	3.0		3.1	2.9	3.0	3.8	3.8	3.2	3.1	3.5
Mean cave Vol. (m^3)						234						474

Table 1: New England and Central Scandinavian Karst Types compared.

where tectonic inception fractures are likely to be created, as at **Eldons French Cave** (MA) and at **Morris Cave**.

The caves in CS were divided among three hydrological classes by Faulkner (2005a): *relict caves* (which are almost all phreatic and are not fed by present allogenic recharge), *mainly vadose* (MV) *caves* (which may contain sumps) and *combination caves* (which contain both relict phreatic passages and levels and MV passages). From Table 2, over half the caves in NE are relict, a third are combination caves, and only 13% are MV caves. This represents a much larger proportion of relict caves and smaller proportions of both combination and MV caves than in CS, suggesting that Holocene vadose development was less important than deglacial phreatic development in NE. However, although combination caves commonly have the largest dimensions, the few MV caves commonly have larger dimensions than the short and extremely epigean relict caves, whose mean VR is only 5.3m. Entrance occurrences decrease in combination caves in the order *Dry Entrance* (DE): *Sink Entrance* (SE): *Resurgence Entrance* (RE), as in CS, but with smaller mean frequencies. Both combination and MV caves have slightly more cave streams per cave (CR), but far fewer sump pools (SP). Whereas relict and combination caves have mean XSs 16% and 31% smaller than in CS, the relatively few MV caves are 62% larger. The reason for the greater development of the active vadose parts of caves is probably that NE interglacial conditions started earlier than in CS (above), giving more time for vadose enlargement and / or entrenchment, and reducing the number of sumps by extra chemical and mechanical erosion of sump roofs and by the deeper down-cutting of pocket valleys. They may also have larger catchment areas and shorter periods of winter freezing (not studied), but, as in CS, there are no glaciers or perennial snowfields to provide sustained meltwater recharge in summer.

As expected from their elevations above probable marine limits, the caves do not contain entrances that were obviously enlarged by marine action. The greater sizes of entrance passages with parallel walls compared with internal passages are diagnostic of a pre-existing passage that has enlarged by ice-wedging as an IDL lowered past it (Faulkner, 2007c). The entrances to **Aeolus Bat Cave** (VT), **Skinner Hollow Cave** (VT), and at the resurgence of **Horse Farm Road Cave** (VT) (Quick, 1994) appear to satisfy these criteria, indicating their existence prior to final deglaciation. However, many entrances in NE are vertical shafts into

	New England				Central Scandinavia				
INTERNAL CAVE ATTRIBUTE	**RELICT CAVES**	**COMBIN-ATION CAVES**	**MV CAVES**	**ALL CAVES**	**RELICT CAVES**	**COMBIN-ATION CAVES**	**MV CAVES**	**ALL CAVES**	**UNITS**
Count	81	52	20	153	279	360	245	884	No.
% of caves	53	34	13	100	31	41	28	100.0	%
Total cave length	1.998	6.189	0.900	9.087	9.417	58.995	6.469	74.881	Km
% of total cave length	22.0	68.1	9.9	100.0	12.6	78.8	8.6	100.0	%
Mean cave length	25	117	45	59	34	164	26	85	M
Mean cave VR	5.3	14.8	10.7	9.3	5.9	14.5	3.9	8.8	M
Mean cave XS	2.6	3.1	3.4	2.9	3.1	4.8	2.1	3.5	m^2
Mean cave Volume	75	473	237	234	131	1020	62	474	m^3
Average of DE	1.16	0.68	1.00	0.97	1.41	0.97	0.40	0.95	No. per cave
Average of SE	0.00	0.38	0.80	0.24	0.00	0.50	0.58	0.37	No. per cave
Average of RE	0.00	0.21	0.20	0.10	0.00	0.21	0.34	0.18	No. per cave
Average of all entrances	1.16	1.27	2.00	1.31	1.41	1.68	1.32	1.50	No. per cave
Average of CR	0.00	1.23	1.15	0.58	0.00	1.13	1.04	0.75	No. per cave
Average of SP	0.00	0.47	0.15	0.18	0.00	0.80	0.39	0.43	No. per cave

Table 2: New England and Central Scandinavian Cave Hydrological Class comparisons.

lower passages, where ice wedging would be less effective, or are themselves steep, shattered, passages. Although an analysis of variation with altitude has not been attempted, it seems likely that carbonate outcrops, cave occurrences and cave dimensions are primarily independent of altitude, as in CS, especially above 300m, up to which Quick (1994) reported that the thicker glacial deposits in the Vermont Valley extend. The absence of reports of entrances situated very near peaks or ridge summits suggests that, also as in CS, few caves exist in a situation that was only submerged by a static nunatak IDL during deglaciation. However, as the NE marble outcrops commonly dip at rather low angles, their vertical distribution may not be as random as in CS, and an absence of very high altitude caves could arise from a corresponding lack of limestone at such elevations (not studied).

A study of the NE cave surveys found only six *relict* vadose passages, which is even less proportionately than in CS. As none appear to lie above subsequently-formed phreatic passages, they provide no evidence that any combination caves started their enlargement prior to the final glacial cycle. Only one occurs in a relict cave (**Bat's Den Cave**, MA), and so relict caves were predominantly formed phreatically, as in CS, and therefore before the area was completely deglaciated. There is no reported dating of speleothems to give any non-geomorphological indication of passage age, and significant speleothems are rare, as in CS, suggesting a Holocene age for those that do occur. The only indication of possible multi-cycle cave development may therefore be the diameter of some passages, as in **Aeolus Bat Cave.** This, and the vertical complexity of the cave, hints that it may have developed over several glacial cycles. However, the mean XS of both relict and combination caves is less than in CS, which suggests that the total time that most of these caves remained submerged by flowing deglacial IDLs was less than the 1,000–2,000 years assumed in CS. This author's observation of two sizes of scallops in **Nickwackett Cave** (about 10 and 30 cm), giving approximate flow-rates of 40 and 13cms^{-1} (both southwards) are similar to the major rates deduced for flows beneath IDLs in CS.

5. New England Summary

Deglacial seismicity (as suggested by Quick, 1994) is confirmed by the existence of many talus and fracture caves and by movements within the karst caves themselves, which are suggestive of tectonic inception, and the area provides much evidence of low-level deglacial IDLs. The mean cave length, XS and volume are rather smaller than in CS, but the mean VR is comparable and subsurface cave distances consistently lie within the one-eighth relationship. There are proportionately less MV caves, but they have larger cross-sections than the MV caves in CS, probably because of the longer period of interglacial conditions. Valley-deepening in CS is probably in the range 15–55m per 100ka glacial cycle (Lauritzen, 1990). A comparable figure for NE is not known, but even if it is as low as 10m, then >50% of these epigean caves will be removed in the next glaciation. Hence, most existing relict and combination caves are probably 'single-cycle' caves that only enlarged after the Wisconsin LGM. They commonly have less vertical complexity than those in CS, and comply with the principles of the TDMO model of cave development. The few MV caves are 'half-cycle' caves, which enlarged to present dimensions after deglaciation and during the Holocene, perhaps after a deglacial phreatic initiation. Multi-cycle caves that developed over more than one glacial-interglacial period seem rare in NE, but may include **Aeolus Bat Cave**, plus **Morris Cave** and **Quarry Cave**. These two caves also contain rare abundant clay deposits (Quick, 1994) that suggest deposition in almost static water, perhaps in a pre-existing passage beneath a subglacial lake at the height of glaciation, or during post-LGM reglaciation phases (above). It is concluded that the marble caves in NE were formed by processes similar to those in CS, but that they developed over several glacial cycles even more rarely.

6. Caves in the Adirondack Mountains of New York

The significant caves in the marbles of the Canadian Shield were not included in the North American Caledonides cave database, being outside the Caledonide terranes. However, visits in 1996 and 2002 to six marble caves in the Adirondack Mountains, which are situated in 1–1.3Ba Grenville-age crystalline marbles with large grain sizes, support a conclusion that these marble caves also fit within the conceptual Caledonide models described by Faulkner (2005a). For example, **Crane Mountain Cave** contains many large dykes and sills, presumably of amphibolite (as does **Browns Cave**), and one of these forms the roof of the downstream sump. Although the cave is primarily in a low angle karst, with a dip of about 30° NE, the first two waterfalls occur where the rock is folded complexly.

A vertical fracture at the entrance shows tectonic movement, apparently with broken calcite, and at the base of the second waterfall is a fault with slickensides 15cm long, weathered to black. The commercial **"Natural Stone Bridge and Caves"** (Fig. 1) consists of a large stream captured by a large, complex, phreatic series of sumps beside a normally-dry limestone gorge. This has small rockmills in its floor,

indicating formation during deglacial outflows. **Rusty Stove Cave** has an obvious tectonic movement along a fracture on the left side of its entrance. The cave itself has formed along a dyke wall, which is breached at an inner chamber. The nearby **Burroughs Cave** has two moved joints orthogonal to the entrance passage that are about 10m apart. It contains the large Breakdown Chamber, formed by upward stoping of collapsed blocks, with no dissolution evident above its lowest level. The karst cave with the greatest VR is **Crane Mountain Cave** (about 30 m). All these caves also fit within the one-eighth constraint for depth of exploited fractures. The local presence of large numbers of talus and fissure caves also supports the concept of fracture generation by postglacial seismicity. These caves were also likely inundated by deglacial IDLs, and thus these and other marble caves in the Canadian Shield probably also comply with the speleogenetic concepts of the TDMO model.

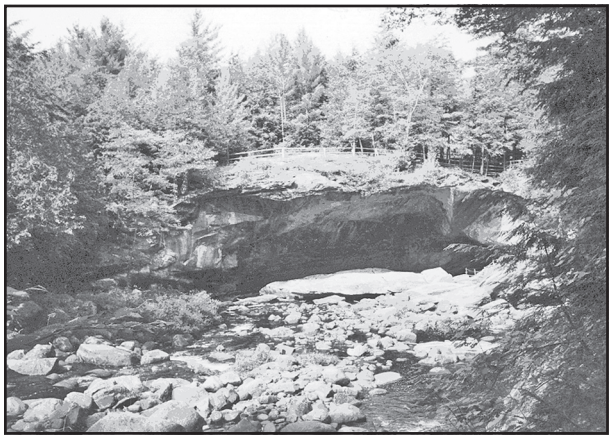

Figure 1: Sink entrance at Natural Stone Bridge (NY) showing the common epigean nature of marble caves.

7. Newfoundland

The island of Newfoundland forms a tectonic structural link between the northern Appalachians and the British Caledonides (van Staal et al*.,* 1998, p213), comprising an assemblage of some six terranes with similarities to those of Britain and Ireland. However, the Dalradian Supergroup of the British Isles, with its metamorphic carbonate outcrops, appears to narrow considerably in Newfoundland, either within the Notre Dame Subzone or in its outlying Fleur de Lys Supergroup. These subzones do not appear to contain significant marbles, and no karst caves are reported there. The scattered outcrops of the Taconic Allochthons on the west of the island mainly consist of igneous and plutonic rocks. The Humber Zone on the St. Lawrence promontory contains large outcrops of sedimentary carbonates of Cambrian and Ordovician age, similar to the Durness Group limestones of northern Scotland (RA Gayer, University of Cardiff, pers. comm., 1998). Higham (2001) reported a 780m-long karst cave in this limestone, together with other exokarst features. He also noted the existence of many sea caves from all over the island, with entrances up to 15m high, but not elevated above sea level. The speleogenesis of caves in sedimentary limestones adjacent to the glaciated Caledonides in Newfoundland and elsewhere awaits detailed study.

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THE GENERAL MODEL OF CAVE DEVELOPMENT IN THE METALIMESTONES OF THE CALEDONIDE TERRANES

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A general cave development model is proposed that applies throughout the metacarbonates of the non-arctic Caledonide terranes in Scandinavia, New England (USA) and the British Isles, which have comparable geological structures and which experienced similar Quaternary glacial events. It builds on a previously-reported four-stage process for the inception and development of >1000 caves in the repeatedly-glaciated metalimestones of Central Scandinavia. The rankings of maximum and mean cave length and vertical range, and mean cave cross-section are commonly in the same order for each of five main Caledonide regions, and this ranking order is similar to that of local icesheet thicknesses at the Last Glacial Maximum, local Holocene uplifts and maximum relief differences. It is therefore concluded that the main control on the extent of karstification in the non-arctic Caledonides is the thickness of the local Pleistocene icesheets. Thus, the greater karstification in Northern Scandinavia arose partly because the thicker icesheets and the higher mountains caused greater deglacial and neotectonic seismic activity. This produced longer and deeper inception fractures and caused deeper deglacial ice-dammed lakes to form that enabled underlying fractures, conduits and cave passages to be enlarged by phreatic dissolution for longer periods of time, and sporadically over more glacial cycles.

1. Introduction

The rocks of the metamorphic Caledonides derive their composition and structure from a highly-complex system of mountain building associated with the plate tectonic opening and closing of the Iapetus Ocean, from Late Precambrian to Mid Palaeozoic times: the Caledonian Orogeny (Gee and Sturt, 1985). After the final thrusting over older basement rocks in the early Devonian, the Caledonian–Appalachian fold and thrust mountain belt formed a continuous linear chain extending some 10000km from what is now Spitsbergen to the modern Gulf of Mexico. Subsequent orogenies and the later opening and spreading of the Atlantic Ocean caused it to be broken up into some 20 geographically-dispersed terranes, which now reside on both sides of the Atlantic (Barker and Gayer, 1985). In Scandinavia, the tectono-stratigraphic structure comprises four allochthons that overthrust and rest unconformably on the Baltic Shield. The more westerly nappes were subjected to deeper subduction and higher-grade metamorphism, so that the grade of the nappe pile generally increases from sub-greenschist facies at the base up to medium amphibolite facies at the top, in an E-W direction. The whole region was covered by an ice sheet 2–3km thick at the Last Glacial Maximum (LGM). The non-arctic terranes in Scandinavia, Shetland, Scotland, Ireland, and New England contain metamorphic carbonates (marbles), most hosting karst caves. Faulkner (2005) studied the speleogenesis of 884 well-reported marble caves in Central Scandinavia (CS), concluding that these caves commonly experience a four-stage, top-down, middle-outwards (TDMO) cycle of cave development that is driven by the glacial cycle (Faulkner, 2008):

1: Rapid deglacial isostatic rebound that follows retreating ice margins causes seismicity and centimetre-scale movements, which form inception fractures to a maximum distance from the surface of one-eighth the depth of the local glacial valley (tectonic inception: Faulkner, 2006a; 2007a; 2007b).

2: Phreatic passages enlarge from inception fractures at high flow rates beneath deglacial ice-dammed lakes (IDLs) at relatively high wall-retreat rates over periods up to ~2000 calendar years, despite low temperatures and low P_{CO2} (deglacial speleogenesis: Faulkner, 2006b).

3: Mainly vadose passages entrench at the lowest levels during interglacials at a rate constrained by the size of the local catchment area (interglacial speleogenesis).

4: Glacial erosion removes whole caves or their upper and outer parts during the next glaciation (glacial removal), but valley-deepening in the range 15–55m (Lauritzen, 1990) produces ever-deeper inception fractures at the next cycle.

Excel cave databases were constructed for most metacarbonate Caledonide regions from the best information available in 2004. These are discussed briefly and their data compared with CS. From the similarities in the geological and glaciological evolution of the various non-arctic Caledonide terranes, they appear to follow similar processes, providing a general model for cave development throughout the marbles of the whole non-arctic Caledonide system.

2. Northern Scandinavia

Northern Scandinavia (NS), north of the Helgeland Nappe Complex (HNC) of CS, contains many karst caves, several being much longer and / or deeper than any in CS. To analyse this large region would be a task even greater than that for CS. Instead, the, hopefully-representative, karstic valley of Gråtådal (St.Pierre, 1966) is considered, together with a few of the longest and deepest systems. The Gråtådal caves commonly lie in long, linear, N–S aligned, outcrops of amphibolite grade marbles that lie along the valley floor and its lower western slope. The foliation commonly dips steeply into the west side of the valley, or is vertical. The outcrop width varies up to some 700m, so that, although caves are commonly strike-aligned, passages also exploit orthogonal joint systems. This geological setting is similar to that in the HNC, except that the western mountains are permanently glaciated. Some 7 km of passages in 42 caves occur in this area, which is characterised by large, almost 'over fit', underground streams that are sporadically too powerful to be explored. The Gråtådal caves have mean dimensions much greater than those in CS (Table 1): their mean length and vertical range (VR) are twice as great, and mean cross-section (XS) is about four times greater, so that this set of caves would *not* fit comfortably within the zones into which CS was divided. However, the deepest cave, **Rønålihullet** (140m), is well within the one-eighth constraint (above), because it lies in a valley some 1100m deep below a valley wall that slopes down above the cave, reducing its maximum subsurface cave distance to c. 30m. As in CS, there are roughly equal numbers of caves in each of the three hydrological classes of *relict caves* (which are almost all phreatic and are not fed by present allogenic recharge), *mainly vadose* (MV) *caves* (which may contain sumps), and *combination caves* (which contain both relict phreatic passages and levels and MV passages). The relict caves have about twice the mean length and XS as those in CS, and the combination caves have twice the mean length and VR, and five times the mean XS. The MV caves follow similar trends, with four times the mean length. The larger mean VRs of the active caves are accounted for by the greater tectonism visible in the valley (Olesen et al., 2004), which probably arose from its considerable depth that caused greater deglacial seismicity. Similarly, the large lengths and VRs in other areas of NS arose from the greater seismic activity north of Ranafjord (Dehls et al., 2000). Increased frequency and magnitude of deglacial and neotectonic earthquakes caused by deeper valleys means that the one-eighth constraint can be approached more closely in more areas, so increasing the overall lengths and densities of inception fractures, thereby providing larger frameworks in which individual cave systems can develop. Because the mountains are higher, it is also likely that caves enlarged beneath deglacial IDLs for longer periods of time in NS, resulting in a larger mean XS for the relict phreatic passages. Holocene vadose entrenchment by enhanced summer recharge from glaciers and perennial snowfields in Gråtådal was much more vigorous, creating the very large stream passages. The roofs of many previous sumps were raised above water level by a combination of chemical and strong mechanical erosion, and resurgence sumps were lowered by the faster down-cutting of the external pocket valleys, to create more caves of the 'late interglacial' stage of the TDMO model (Faulkner, 2008). From the Gråtådal observations and those of other northern caves, it seems likely that most of these caves developed generally as in CS, some with possible enhanced vadose entrenchment from Holocene glacial recharge.

Elsewhere in NS, the shafts and passages in the deepest cave, **Rågge Javre Raige** (>580m to a submarine resurgence), remain within 173m of the wall of a fjord that is 455m deep below peaks at 1200m, and thus this cave also remains within the one eighth constraint. However, the constraint is dramatically breached in at least three deep caves. The **Greftkjelen / Greftsprekka** system is formed in high-grade complexly-folded marbles. Here, inception seems to be tectonic, with synclinal / anticlinal folding enhancing the formation of deep, probably open, joints, but this tectonic activity may have been caused by much longer-timescale, possibly aseismic, processes, such as the general uplift of the Scandinavian landmass, or the spreading of the Atlantic Ocean, rather than by deglacial seismicity. Thus, with a completely different process involved, the one-eighth constraint need not apply. Such a mechanism may also contribute to the depths of **Tjoarvekrajgge** and **Okshola / Kristihola**, which occur in only medium grade low angle karsts, and which both form long and deep maze networks. The deepest cave in CS (**Ytterlihullet:** 180m deep) has also formed in low angle karst, although it is in high-grade marble and complies with the one-eighth constraint. Thus, it seems that endokarst formation in low angle marbles is more likely to favour fractures that are aligned with the foliation,

CAVE CLASS and AREA	No. of caves in class	% of caves in class	Total cave length in class (m)	% of total cave length in class	Mean cave length (m)	Mean cave VR (m)	Mean cave XS (m^2)	Mean cave volume (m^3)
RELICT								
Gråtådal	13	31	963	13	74	4.7	6.3	168
C. Scandinavia	280	32	9437	13	34	5.9	3.1	131
S. Scandinavia	*11*	*23*	*117*	*3*	11	5.7	2.0	18
New England	81	53	1998	22	25	5.3	2.6	75
Scotland	42	28	745	18	18	5.9	1.9	44
Ireland	*8*	*67*	*142*	*34*	18	5.6	2.8	70
RC TOTALS	**435**	**34***	**13401**	**13***	**31**	**5.7**	**3.0**	**110**
COMBINATION								
Gråtådal	14	33	4925	67	352	33.6	24.9	3372
C. Scandinavia	360	41	58995	79	164	14.5	4.8	1020
S. Scandinavia	*16*	*34*	*3454*	*81*	216	17.6	5.9	1902
New England	52	34	6189	68	117	14.8	3.1	473
Scotland	55	36	2736	64	50	8.9	2.8	175
Ireland	*4*	*33*	*276*	*66*	69	12.5	5.1	314
CC TOTALS	**501**	**39***	**76575**	**76***	**153**	**14.5**	**5.0**	**959**
MAINLY VADOSE								
Gråtådal	15	36	1474	20	98	10.2	8.8	808
C. Scandinavia	244	28	6449	9	26	3.9	2.1	62
S. Scandinavia	*20*	*43*	*667*	*16*	33	4.3	2.5	96
New England	20	13	900	10	45	10.7	3.4	237
Scotland	55	36	744	18	14	2.9	1.6	25
Ireland	*0*	*0*	*0*	*0*	0	0.0	0.0	0
MV TOTALS	**354**	**27***	**10234**	**10***	**29**	**4.4**	**2.4**	**100**
ALL CLASSES								
Gråtådal	42	3.3*	7362	7.3*	175	16.3	13.4	1465
C. Scandinavia	884	68.5*	74881	74.7*	85	8.8	3.5	474
S. Scandinavia	*47*	3.6*	*4238*	4.2*	90	9.1	3.5	692
New England	153	11.9*	9087	9.1*	59	9.3	2.9	234
Scotland	152	11.8*	4225	4.2*	28	5.9	2.1	84
Ireland	*12*	0.9*	*418*	0.4*	35	7.9	3.6	151
GRAND TOTALS	**1290**	**100**	**100211**	**100**	**78**	**8.8**	**3.6**	**437**

*Table 1: Caledonide Caves - hydrological classes and major dimensions. *= % of all caves. Values in Tables 1 and 3 for areas with small sample size or lower quality data are shown in italics.*

and can thus carry water to deep outlets in favourable local topography. In these cases, the fractures can act more like the inception horizons of sedimentary limestones (Lowe and Gunn, 1997), so that chemical inception may become more important than tectonic inception, especially if the limestone is only weakly metamorphosed.

3. Southern Scandinavia

Southern Scandinavia (SS) comprises the Caledonide nappes south of CS. These caves are reported poorly, but a database of 47 better-documented caves (out of c. 70) was constructed that includes some estimates of VRs and XSs. Nothing seems remarkable about these caves, which are assumed to follow the processes described for CS.

4. New England

The Caledonide area of interest in northern America comprises the northern Appalachians on the western side of Vermont, Massachusetts and Connecticut. Its >150 caves with >9km of passages are compared with CS in a companion paper (Faulkner, 2009). Deglacial seismicity is confirmed by the existence of many talus and fracture caves and by movements within the karst caves themselves, and local deglacial IDLs have also been reported. The mean length, XS and volumes are rather smaller than in CS, but the mean VR is comparable and subsurface cave distances consistently lie within the one-eighth constraint. There are proportionately less MV caves, but they have larger XSs than those in CS, probably because this area was deglaciated c. 4000 years earlier than CS.

5. British Isles

In Scotland, the Caledonide Dalradian Supergroup (Grampian) terrane correlates with the eastern part of Shetland, with the Dalradian Supergroup in Donegal, and with a displaced Dalradian terrane in Connemara. Whereas the Grampian terrane and the Uppermost Allochthon of Scandinavia *"have never been correlated, it would be fair to say that they have similar tectonic status and position"* (R. Gayer, University of Cardiff, pers. comm., 1998). This explains the great similarities between the metacarbonate outcrops and their karst caves in Scotland and those in the HNC. British and Irish glacial history followed the CS pattern but, being farther south in a more oceanic setting with smaller and thinner ice caps (especially at Shetland), the glaciations were less intense, and more difficult to interpret, and deglacial IDLs more short-lived, although perhaps more frequent. Several "tectonic fissure" or "fracture" caves support the evidence that this area also experienced seismic shocks and tectonic movements following rapid deglaciation and uplift at the start of both the Windermere Interstadial and the Holocene (Davenport et al., 1989), and the author has always been successful when looking for signs of tectonic movement in the Scottish marble caves (e.g. Fig. 1). Thus, the formational processes are probably similar to those in CS. The Grampian Terrane also contains >150 karst caves, with >4km of passages. Although the proportion in each hydrological cave class is similar to that in CS, they have much smaller mean dimensions, with less vertical complexity. Only 12 caves are recorded in the Irish Caledonides, with a sparse written record. Their mean cave dimensions are slightly larger than those in the Scottish Caledonides, but no MV caves are recorded. Probably more caves wait to be found, and the dimensional similarities with Scotland will be strengthened.

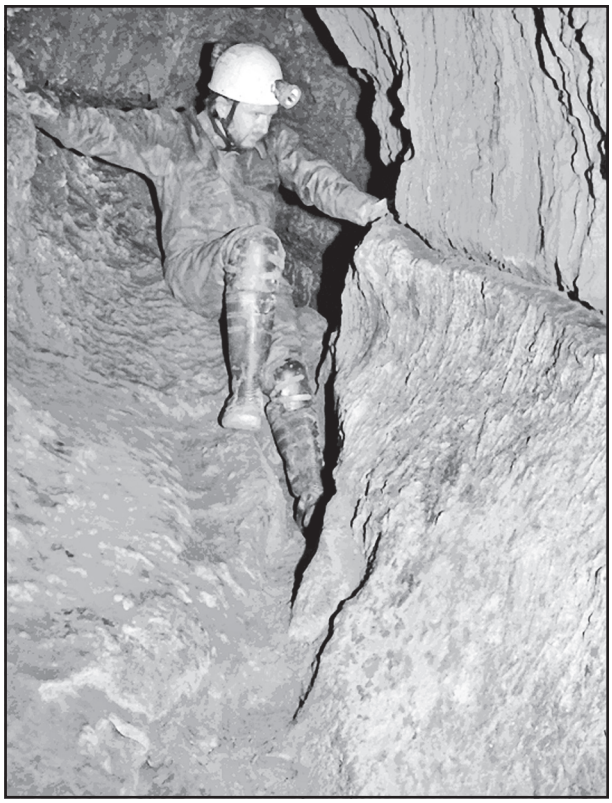

Figure 1: Tectonic movement in Poll Seomar. Movement of ~10cm after the formation of the passage in angled stripe karst. Both photos by Ivan Young.

The absence of endokarst and the paucity of exokarst (with dolines <2m deep) on Shetland, confirmed during a visit in 1999, seem paradoxical. However, the greatest relief across a limestone valley is only 250m. Thus, the maximum depth of tectonically-produced inception fractures is only some 30m, from the one-eighth constraint, but even this is too generous, because the probable maximum thickness of ice of only 200–300m (Mykura, 1976) would only permit much lower intensity deglacial seismic shocks. An

even more important factor is that the sea level has been continuously *rising* during the Holocene, creating inland waterways (Mykura, 1976). Shetland lies in the forebulge area of both Scandinavia and Scotland, so that as these lands were depressed isostatically during each glaciation, Shetland actually rose. The process was then reversed during interglacials, with Shetland falling as Scandinavia and Scotland re-adjusted upwards. This interglacial depression of Shetland suppressed neotectonic seismicity in its immediate area (Bungum, 1989), as did the smothering effect of ice during its enforced isostatic uplift (Johnston, 1987). Hence, Shetland did not experience the seismic activity necessary for the creation of inception fractures at any time during the last glaciation, could not enter the phreatic phase of passage enlargement, and has not been able to develop any conduits deeper than c. 2m during the Holocene. Mykura (1976) also reported that Shetland has fallen by at least 82m during the Quaternary. Thus, previous glacial and interglacial conditions at Shetland were similar to those observed for the Devensian and Holocene, so that karst caves probably *never* developed on Shetland during that period.

6. The General Caledonide Model for Cave Development

The similarities in many mean cave dimensions (Table 1) and in the numbers of entrances, cave streams and sump pools per cave (Faulkner, 2005) across all areas for each hydrological class do suggest that similar processes have operated across most Caledonide terranes, but with two extra processes applying to NS and a null-process applying to Shetland (Table 2). The rankings of maximum and mean cave length, maximum VR, and mean cave XS (Table 3, columns 2, 3, 4 and 6) are in the same order for each of the five better-documented areas: NS (largest caves, using Gråtådal as an example for mean cave dimensions); CS; New England; Scotland; and Shetland (zero caves). Only the ranking of the mean cave VR (column 5) is slightly different, probably because of the meticulous recording of small caves in CS. This uniformity in ranking of the major cave dimensions suggests that the differences *between* the

Caledonides	Observations	Processes and Controls
Scandinavian -Northern	Has the longest, deepest and largest caves, as exemplified in Gråtådal. Mean cave dimensions for the whole of NS are unknown, but they are probably greater than those of CS.	Commonly, high local relief caused large deglacial seismic shocks. Exceptionally, **very deep tectonic movement** violates the one-eighth constraint, as can also occur in extensive low angle karsts (which may utilise inception horizons). Locally, **recharge from permanent glaciers** produced larger relict passages, greater vadose entrenchment and fewer sumps.
Scandinavian -Central	The author's main study area (Faulkner, 2005; 2008).	Provides the 'standard' four-stage process against which other areas may be compared
Scandinavian -Southern	Less well studied, and small sample size. No caves in Vertical Stripe Karst.	Follows the 'standard' process, with controls similar to those in CS.
Laurentian - New England	Reduced cave dimensions (except VR) and proportionately more Relict and less MV caves compared with CS. No caves in VSK.	Follows the 'standard' process. This may also apply to caves in metacarbonates of the Grenville-age Canadian Shield.
British -Scotland	Reduced cave dimensions, compared with CS and New England. No caves in low angle karst.	Follows the 'standard' process, but with smaller phreatic enlargements under shorter-lived IDLs, and less vadose entrenchment from shorter spring melts. The one-eighth relationship is too generous in the east, where the Devensian icesheet was not continuous.
British -Ireland	Less well studied, and small sample size. Mean dimensions comparable with Scotland.	Probably follows the 'standards' process. Unknown reason for apparent absence of MV caves.
British -Shetland	There are long metacarbonate outcrops in this terrane, but no karst caves.	Low relief, thin icesheets, and **continual interglacial isostatic depression** has suppressed tectonic inception and always prevented cave formation.

Table 2: Caledonide caves and karsts - major observations, processes and controls. Processes and controls in bold are additional to the main processes that apply in Central Scandinavia.

five areas are greater than the differences *within* each of them. The placement of SS and Ireland is more difficult. Both these areas comprise several geographically-dispersed distinct regions, which would be better considered individually. However, if the quality of this data is improved in future, these two areas would probably fit in the rank order shown in Table 3, with the mountainous Jotunheimen area ahead of the rest of southern Scandinavia, and Donegal ahead of Connemara in Ireland. The final demonstration of these relationships is presented in Table 3, columns 7–9. These show that the ranges of local icesheet thicknesses at the LGM, the local Holocene uplifts, and the maximum topographic relief differences also follow similar ranking orders.

The prime conclusion is that the main control on the extent of karstification in the non-arctic Caledonides is the maximum weight and thickness of each of the various Pleistocene icesheets. The icesheets caused isostatic depression, and therefore the previous thickness determined the amount of postglacial uplift. The greater this was, the faster was the initial acceleration of the uplift, by Hooke's Law. This, in combination with the change of local relief experienced by a retreating ice margin determined the magnitude of local deglacial earthquakes. These in turn controlled the density and the depth of tectonic inception fractures that were wide enough to permit enlargement to explorable cave passages within the timescales of the deglacial and interglacial hydrological regimes that the karst subsequently experienced (Faulkner, 2006b). Hence, because the Pleistocene glacial–interglacial cycles were approximately synchronous globally, these timescales were similar for all Caledonide terranes. Their cave developments therefore kept in step and total explorable cave lengths, VRs and XSs are functions of previous local icesheet thicknesses.

A supplementary mechanism for phreatic enlargement is that the more ice there was to melt at the end of each glaciation, the longer the caves and fractures remained submerged under IDLs, and the more water flowed through them. Greater flows in turn caused a greater widening of cave passages, increasing their XS and permitting smaller conduits to enlarge to explorable size, so increasing the measured length of each cave.

Caves in the Caledonide areas outside NS and CS tend to be simpler and smaller, indicating less development stages over shorter timescales. It is concluded that all these caves were commonly produced by similar processes within the TDMO model, but their more epigean nature, the rarity of both relict MV caves and complex passage tiers, their commonly-smaller phreatic passage XS, and absence of large speleothems (e.g. Fig. 2) suggests that their relict and combination caves are commonly "single-cycle" caves that only enlarged during and after the Weichselian / Wisconsin / Devensian deglaciation. They have few older passages: most previously-existing higher passages were eroded away during this (and earlier) glaciations, because valley deepening is greater than mean cave depth. The MV caves are "half-cycle" caves, which enlarged to present dimensions only after deglaciation and during the Holocene. The caves may perhaps be described as *epikarstic*, but in this case it is an epikarst that can support a wide range of cave morphologies, without any passages lying in the deeper unfractured rock mass. The concept of a "watertable" has little validity in the metamorphic Caledonides, because water storage and flow is contained within discrete fractures, conduits and cave passages. In contrast, CS and especially NS have many longer, deeper, larger, more complex and older caves. Some caves in NS exceed the constraints of the "standard" process and there are probably more "multi-

CALEDONIDE AREA	Max. cave length (m)	Mean cave length (m)	Max. cave VR (m)	Mean cave VR (m)	Mean cave XS (m^2)	Max. local icesheet thickness (m)	Local Holocene uplift (m)	Max. relief difference (m)
N. Scandinavia	17000	?	580	?	?	2000–3000	40–200	1655
- (Gråtådal)		175		16.3	13.4	2000	140	1174
C. Scandinavia	5600	85	180	8.8	3.5	1800–2800	120–280	900
New England	900	59	82	9.3	2.9	1500–2500	60–180	790
S. Scandinavia	*560*	*90*	*46*	*9.1*	*3.5*	1200–2400	120–360	1200
Scotland	340	28	48	5.9	2.1	1000	≥40	980
Ireland	*220*	*35*	*25*	*7.9*	*3.6*	500?	15?	>300
Shetland						200–300	-9	250

Table 3: Caledonide caves, glaciation, uplift, and local relief difference.

cycle" combination caves than in CS, as supported by the greater ages of some dated speleothems (up to 800ka: Lauritzen, 1993). The oldest Caledonide marble cave is perhaps **Rågge Javre Raige,** where upper passages may have survived for ~1Ma. Such passages may still exist in NS because reduced glacial erosion, away from the 'saddle' area of CS that focussed E-W ice streaming, preferentially protected the older, higher, passages.

Figure 2: Speleothems in Poll Seomar, Scotland. The small sizes and the fragility of the stalagmites and stalactites suggest formation during the Holocene.

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FLOW DISTRIBUTION AT EARLY STAGE OF KARSTIFICATION AND 3D GEOMETRY OF CAVE SYSTEMS

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Simple groundwater numerical modeling allowed us to understand the influence of the primary permeability distribution on the flow conditions during early speleogenetic phases and to recognize the crucial role of the geometry of the inception horizons and of the landscape evolution for the final geometry of the cave system. Results of the numerical simulations indicate that under (deep) phreatic conditions the vertical distribution of groundwater flow mainly depends on the permeability distribution and is independent of the geometrical setting as well as on the distance between inception horizons. Therefore, karstification may take place at any depth within the rock mass but is mostly concentrated along horizons with the highest permeability. The hydrologic behavior changes dramatically when an inception horizon becomes close to the spring area, for instance after the incision of a valley floor. Under these conditions the flow is no longer controlled only by the permeability distribution but also by the distance between spring area and inception horizons. Flow is increased in a zone close to the spring, which is typically some tens of meters thick and some hundred meters wide.

The obtained findings allowed us to propose speleogenetic zones with characteristic hydraulic properties and conduit characteristics. This is an important step toward a probabilistic prediction of karst occurrences.

1. Introduction

Analyses of the 3D geometry of some of the largest conduit networks in the World (almost 2000 km of analyzed cave conduits) showed that the development and position of karst conduits under phreatic conditions is related to a restricted number of inception horizons (e.g., Filipponi et al. 2008). An "inception horizon" is a part of a rock succession (usually in the order of some centimeters to decimeters) that is particularly susceptible to the effects of the earliest cave-forming processes by virtue of physical, lithological or chemical deviation from the predominant carbonate facies within the surrounding sequence (Lowe 1992, 2000). Probably fewer than 10% of the existing bedding partings of a limestone sequence are inception horizons but guide more than 70% of the phreatic conduits (Filipponi et al. 2008). It is also clear that the influence of these horizons on the 3D geometry of cave systems is high (Fig. 1) (Filipponi and Jeannin 2008a).

Permeability measurements on such preferential karstified stratigraphic horizons demonstrated that it is possible to identify distinct inception horizons that have a slightly higher primary permeability than the surrounding rock mass, as well as another type of inception horizon with lower permeability (Filipponi and Jeannin 2008b; Filipponi et al. 2009). Also we can assume that the primary permeability distribution is one of the main factors controlling the early karstification and therefore determining the later geometry of the karst system (Filipponi 2009; Filipponi and Jeannin 2009).

The inception horizon hypothesis (Lowe 1992, 2000) distinguishes between three different phases of speleogenesis (Fig. 1). The karstification of inception horizons is supposed to start during the so-called phase of ***cave inception***; it can be defined as starting as soon as the permeability of the rock mass increases steadily due to dissolution processes (Filipponi and Jeannin 2008b; Filipponi et al. 2008). One may expect that, at this early stage, hydraulic gradients are low and not directly controlled by well-defined boundary conditions. This may correspond to unexposed limestone, to exposed limestone in flat terrain, or to parts of a limestone mass located below a well-defined active karst system. Flow is laminar and poorly organized. In other words, dissolution is low, slow, diffuse, and distributed within the whole volume of the phreatic zone ("deep phreatic setting"). In this context however, some horizons tend to increase their permeability slightly faster than others preparing the later development of karst conduits. They are becoming inception horizons. When hydraulic gradients become strongly controlled by the respective positions of the

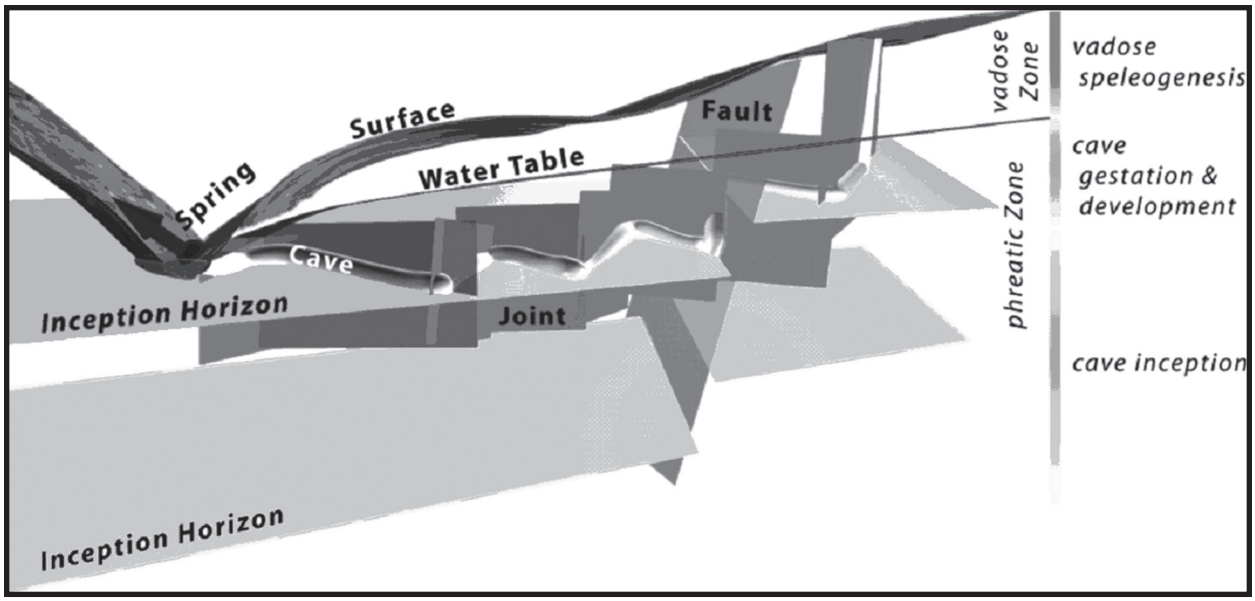

Figure 1: Schematic 3D model of a karst conduit system: The geometry of phreatic conduits is determined by inception horizons, joints, and faults as well as by the hydraulic gradient. The inception horizon hypothesis expects that the karstification of a rock mass pass through different speleogenetic phases, whereas different parts of the rock mass are in different karstification states at the same time.

recharge/discharge areas, flow becomes organized in order to drain the aquifer. Thus the flow selects a few horizons which provide the weakest resistance to flow. From this point on, conduit development is faster and organized. This phase is called the phase of ***cave gestation***. After a given time, some flow paths reach a sufficient size (about 1 cm in diameter) for turbulent flow to occur, which strongly increases the dissolution kinetics. Conduits can thus reach human size within a few thousands of years (White 1988; Dreybrodt and Gabrovšek 2000; Kaufmann 2002; Palmer 2002). This is the phase of ***cave development***.

The inception horizon hypothesis is based mainly on field observations and speleogenetic hypotheses on conditions occurring in the early phase of speleogenesis. Direct verifications being difficult, and the primary permeability distribution being significant, groundwater flow modeling can help us understand how caves could develop in these conditions. This paper presents the results of simple hydrologic numerical modeling and addresses the following questions: What is the influence of the primary permeability distribution on flow conditions within the inception phases? What characterizes the change between cave inception and gestation phases? What is the influence of the geometry of the inception horizons and of the landscape evolution on the final geometry of the cave system?

2. Method

To better understand the influence of primary permeability distribution to the pre-karstification and cave inception phases, we analyzed different scenarios with 2D vertical finite-element flow models (FeFlow). These model scenarios represent simplified generic settings that were not designed to account for features at specific sites, but were still useful to gain general insight into the flow conditions during the inception or gestation phases of speleogenesis. The design of the selected scenarios was done within the inception horizon concept, assuming that within a rock mass some stratigraphic horizons are particularly susceptible to the effects of the earliest cave-forming processes due to a slightly higher (or lower) primary permeability than the surrounding rock mass (e.g. Filipponi and Jeannin 2008b). Therefore our numerical model consists of a homogeneous rock mass that is pervaded by horizons with a permeability contrast with respect to the surrounding limestone. The occurrence of fractures was neglected, with the assumption that at early stages, as well as at depth, major fractures have only a very low frequency (Hillis 1998; Ortega et al. 2006).

Our basic model (e.g., Fig. 2) consists of a 5000 m long limestone block 500 m thick. The width is divided into a 800-m-long spring area and a 4200-m-long recharge area. The elevation of the spring area in the model is changed in the various scenarios, ranging between 350 and 260 m to define different hydraulic heads at the spring area. The recharge area is usually held at 500 m. At the recharge area we keep the head constant at the land surface because we assume that at early stages of karstification the drainage

capacity of the rock is lower than the precipitation rate, so the water table will stay near the surface. No-flow conditions are assumed for all other boundaries. The permeability of the limestone block was assumed to be constant and isotropic, the only exceptions being two (inception) horizons with thicknesses of 1 m. Their permeability is varied relative to the permeability of the rock mass with factors of 0.01; 0.1, 10, and 100. Real-world inception horizons have a thickness of some centimeters to decimeters (e.g. Filipponi 2009), but because of mesh-generation difficulties, 1 m is a reasonable compromise. The permeability of the rock mass was set at 10^{-4} m/s to reduce computing time. In the real world the permeability is about 10^{-9} m/s; the contrast between primary permeability of the modeled inception horizons and the surrounding rock mass was up to ±50 to ±70% (Filipponi 2009; Filipponi and Jeannin 2008b; Filipponi et al. 2009). However, note that the absolute value of permeability has only a subordinate role; more significant are its contrasts to the inception horizons. We analyzed four geometric configurations of horizons: horizontal, dipping toward the spring, dipping in the opposite direction, anticline, and syncline structure. For each configuration a series of simulations has been run with different combinations of permeability distribution, distance between inception horizons, and distance to the spring area. We evaluated more than 100 simulations. Evaluation was based on head and flow distribution at steady state.

3. Results

A first set of numerical simulations was run to understand the influence of the contrast between the (inception) horizon permeability and the rock mass in (deep) phreatic settings. Therefore we used a simple geometric configuration: spring area at 350 m, recharge area at 500 m, horizon 1 at 100 m, and horizon 2 at 250 m. The permeability of the horizon was varied in the different runs between 0.01 and 100 times the permeability of the surrounding rock mass. *As expected, results of the finite-*

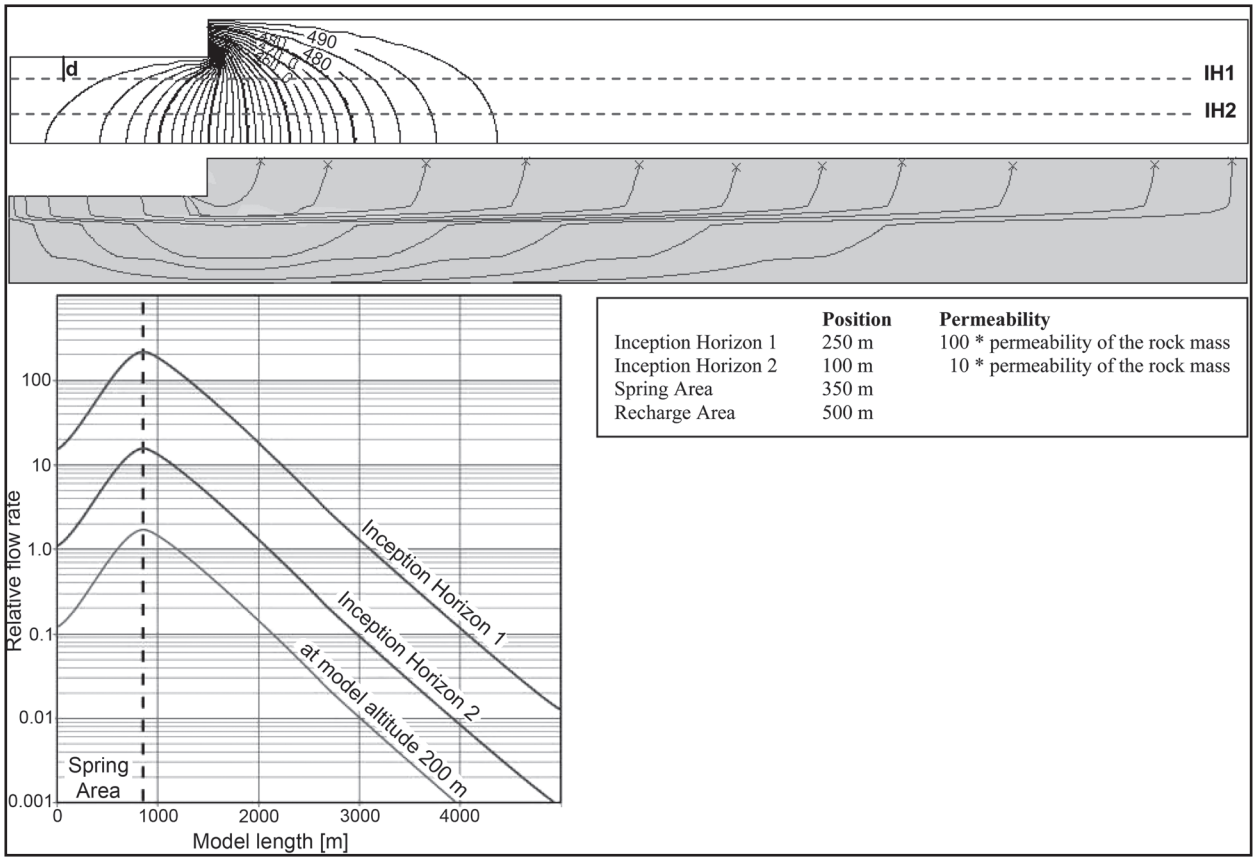

Figure 2: Selected model scenario with one horizontal inception horizon at 250 m (permeability = 100 times that of the surrounding rock mass), and a second inception horizon at 100 m (permeability = 10 times that of the surrounding rock mass). Spring area at model altitude is 350 m and recharge area is at 500 m. The plots illustrate the distribution of hydraulic head (top), flow tracks (middle) and flow rate along the inception horizons as well as at the rock mass at 200 m (bottom) at steady state. The model scenarios show that the vertical flow distribution is proportional to the permeability distribution and is independent of the order of the inception horizons.

element model show that the vertical distribution of flow depends on the permeability distribution (e.g., Fig. 2). This means that horizons with a given ratio of permeability compared to the surrounding rock will have flow rates that are directly proportional to the permeability contrast. Refraction of flow lines causes an increased horizontal flow within high-permeability horizons but a reduction of horizontal flow within horizons of lower permeability. In other words, flow is relatively horizontal in more permeable horizons and relatively vertical in less permeable horizons. Low-permeability horizons not only cause flow lines to be steeper within those horizons (relative to the permeability boundary), but also at shallower angles in the rock mass below. This should lead to a remarkable diminution of flow in the rock mass below the horizon. This decrease depends mainly on the low-permeability horizon characteristics (thickness, permeability), but also on the length of the recharge area. However, for the thickness of the horizons (1 m) assumed in our model, as well as for the length of the recharge area (length = 4200 m), the flow diminution is not considerable. *Therefore we can assume that the relative position of horizons with various permeabilities has no major effect on the vertical flow distribution.* Model results show that the flow rate along the (inception) horizons, as well as in the surrounding rock mass, decreases with the distance to the spring area. In other words, the highest flow rate can be observed shortly upstream from the spring area and decreases exponentially at greater distances. Further scenarios with different distances between horizons and different geometry of inception horizons show that flow distribution is independent of distance between inception horizons. The *geometric setting has no influence on the vertical distribution of flow rates. Vertical flow is governed by the permeability distribution only.*

In models presented so far, we simulated flow along inception horizons that are "far" from the spring area. However, one can assume that the hydrologic behavior will change dramatically when a given inception horizon becomes close or even directly connected to the spring area. To this purpose, we designed a series of simulations to understand the role of distance between the spring area and the inception horizons on delineating the spring influence zone. To describe this influence, we analyzed the vertical distribution of flow for a series of scenarios with various distances. We assumed a rock mass with two horizontal inception horizons (at 100 m and 250 m) with the same permeability (100 times higher than the surrounding rock mass). The distance between the spring area and the uppermost inception horizon (distance **d** in Fig. 2) was varied between 5 and 50 m (Fig. 3). The finite-element model shows that the flow along (inception) horizons in the area near the spring is no longer proportional only to the permeability of the horizon, but decreases with the distance between the spring and the upper horizon. Flow in the deepest horizon remains proportional to the permeability difference to the surrounding rock. Therefore, flow rates along the upper inception horizon depend on the permeability as well as on the distance of the horizon to the spring area. Spring influence decreases with the distance between the inception horizon and the spring. Thus a zone of spring influence can be defined. This zone has a thickness of around 20 to 30 m below the spring area (Fig. 3). The zone of increased flow is laterally restricted and becomes thinner with distance to the spring area. *Based on simulations we can estimate that the lateral elongation of this zone is on the order of hundreds of meters. It depends on the hydraulic head and the contrast in permeability between the rock mass and the more permeable horizon.*

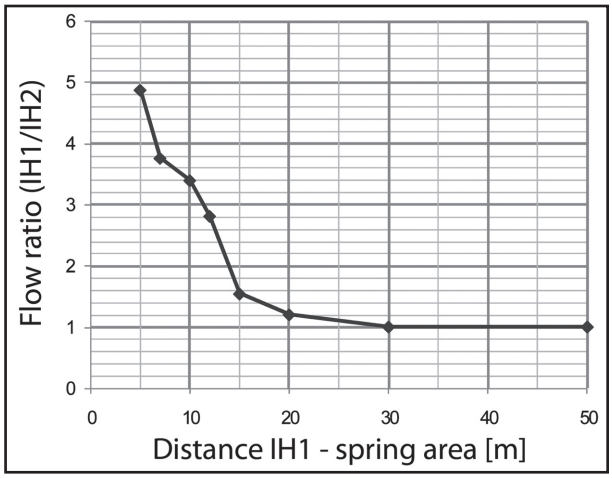

Figure 3: Relationship between flow rate and distance of an inception horizon to the spring area. The flow rate is expressed in proportion to the uninfluenced lowermost inception horizon. The diagram shows that the flow rate strongly increases close to the spring. From a distance greater than about 30 m the influence of the spring becomes negligible.

4. Discussion and Conclusion

Flow simulations show that flow concentration is moderate, non-selective, and controlled only by the initial permeability of inception horizons as long as they are far enough from the discharge area. The hydrologic behavior changes dramatically when one inception horizon becomes close to the spring area, for instance following incision of a valley floor. Under these conditions, flow is no longer controlled only by the permeability distribution but also by the distance between the spring area and the inception horizon. Flow increases in a zone of some tens of meters below the spring area and a few hundreds of meters laterally.

The size of this zone depends on the hydraulic head and the contrast in permeability between the rock mass and the more permeable horizon. From a speleogenetic point of view the zone of spring influence can be considered the zone of cave gestation. Later, when flow within karst conduits becomes turbulent, it is the zone where phreatic cave development takes place (Figs. 1 and 4). In the area below this zone, speleogenesis is in the cave inception phase (Figs. 1 and 4). Note the difference between the cave inception/gestation/development ***phases*** (Lowe 1992, 2000), which represent the state of development (dissolution seams for the inception phase; karst conduits for the gestation phase; cave conduits for the development phase), and the inception/gestation/phreatic development/vadose development ***zones*** (Filipponi 2009), which represent zones of characteristic flow conditions: (a) the ***cave inception zone*** is characterized by laminar flow under low hydraulic gradient conditions; (b) the ***cave gestation zone*** is characterized by laminar flow under higher hydraulic gradient conditions caused by the "spring influence" and a gradual development of a karst conduit network; (c) the ***phreatic cave development zone*** is characterized by turbulent flow and low hydraulic gradient in conduits; and (d) the ***vadose cave development zone*** is above water table, where cave passages are air- and water-filled with permanent or occasional water flow during snowmelt or rain events. In this zone the flow is ultimately controlled by gravity, i.e. mainly vertical. As water can only flow downward, vadose conduits are mainly vertical shafts or sloping, meandering canyons (e.g. Lauritzen and Lundberg 2000) and are guided by inception fractures as well as inception horizons (e.g., Filipponi et al. 2008).

With time, it must be expected that within the "drop-shaped" cave gestation zone the hydraulic gradients will flatten down to the spring level because of gradual development of a karst conduit network. Successively the gestation zone will move upstream. This flattening happens mainly when a "victor tube" is large enough to allow turbulent flow (breakthrough; e.g., White 1988; Dreybrodt et al. 2005) and therefore at the change between the cave gestation and cave development phases (Lowe 1992). Once the gradient is flat the steep gradient moves upstream and a new gestation zone will form upstream from the previous one. The karst conduit network will thus develop step by step in the upstream direction. *Note that the only "motor" for karst development is the hydraulic gradient, which varies throughout the massif and changes over short (horizontal shifting of the gestation zone) and long (valley incision) time scales.*

This influence the upstream migration of the gestation zone has also been noticed in various numerical speleogenetic

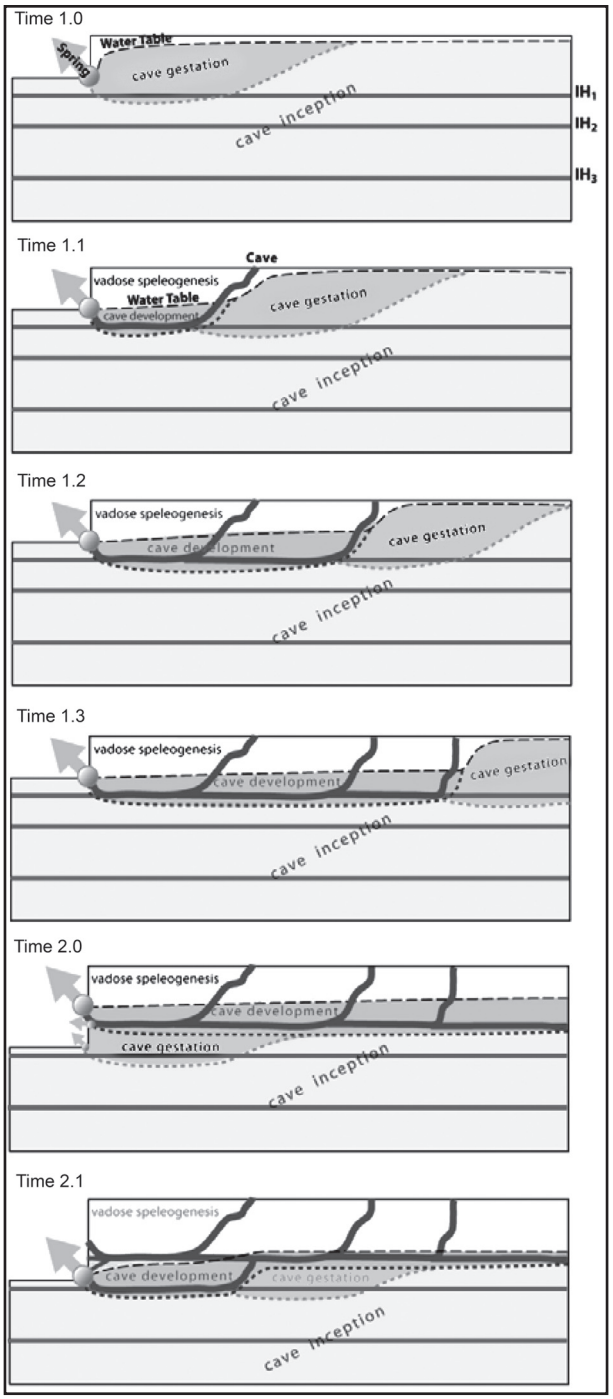

Figure 4: Schematic development of a karst system in time and space (vertical section) with horizontal inception horizons (IH): Different parts of the rock massif are in different karstification zones at the same time. Shortly after a valley incision event (time 1.0 and 2.0) the gestation zone is located near the spring. Karst conduit network begins to develop along the inception horizons within the gestation zone. As a conduit within this zone begins to allow turbulent flow, the water table drops. The gestation zone becomes a cave development zone and a new gestation zone develops upstream. This upstream shift of the gestation and development zones produces typical cave levels.

models (e.g. Gabrovšek and Dreybdodt 2001). However it was not discussed in detail and not related to the concept of inception horizons. Speleogenetic models describe an upstream migration of the "turbulent flow regime" and a flattening of the hydraulic gradient. However, most numerical models deal with karstification along an initial fracture network, with initial openings of some 0.1 mm (equivalent to a permeability of some 10^6 mD) and do not consider the cave inception phase (e.g., Groves and Howard 1994; Dreybrodt and Gabrovšek 2000; Palmer 2002; Kaufmann 2003; Bauer et al. 2003). The lateral shift of the gestation zone causes a step-by-step adjustment of the flow path. This numerical observation is also confirmed by cave geomorphologists (e.g., Häuselmann et al. 2003; Audra et al. 2007) who described in detail the development of phreatic cave systems and observed the same type of stepwise development of new conduits from downstream towards upstream ("soutirage") (Fig. 4 – time 2.1). In real systems this phenomenon is reinforced by the existence of an epiphreatic zone in which hydraulic gradients are steeper than in the water below.

Based on the concept of speleogenetic zones deduced from our approach, we have been able to understand the 3D cave pattern of different types of cave systems by considering the position and orientation of inception horizons as well as the history of landscape evolution (Filipponi and Jeannin 2008a; Filipponi 2009). A concept taking into account the position of inception horizons in a rock mass as well as the reconstruction of the hydrogeologic history offers substantial progress toward a probabilistic prediction of dissolution voids for applied proposes (e.g., Filipponi and Jeannin 2008c).

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MORPHOLOGY OF TJOARVEKRAJGGE,- THE LONGEST CAVE OF SCANDINAVIA

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Tjoarvekrájgge (Tjorve), with a surveyed length of 21,814 meters, the longest cave of Scandinavia, is found in one of four marble bands of stripe karst in Bonå, some miles north of the Polar circle in Norway. The cave is a two-dimensional labyrinth system situated close to a shoulder of a "U" shaped valley. Morphometric and fractal analysis can be made with over 99 % of the passage dimensions.

Morphometric parameters of Tjorve yield a passage density of 47.5 km/km^2 and a cave porosity of 0.8 %, intermediate between the values of confined and unconfined settings, and an areal coverage of 21.8 %, close to the values for confined settings. Values for the uppermost part of the cave (cave porosity: 3.6 %, areal coverage: 32.6 %) are closer to or within the values for confined settings. The values might reflect a cyclic development of the cave over several glacial-interglacial cycles. Four levels in the cave can be discerned in vertical profile, possibly corresponding to ancient water tables that have been step-wise lowered in successive glacial periods. Tjorve may have developed over a long time-period, from perhaps the Tertiary.

The Linked Modular Element (LME) method (Curl 1986: http://tinyurl.com/6o53kd) is applied to Tjorve to determine the distribution of cave passage sizes. The distribution of LME sizes fit a power-law function from 1.8 to 5.9 m and exhibits a fractal dimension of 2.929 (s.d. 0.068), similar to Little Brush Creek Cave (LBC), Utah (fractal dimension 2.79). The proper modulus is near 1.1 m, compared to 0.6 m for LBC, indicating perhaps less complete exploration.

1. Introduction

Tjoarvekrájgge (Tjorve), with a surveyed length of 21 814 meters and a depth of c. 497 m, - the longest cave of Scandinavia - is found in one of four marble bands of stripe karst (Horn 1937) in Bonådalen, Nordland county, some kilometers north of the Polar circle in Norway.

Bonådalen is a north-south "U"-shaped valley, widened and deepened by the glaciers in the last 2.5 million years. Tjorve is situated close to the western shoulder of the valley. The marble band is 50 to 60 m thick, surrounded by insoluble mica schist. The marble dips 25 to 40 degrees to the south and southeast (following the local folding), adding depth to the cave system. The resurgence is at 84 masl, close to the valley bottom. Tjorve has five known proper entrances. They have no drainage area today. There is a short cave above Tjorve, Stoppenålen (496 m long and 190 m deep), leading straight toward Tjorve, but without obvious proper connections.

Tjorve has tubes, canyons, rock blocks, and clay. The tubes follow the "Tjorve plane" (Fig. 1) – horizontal in an east-west direction (the strike) and sloping in the dip direction. Canyons above the groundwater level also follow the dip. Large areas of the upper parts of Tjorve contain boulders, mostly from breakdown, but also injected during glaciations. The clay deposits are especially prominent in the phreatic tubes in the upper part of the cave, but can be found in most other places, including on breakdown.

The survey is done to BCRA grade 5, using Suunto compass and clinometer, tape and in recent years laser meters and digital clinometers. Due to many loops and side passages, stations are placed on bedrock, boulders and clay, and are normally properly marked. The survey includes 214 loops, with an average loop closure of 2.1 %. Survey data are downloaded into an Excel file developed for the Tjorve project. Export can be done to Compass, Therion and Excel workbooks for additional analysis. A total of 2 805 valid survey shots have been recorded. Over 99 % of the shots have passage dimensions, which allow morphometric and fractal analysis.

2. Morphometric Analysis

Morphometric parameters (Klimchouk, 2003) of Tjorve

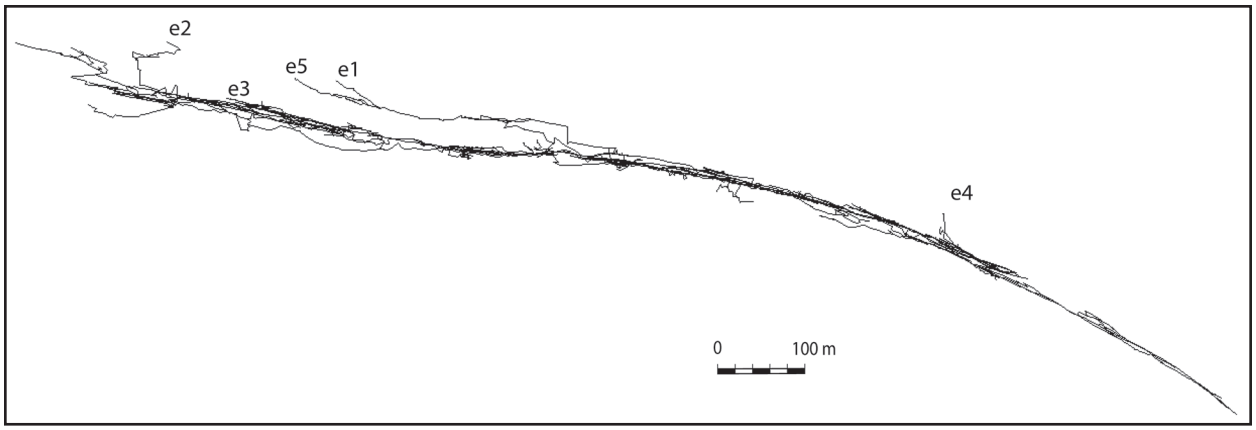

Figure 1: Tjorve looking northeast (40o) and looking up a slope (+24o). From this view the Tjorve plane is a thin line. The invasion passages can be identified. (from Finnesand et al. 2007). Proper entrances are numbered.

and parts of Tjorve (Table 1) can be calculated in different ways. Our definitions are:

1 Surveyed passages (column 2, 3, 4 and 5 in Table 1) use survey data: Length is given as surveyed (3D) and projected horizontally (2D). Surveyed area is the plan area of the passages (seen from above, i.e. passages situated above others (seldom found in Tjorve) are not included). Volume is the horizontal length multiplied with an elliptical cross-sectional area (from left-right and up-down (LRUD) measurements at stations).

2 Cave extent (column 6, 7 and 8 in Table 1) is the two- and three-dimensional area that the cave occupies. The two dimensional extent is a horizontal area (cave field) calculated from a polygon surrounding the cave. The height is calculated at the location where the vertical distance between the lowest and highest point is largest (minimum value would be the highest passage). Volume is the part of the rock volume (cave field x height) in which the cave is developed.

The passage density (47.5 km/km^2) and the cave porosity (1.0 %) are intermediate between the values of confined and unconfined (after Klimchouk, 2003) settings, and areal coverage (22.1 %) is close to the values for confined settings. Almost all (93 % of the length) of Tjorve lies in the Tjorve plane (Fig. 1), which has a higher porosity (2,2 %) than Tjorve. The missing 7 % is mainly the first few hundred meters of passages from three entrances, which appear to be invasion systems (Fig. 1).

Values for the uppermost and old part of the cave such as Galleries (cave porosity: 3.6 %, areal coverage: 32.6 %) are closer to or within the values for confined settings. These intermediate values might also reflect a cyclic development of the cave over several glacial-interglacial cycles. In a vertical profile (Fig. 2) one can possibly discern four levels in the cave, corresponding to ancient water tables that have been step-wise lowered by glacial erosion during the glacial periods. If this model holds true, Tjorve must have developed over a long time-period, perhaps originating in the Tertiary.

Cave, or part of the cave	Surveyed passages				Cave extent			Specific volume	Passage density	Areal coverage	Cave porosity
	length (3D) km	length (2D) km	area km^2	volume m^3*10^6	area km^2	height m	volume m^3*10^6	m^3/m	km/km^2	%	%
Tjoarvekrajgge	21.814	19.658	0.090	0.224	0.414	64.0	26.5	10.3	47.5	21.8	0.8
- Tjorve plane	20.279	18.409	0.087	0.199	0.414	22.0	9.1	9.8	44.5	20.9	2.2
- Galleries	8.807	8.037	0.051	0.120	0.157	21.0	3.3	13.6	51.2	32.6	3.6
- Down below	2.239	1.975	0.007	0.009	0.064	6.5	0.4	4.0	30.9	11.6	2.2
Average values from 4 unconfined caves (Klimchouk 2003)									16.6	6.4	0.4
Average values from 21 confined caves (Klimchouk 2003)									167.3	29.7	5.0

Table 1: Morphometry, derived from surveyed (proper) passages. Specific volume is the sum of passage volume divided by the sum of passage length (3D). Passage density is the sum of horizontal passage length (2D) divided by the cave field. Areal coverage is the ratio of the sum of the horizontal passage area seen from above to the cave field. Cave porosity is the ratio of the sum of the passage volume to the rock volume. Data 1993-2008.

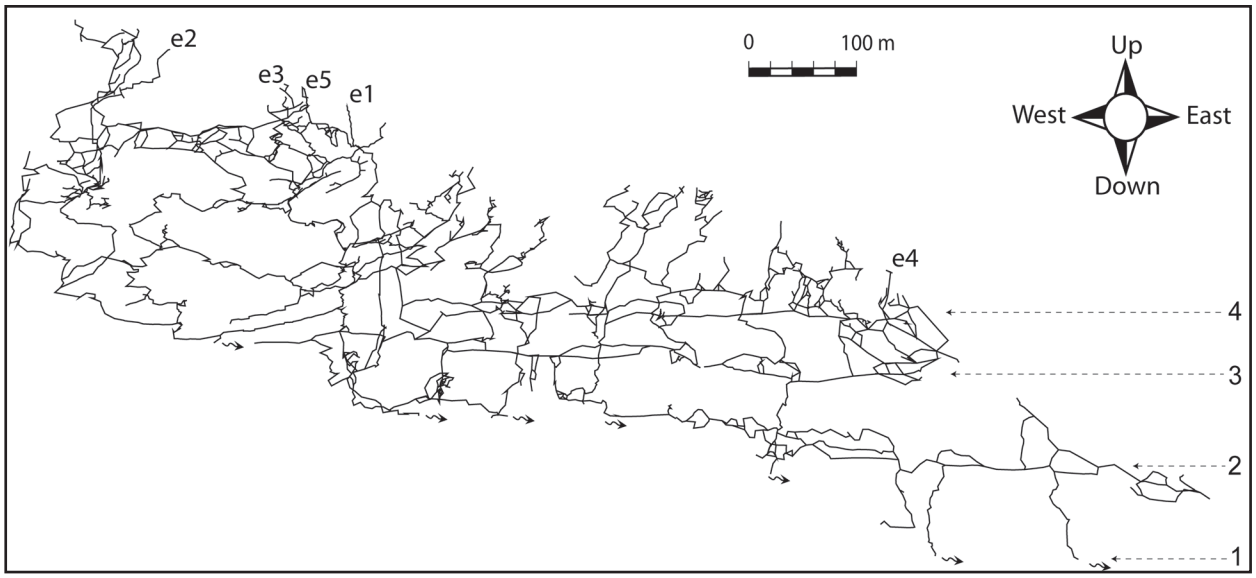

Figure 2: Tjorve profile, looking north. The bottom of the cave is closer to the observer and the top is further away. Level 1 is the river of today. Level 2 is the tubes in "Down below". Level 3 is the lower part of the "Galleries". Level 4 is in the main part of the Galleries (the Galleries have passages that extend towards the surface). Canyons are often found between the levels, in particular between level 1 and 2, and level 2 and 3. Since the cave dips 25o-40o to the south, the plan map of Tjorve is quite similar to the profile map. 19 line segments are needed to identify a polygon that includes the centerline.

The method by which the cave field is calculated is of great importance to the passage density, areal coverage and cave porosity (Klimchouk 2003). We calculated the "Minimum Horizontal Polygon Field" – defined such that any line segment of the polygon 1) is as long as possible and 2) does not cross a shot (Finnesand et al. 2007). This polygon in Tjorve has 19 line segments. Perhaps more common (and easier) is to calculate the area from the smallest rectangle that includes the cave (the cave field of Tjorve would then increase from 0.41 km^2 to 0.63 km^2). Klimchouk (2003) identified polygons by using a lot of line segments, - the goal is to have a polygon that reasonably closely embraces the plan array of a cave. The polygon can be drawn in many ways, but in practice the cave field would have values within 10-15 % (Klimchouk, 2003). Doing that in Tjorve, the cave field become 0,34 km^2 (75 stations), which would increase the three affected parameters by 23 %. In theory, one can increase the number of line segments in the polygon until the cave field will be the sum of the passage area and the area within the "loops" which would occur in plan view.

There are still some passages to be surveyed in Tjorve, although the extent of the cave would probably not change. Average size of remaining passages are probably small, which will reduce the specific volume. The passage density, areal coverage and cave porosity would increase somewhat, in particular in the Galleries.

3. Fractal Analysis

A fractal analysis of Tjorve was done to determine whether the cave exhibited self-similar fractal structure and, if so, to estimate the unsurveyable (non-proper) length and volume of the cave and possibly that of the entire karst terrain. The method used was that of Curl (1986 – hereafter cited as **RC**) and discussed further in Curl (1999). This is done by placing virtual spherical *linked modular elements* (LME) of diameter η (cm) at survey stations and interpolating additional LMEs linearly between stations, as explained in **RC** (pp 776-777, Fig 7). The diameter of LME at stations is chosen as the lesser of the measured or estimated LRUD distances because this is what limits exploration and hence defines the limiting scale of the proper cave. Counts of LMEs were sorted into a histogram using equal logarithmic interval binning corresponding to 2 % differences in η, with q_i LME per bin centered at η_i. These are shown in log-log coordinates in Figure 3.

Tjorve yielded 15 768 LME between 10 and 1 305 cm. The q_i fall off rapidly at η smaller than at the data peak (at approximately 110 cm) because of the physical difficulty or impossibility of surveying in smaller passages, and are also truncated at large η because of such factors as limited strata thickness, rock strength, and extent of solution. The nearly linear slope in a range of η larger than at the data peak suggests a power-law model of the form

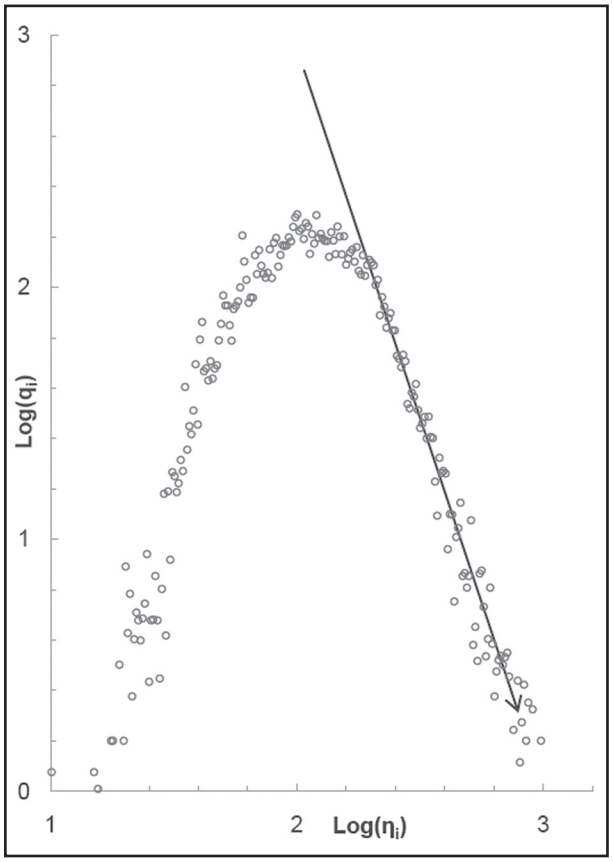

Figure 3: Histogram of LME number distribution with logarithmic interval binning of 2 % of size (cm). The apparently linear power-law range was chosen to be 184 to 591 cm for the estimation of the fractal dimension of the cave. The peak is at the nominal proper modulus (1.1 m) of the cave.

$$q_i = c\eta_i^{-D} \qquad (1)$$

where D is the *fractal dimension*. This is characteristic of self-similar geometric fractals (Mandelbrot 1983).

The data may also be plotted as the more conventional cumulative, defined as the number Q(η) of LME larger than a value η, as shown in Figure 4. Here Q(η) appears to also exhibit a power-law range, as in Eqn. 1 (but with a different constant c). Newman (2005) gives numerous examples of similar power-law distribution behaviors of number versus size, known as Zipf's Law, a Pareto distribution, and 'rank-frequency' plots, for such phenomena as word frequencies, earthquake magnitudes, moon crater sizes and population data. The causes of power-law behavior have seldom been explained, but it is related to there being no unique defining scales for the phenomenon.

The least-square slope of the apparent power-law part of the cumulative plot was used in **RC** (p. 778, Fig. 8) to estimate D. There are, however, two problems with this: Q(η) data are not statistically independent or homoscedastic, and an upper cutoff at large values of η due to the factors noted previously. The first problem has been addressed by

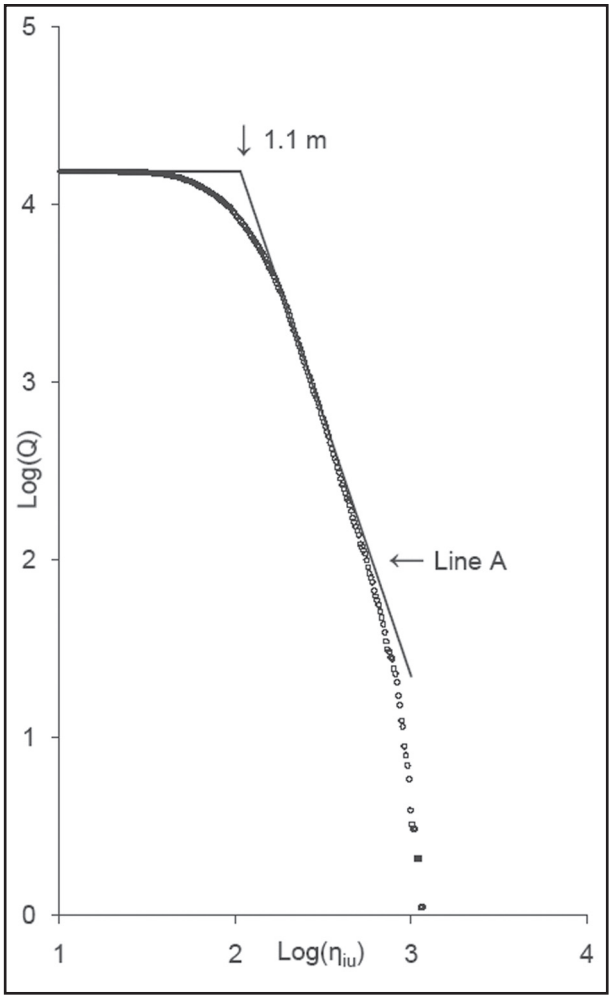

Figure 4: Number of LMEs, Q(η,) larger than η(cm). The slope in the apparently linear range of a log-log plot approximates D, but is too high due to the truncation of Q(η) at large η. A correction for truncation is shown by line A, which has slope $-D$

using a maximum likelihood (ML) estimator for D from the histogram data. Geyer (2007) details the general ML theory. Newman (2005) derived an ML estimator for power-law data not truncated above. We have derived the following estimators for D and its standard deviation σ_D for data truncated to the range $\eta_l < \eta < \eta_u$ where η_l and η_u are the lower and upper bounds of the chosen range of η. Derivations are included in Supporting Online Material:

$$\left[\frac{1}{\hat{D}}+\frac{r^{\hat{D}}\ln(r)}{\left(1-r^{\hat{D}}\right)}\right]=\frac{1}{n}\sum_{l}^{u}q_i\ln\left[\frac{\eta_i}{\eta_l}\right] \quad (2)$$

$$\sigma_D=\frac{\hat{D}}{\sqrt{n}}\left[1-\frac{\hat{D}^2r^{\hat{D}}\left(\ln(r)\right)^2}{\left(1-r^{\hat{D}}\right)^2}\right]^{-\frac{1}{2}} \quad (3)$$

where r = η_l/η_u and n is the sum of q_i over the range. Eqn. (2) must be solved iteratively for the D estimator $\hat{D}$. An Excel spreadsheet and instructions for performing these calculations are in the Supporting Online Material.

The second problem with using a least-squares regression for the data in Figure 4 to estimate D is the necessity of correcting for the truncation of Q(η) data at large η: this correction is shown by line A, now with the lower slope $-\hat{D}$, calculated by adding a derived constant to all the Q(η) up to η_u. D must be estimated from the histogram to apply this correction, so regression of Q(η) data themselves does not provide an unbiased estimate of D.

The value for $\hat{D}$ is somewhat sensitive to the range (η_l, η_u) chosen because of the inaccuracy with which LRUD are measured at survey stations, often only to the nearest integer meter in large passage. The values of L, R, U and D at each survey stations were randomized uniformly over a local interval of ± 5 % to reduce this effect. This adjustment is less than the precision of surveyed LRUD distances, but reduces the apparent scatter of the data in Figure 3. For η_l = 184 cm and η_u = 591 cm, with station LRUD randomization, $\hat{D}$ = 2.929 and σ_D = 0.068. Previous analyses have reported values for of 2.79 (Little Brush Creek Cave, (LBC; Colorado: **RC**), and 2.5 (Stagebarn Crystal Cave, South Dakota: Curl and Nepstad 1991). The earlier applications were less thorough than the current one.

The estimate of D permits estimating the total volume of non-proper cave (smaller than surveyable) if it is assumed that the known proper cave is fully connected. That is, that there exists no unknown connected cave passages larger than the proper modulus of the survey. This is true of the Menger Sponge (**RC**, p. 775, Fig. 6) but it is likely that if smaller passages could be explored, additional large proper passage would be found. Therefore an extrapolation of the data in Figure 3 to η = 0 will provide only a lower limit to the remaining volume in the karst terrain.

The volume of known proper cave can be estimated from the sum of $q_i\eta_i^3$ from η_l up. The estimated volume of cave below η_l from a theoretical extrapolation of η to 0, is given by

$$V(0,\eta_l)=\frac{n\hat{D}\eta_l^3}{(1-r^{\hat{D}})(3-\hat{D})} \quad (4)$$

which gives $V(0,\eta_l)$ = 831 000 m³ (19 600 m³ known), compared to 108 800 m³ for the cave above η = 1 m.

4. Discussion and Conclusions

One of the major problems when surveying in Tjorve (as in most caves) is the often ill-defined walls due to the sloping marble, and usually the width and height of difficult passages have been very roughly estimated. The labyrinthine nature of Tjorve, with numerous side passages, also add to the challenge. There are still probably some more kilometers of minor passages unsurveyed and unexplored in Tjorve.

Likewise, unresolved problems in the fractal analysis are the inaccuracy of passage profile measurements and the more general question of how a passage profile should be used as a local measure of passage size. The cave defined by the current LME mehod of analysis does not represent the complexity of cave passages, but rather some measure of *proper* size – that is, an anthropomorphic size. Nevertheless the fractal analysis provides estimates of cave morphology that can otherwise not be measured.

The relations between the parameters of the above morphometric and fractal analyses are unclear. A related question was asked some time ago (Curl 1963) when the modulus of a cave was first defined: are there defining scales for speleogenesis that imprint themselves upon caves? If there were, one would expect to find multiple peaks in the histogram of the distribution of passage size. From this and previous analyses, there appear to only be two: the size of explorers (which has nothing to do with speleogenesis) and the upper LME cutoff above about 5 meters, probably due to limits in strata thickness, rock strength, and extent of solution.

The proper modulus is near 1.1 m, compared to 0.6 m for LBC, indicating perhaps less complete exploration. In the power-law range there appear to be no defining scales, or

so many that they overlap in a way to produce a power-law dependence of LME size. How this works has not as yet been determined.

The total volume of the karst terrain including Tjorve and nearby caves, for any given modulus, cannot yet be estimated by the method of **RC** (p. 774, Eqn. 20) because the karst terrain has not as yet been analyzed to estimate the number and lengths of all caves in the terrain, with and without entrances.

Acknowledgements

Since Tjorve was discovered by Torbjörn Doj and Johannes Lundberg 29 July 1993, surveying has been done while exploring. Acknowledgements are due to the 75 cavers from Norway, Sweden, and four other countries who surveyed the cave.

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Supporting Online Material

http://www-personal.umich.edu/~ranecurl/2009ICS/SOM_09-0338.pdf

Derivations

Excel Spreadsheet

CORRELATION BETWEEN PASSAGE LEVELS IN THE BELLAMAR CAVE SYSTEM AND MARINE TERRACES SURROUNDING THE BAY OF MATANZAS, CUBA

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Abstract

The region under study is located in a continental erosion surface named the Bellamar Surface. It is a flat karstic area, at elevations between 50 and 70 m, although it can reach maximum altitudes of 100 m, and a minimum of 40 m. It constitutes the southern portion of the Bay of Matanzas, rimmed along its north flank by a system of marine terraces. A system of fissures is oriented almost parallel to the coast, and it guides the development of large cavities, which shows a correspondence with the genesis of the Bay. The main cave in the area is the Bellamar Cave System, which currently contains 27 km of surveyed passages.

In order to study the correlation between terrace levels and cave passages, we used 1:500 surveys of the different caves of the area, several generations of aerial and satellite images, as well as topographic maps at 1:2000 and 1:25,000 scale. This analysis allowed us to make longitudinal profiles in various places, in the surface as well as in the underground galleries. Three-dimensional digital models of the area were also used, obtained by the digital processing of the surface and the underground survey.

HOW KARST WORKS IN GRAND CANYON, ARIZONA, USA

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Caves in Grand Canyon, Arizona, USA fall into two main categories: unconfined (vadose) and confined (artesian). This study focuses on the artesian caves of the Redwall-Muav aquifer, where groundwater was confined by the overlying series of Supai rocks and by the underlying Bright Angel Shale. Discharge for artesian groundwater was, as it is today, primarily from the Redwall Limestone where it has been incised by the main canyon or its tributaries and where it has converged along a structural low or fault. Descent of the "water table" (potentiometric surface) over time is recorded by seven mine/cave episodes: (1) Cu-U ore episode, (2) iron-oxide cave episode, (3) cave-dissolution episode, (4) calcite-spar lining episode, (5) mammillary episode, (6) replacement-gypsum episode, and (7) subaerial-speleothem episode. Grand Canyon artesian caves are the result of: (1) being formed under confined conditions where the Redwall aquifer has carried most (>95%) of the water in the total system, (2) the mixing of epigenic ("upper world") waters with hypogenic ("lower world") waters so that undersaturation is achieved, and (3) discharge toward spring points that have reorganized and adjusted with respect to ongoing canyon incision.

1. Introduction

Grand Canyon of Northwest Arizona (Fig. 1) is located within the Colorado Plateau Province of western North America. The stratigraphic section exposed by Grand Canyon is over 1.6 km (1 mile) deep and consists of rocks of Proterozoic to Mesozoic age. The elevation of the Colorado River at Lees Ferry (Mile 0) is 960 m (3116 ft) and at Lake Mead (Mile 278) is 353 m (1157 ft), which provides an average gradient of 2.5 m/km (8.3 ft/mile). Most of the tributaries draining into the Colorado River along its Grand Canyon section are intermittent. Where flow is perennial, it is supplied by groundwater (spring) discharge. The aquifer system in Grand Canyon is – and has been for millions of years – karstic. In our ten year-long study of the canyon, we have visited over 50 caves on both the North and South Rims of the canyon, along the Colorado River, and in the region surrounding the canyon.

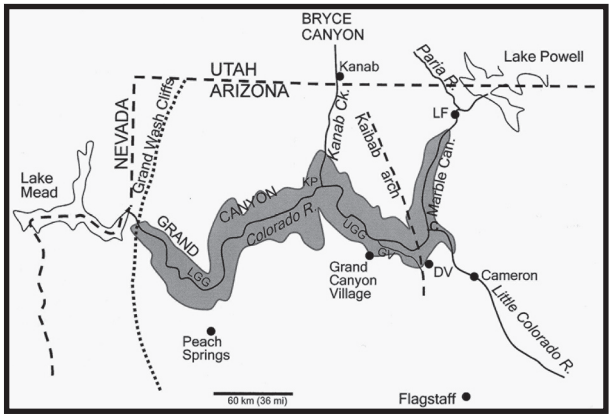

Figure 1: Grand Canyon of northern Arizona, USA. LF = Lees Ferry, C = Confluence, DV = Desert View, GV = Grandview monocline, UGG = Upper Granite Gorge, KP = Kanab Point, LGG = Lower Granite Gorge.

2. Past Work

The person who has done by far the most work on the karst hydrology of Grand Canyon is Peter Huntoon. The primary water-bearing unit is the Redwall-Muav aquifer, where the Redwall and Muav Limestones behave as a single hydrostratigraphic unit, together discharging a vast amount of water. The Redwall-Muav aquifer contains both vadose (unconfined) and artesian (confined) caves (Huntoon 2000a, b).

2.1. Unconfined or vadose caves

Grand Canyon caves formed under unconfined hydrologic conditions are simple linear drains in the vadose zone where water recharges on the Kaibab Plateau and moves down along faults or master joints usually (but not always) to discharge from the base of the Muav Limestone and above the Bright Angel aquiclude. Some examples of North Rim, Kaibab Plateau vadose caves are Tapeats, Thunder River, and Roaring Springs, which discharge along the south edge of the North Rim/Kaibab Plateau. Vadose caves are hydrologically active and have water flowing through them. They do not contain phreatic speleothems such as calcite spar or water-table speleothems such as mammillaries, as do artesian caves.

2.2. Confined or artesian caves

The majority of Grand Canyon artesian caves are found in the Redwall Limestone, primarily in the Mooney Falls

Member. Modern confined-aquifer caves include those forming today in the Marble Canyon area where the Colorado River is near Redwall Limestone level. Relict confined-aquifer caves formed like modern confined caves (i.e., under artesian conditions), but have been dissected and dewatered by canyon erosion. They are now exposed in the Redwall Limestone high above the Colorado River. Most artesian caves are not extensive (most are less than a kilometer long) and they are usually horizontally confined within the Mooney Falls Member of the Redwall Limestone. None of these caves contain deep vertical passages. Over the past decade we have studied the artesian caves, and not the vadose caves, because it is *only* in artesian caves that speleothems are preserved that record the descent of the water table and incision of Grand Canyon over time (Hill et al. 2001; Hill and Polyak 2005; Polyak et al. 2008).

2.3. Groundwater basins

Huntoon (1974, 2000b) identified four modern groundwater basins in the central-eastern part of Grand Canyon: the Cataract, Black Mesa, Kaiparowits, and Kaibab Plateau. Huntoon (2000a, b) established two very important hydrologic principles for the groundwater basins in Grand Canyon: (1) the discharge for artesian spring water is from the Redwall Limestone where it has been incised by the main canyon or its tributaries, and (2) the discharge is along a structural low or fault. In addition, Huntoon (1995) applied another principle of karst hydrology to Grand Canyon: flow in karst aquifers can cross faults and folds, move opposite to dip, and go under or through structures as it pursues a path along the steepest hydraulic gradient to discharge. Still another important principle involves the geochemical aspects of groundwater. Saturated water cannot dissolve caves: they must be dissolved by water undersaturated with respect to calcite. This is especially true in a limestone-karst setting such as Grand Canyon where saturated artesian water converges on springs from large-area groundwater basins. It is only at points where the mixing of different geochemical waters has achieved undersaturation that the artesian caves of Grand Canyon have formed.

Another important hydrologic model for Grand Canyon was introduced by Crossey et al. (2006), and this was their concept of "upper world" versus "lower world" waters. These authors analyzed waters discharging from both above and below the Bright Angel Shale aquiclude and found vast differences in their quality and quantity. Epigenic ("upper") waters are characterized by cool temperature (<20°C), high discharge, low conductivity, neutral to slightly alkaline pH, and low CO_2 content. Endogenic or hypogenic ("lower") waters, on the other hand, are associated with faults and typically exhibit warmer temperatures (20-35°C), low discharge, high salinity, lower pH, high CO_2, and mantle-derived helium. Such differences in water chemistry and temperature are typical of a hypogene speleogenesis (Klimchouk 2007).

3. "Water Table" Lowering as Evidenced by Cave Deposits

In a former ICS talk and paper, Hill and Polyak (2005) discussed the different ore and cave deposits displayed in the mines and caves of Grand Canyon: (1) Cu-U ore episode, (2) iron-oxide cave episode, (3) cave-dissolution episode, (4) calcite-spar lining episode, (5) mammillary episode, (6) replacement-gypsum episode, and (7) subaerial-speleothem episode. Since that talk, the cave episodes – especially the mammillary episode – have been used to determine the descent of the water table in the canyon over time. Only episodes (3), (4), (5) and (6) will be discussed in this paper since they offer information on the water table and its descent relative to canyon incision.

3.1. Cave dissolution episode

As convective water rises and cools, the solubility of calcite gradually increases so that small caves can dissolve in the deep solutional zone (Dublyansky 2000). It was in this phreatic regime that the artesian caves in Grand Canyon most likely formed. Figure 2 shows a graph of the solubility of calcite with depth for a thermal-water system, with an estimated maximum solubility at about 200 m below the water table. However, the depth of peak calcite solubility varies with P_{CO2}, salinity, and temperature, so the solubility peak moves along the depth axis depending on actual conditions. The caves probably formed as rising groundwater reached its maximum solubility where it mixed with descending meteoric water.

3.2. Cave spar lining episode

As the water table descends, caves formed in the solutional zone are shifted into the depositional zone because the solubility of calcite drops sharply due to the loss of CO_2 (Fig. 2). Since the loss of CO_2 is very slow in the deeper phreatic zone, large-spar crystals can precipitate, lining previously formed cave passages. Then, as the water table drops, slow CO_2 loss causes these saturated waters to precipitate their calcite. In this model, a small descent of the water table would have affected the equilibrium of the system so that solutions would have changed from aggressive to precipitative. The fact that spar linings directly overlie cave bedrock, without any type of a weathering episode in

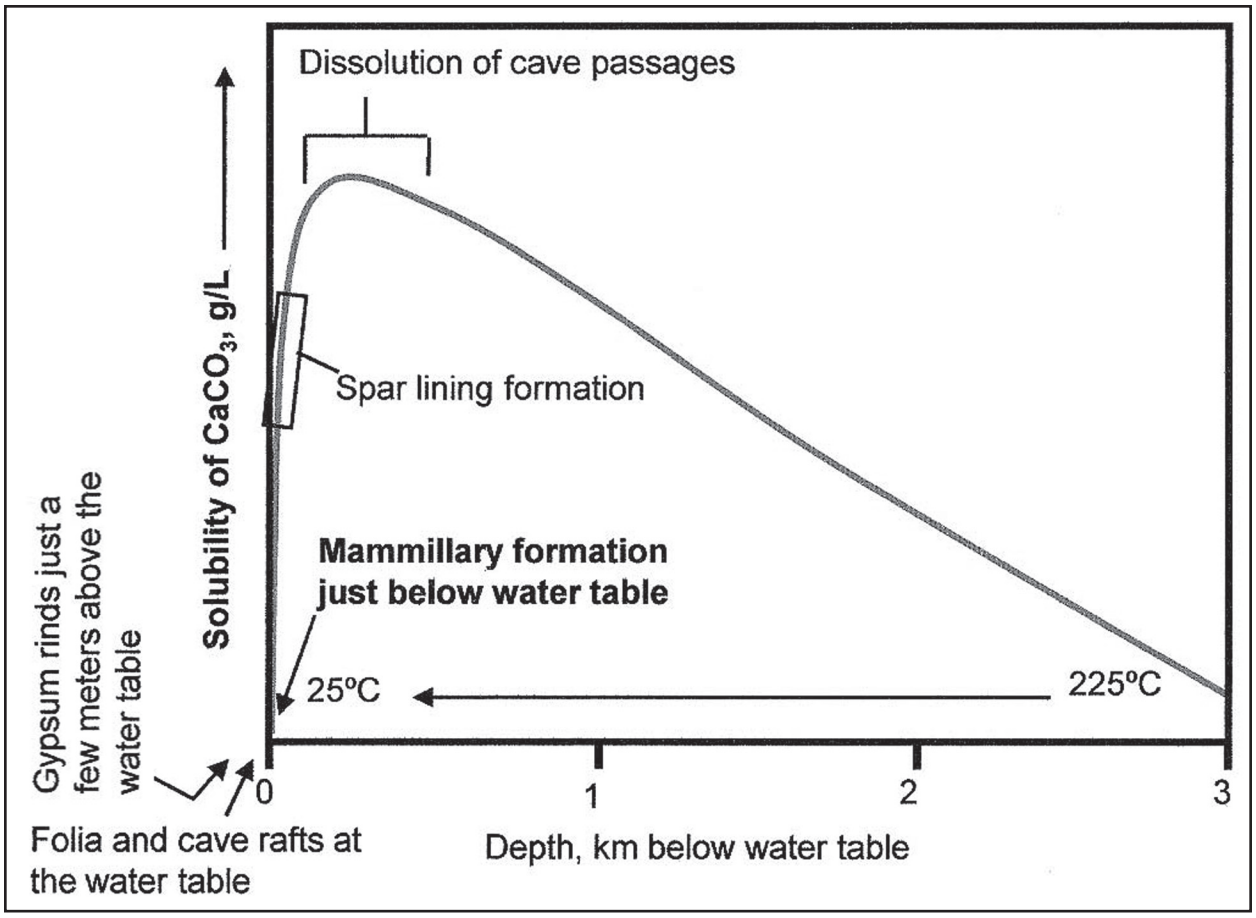

Figure 2: As convective water rises and cools, the solubility of calcite gradually increases so that small caves dissolve in the phreatic "solutional zone." As the water table descends, caves formed in the solutional zone are shifted into the "depositional zone." When this happens the solubility of calcite drops sharply due to the loss of CO2 and solutions change from aggressive to precipitative. Since the loss of CO2 is very slow in the deeper phreatic zone, large spar crystals line previously formed cave passages. Just below or near the water table in the shallow phreatic zone the loss of CO2 is much more rapid and therefore fine-grained mammillary coatings form instead of spar linings. At the water table-air interface folia and cave rafts form, and just above the water table replacement gypsum rinds form. After Dublyanksy (2000).

between, supports the idea of a close connection in time and origin between cave dissolution and spar precipitation.

3.3. Mammillary episode

Mammillaries are water-table speleothems that coat bedrock walls and ceilings or other speleothems. The mammillaries in Grand Canyon caves are known to have formed near the water table because they are associated with two speleothem types – cave rafts and folia – that form at the surface of the water table (Hill and Forti 1997). Figure 3 shows the type of speleothem deposited with respect to the lowering of the water table through a cave. Spar linings form when the cave is in the phreatic zone, the mammillary coatings form just below the water table, the folia and cave rafts form at the surface of the water table, the gypsum rinds form just above the water table, and dripstone and flowstone form above the water table after the cave becomes air-filled.

The Grand Canyon mammillary coatings are fine-grained as opposed to the coarse-grained calcite-spar linings. This fine-grained, densely packed, fibrous nature attests to the rapid degassing of CO_2 and precipitation of calcite near the water table, and also makes them suitable for dating by the uranium-lead (U-Pb) method (Polyak et al. 2008) – which is the necessary dating method because Grand Canyon mammillary ages exceed the ~600,000 YBP limit of the U-series method. Since this speleothem type is common in the artesian caves of Grand Canyon, and since they denote the approximate position of the water table (Fig. 3), Polyak et al. (2008) used them as their primary basis for dating Grand Canyon incision.

3.4. Replacement gypsum episode

Replacement gypsum rinds in Grand Canyon caves often directly overlie mammillary coatings, which sequence

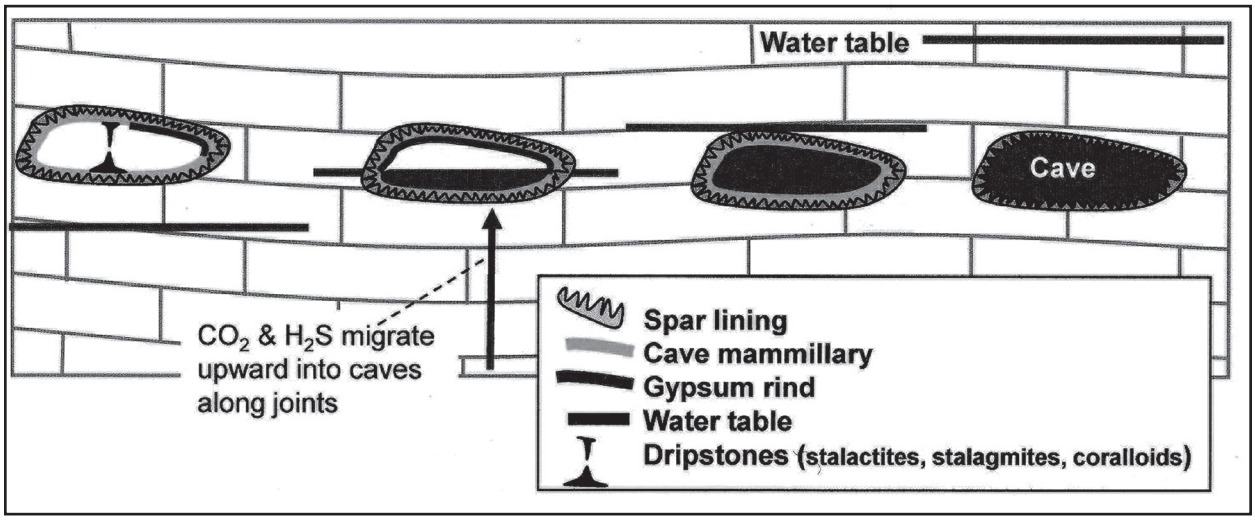

Figure 3: A diagram illustrating the progression of speleothem deposition related to the descending position of the water table. Spar lines cave walls in the phreatic zone below the water table, mammillaries form just below the water table, folia and cave rafts form along the surface of the water table when the water table descends to cave level, replacement gypsum rinds form just above the water table, and speleothems like stalactites and stalagmites form above the water table in the subaerial zone. The small-scale folia and cave rafts are not illustrated.

further supports a mammillary association with the water table (Fig. 3). Gypsum rinds up to 6 cm thick have been seen lining the walls of Grand Canyon caves or overlying earlier-formed speleothems. These rinds form from a *speleogenetic* mechanism rather than from a *speleothemic* mechanism. Speleogenetic gypsum rinds form where H_2S in ascending water diffuses upward into the cave air as the water table drops through the caves (Palmer 1991; Fig. 3). The oxidation of this H_2S at or just above the water table forms sulfuric acid which dissolves the limestone and produces replacement gypsum as a by-product of speleogenesis.

4. Generic Model for Grand Canyon Caves

Grand Canyon artesian caves are the result of: (1) being formed under confined conditions where the Redwall aquifer has transported >95% of the water in the total system, (2) the mixing of epigenic waters with endogenic (hypogene) waters, and (3) discharge toward spring points that have reorganized and adjusted with respect to ongoing canyon incision and dissection. In the following discussion refer to Figure 4 where the numbers (1) to (6) correspond to sections *i* to *vi*:

(i) Surface water descends via fractures from the Kaibab Limestone down through the Supai Group of rocks to recharge the Redwall aquifer (Redwall Limestone + Muav Limestone). Because of this fracture-restricted permeability, there never was a connected "water table" in the units above the Redwall aquifer – only a potentiometric surface determined by the Redwall aquifer artesian system. It was

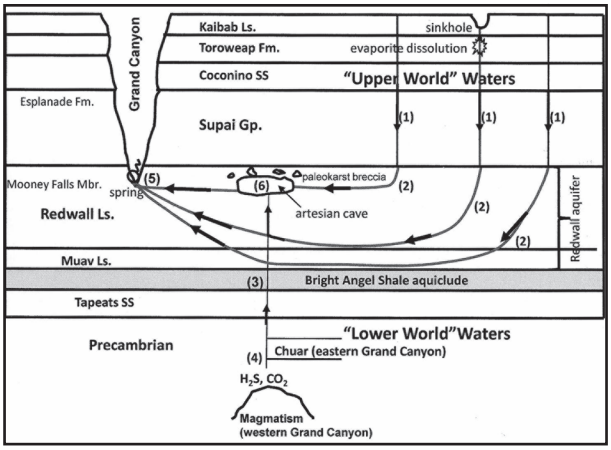

Figure 4: A generic model for cave formation in Grand Canyon. Meteoric groundwater descends along fractures in the Kaibab to Supai units and recharges the Redwall aquifer. Most of the flow in the aquifer is concentrated along the Mooney Falls Member, while deeper flow is constrained downwards by the Bright Angel Shale aquiclude. Although water discharges at spring points where canyon incision has intersected the Redwall Limestone, artesian caves do not form directly at these spring points. They form along brecciated zones of enhanced permeability and where "lower world" waters are ascending and mixing with "upper world" waters so as to achieve undersaturation with respect to calcite.

only when the artesian-head level reached the most karstic levels in the Redwall aquifer that a relatively flat, semi-connected water table could have existed. This is where the mammillaries formed: in caves that were dissolved during an

earlier period of phreatic speleogenesis, but which were later subjected to water-table conditions.

(ii) Once downward recharge along fractures reached the Redwall aquifer, some of this water circulated "deep," but most of it stayed concentrated along the more porous Mississippian paleokarst horizon in the Mooney Falls Member. "Deep" circulation in the Redwall aquifer only descended as low as the top of the Bright Angel Shale because this impermeable unit prevented further downward circulation. The maximum solubility for cave dissolution was probably achieved where hypogenic ascending groundwater mixed with meteoric groundwater (Fig. 4).

(iii) The Bright Angel Shale is an aquiclude that separates descending, meteoric "upper world" waters from ascending, hypogene "lower waters" (Crossey et al. 2006). Because of the presence of the Bright Angel aquiclude, most vadose caves and springs discharge to the canyon along the base of the Muav Limestone, just above the Bright Angel Shale. This impermeable shale barrier is also a prime horizon for travertine deposits in Grand Canyon, where descending, carbonate-saturated, vadose water emerges as springs along the top of the Bright Angel horizon.

(iv) Since almost all Grand Canyon artesian caves have replacement gypsum rinds in them, and since sulfur isotope values on this gypsum do not match those of bedrock evaporite units in the overburden, there must have been a source of reduced sulfur from the "lower world" regime. The sulfur isotopes of the replacement gypsum in eastern Grand Canyon caves have negative $\delta^{34}S$ values, and the only known organic source corresponding to these light sulfur isotope values is the Chuar-Walcott hydrocarbon unit in the Precambrian basement of the eastern Grand Canyon. In the western Grand Canyon, there is no Chuar in the Precambrian crystalline basement, and the replacement gypsum rinds in these caves display positive sulfur isotope values typical of a volcanic/magmatic source.

(v) Redwall artesian flow converges on springs along the Colorado River. However, these spring points are *not* the loci for artesian cave dissolution. The conclusion that Grand Canyon artesian caves did not form *at* spring outlets but rather along flow paths leading *toward* spring outlets is supported by the following factors:

(a) There are no features in these caves, such as scallops, that would indicate high-velocity flow from a spring.

(b) The calcite spar that lines these artesian caves had to have formed under very stagnant aquifer conditions – not at springs with flow rates of 410 l/sec (6500 gal/min), such as has been monitored by Huntoon (1981) at Fence Springs.

(c) Mammillary speleothems, while formed near the water table, still have to precipitate from saturated water in regions where the flow rate is not high.

(d) It is typical of hypogene speleogenesis not to be associated with terminal discharge regimes of basinal groundwater flow systems, but with intermediate discharge limbs of these systems (Klimchouck 2007). This appears to have been the case for Grand Canyon artesian caves.

Rather than at spring outlets, the locations of Grand Canyon artesian caves seem related to:

(a) Permeable zones in the Redwall aquifer where water diffused along a joint-dominated path to a spring outlet. One zone of maximum permeability seems to have been along the Mississippian paleokarst horizon in the Mooney Falls Member of the Redwall Limestone (Fig. 4), and a number of caves display paleokarst breccias in their walls or ceilings.

(b) The caves are related to places where "lower world" H_2S-CO_2-rich solutions must have ascended through the Bright Angel Shale along faults/joints because practically every artesian cave displays replacement gypsum rinds. This H_2S-CO_2 could have helped caves dissolve in the phreatic zone by the process of mixing corrosion, and later in time it could have caused cave enlargement just above the water table by the process of condensation-corrosion, where high CO_2-H_2S in the air weathers limestone (Palmer 2007).

Let us now take our generic artesian cave and trace its evolution with respect to the lowering of the water table and canyon incision. The artesian cave shown in Figure 5 was below the potentiometric surface until the time that the canyon incised to the level of the Redwall aquifer; then once the Redwall Limestone horizon was reached, unconfined "water table" conditions began to prevail. This incision also caused the aquifer to be breached and springs to flow towards a canyon outlet. Let's say that the mammillaries in this generic cave (formed just below the water table) have a U-Pb date of 3.5 Ma, as shown in Figure 5. Thus, neglecting dip and other local factors, the age of these mammillaries approximately equals the time it has taken for the canyon to incise from this 3.5 Ma level to where it exists today – which concept was the basis for Polyak et al.'s (2008) correlation of the age of Grand Canyon incision with the age of mammillary speleothems.

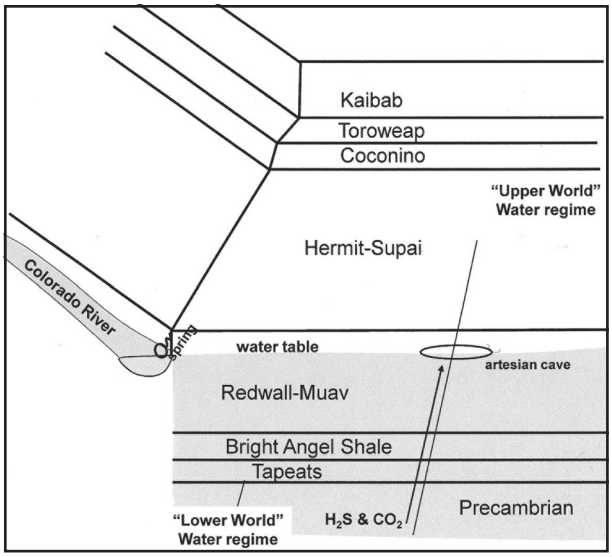

Figure 5: A generic model for how artesian caves correspond to the water table and incision of Grand Canyon. Figure 5 shows the Colorado River having incised the canyon down to Redwall Limestone level, with a spring exiting from the Redwall aquifer to this incised canyon. Because the water table has dropped to cave level, this is where and when any mammillaries would have been deposited in this cave. Therefore the age of the mammillaries is approximately equivalent to the time it took for the canyon to incise from this 3.5 Ma level to where it exists today.

Acknowledgments

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THE POSSIBLE SPELEOGENE-HYPOGENE ORIGIN OF THE WARDA IRON ORE MIME DEPOSIT (JORDAN)

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The iron ore deposit of the historic Warda mine (District of Ajloun, northern Jordan) and its speleological importance is discussed. Former prospecting results show that the deposit has a size of 300 x 200 m with a maximal thickness of about 10 m. The Warda Iron Deposit was mined during the time of the crusades by the Arabs in the time of Saladin to supply the castle of Ajloun. The historic mine consists of two larger rooms, ca. 1000 m^2 in area. Much of the mine's floor is now covered with recent flood sediments (680 m^2), up to over 2 m deep. The mine cuts small natural cavities with a few speleothems and a breakdown hall in limestone that may or may not have been created by the collapse of a mine cavity. Conservative calculation of the mine volume suggests that a total of about 1100 t of Fe may have been extracted. Mineralogical investigation (XRD) shows that the iron ore is goethitic/limonitic with a noticeable hematite content. Presence of greigite may be indicated by a few XRD d-values and an S-content of >3% in one sample from the center of the deposit exposed in a modern quarry. Geochemical (XRF) analysis shows that the goethite is very pure; impurities of main elements sum up to only 1%. Textural, mineralogical and geochemical criteria suggest that the ore body could have a speleogenetic origin, i.e. deposited in a hypogene, deep phreathic setting, possibly before regional uplift or even prior to the maximal burial depth. The geochemistry excludes a synsedimentary origin while the mineral-paragenesis excludes a hydrothermal origin. A possibly similar ore-body was described from the gigantic, sand-filled Lower Cretaceous cave of Wülfrath (North Rhine-Westphalia, Germany) (Drozdzewski et al. 1998). The number of known limestone caves in Jordan is very small even though large sections of the country are underlain by carbonates. The largest one, Al-Daher Cave, is also a hypogene cave forming a maze within an area of 70x70 m (Kempe et al., 2006), underscoring the importance of hypogene speleogenesis for Jordan. The discussed model, developed according to the present state of knowledge, could serve as a starting point to investigate similar deposits and the Warda Iron Deposit could serve as a *locus typicus* for a new type of iron ore deposit not well studied yet.

1. Introduction and Geologic Setting

Since 2003 the authors have systematically explored caves and karst and their genesis in Jordan. While the eastern part of Jordan is a lava plateau with lava caves (Kempe et al., 2008), much of eastern Jordan is formed by Upper Cretaceous limestone. Nevertheless only a few dissolutional caves are known in Jordan at present (Kempe et al. 2006; Al-Malabeh et al. 2007).

Here we report on a cavity mostly created by historic mining that extracted oxidic iron ores. Iron was an important commodity to ancient Near East cultures since the beginning of the Iron Age at 1200 B.C. Since Jordan is lacking large-scale iron ore deposits (e.g., Bender 1974), small ore occurrences were mined locally and extracted at the surface in open pits or underground in short tunnels. Natural cavities, made it much easier to extract the ore. One of these areas is near Ajloun (Fig. 1), where a mine is still accessible and several entrances are found. This mine is, however, threatened by a nearby quarry and road development.

Many prominent structural features are present in Jordan. They are closely related to the regional geology and tectonics of the Eastern Mediterranean area. Several intraplate deformation phases affected the northern Arabian Plate between the Late Paleozoic and the Cenozoic. Major rifting episodes occurred in the Late Carboniferous to Permian, Middle to Late Triassic, and at the end of the Early Cretaceous (e.g., Garfunkel et al. 1981; Freund et al. 1970; Barazangi 1983).

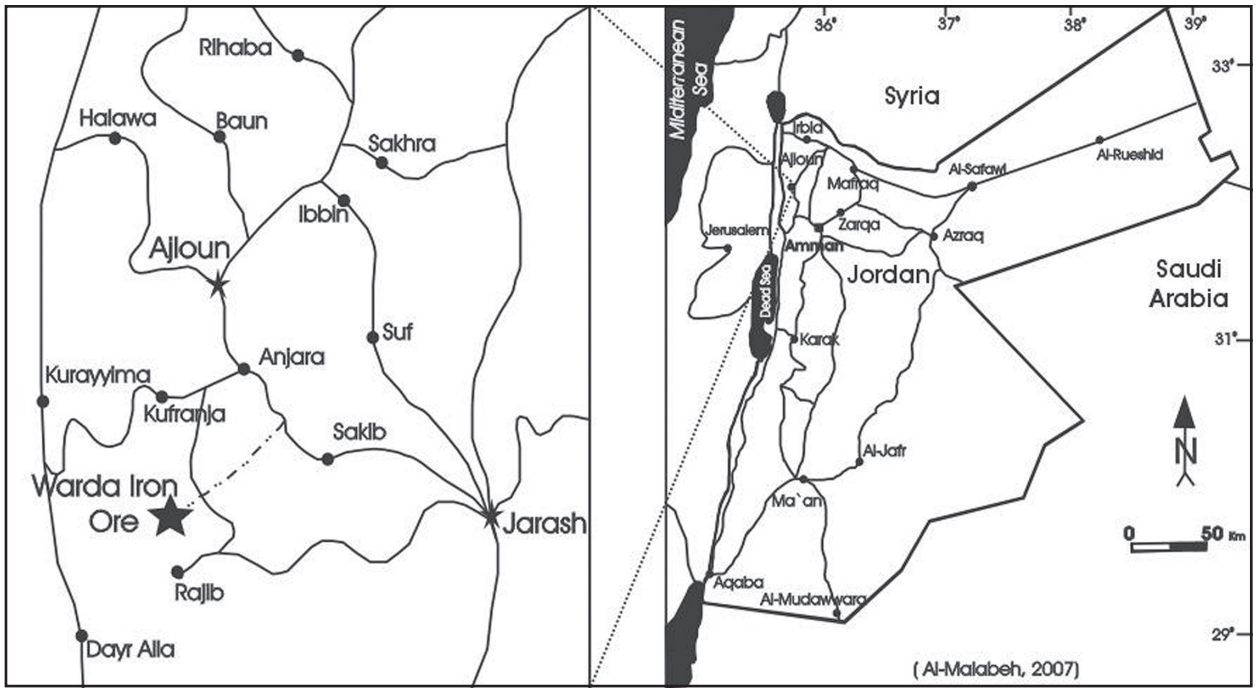

Figure 1: Location map of Warda Iron Deposit in the northern part of Jordan.

Major structural trends are N-S, E-W and NNE-SSW. Along these directions, the rocks have been substantially jointed and fractured. Field investigation shows that the Warda Iron Ore Deposit (WID) occurs as a belt extending in a NNE-SSW direction. Along this direction a fault with fault breccia is recorded. The ore occurs in Upper Cretaceous limestone of Cenomanian-Touranian age in what locally known as the Wadi Al-Sir Formation.

2. Warda Iron Ore Deposit

The Warda Iron Ore Deposit (WID) is situated east of the Dead Sea Transform Fault at 32° 15'9"N and 35°44'32"E at an altitude of about 620 m. The area was called locally Jabal Al-Aqra', i.e. "bald mountain" because of the former absence of trees. Now the area was reforested by the Ministry of Agriculture and it is called Jabal Al-Akdar, i.e. "Green Mountain". Warda means "rose" in Arabic, denoting the brilliant colors of the iron ore. The pit mining exposed an ore body about 10 m thick. It occurs as a band that is about 300 m long and 150 m wide striking NE-SW to NNE-SSW. The iron ores are oxidic, mostly of brown colors with yellow and black sections. The WID seems to be the only iron ore deposit in Jordan extensively mined historically and today.

3. Mine and Cave

The entrance to the Warda Iron Mine is located below the road from Ajloun to the Jordan valley. A small agricultural field is nested in a sharp W-turn in the road. The field and a neighboring plot are partly surrounded by low cliffs that have several artificial openings (st. 2, 5 and 6, Fig. 2). Only one of them, leading north underneath the road, gives access to an old mine (Fig. 2). The underground cavity consists of two larger, SE-NW striking, 40 m-long rooms, connected by a low crawl (st. 13–14). The entrance room leads steeply down over blocks to the smooth floor of the mine, 12 m below st. 1. This floor is the surface of consecutive flood deposits, washed into the mine during severe rains. Here reddish, silty sediments cover the original floor meter-deep, as shown by two archeological digs, one, in the entrance hall, being 2.2 m deep and the other, in the furthest corner of the second hall, being 1.5 m deep (Fig. 3). In the SE corner of the entrance hall, adjacent to breakdown blocks, jamming parts of the former, much larger entrance, two little mining chambers (st. 10 and 11) are found. Much of the lower part of the entrance chamber (st. 12–13) is developed in the massive ore body. The far end (st. 15–16) of the second chamber is also dug out of the massive ore body while its northern parts are different. To the west, a large pile of breakdown blocks leads upwards, exposing SW - at ca. 40° - dipping limestone strata in a large cupola. This part of the cavity does not look artificial it may though be a collapse of the mine roof into a once larger and deeper mining chamber. Here lives a sizable colony of bats. Bags show that the local inhabitants mine the bat-guano for fertilizer. In the SE corner, several passages are encountered that follow natural fissures through a brecciated ore body. The walls of these fissures are sparsely covered with speleothems, showing that the miners found some small natural cavity when

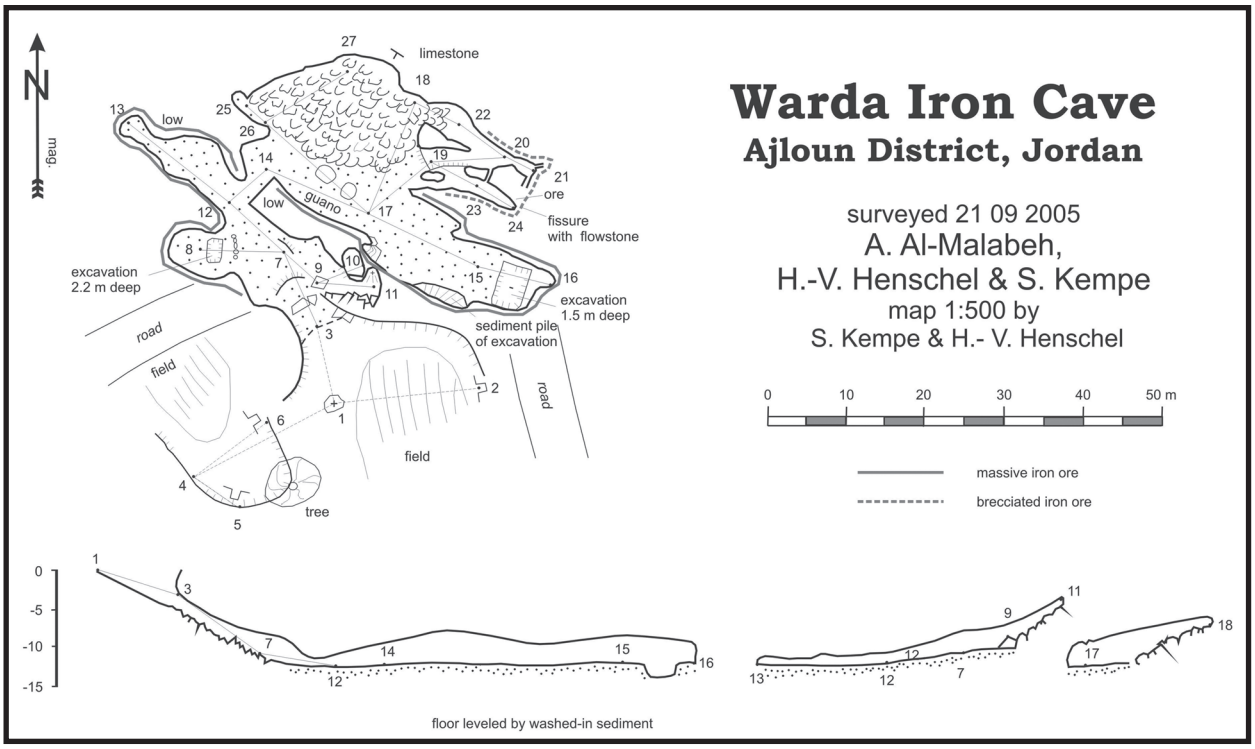

Figure 2: Map and cross-sections of the historic Warda Iron Ore Mine/Ajloun District.

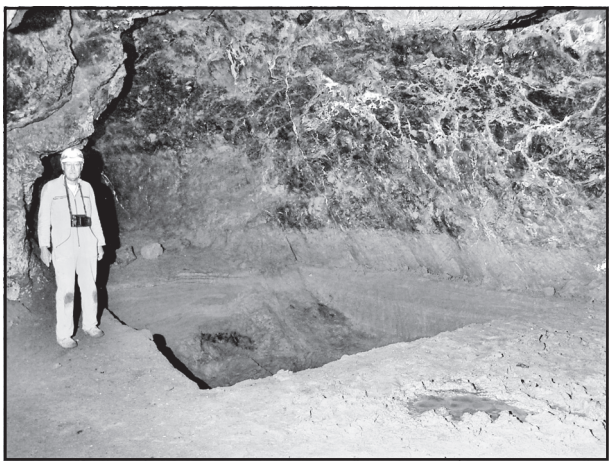

Figure 3: View of inner hall and archeological dig.

working the ore body. These fissures and their strike are most probably parallel to a fault, governing the valley in the cave area. The mine may have had more passages originally that are now either buried under the red dirt or by the breakdown pile.

The area of the surveyed cave is 980 m^2 of which up to 640 m^2 seem to be covered with flood sediments (entrance hall and southern section of inner hall). 230 m^2 are occupied by the breakdown hall and the fissure-determined passages cover 100 m^2. Much of the mine's floor is now covered with recent flood sediments (680 m^2), up to over 2 m deep.

4. Results

4.1 XRD mineral identification

A total of five samples were investigated by XRD (Table 1) (courtesy H. Hofmann Techn. Univ. Darmstadt). The following minerals were detected: Calcite, hematite and goethite. In Sample W1 a mineral is present that could not be clearly identified (d-values = 2.983, 1.906, 1.749). In review it was suggested that this mineral may be greigite $(Fe^{2+}Fe^{3+})S_4$. Its d-values (relative percentage intensities in brackets) are: 2.980 (100), 1.746 (77), 2.470 (55), 3.498 (32), 1.008 (31), 1.901 (29), 1.105 (16) (quoted from http://rruff.geo.arizona.edu/doclib/hom/greigite.pdf).

4.2 EDAX chemical analysis

EDAX analysis was performed on the same samples that were analyzed by XRD. Samples were scanned at a magnification of 60 times at 25KV with a Fei-Quanta 200FEG and an EDAX. Spectra accumulated over 30 s were recalculated for elemental composition by the ZAF method (Genesis Software by EDAX). The following elements were included in the calculations: C, O, Na, Mg, Al, Si, S, K, Ca, Fe (Table 2). No other element peaks occurred.

The results match those of the XRD analysis. Fe is by weight the most important element ranging between 24.6 and 71.3% followed by Ca with 0.9 to 24.0 %. The oxygen concentration is not in proportion to its real content; for

Sample W1	W2	W3	W4	W5
dark brown orange	dark orange brown	blackish brown	blackish ochre	blackish ochre brown
Calcite XXX	Calcite XXX	Hematite XXX	Goethite XXX	Goethite XXX
Greigite?? XX	Goethite XX	Calcite XX	Calcite XX	Hematite XXX
Hematite X	Hematite X	Goethite XX	Hematite X	Calcite X
(Goethite)				

Table 1: XRD Results (XXX = most prominent mineral; XX = abundant; X = clearly detectable; ( ) = possibly present). The second line is giving the color description of the ground sample according to Michel Farbenführer, 2000.

SampleNumber	W 1		W2		W3		W4		W5	
Element	Wt%	At %	Wt%	At%	Wt%	At%	Wt%	**At%**	**Wt%**	**At%**
C	11.94	22.30	3.87	10.09	2.88	8.52	8.50	18.00	2.65	6.71
O	34.32	48.11	22.57	44.12	16.78	37.27	32.91	52.29	27.33	51.99
Na	0.64	0.62	0.37	0.50	0.00	0.00	0.56	0.62	0.43	0.57
Mg	0.38	0.35	0.94	1.20	0.08	0.12	0.58	0.61	0.47	0.58
Al	7.40	6.15	0.85	0.98	0.78	1.03	0.37	0.35	1.49	1.68
Si	2.02	1.61	1.51	1.68	1.00	1.27	0.53	0.48	2.37	2.57
S	3.56	2.49	0.21	0.21	0.27	0.30	0.24	0.19	0.24	0.23
K	1.17	0.67	0.32	0.26	0.23	0.21	0.15	0.10	0.16	0.13
Ca	13.96	7.81	9.57	7.46	6.71	5.94	10.02	6.36	0.91	0.69
Fe	24.60	9.88	59.79	33.49	71.26	45.33	46.12	21.00	63.95	34.85
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 2: EDAX analysis Samples W1 – W5.

example in W3, if one takes the atom ratio of Ca (ca. 6) and subtracts 6x3 oxygen (because in $CaCO_3$ we have three O for each Ca) then only 19 atom% of O remains. That is not enough to accommodate the 45 atom% of Fe as either goethite or hematite. This mismatch is due to the fact that light elements (C and O) are generally not well represented in the EDAX analysis.

Sample W1 has a high concentration of Al and S and a noticeable K peak is present. Thus one could also speculate that these elements may constitute the unidentified mineral found in the XRD spectrum. At first one thinks of potassium-alum ($KAl(SO_4)_2x12(H_2O)$) or a mixture of it with Na-alum. However, neither the d-values of the XRD agree with those of K-alum (strongest d-values: 4.298 (1); 3.25(0.55); 4.053(0.45)) or Na-Alum (d-values: 4.314 (1); 2.962(0.35); 3.526 (0.14)), nor do the elemental ratios of Al/S match (i.e. they should be 0.5 instead of ca. 2 as measured for W1). Thus greigite currently remains the best option.

4.3 XRF chemical analysis

Major elements (Table 3) were determined for five more samples using the XRF at the Geological Institute, Erlangen University, Germany (courtesy Prof. Dr. H.J. Tobschall). Sample IC 1 is from the flash flood sediment in the historic mine. Samples IC 2, 3 and 4 are samples of the ore body in the historic mine and sample IC5-calcite is a speleothem sample from the cave cut by the mine.

5. Discussion of Results

5.1 The ore body

In places, the WID shows a brecciated nature, possibly a consequence of the NNE-SSW striking faults in the area. Smaller fissures were filled with multi-generation calcite veins. Larger, open fractures were partly filled with speleothems. Large natural chambers may have existed within the ore body, as suggested by the irregular form of the mine and by the existence of a large breakdown cupola in limestone.

Sample	IC1(sediment) RF 9863	IC 2 RF 9856	IC 3 RF 9861	IC 4 RF 9862	IC5-calcite RF 9854
Oxide	**%**	**%**	**%**	**%**	**%**
$Si0_2$	6.4	0.1	**12.0**	*<0.1*	<0.1
$Ti0_2$	0.07	0.13	**0.41**	*0.02*	<0.01
AI_20_3	**0.08**	*0.01*	0.1	0.07	0.01
$Fe_20_3{}^t$	36.77	62.29	*27.31*	**73.76**	0.07
Mn0	**0.004**	*0.003*	*0.003*	**0.004**	0.002
Mg0	0.39	0.28	**0.65**	*0.07*	0.51
Ca0	29.41	17.63	**32.84**	*0.06*	55.13
Na_20	<0.01	<0.01	<0.01	<0.01	<0.01
K_20	*<0.01*	**0.01**	<0.02	*<0.01*	0.01
P_20_5	*0.033*	0.061	0.068	**0.116**	0.004
$S0_3$	**0.39**	0.32	*0.05*	0.17	<0.01
Cl	**0.08**	**0.08**	0.07	*0.06*	0.09
F	0.02	0.25	*<0.01*	**0.48**	<0.01
LOI	27.5	15.22	**27.89**	*10.34*	43.78
SUM	101.0	96.3	101.4	84.9	99.0

Table 3: Major elements (XRF) of the studied samples. (RF = Lab. No. Erlangen; LOI = Loss On Ignition; Fe2O3t = total iron). Bold = highest values; italics = lowest values of ore samples (excluding IC5-calcite).

5.2 Geochemistry

The major element composition of the WDI (Table 3) shows that it is mainly characterized by high Fe_2O_3 concentrations, ranging from 27.3 to 73.8 wt% in the rock samples corresponding to the high Fe-concentrations found in the EDAX-analysis (Table 2). The highest amount is found in sample IC4, representing the most characteristic and unaltered ore composition. Even the sediment sample still has 36.8 wt% Fe. The Fe-concentration falls within the averages reported for WID by different authors (e.g., Saffarini 1988).

The CaO ranges from 0.06 to 32.84 wt% in the rock samples (with IC4 having the lowest value) and is 29.41 wt% in the sediment. The speleothem sample expectedly has the highest CaO content, i.e., 55.1 wt%. The SiO_2 content ranges from < 1 to 12.0 wt% in the rock samples and reaches 6.4 wt% in the sediment. It is interesting to note, that we did not find any quartz in the XRD samples so that the SiO_2 most probably is in the form of amorphous chert. The TiO_2 ranges from 0.02 to 0.41 wt% in the rocks sample and reaches an intermediate concentration in the sediment, i.e. 0.07 wt%. MnO, Al_2O_3 and P_2O_5 are all low in concentrations ranging from 0.003 to 0.0004, 0.01 to 0.1, and 0.06 to 0.116 wt%, respectively. Similarly Na_2O and K_2O are very low, i.e., below < 1 wt%.

6. Conclusions

Many models can be discussed regarding the potential genesis of the WID, among them: 1) syn-sedimentary deposition, 2) hydrothermal marine, 3) metasomatic, 4) weathering of a basaltic precursor or 5) speleogenetic (phreatic-hypogene).

Model 1 can be excluded, because of the texture of the ores and the fact that the goethite is very pure. Model 2 can be excluded because of the low Sr values in our samples (Hendricks et al. 1969). Model 3 most probably can also be excluded since high-temperature metasomatic deposits have a different paragenesis, including originally deposited siderite, veins of quartz, barite and co-precipitated heavy metal sulfides, all of them missing in the WID (e.g., Kempe 1998). The weathering of basalts (Model 4), a process that can also lead to pure iron oxides (i.e., Al-Malabeh and Kempe 2005), is also not very likely.

Thus the last, the speleogenetic model remains. In speleology it is now an accepted fact (for an overview see Klimchouk, 2007, and review by Kempe, 2007) that many limestone caves, and among them some of the largest

known, were formed by ascending waters below the water table (i.e., deep-phreatic) by slow gravity-driven convection. In order to generate in-situ dissolutional capacity for these very large cavities, the bacterially mediated reaction, between an anaerobic, ascending phase and an aerobic descending phase at low temperatures is assumed. The reaction between both can then generate protons that serve to dissolve the limestone around the ascending plume of water. Water loaded with H_2S or CH_4 is not aggressive, but if oxidized, the resulting acids (H_2SO_3 and H_2CO_3) would provide dissolutional capacity. In the case of Carlsbad Cavern internal gypsum deposits show that the ascending gas was mostly H_2S. CH_4, its oxidation and the consecutive dissolution does, however, not leave any traces, possibly with one exception: Goethite. Under anaerobic conditions, when sulfide is missing, iron could be mobilized as Fe^{2+}. If mixed with sinking O_2-containing water, the CH_4 would be oxidized bacterially; CO_2 would be produced to dissolve the limestone and at the same time goethite would be precipitated. Thus, it is conceivable that under such conditions, small-scale goethitic ore bodies could be formed speleogeneticly. Similarly, $W^{4+}O_2$ (solubility 10 mg/l not depending on pH if <10) is more soluble than $W^{6+}O_3$ (0.1-2 mg/l depending on increasing pH) (Dermatas et al. 2004), thus being co-precipitated with Fe upon oxidation and explaining the high tungsten concentration in sample IC4.

To our knowledge there are several examples of goethite deposits in hypogene caves. None of them are well published. The most impressive one is the goethite deposit in the gigantic cave found near Wülfrath/ North Rhine-Westfalia/Germany. A quarry (Rohdenhaus-Süd) in Devonian massive limestone uncovered an enormous, at least 700 m long, 200 m wide and 20 m high cavity filled completely with quartz sand that contained lower Cretaceous plant remains (Drozdzewski et al. 1998). In the centre, a 10 m thick limonitic ore deposit at least 50 m wide was discovered, filling the space above the sedimentary deposits. This ore body could mark the site of the ascending waters, comparable to the deep sea chimneys of black smokers. This cave is one of the largest natural cavities yet discovered and clearly of hypogene origin, created by some sort of in-situ acid generating reaction. The iron ore has not yet been investigated in detail. In a more recent cave, the Bismarck Cavern, Frankonia/Germany, we also observed stalactitic or chimney-like goethite deposits on the floor. This cave is also of hypogene origin and the goethite may be the only clue as to its real formation mechanism.

Therefore, it is conceivable that the WID formed in a similar way. This speleogenetic lagerstaetten-model, while quite hypothetical, would account for the stratiform character of the deposit, for its situation within a marine limestone sequence, for the missing marine trace metal imprint in the ore and for the missing high temperature signature of the mineral paragenesis. The model would also account for the observed limestone blocks floating in the ore; they could be interpreted as roof collapse of the original cave. When looking at the geological development of the area and assuming the speleogenetic model to be correct, then the deposit could have formed at the end of marine sedimentation in the area, when plate stress began to open up fractures into the basement. From there, methane (and Fe^{2+}) rich solutions could have ascended upward into the limestone series. Where they met sinking, oxygen-rich surface waters, bacterial oxidation and the resulting H_2CO_3 would have provided for the formation of a large cave. At the same time the ferrous iron would be oxidized and precipitated as water-rich goethitic limonite in the growing cave. As pressure and temperature increased, the bacterial reaction ceased and some of the goethite was dehydrated to hematite. Further increase of the N-S pressure on the plate led to a brecciation of the ore body and to the formation of calcite veins. Once lifted to altitudes of several 100 m asl, water, circulating through the breccia, could form small cavities and speleothems could start to grow. For an extended discussion of the WID see Al-Malabeh et al. (2008).

This model, developed according to the present state of knowledge, could serve as a start to investigate similar deposits and the WID could serve as a *locus typicus* for a new type of iron ore deposit not well studied yet. In a sense, the finding of Al-Daher Cave as described in the introduction and its hypogene nature, illustrates that effective speleogenetic systems involving ascending water plumes have existed in Jordan in the past. They therefore may have played a much more important role than hitherto acknowledged.

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THE DEEPEST CAVE IN THE WORLD IN THE ARABIKA MASSIF (WESTERN CAUCASUS) AND ITS HYDROGEOLOGICAL AND PALEOGEOGRAPHIC SIGNIFICANCE

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Arabika is an outstanding high-mountain karst massif in the Western Caucasus composed of Upper Jurassic and Lower Cretaceous limestones continuously dipping southwest to the Black Sea and plunging below the sea level. The central sector (elevations 1,900–2,700 m) is characterized by pronounced glacio-karstic landscape and hosts several deep caves, including the deepest cave in the world, Krubera (Voronja), recently explored to the depth of -2191 m. Dye tracing experiments conducted in 1984-1985 revealed that the Krubera Cave area is hydraulically connected with major springs at the shore of the Black Sea by submarine discharge, and with the flow directed across the strike of major fold structures.

Krubera Cave has an extremely steep profile and reveals a huge thickness of the vadose zone. The lower boundary of the vadose zone (the top of the phreatic zone) is at an elevation of about 110 m at low flow, which suggests a low overall hydraulic gradient of 0.007-0.008. Low-TDS groundwater is tapped by boreholes in the shore area at depths of 40–280, 500, 1,750, and 2,250 m below sea level, which suggests the existence of a deep flow system with vigorous flow. Submarine discharge along the Arabika coast is reported at depths up to ~400 m bsl. A huge closed submarine depression is revealed at the sea-floor next to the Arabika, with its deepest point at ~400 m bsl. These facts point to the possibility that the main karst system in Arabika could have originated in response to the Messinian salinity crisis (5.96–5.33 Ma) when the Black Sea (Eastern Paratethys) could have almost dried up, as did the adjacent Mediterranean where a dramatic sea-level drop of ~1,500 m is well established. Further development of the huge vadose zone and the super-deep caves has been caused by subsequent uplifts during the Pliocene-Pleistocene, with a great difference between the shore sector (0.1–0.2 km of total uplift) and the central sector (2–2.5 km) of Arabika.

It is not by chance that the deepest cave in the world, with its exceptionally high vertical range of almost 2,200 m, has been discovered in the Arabika massif. There were unique geological and paleogeographic pre-conditions for that. The study of the Arabika karst system and exploration of the Krubera Cave constitutes new arguments supporting the response of the Black Sea to the Messinian salinity crisis.

1. Introduction

Arabika is one of the largest high-mountain limestone karst massifs in the Western Caucasus. Cave exploration in Arabika during the 1980s by speleologists from Ukraine, Russia, Belorussia and Moldova, and dye-tracing experiments performed in 1984–85 by the Institute of Geological Sciences of the Ukrainian Academy of Sciences, radically changed previous hydrogeological models for the massif and revealed its outstanding potential for deep caves (Klimchouk, 1990). During 1999–2007 this potential was realized in full in Krubera (Voronja) Cave by the expeditions of the Ukrainian Speleological Association. The cave became the deepest in the world in 2001 (-1,710 m). In 2004, for the first time in the history of speleology, the 2,000 m depth mark was passed in Krubera and the cave was pushed to -2,080 m. In 2006 a depth of -2,158 m was reached, followed by the current record of -2,191 m in 2007.

Krubera Cave has an extremely steep profile and reveals a huge thickness of the vadose zone. The top of the phreatic zone is reached at an elevation of about 110 m asl. This, along with evidence for vigorous karst groundwater circulation deep below the present level of the Black Sea, point to a possibility that karst systems in Arabika could have originated in response to a base level at a much lower position in the past than is suggested by the Pleistocene glacioeustatic oscillations.

2. Location and Physiography

The Arabika Massif is located in the Western Caucasus (Fig. 1, A-B), in Abkhazia, a republic which officially belongs to Georgia but holds claim to being an independent state.

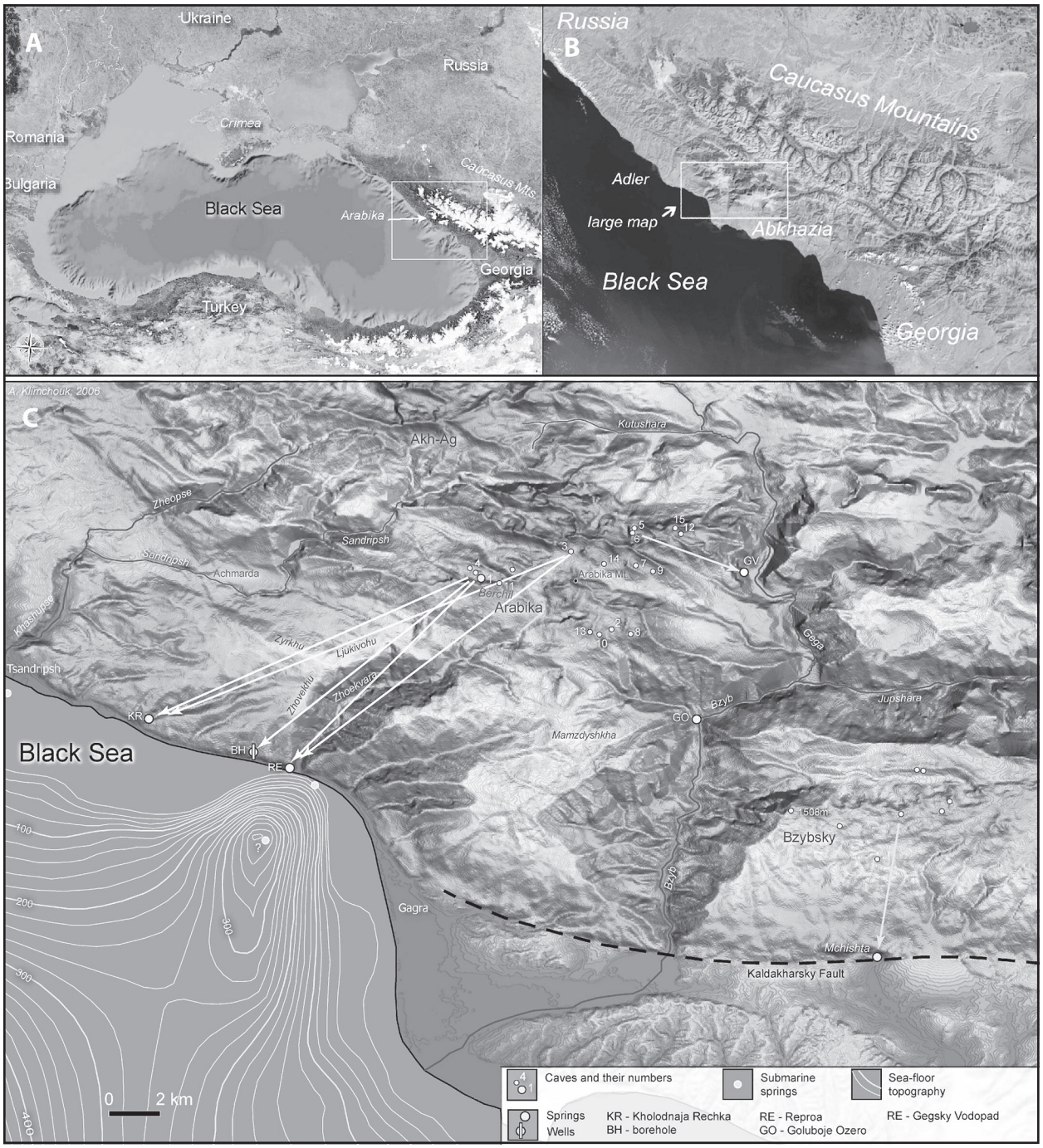

Figure 1: Location (A and B) and shaded map of the Arabika and Bzubsky massifs. The sea-floor topography is based on the global digital bathymetric data that combines depth soundings and high-resolution marine gravity data (Smith and Sandwell, 1997). Deep caves are indicated by dots and numbers (explained in the text) and major springs are specified by two-character indexes (explained in the legend). Arrows indicate hydrologic connections proved by dye-tracing experiments.

To the northwest, north, northeast, and east, Arabika is bordered by the deeply incised canyons of Sandripsh, Kutushara, Gega and Bzyb rivers. The Bzyb River separates Arabika from the adjacent Bzybsky Massif, another outstanding karst area with many deep caves, including the Snezhnaja-Mezhonogo-Iljuzia system (-1,753 m) and Pantjukhina Cave (-1,508 m). To the southwest, Arabika borders the Black Sea, with limestones dipping continuously below the sea level (Fig.1, C).

Arabika has a prominent high central sector with elevations above the tree line at ~1,800–1,900 m. This is an arena

of classical glaciokarstic landscape, with numerous glacial trough valleys and cirques, with ridges and peaks between them. The bottoms of the trough valleys and karst fields lie at elevations of 2,000-2,350 m, and ridges and peaks rise to 2,500-2,700m. The highest peak is the *Peak of Speleologists* (2,705 m) but the dominant summit is a typical pyramidal horn of the *Arabika Mount* (2,695m). Some middle- to low-altitude ridges covered with forest lie between the central sector and the Black Sea. A plateau-like middle-altitude outlier of the massif in its south sector is Mamzdyshkha, with part of the plateau slightly emerging above the tree line.

3. Deep Caves

Among several hundred caves known in the Arabika massif, fifteen have been explored below 400 m and five below 1,000 m (shown in Fig. 1, C). Several are located within the Ortobalagan valley, a perfectly shaped, relatively shallow, glacial trough of the sub-Caucasian stretch, which holds the advanced position in the central sector toward the seashore. Since 1980, Ukrainian cavers have been undertaking systematic efforts in exploring deep caves in the Ortobalagan Valley resulted in exploration of the *Krubera (Voronja) Cave* (number 1 on Fig. 1, C), the deepest cave in the world with its current depth of -2,191 m, and the Arabikskaja System (number 4), which consists of *Kujbyshevskaja Cave* (-1,110 m) and *Genrikhova Bezdna Cave* (-965 m to the junction with Kujbyshevskaja). Another deep cave in the valley, located in its very upper part, is Berchilskaja Cave (-500 m; number 11) explored by Moldovian and Ukrainian cavers.

The Ortobalagan valley extends along the crest of the Berchilsky anticline, which gently dips northwest. The cave entrances are aligned along the anticlinal crest (Figs. 2 and 3) but the caves are controlled by longitudinal, transverse, and oblique fractures and faults and comprise complex winding patterns in the plan view, remaining largely within and near the anticlinal crest zone. All large caves of the Ortobalagan Valley likely belong to a single hydrologic system. The direct connection of Krubera Cave with the Arabikaskaja System is a sound speleological possibility. The caves are predominantly combinations of vadose shafts and steep meandering passages, although in places they cut apparently old fossil passages at different levels (e.g., at 2,100-2,040 m in Kujbyshevskaja and Krubera caves, 1,200-1,240 m and 980-1,150 m in the Non-Kujbyshevskaja branch of Krubera Cave, etc.). The antiquity of these passages is supported by the ages of speleothems falling beyond the ^{230}Th dating limit (>500 ka; Klimchouk et al. 2009). The deep parts of Krubera display a more pervasive conduit pattern with a mixture of phreatic morphology, characteristic of the zone of high-gradient floods, which can be up to 400 m above the low-flow water table, and vadose

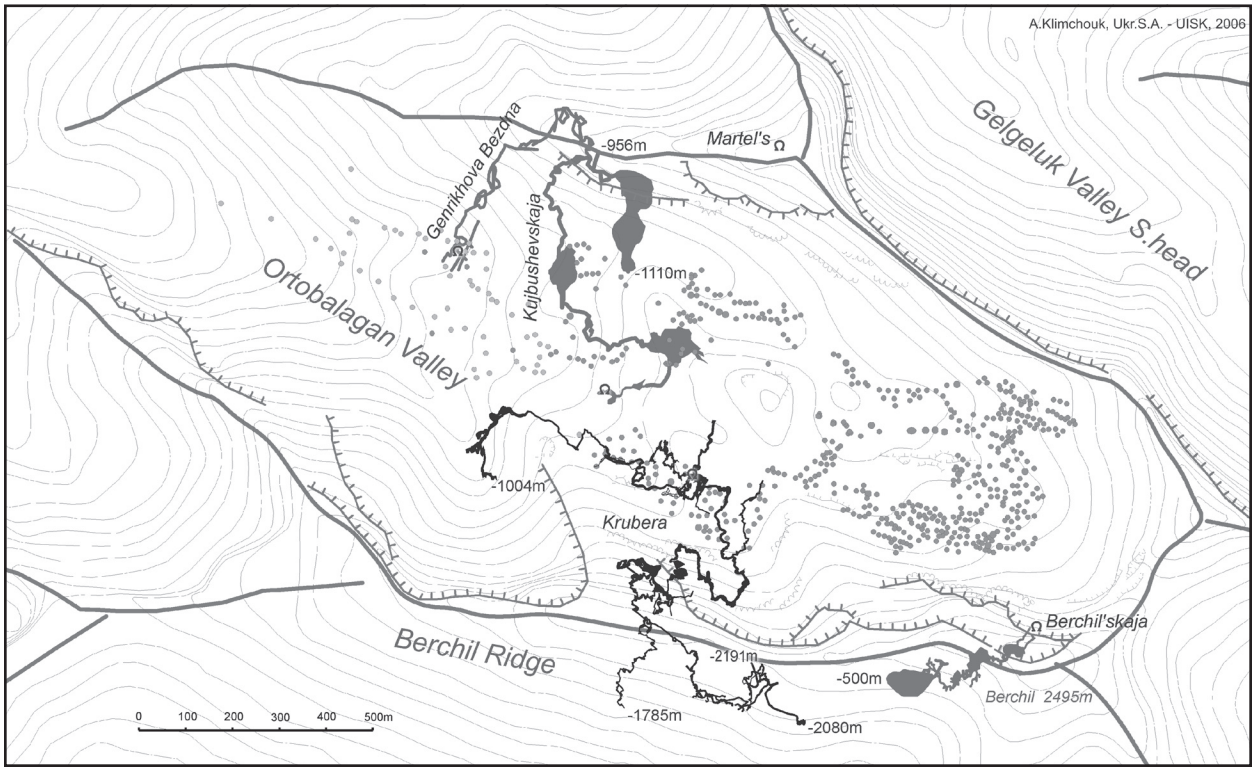

Figure 2: Major caves in the Ortobalagan valley. Dots indicate dolines.

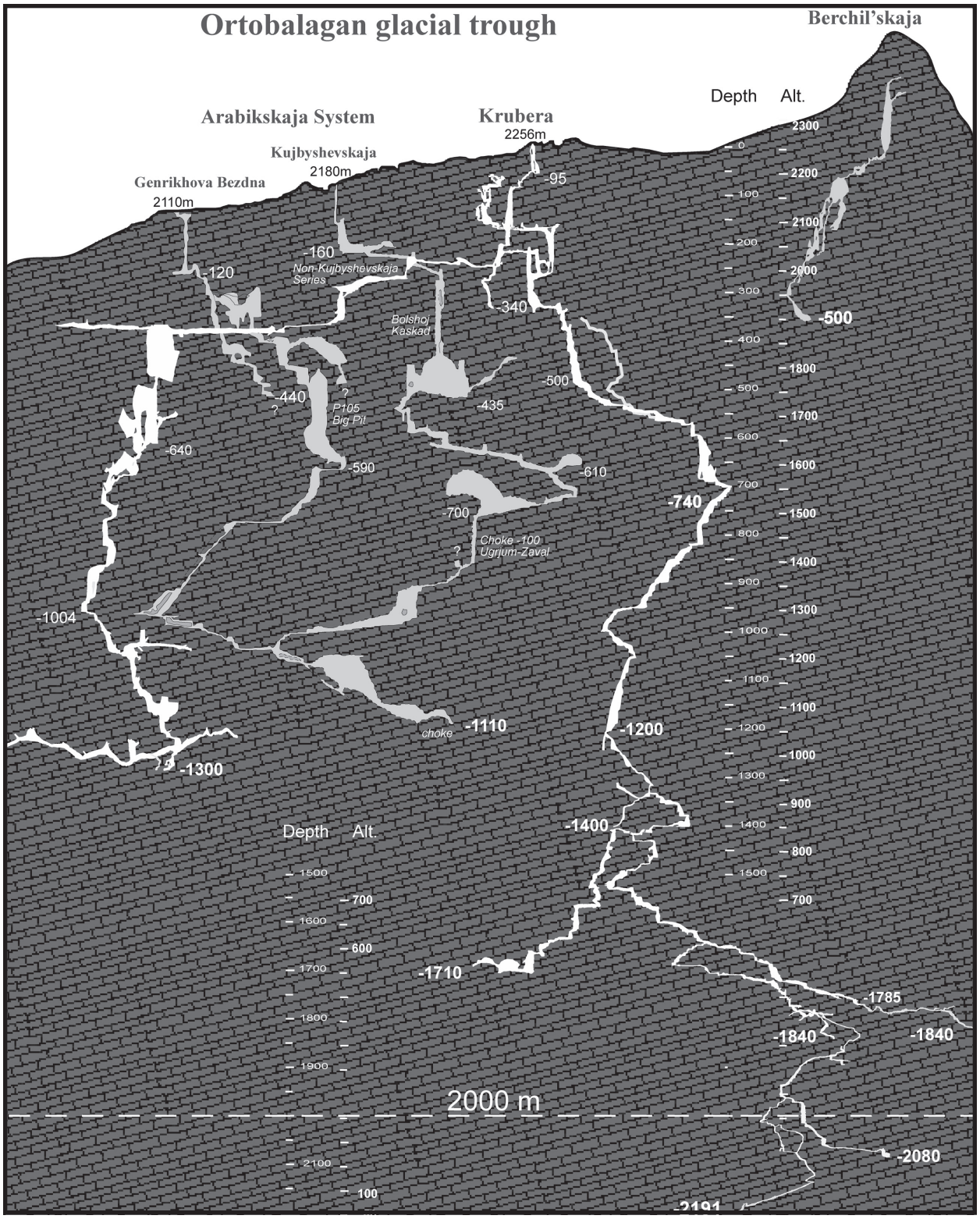

Figure 3: Combined cave profile along the axis of the Ortobalagan valley. Krubera Cave is shown in white, other caves in light grey.

downcutting elements that are observed even below the water table.

Other deep caves in Arabika include the Iljukhina System (-1,273 m; number 3) located in the center of the massif, Dzou Cave (-1,090 m; number 5) and Moskovskaja Cave (-940 m; number 6) in the north-eastern part, and Sarma Cave (-1,540 m; number 13). The latter, the second deepest

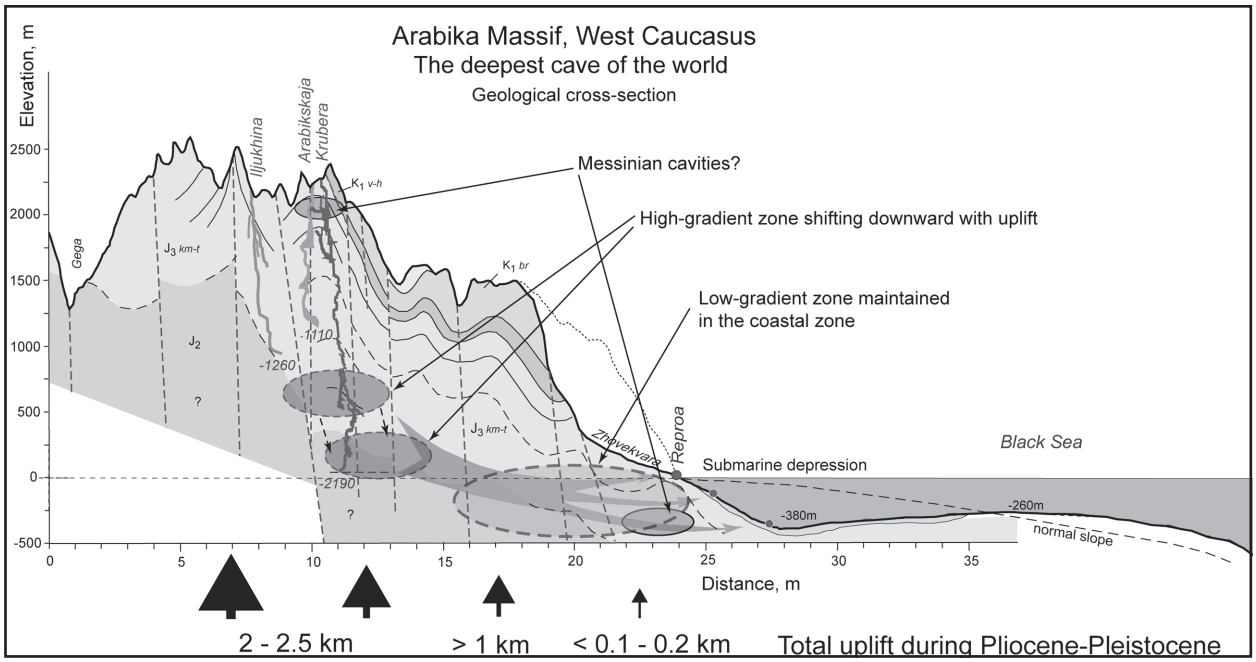

Figure 4: Schematic geological and speleo-hydrological section of the Arabika massif. See text for explanations.

cave in Arabika, is located along the same anticline as Krubera, at the similar advanced position relative to the seashore.

4. Geology

The Arabika Massif is composed of Lower Cretaceous and Upper Jurassic limestones that dip continuously southwest to the Black Sea and extend below the modern sea level (Fig. 4). In the central part of Arabika the Cretaceous cover is retained only in a few ridges and peaks, as well as in small patches within the trough valleys (Valanginian and Hauterivan limestones, marls and sandstones). In the south and southeast, the Cretaceous succession includes Barremian and Aptian-Senomanian limestones and marly limestones with abundant concretions of black chert. The core part of the massif is composed of the Upper Jurassic succession resting on the Bajocian Porphyritic Series, which includes sandstones, clays and conglomerates at the top, and tuff, tuff sandstones, conglomerates and breccia, porphyry and lava. The Porphyritic series forms the non-karstic basement of Arabika, which is exposed only on the northern and eastern outskirts, locally in the bottoms of the Kutushara and Gega River valleys.

The Upper Jurassic succession begins with thin-bedded Kimmeridgian-Oxfordian cherty limestones, marls, sandstones and clays, which are identified in the lower part of Krubera Cave. Above lies the thick Titonian succession of thick-bedded limestones with marly and sandy varieties. Sandy limestones are particularly abundant through the upper 1000 m sections of deep caves of the Ortobalagan Valley.

The tectonic structure of Arabika is dominated by the axis of the large sub-Caucasian anticline (oriented NW-SE), with the gently dipping southwestern mega-flank, complicated by several low-order folds, and steeply dipping northeastern flank. The axis of the anticline roughly coincides with the ridge bordering the Gelgeluk Valley to the north. Located on the southwestern flank of the major anticline is another large one (Berchil), in which the crest is breached by the Ortobalagan Valley. There are several smaller sub-parallel anticlines and synclines farther southwest, between Berchil and the coast.

The plicative dislocation structure of the massif is severely complicated by faults, with the fault-block structure strongly controlling both cave development and groundwater flow (Klimchouk 1990). Major faults of the sub-Caucasian orientation delineate several large elongated blocks that experienced uplift with different rates during Pliocene and Pleistocene. This had a pronounced effect on the development of deep groundwater circulation and of Krubera Cave in particular. Both longitudinal and transverse faults and related fracture zones play a role in guiding groundwater flow; the latter guide flow across the strike of major plicative dislocations, from the central sector toward the Black Sea.

5. Hydrogeology

Major on-shore karst springs with individual average discharges of 1 to 2.5 m^3/sec are located at altitudes ranging from 1 m (Reproa Spring) to 540 m (Gegsky Vodopad). Two of them are located in the shore area; these are Reproa (average discharge 2.5 m^3/sec; alt. 1 m asl) and Kholodnaja Rechka (1.2 m^3/sec; 50 m asl). Other two major springs are located in the river canyons bordering Arabika to the east: Goluboe Ozero in the Bzyb canyon (2.5 m^3/sec; 90 m asl) and Gegsky Vodopad in the Gega canyon (1 m^3/sec; 540 m asl). There are also several smaller springs in the Gagra town.

Some boreholes located along the shore of the Black Sea yield karstic groundwater from depths of 40–280 m below sea level. Other much deeper boreholes tapped low-salinity karstic waters at depths of 500 and 1,750 m in the Khashupse Valley near Tsandripsh and 2,250 m near Gagra (Buachidze and Meliva 1967; Meliva et al. 1969). This suggests the existence of deep karst system and vigorous karst groundwater circulation at depth.

Submarine springs are known in the Arabika area, emerging from the floor of the Black Sea in front of the massif. Shallow springs at depths of 5–7 m can be reached by free dive near Tsandripsh. Kiknadze (1979) reported submarine springs near the eastern part of Gagra at depth of 25-30 m and Buachidze and Meliva (1967) revealed submarine discharge at depths up to -400 m by hydrochemical profiling. Recently (Klimchouk 2006), an outstanding feature of the seafloor topography near Arabika has been revealed from a digital bathymetric map that combines depth soundings and high-resolution marine gravity data (Smith and Sandwell 1997). This is a huge submarine depression in front of the Zhovekvara River mouth, which has dimensions of about 5 x 9 km and a maximum depth of about 380 m. The Arabika Submarine Depression (ASD; shown on Fig. 1, C) is a closed feature with internal vertical relief of about 120 m (measured from its lowest rim) separated from the abyssal slope by the bar at a depth of about -260 m. It has steep northern and northeastern slopes (on the side of the massif) and gentle south and southwestern slopes. Its formation is apparently karstic. Presently ASD seems to be a focus of submarine discharge of the karst systems of Arabika. The existence of ASD, along with other lines of evidences, points to the possibility of much lower sea-level positions in the past than is suggested by Pleistocene glacioeustatic oscillations (Klimchouk 2006).

The hydrogeologic model for the Arabika massif that dominated before the 1980s did not allow the possibility of a hydrologic connection between the central high sector and the coastal springs. The model implied that the aquifer structure in Arabika is subordinate to the sub-Caucasian synclines and anticlines, and that minor "non-karstifiable" beds within the carbonate succession separate the system into several superimposed aquifers (Kiknadze 1972; 1979). According to this model, groundwater recharged within the central part of the massif flows to northeast, beneath the non-karstic cover, and southwest to the Goluboje Ozero spring. The recharge areas for the coastal and submarine springs were assumed to be the proximal low-altitude ridges.

This model was disproved by speleological explorations and dye tracing studies during the 1980s under the coordination of the Institute of Geological Sciences of the of the Ukrainian Academy of Science (Klimchouk 1990). A series of large-scale dye-tracing experiments was conducted in Arabika in 1984 and 1985. Tracers injected in the Kujbyshevskaja and Iljukhina caves were detected in the Kholodnaja Rechka and Reproa springs, proving groundwater flow to the south-southwest across major tectonic structures over a distance of 13-16 km as the crow flies (Fig. 1, C). The tracer from Kujbyshevskaja was also detected in a borehole located between these two springs, which yields groundwater from a depth of 200 m below sea level. This has been interpreted as an indication of the connection of the cave with the submarine discharge. The large Central Karst Hydrologic System, which encompasses most of the southeastern flank of the Arabika anticline, had been identified in this way. The system became the deepest in the world with its overall vertical range of about 2,500 m (measuring to the borehole water-bearing horizon) or even 2,700 m (measuring to the deepest reported submarine discharge points). Another tracer was injected in the Moskovskaja Cave (-970 m) and detected at the Gegsky Vodopad spring, indicating the presence of a karst hydrologic system comprising the northeastern flank of the Arabika anticline (the Northern System). No connections have been revealed with yet another major spring, Goluboje Ozero in the Bzyb River canyon, although it apparently drains a large area of the eastern sector of the massif (the hypothetical Eastern Karst Hydrological System). It is not clear where Sarma Cave (-1,550 m) drains to, Goluboje Ozero to the southeast or Reproa to the southwest, at the shore.

The results of the dye-tracing tests have radically changed notions of the hydrogeology of Arabika and revealed its outstanding speleological perspectives and strongly stimulated further efforts for exploration of deep caves. They demonstrated that groundwater flow is not subordinate to the fold structure but is largely controlled by faults that cut

across the strike of major folds, and that the large part of the central sector of Arabika is hydraulically connected to the springs along the seashore and with submarine discharge points.

6. Discussion

Krubera Cave has an extremely steep profile and reveals a huge thickness of the vadose zone. The lower boundary of the vadose zone (the top of the phreatic zone) is at an elevation of about 110 m at low flow, which suggests a low overall hydraulic gradient of 0.007–0.008. Low-TDS groundwater is tapped by boreholes in the shore area at depths of 40-280, 500, 1,750, and 2,250 m below sea level, which suggests the existence of a deep flow system with vigorous flow. Submarine discharge along the Arabika coast is reported at depths up to ~400 m bsl. A huge closed submarine depression is revealed at the sea floor next to Arabika, with the deepest point of ~400 m bsl. It is difficult to interpret these facts in terms of the development of karst systems controlled by contemporary sea level, or within the range of its Pleistocene fluctuations (up to -150 m).

Klimchouk (2006) suggested that karst systems in Arabika could have originated in response to the Messinian salinity crisis (5.96–5.33 Ma) when the Black Sea (Eastern Paratethys) could have almost dried up, as did the adjacent Mediterranean, where the dramatic sea level drop of ~1500 m is well established. It has been demonstrated by the recent studies of French karstologists (e.g., Mocochain et al. 2006) that the Messinian crisis played a great role in karst development in the Mediterranean region, where deep conduits formed in response to lowering of the base level and imposed a strong influence on subsequent karst evolution.

The hypothesis that the dramatic sea-level drop could have take place in the Black Sea basin during the Messinian time had been put forward 30 years ago (Hsü and Giovanoli 1979) mainly on the basis of deep-sea drilling data (DSDP Sites 379, 380, 381). It has been strongly corroborated by recent studies of regional geology, including data from bio- and magnetostratigraphy of the key sedimentary sequences (Semenenko and Olejnik 1995; Clauzon et al. 2005; Popesku 2006; Snel et al. 2006), seismic profiling (establishing the Messinian erosional surface in the Eastern Paratethys; Gillet 2003), studies of deep-water delta complexes, etc.

Before the late Miocene, the present coastal Western Caucasus was a low- to middle-altitude mountain terrain. Temporary desiccation of the Black Sea in response to the Messinian salinity crisis in the Mediterranean established the base level at many hundreds meters below the present level and caused conduit initiation and development within deep sections of the Arabika massif. These early systems were flooded after the Pliocene transgression. Uplifts of the Arabika area during Pliocene and especially Pleistocene were highly differentiated by elongate zones (blocks) of the sub-Caucasian stretch (parallel to the coast). The total uplift amounted to 2-2.5 km in the central sector of Arabika, whereas it was minimal (0.1–0.2 km) in the zone proximal to the coast. Hydraulic continuity was always maintained across the zones, between the main recharge area in the central sector of Arabika and the coastal zone and submarine springs. The presence of high conduit porosity of Messinian origin in the coastal/submarine sector allowed the zone of high hydraulic gradient during uplift to be pushed far inland, beneath the rising central sector (Fig. 4). This created favorable conditions for the enhanced conduit development at depth in the central sector, quick adjustment of the water table to new uplift pulses, and eventual development of a huge vadose zone and extremely steep and deep cave systems such as Krubera Cave. This was further favored by recurring sea-level drops up to -150 m during the Pleistocene, which caused the steepening of hydraulic gradients beneath the central sector of Arabika and enhancement of conduit porosity in the upper part of the present phreatic zone.

The evolution scenario outlined above is indirectly supported by ^{230}Th dating of speleothems from the deep parts of Krubera Cave (Klimchouk et al. 2009). Stalagmites from depths of -1640 m and -1820 m (elevations 640 m and 436 m asl) have yielded ages older than 200 ka (max. 276 ka), which suggests that the deep parts of the cave were already in the vadose zone before the Middle Pleistocene.

6. Conclusion

It is not by chance that the deepest cave in the world with the exceptionally high vertical range of almost 2200 m has been discovered in the Arabika massif. There were unique geological and paleogeographic pre-conditions for that. The study of the Arabika karst system and exploration of the Krubera Cave constitutes new arguments supporting the response of the Black Sea to the Messinian salinity crisis.

Acknowledgement

This study is an outcome of enormous efforts of several generations of cavers who have explored the deep caves in Arabika during past 30 years.

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HYPOGENIC SPELEOGENESIS IN THE PIEDMONT CRIMEA RANGE

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Abstract

The intense development of the theory and criteria of identification of hypogenic speleogenesis during last few years has stimulated re-interpretation of karst phenomena in many regions of the world. Recent research strongly suggests that solution features in the Piedmont Range of the Crimean Mountains, previously believed as being the result of epigenic karstification, were in fact formed in hypogenic environment due to ascending transverse flow in a stratified artesian system.

Tectonically, the Piedmont Range of Crimea is an edge of the Scythian Plate, uplifted and partially eroded along the regional fault separating the plate from the folded region of the Mountain Crimea. The Cretaceous and Paleogene sequence dips 5 to 20° to the north and north-west, where it plunges beneath the Neogene cover. It is exposed within the Piedmont Range as a series of distinct cuestas generally facing southeast. Karst features are represented by 26 caves and abundant and diverse solution forms at the cuesta scarps. Most of karst features have developed in two distinct limestone units of Paleocene (Danian) and Eocene age, but some are present in the underlying Maastrichtian unit of the Cretaceous. There is strong and systematic evidence that the caves have hypogenic origins and that most of the solution features at the scarps are remnants of morphologies of hypogenically karstified fractures, whose walls are now exposed by block-fall scarp retreat. The features in various beds demonstrate strong lithostratigraphic control in their distribution and are vertically stacked into transverse complexes. Caves are fracture-controlled, linear, or crude maze clusters, demonstrating the complete suit of morphologies indicative of hypogenic origin. Isolated cavities, expressed in the contemporary scarps as grottos and niches, as well as zones of spongework porosity, developed where laterally conductive beds of higher initial porosity were crossed by vertical fractures that once conducted rising fluids from a regional flow system.

The Piedmont Range of Crimea was a part of the Plain Crimea artesian basin before the Middle Pliocene. Subsequent uplift and initial erosional entrenchment through the Early and Late Pliocene caused the pattern of tectonically and geomorphically guided zones of upward cross-formational discharge and hypogenic speleogenesis to establish. Further valley entrenchment in the region during the Pleistocene shaped the modern cuesta-like relief and drained the Cretaceous-Paleogene sequence. Hypogenically karstified fractures and caves, sub-parallel to valleys, provide zones of structural weakness along which blocks fall at the cuesta scarps, exposing relict hypogenic morphologies.

The Piedmont Crimea Range, with its perfect and extensive exposures of hypogenically karstified sequences, provides outstanding possibilities for studying patterns and morphologies of hypogenic speleogenesis, which is important for understanding its hydrogeological functioning and roles in reservoir formation, especially with implications about the adjacent Plain Crimea artesian basin.

BATHYPHREATIC SPELEOGENESIS OF SOME LARGE KARST SPRINGS IN CROATIA

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Abstract

The Karst Dinarides cover about 26,000 km^2 in Croatia, which is 46% of the national territory. They are composed of carbonate deposits that represent relics of several vertically stacked carbonate platforms, in places more than 8000 m thick, with a stratigraphic range from Middle Permian to Eocene. The largest part of the carbonate succession was deposited on the Adriatic Carbonate Platform. The thickness of these deposits, formed during the 125 million years of the platform history (lower Jurassic to uppermost of Cretaceous) ranges from 3500 to 5000 m. The carbonates are interbedded with Paleozoic, Triassic and Paleogene clastic deposits. The entire area is intensely tectonized. The final uplift of the Dinarides reached its maximum in the Oligocene-Miocene. The recent geomorphology, as well as the speleogenesis and evolution of karst aquifers, have been strongly affected by Neotectonic deformation.

The great thickness of carbonates, intense tectonic disturbance, and endogenetic processes result in very deep and irregular karstification and complex hydrogeology in the area. Besides many surface landforms, and more than 10,000 explored caves in the underground, the strong karstification of the carbonate rocks is confirmed by large karst springs, some which discharge more than 100 m^3/sec. During the past decade, deep cave-diving explorations have been conducted in some of the most significant springs. The results are impressive. The Una River spring was explored to the depth of -205 m, the Kupa River spring to -154 m, and the Sinjac spring to -155 m. In addition, significant depths have been reached in the springs Glavaš (115 m, Cetina River), and Kamačnik (95 m). All of these springs are of the ascending type, with simple shaft morphologies that continue beyond the depth of exploration. Different morphological characteristics were determined in the Majerovo vrilo spring (Gacka River), where divers not only reached the considerable depth of 104 m, but also discovered a 942-meter-long phreatic cave system. A typical example of shallow-phreatic zone development is 22-meter-deep Zagorska Mrežnica River spring, in which the total length of discovered horizontal channels exceeds 1,100 m.

In this paper, the geomorphology of some the most significant active springs of Croatian Karst Dinarides and discussion on their speleogenesis is discussed within the framework of regional geologic and hydrogeologic conditions. The most important factors that affected the internal dynamics of the karst aquifers and genesis of the bathyphreatic conduits are evaluated. Although information about the system is incomplete, it is suggested that the development of the bathyphreatic caves is strongly conditioned by regional compressional tectonics, i.e. the structural position of the less permeable or impervious deposits caused by overthrusting and reverse faulting. Moreover, there has been significant impact caused by the difference in elevation between the recharge and discharge areas, which produces a large hydraulic potential and consequently deeper water circulation.

FIRST ELEMENTS OF THE KARSTIC EVOLUTION OF A CONTINENTAL CHALK CATCHMENT AREA OF THE PARIS BASIN, UPPER AVRE RIVER (NORMANDY, FRANCE)

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Abstract

In the Western Paris Basin, the Avre River feeds the Eure River, a major tributary on the left bank of the Norman Seine River. Located 100 km from Paris and Rouen and 40 km from Chartres, its catchment covers approximately 400 km². It is developed over a long back slope of a cuesta in the Turonian chalk (Upper Cretaceous) at the southern limit of the Seine basin.

The Upper Avre River joins the Vigne River approximately 40 km downstream from its sources in the Perche country. The short upstream Vigne River originates from karstic springs that provide approximately 15% of the total water supply of the City of Paris. At the catchment scale, superficial perennial and temporary flows represent a 157-km linear course and are deeply impacted by numerous sink points. Many tracer tests conducted over the last century demonstrate that these sink points supply both the Vigne resurgences and also several springs along the Upper Avre that function as estavelles, notably those near the town of Verneuil-sur-Avre.

Geomorphic and hydrologic analysis reveals flow anomalies (disjunction between underground and surface circulation, specific flows that do not correlate with the sizes of catchment areas, heterogeneity in piezometric levels in wells, changing functions of karstic phenomena under various hydrological conditions). It also permits discrimination of elementary units within the hydrographic basin: a recharge zone to the Upper Avre functioning as a main surface collector, a recharge zone to the Vigne springs including the Butenay and Lamblore Creeks, and finally the confluence of these two previous elements resulting in the Lower Avre River, along which no karstic phenomena interfere with its course.

At the current level of investigation,, a geomorphic evolution model in three main stages can be proposed:

(1) The Avre Basin rests on two individual systems: in the North, the Upper Avre is elongated in the WSW-ENE direction toward the center of the Paris Basin. In the southeast is a small independent river, the Lower Avre.

(2) Tectonic reactivation of a fault downstream from Verneuil dammed the flow of the Upper Avre, generating the development of a polje. Leakage by karst piracy to the Vigne springs now augments the Lower Avre. Thus, the Buternay and the Lamblore increasingly feed the Vigne at the expense of the Verneuil polje.

(3) A very narrow valley located along N-S fold axes captures the course of the Upper Avre, reducing the activity of the Verneuil polje. The Lower Avre is directly sustained by the Upper Avre and by the springs of the Vigne. The karstic connections between the polje and the springs are only temporary, as demonstrated by hydrochemistry and tracer tests.

SPELEOGENESIS OF THE HYPOGENIC CAVES IN CENTRAL ITALY

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In Central Italy, from the Tyrrhenian to Adriatic coast through the Apennine karstic mountains, there are many limestone caves of various sizes and origins. Several of them consist of three-dimensional maze systems with several tens of kilometres of solutional phreatic passages with galleries and shafts characterized by large rooms, cupola roofs, blind pits, anastomotic passages. They contain fossil galleries as well as phreatic conducts with active streams of highly mineralized water, mainly rich in hydrogen sulfide. Here the limestone walls are still corroding and transforming calcium carbonate to gypsum. This main cave-forming processes is related to the H_2S oxidation to sulfuric acid, in the groundwater and in the atmosphere where the redox reactions involve chemotrophic microbial activity. The whole region is presently rich in volcanic, crustal, and mantle-derived CO_2 and H_2S emissions and outcrops of Quaternary travertine deposits. Hypogean speleogenesis is the main process for the largest caves forming in Central Italy and can be supposed for many other surrounding karst systems with similar geology and fluid chemistry.

1. Introduction

In the past few decades there has been an interest in speleogenesis related to deep-seated hydrogeologic recharge, where limestone corrosion is driven by endogenic agents (Klimchouck, 2007). Hypogenic caves are well known in different part of the world from Central Asia to North and South America (Palmer, 2007; Klimchouk, 2007), and especially in the underground fossil system in the Guadalupe Mountains in New Mexico and Texas (Du Chene et al., 2000). The important role played by microbial activity in sulfuric acid speleogenesis is recognized, as are the associated sulfur-redox bacterial communities that generate sulfuric acid as a metabolic product (Hose et al., 2000; Engel et al., 2004; Macalady et al., 2006). Caves in Central Italy north of Rome are probably the world's best place to observe active sulfuric speleogenesis (Galdenzi and Menichetti, 1989; 1995). Here there are many limestone caves with different variety and size of morphologies composed of three-dimensional maze systems and deep wells with active sulfuric streams, where both active and fossil gypsum deposits can be observed. The whole region is presently rich in volcanic, crustal, and mantle-derived CO_2 and H_2S emissions, as well as many Quaternary travertine deposits (Fig. 1). Karst systems associated with active sulfur springs are scattered in many other regions in Italy from marine springs of Capo Palinuro in southern Italy (Mattison et al., 1998) to southwestern Sardinia, Sicily, and Apulia (Fig. 1; Menichetti, 1994). The geological factors associated with sulfuric acid cave formation show great variety and unusual characteristics in central Italy. Although the main speleogenetic reactions are known, the geological, hydrogeological, and geochemical conditions need to be documented, especially the activities of the gases (H_2S – CO_2) and their association with mineral species. Hydrogeology and especially hydrochemistry are essential for understanding the space-time evolution of these hypogenetic karsts.

2. Geological Setting

The geology of central Italy is mainly the result of the continental collision processes between the Corsica/Sardinia and the subducted Adriatic plates during the Cenozoic. The geological and geophysical data highlight two main sectors within the region: a western Tyrrhenian side with Neogene-Quaternary active back-arc extensional tectonics, and an eastern Adriatic side with an active compressional stress field (Cavazza and Wezel, 2003). The karstic carbonate Apenninic fold-thrust belt is located in a transitional area between these two domains (Fig. 1).

The Tuscan-Umbro-Marchean sedimentary cover, which hosts the caves and is part of the Meso-Cenozoic basin, consists of three main lithological units: the lower one is about 1 km of Upper Triassic dolomites and anhydrite unconformably overlying Paleozoic phyllitic basement rocks; an intermediate sequence of limestone and pelagic cherty-marly-carbonates, about 2500 m thick, dates from the Jurassic to the Paleogene. This in turn underlies Neogene turbidite foredeep sediments a few thousand meters thick. In western Tuscany, and especially in the Apuane Alps, the carbonate succession is metamorphosed to greenschist facies and represents the deep roots of the collisional orogen.

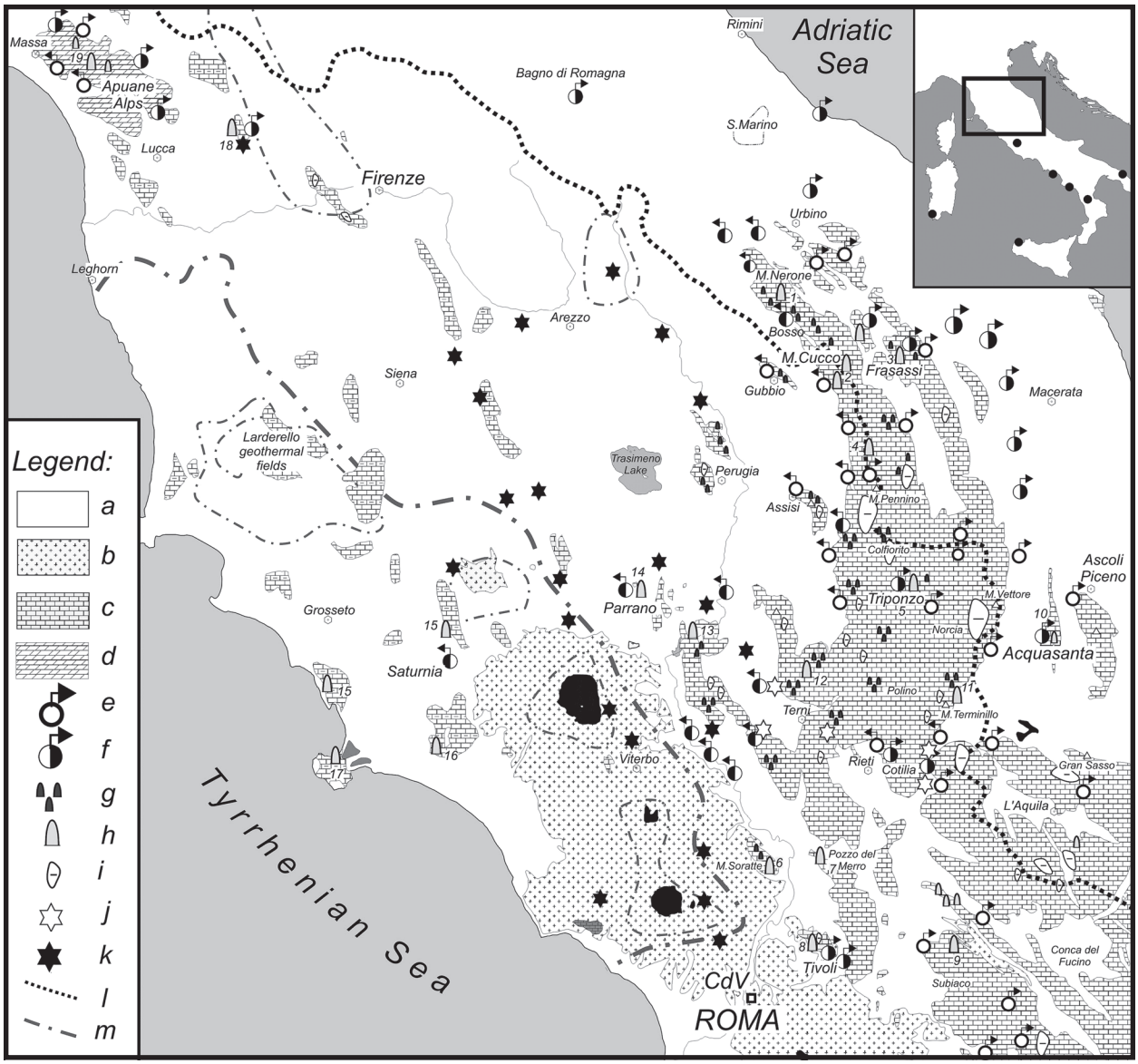

Figure 1: Map of the main karst features in central Italy. Upper right: location map of documented hypogenic caves in Italy (circles). Legend: a – Stratigraphic sequence from Quaternary to Cretaceous; b – Quaternary volcanic rocks; c – Main calcareous sequence from Jurassic to Cretaceous; d – metamorphosed calcareous stratigraphic sequence from Jurassic to Cretaceous; e – major karst spring; f – major mineralized spring; g – important caves; h – caves with gypsum deposits; i – closed valley with karstic drainage; j – spring rich in CO2 gas; k – CO2-rich gas vent; l – Apennines drainage divide; m – Tuscany geothermal anomaly (thick dotted line represents 100mW/m, in Larderello geothermal field; the heat flux reaches 400 mW/m).

In the Rome area, since mid-Pleistocene (about 700 Ka), and remaining intermittently active until recent, there has been a rich K-undersaturated volcanism associated with some carbonatite magmas extruded in several places in the Apennine chain (Cavazza & Wezel, 2003).

On the Tyrrhenian side of the Apennine belt, the results of the Neogene-Quaternary backarc extensional process are a reduced thickness of the lithosphere, a system of NW-SE -striking normal faults and associated basins, and high heat flow, with many hydrothermal vents rich in H_2S and CO_2 (Minissale, 2004). On the Adriatic side of the Apennines, mud volcanoes, salt springs, and CH_4 emissions are well documented with many data derived from hydrocarbon explorations (Conti et al., 2000).

The largest caves in the area are developed in a thick 1000 m carbonate bank of Jurassic age, where a syngenetic porosity with sedimentary facies of packstone and grainstone is well developed. In places, small caves are hosted by a Cenozoic

marly-carbonate sequence confined by sandstones and marls (Menichetti, 1987). Quaternary travertine deposits are scattered throughout the area, especially in Tuscany and Latium but in only a few localities in the Apennine chain associated with both thermal and cold springs (Fig. 1; see Minissale, 2004).

The main phase of Apennine uplift related to cave development took place within the Pleistocene (Mayer et al., 2001).The primary tectonic features that control the underground Apennine karst morphology and the carbonate aquifer drainage are a system of transpressive faults with a N-S trend and networks of conjugated joint sets, distributed in a primary NE-SW and secondary NW-SE directions. In particular, the N-S faults have guided the main galleries and rooms and controlled the development of the larger underground passages, while the joint systems locally guide the smaller solutional passages (Menichetti, 1987; Mayer et al., 2001).

3. Hydrogeology and Geochemistry

The regional drainage network is quite complex because of the vertical range between the highest elevations and the drainage divide, in consequence of the eastward migration, since Neogene, of the compressional and extensional tectonic stress field (Fig. 1; see Cavazza & Wezel, 2003). In many cases there have been superimpositions, antecedences, and regressions of the river networks with respect to the anticlinal structures.

The regional aquifers are located in the Jurassic carbonate strata, and groundwater supplies the springs in the lower valleys and along the main fault zones with an average base flow of 22 L/sec/km^2 (Galdenzi & Menichetti, 1995). Aquicludes, represented by marly layers, are distributed at various levels in the stratigraphic succession. Groundwater flow in the transfer zone is controlled by karst conducts and fissures, while faults and joints guide the regional drainage in the carbonate reservoirs. The hydrodynamics of larger springs is influenced mainly by the base flow, while in some cases rapid flows take place in the transfer zone. All karst systems have basal input points along faults and joints at the bottom of the oxidizing zone, where mineralized water rises from deep-seated flow systems with transit times of many months. Flow in the vadose zone is regulated by conduit systems, with transit times of a few weeks (Sarbu et al., 2000).

In several karst areas, close to the water-table, are sulfide-sodium-chloride mineralized groundwaters combined with CO_2-rich meteoric circulation. The carbonate waters are from infiltration and seepage from the surface, with about 500 mg/L of total dissolved solids. Mineralized waters, with temperature ranging from 14° to 40°C, and more than 2000 mg/L TDS, rise from depth, involving Triassic anhydrite

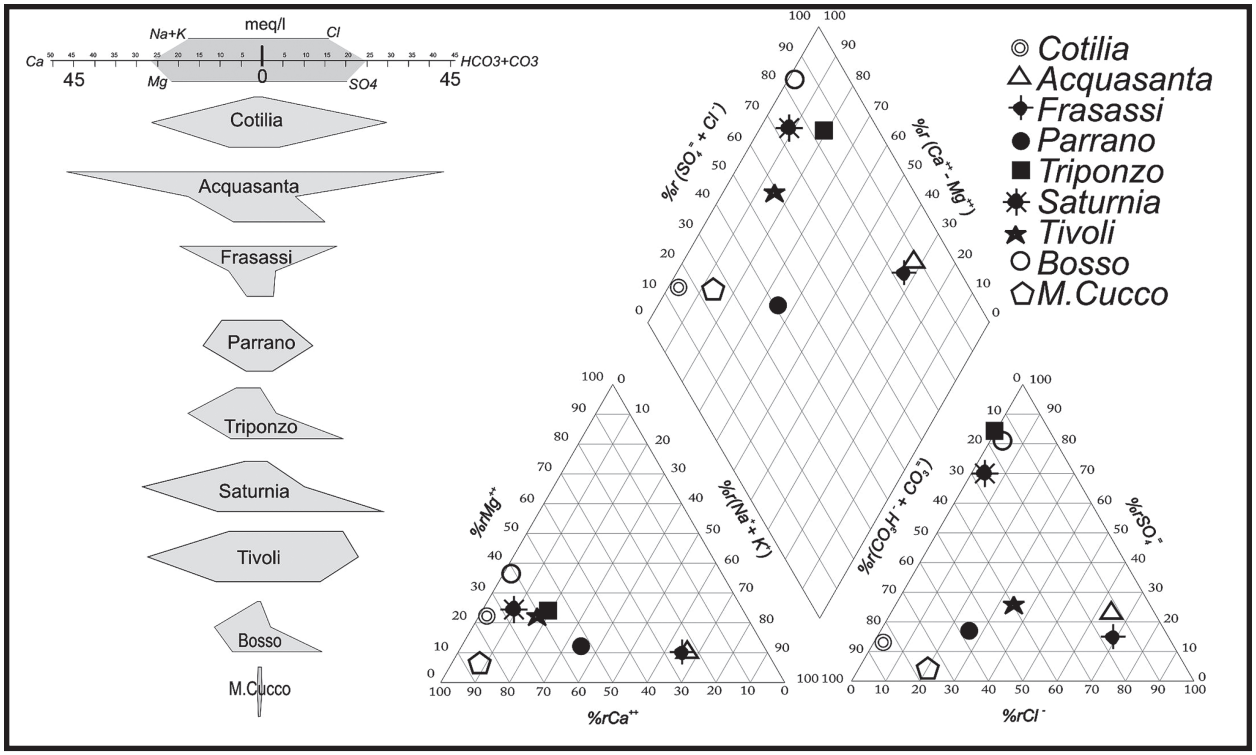

Figure 2: Geochemistryl of the karst waters in central Italy. Stiff diagrams on the left and Piper diagram on the right. Location of the springs is shown in Figure1.

in a complex underground regional flow path. Here, the H_2S can reaches concentrations up to 0.5 mMol/L and the endogenic CO_2 in the water can have values close to 100 mg/L (Fig. 2). The $\delta^{18}O/\delta D$ isotopic content shows that the groundwater circulation involves large structures, with a recharge area in the highest Apennines. The hydrothermal circulation can reach the Triassic anhydrites at depth, and after a journey of some decades, rises to the springs located close to the master faults along the border of the main karstic structures (Menichetti et al., 2008).

Throughout central Italy are several H_2S, CO_2, and CH_4 low-temperature gas emissions, many of them localized close to the important karst systems (Fig. 1). The volume of fluid flow through the carbonate rocks is very large, especially considering a CO_2 estimate in 10^{11} mol/yr (12,000 t/day) (Rogie et al., 2000) according with the relevant outcrop of travertine deposits. The origin of the gases is still debated, both for CO_2 and H_2S, but is often associated with CH_4 and He (Minissale et al., 2004). The origin of non-volcanic CO_2 seems to be mantle degassing and subsequently by thermogenic reaction with carbonates. The H_2S results from gas reactions and re-equilibration in rock/mineral-buffered geothermal systems within the buried Triassic anhydrites (Minissale et al., 2000).

4. Cave patterns and speloegenesis

In Central Italy the main caves consist of systems with a few tens of kilometres of phreatic and vadose solution passages and shafts, with large rooms, cupola forms, blind pits, and anastomotic passages (Fig. 3). Throughout the region all the developmental stages of the hypogean caves are present in still-active caves in the Frassassi Gorge, Parrano Gorge, Saturnia area, Acquasanta Terme area, and Pozzo del Merro. Here the rising of highly mineralized water rich in sulfur can be observed in underground streams and pools. Elsewhere are fossil caves such as those in Monte Cucco, where large gypsum speleothems are present more than 1000 m above the current regional water table. The Pozzi della Piana Caves are developed in Quaternary travertine, where gypsum deposits are associated with the phreatic passages, along with cupola and blind pits (Fig. 2). Fossil gypsum deposits can also be found in many caves, such as Pozzi della Piana, M. Rotondo, and Città Reale (Fig. 1). Many of these caves have no relation to external drainage networks, and several entrances have volumes that are inconsistent with classic carbon dioxide karst corrosion. The caves in both active and fossil systems consist of large rooms and mazes with galleries branching outward from them with frequent phreatic features and horizontal tubes. Phreatic passages, many of them anastomotic, also extend over large parts of the cave, where they constitute some network zones (Fig. 3b). Shafts and fissures in the cave floor represent the original sources of these H_2S-rich waters. Large rooms, such as the Abisso Ancona Hall in Grotta Grande del Vento-Frasassi (about one km^3 in volume) and those in Monte Cucco (in which many galleries are voids > 0.2 km^3) are usually regular in pattern and controlled by joints and faults that governed the flows of meteoric groundwater and rising sulfuric water. Very deep pits show a corkscrew solutional pattern in the fossil caves of Monte Cucco in the Apennines, and in the still-active Pozzo del Merro near Rome (Fig. 3a), which reaches 332 m below sea level (Caramanna and Malatesta, 2002). Rising sulfuric water is the main mechanism of the hypogenic corrosion of these shafts along deep hydrothermal flow paths guided by the principal tectonic lineaments of the region. On the other hand, several caves, such as Monte Cucco and Frasassi, are developed at different levels with vertical ranges of 100 m linked to the evolution of the regional groundwater base level. Smaller karst systems have a ramiform pattern of several large rooms with wide ceilings that end abruptly in narrow passages or fissures (Fig.3b).

Phreatic morphologies with bubble trails are widespread in both active and fossil karst systems, indicating the action of aggressive gases during the ascent into the upper portions of the phreatic zone. In the whole region, the main cave-forming processes can be related to H_2S oxidation to sulfuric acid acting in the groundwater as well as in the atmosphere, where the redox reactions involve chemoautotrophic microbial activity (Galdenzi et al., 1999). The carbonate corrosion produces sulfate ions in the phreatic zone and gypsum replacement of the limestone walls of the vadose sectors of the caves (Menichetti et al., 2008). The sulfuric pools contain stratified water with significant physico-chemical variations of temperature, TDS, and pH at the interface between carbonic and sulfuric groundwater (Sarbu et al., 2000). Surfaces of sulfuric streams contain much organic matter, such as white filaments that in the deep flooded pits can result in meter-long seaweed-like strands. Sulfur-oxidizing bacterial communities are known in the Frasassi caves that use H_2S as an energy source in chemoautotrophic aphotic ecosystems that support invertebrate life (Sarbu et al., 2000; Macalady et al., 2006). The role played by this microbial community on the limestone corrosion in not well defined, nor is the relationship between the presence of organic matter and the released H_2S in the atmosphere in other karst systems (Engel et al., 2004).

Close to the sulfuric streams the air is rich in H_2S released from the groundwater, and this accounts for most of the limestone wall corrosion. The corrosion operates on

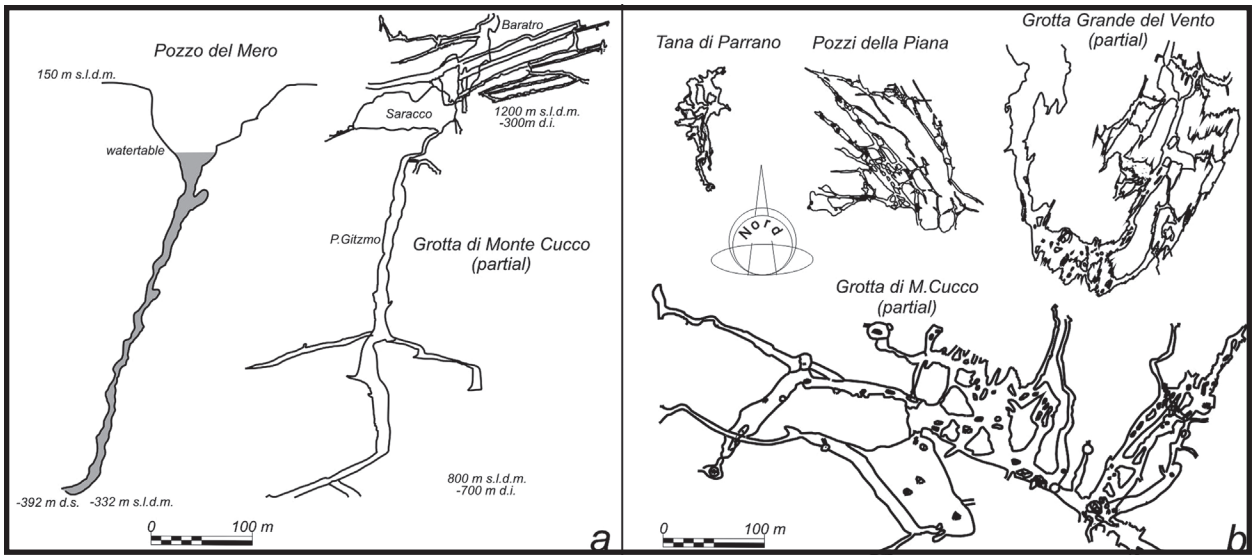

Figure 3: Patterns of caves in central Italy. a – cross section of the Pozzo del Merro compared with the deeper part of the Monte Cucco Cave; b – plan view of major hypogenic caves compared with a few branches of the Grotta Grande del Vento (Frasassi) and Monte Cucco Caves.

limestone as small white spots about one cm in diameter, where calcium carbonate is replaced by gypsum. This microcrystalline gypsum is often soft and can fall easily to the floor, building larger deposits and possibly flowing as "gypsum glaciers." Otherwise, wall-replaced gypsum crusts can contain centimeter-size recrystallized selenite crystals from preexisting gypsum in solution. In both cases the resulting wall morphology consists of limestone solution pockets that give evidence for the corrosion by sulfuric acid. At the limestone/gypsum interface a sulfur-oxizing bacteria biofilm plays an important role in the limestone corrosion. This biofilm consist of organic mucous matter arranged in small strands like spider webs and thin "stalactites" with acid droplets of pH <1 (Galdenzi et al., 1999; Sarbu et al., 2000).

The gypsum deposits have $\delta^{34}S$ ratios between -1‰ and -20‰ in the fossil deposits of Monte Cucco, Frasassi Gorge, Pozzi della Piana, and Acquasanta caves. The presently forming gypsum has $\delta^{34}S$ values ranging from - 6‰ to -10‰, with lighter values in the recrystallized crusts. In the mineralized groundwater, $\delta^{34}S$ in the sulfate varies from +19‰ to +21‰, while $\delta^{34}S$ in sulfur is -14.3‰, which is close to the values of the actively forming gypsum. This gypsum is later derived from the oxidation of H_2S released from the groundwater (Menichetti et al., 2008).

The limestone corrosion rate by sulfuric acid was tested over a 5-year experiment with calibrated limestone tablets, located in the sulfuric branch of the Frasassi caves, both in air and in the water. The tablet surfaces were replaced with gypsum at a rate of limestone corrosion of about 0.05 mm/y (Galdenzi et al., 1997).

5. Discussion

Understanding the unusual pattern and morphologies of the caves of central Italy needs to take in account the geology, hydrogeology, and the water and gas chemistry that leads to hypogean speleogenesis. Karst in the region is not homogeneously distributed, and in many places the cave patterns are not related to the surface geomorphology. In the Acquasanta and Saturnia caves, and those north of Rome, the thermal water, rich in H_2S as well as endogenic CO_2, plays a supplemental role in cave evolution. It is important to consider the positive feedback between H_2S oxidation and the releasing of new CO_2 in the upper part of the groundwater to provide a complementary aggressiveness toward carbonates. The cave patterns show that the oxidation zone for H_2S is not restricted to shallow groundwater levels but can extended through the deep parts of the aquifer where there has been input of fresh water in complex regional flow systems.

The presence of a large fluid flows opens further questions about the role of the aggressive gases CO_2 and H_2S in the speleologensis processes. The values of P_{CO2} in groundwater of central Italy range from 0.03 to 0.1 atm, which provides more than ten times the $CaCO_3$ solubility than normal karst waters. The breakthrough mechanism involving progressive fracture widening by epigenic CO_2 corrosion is modified to a homogeneous corrosion of the fracture walls along their entire length by the presence of endogenic CO_2. An increase of endogenic P_{CO2} of 0.002 atm, is sufficient to reduce the

breakthrough time for a fracture to about half (Gabrovsek & Dreybrodt 2000). Moreover, the cooling during the ascent of thermal water along the conduits increases the CO_2 aggressiveness, with the corrosion acting almost uniformly along the surfaces, producing a dramatic increase in karst void development and flow rate (Andre & Rajaram, 2005).

The complex chemical reactions between the different minerals in contact with the carbonate rocks, and the presence of significant concentrations of Cl and Na in several karstic groundwaters, gas/water reactions, and the role played by organic matter are topic for future research.

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UNIQUE DISSOLUTIONAL MORPHOLOGIES IN CAVES: A RESULT OF CONVECTIVE FLOW REGIMES?

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A major group of caves, confined hypogenic caves, form gradually by slow flow under confined conditions and are said to have a diagnostic suite of dissolutional features including, but not limited to: cupolas, domepits, ceiling channels, fissures and rift-like infeeders, and thin bedrock partitions. The existence of these dissolutional features in epigenic stream caves is interpreted to indicate that speleogenesis had earlier initiated under confined, and most likely deep, conditions and had been overprinted by shallow epigenic conditions. It has since been demonstrated that flank margin caves in the Bahamas and Isla de Mona contain identical dissolutional features, yet these caves formed in a shallow environment in carbonate rocks that are still eogenetic and have never been in a deep burial or confined setting. Other workers had previously considered many of the diagnostic speleogens to be indicative of backflooding in epigenic caves.

What are the flow characteristics that create such dissolutional features? Flank margin caves are produced by fresh-water lens flow similar to the slow flow described for confined soluble rock settings. Vertical fluid transfer can therefore occur within dissolutional voids by density flow without disruption by lateral fast flow. The density differences for vertical flow can be produced by thermal variation, solute differential, or fluid degassing and entraining, or convection can be forced by pressure flow. In shallow flank margin caves, thermal variation is unlikely, however mixing of vadose fresh and phreatic water at the top of the lens can create a fluid with higher solute load, and therefore density, than either starting fluid. That fluid would descend within the flank margin cave to set up a vertical flow regime. Organic material collects at the fresh-water boundary with underlying marine water, where it has been demonstrated that organic decay produces excess CO_2, and also H_2S. Degassing as a result of organic decay, with vertical bubble migration, could also entrain fluid flow into vertical motion, with renewed dissolution at the cave roof by mixing with descending vadose water. In epigenic caves, backflooding and downstream hydraulic damming can create stagnate, slow flow conditions. Vertical flow driven by density differences becomes possible when lateral fast flow ceases. In this case, the unique speleogens produced are an overprint of an epigenic process, as opposed to being a confined flow speleogen overprinted by later epigenic processes.

1. Introduction

The recent development of a model to describe cave genesis in deep, confined karst aquifers by slow flow ascending across confining aquicludes proposes that many epigenic caves are relict hypogenic caves participating in modern fast-flow regimes (Klimchouk 2007 and references therein). This model, called herein the *confined hypogenic cave model*, is identified in the field by a suite of dissolutional bedrock forms, or speleogens, including but not limited to: cupolas, domepits, ceiling channels, fissures and rift-like infeeders, and thin bedrock partitions. The model explains that the appearance of these features in epigenic stream caves is the result of inheritance from a previous mesogenetic phase. It has been demonstrated (Mylroie and Mylroie 2008; in press) that identical speleogens are found in flank margin caves (Fig. 1). These caves develop in the eogenetic environment of the fresh-water lens contained in carbonate islands and coasts (Fig. 2), and have never been confined or undergone deep burial (Mylroie and Mylroie 2007 and references therein). The presence of these speleogens in flank margin caves as well as confined hypogenic caves raises the question of whether these diagnostic speleogens might also be generated in stream caves by epigenic processes.

2. The Flow Regime for Speleogen Development

The processes that create the diagnostic speleogens observed in confined hypogenic caves cannot be observed directly, but the confined hypogenic cave model indicates that ascending flow is the critical component (Klimchouk 2007). Many speleogens show a geopetal orientation, that is, a response to the earth's gravity field resulting in a distinct vertical aspect.

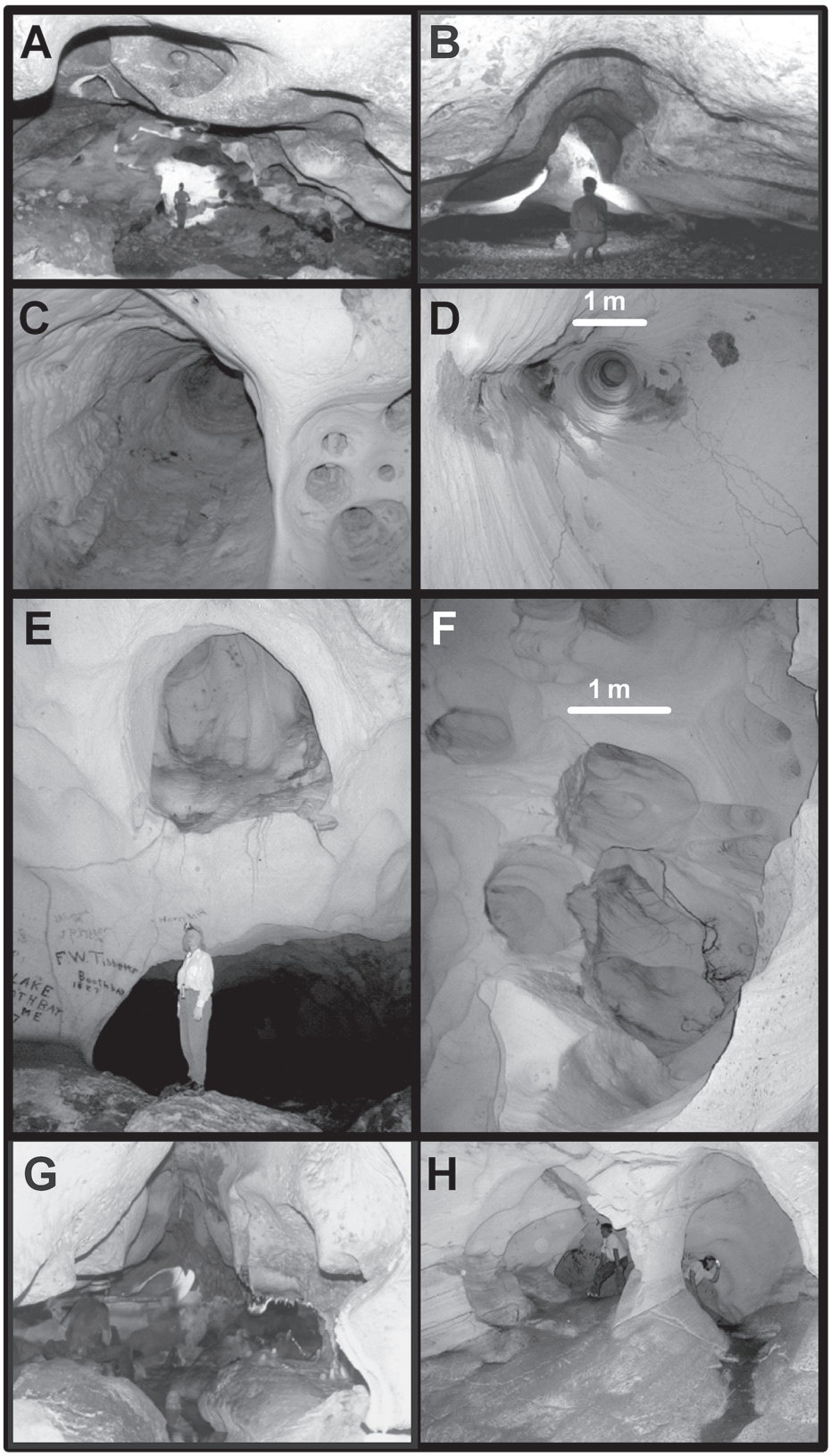

Figure 1: Bedrock dissolutional morphologies, or speleogens, from flank margin caves in the Bahamas and Isla de Mona, Puerto Rico. These dissolutional features are nearly identical to those described in Klimchouk (2007) as being produced solely by confined hypogenic conditions in karst aquifers. (A) Rising chain of cupolas, Cueva del Agua Punte los Engelses, Isla de Mona. Compare to Plates 6C and 6D in Klimchouk (2007). (B) Ceiling channel, Cueva del Agua Sardinera, Isla de Mona, Puerto Rico. Compare to Plates 6G and 7A in Klimchouk (2007). (C) Domepit (sensu Klimchouk, 2007), Cumulous Cave, Crooked Island, Bahamas. Ruler in right center is 10 cm long for scale. Compare to Plate 9J in Klimchouk (2007). (D) Cupola with outlet, Hamiltons Cave, Long Island, Bahamas. Compare to Plate 9D in Klimchouk (2007). (E) Large Cupola, Hatchet Bay Cave, Eleuthera Island, Bahamas. Compare to Plate 6D in Klimchouk (2007). (F) A variety of ceiling cupolas, Hatchet Bay Cave, Eleuthera Island, Bahamas. Compare to Plates 6B, 6 C, 6I, 9B, and 11A in Klimchouk (2007). (G) Fissure and rift-like passage, Cueva del Agua Sardienra, Isla de Moan, Puerto Rico. Compare with Plates 5H and 5I in Klimchouk (2007). (H) Bedrock partition, Goat Cave, Long Island, Bahamas. Compare to Plates 12 E and G in Klimchouk (2007).

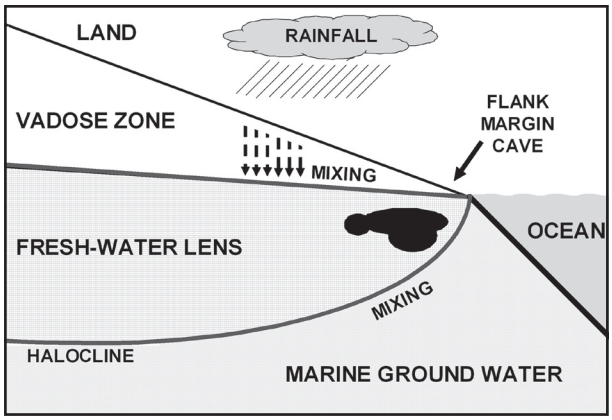

Figure 2: Diagram of the fresh-water lens in a carbonate island, showing the upper and lower lens boundaries and mixing areas, and the development of flank margin caves under the flank of the enclosing landmass, in the distal margin of the lens. The vertical scale has been exaggerated, the lens does not dip as steeply as shown.

Cupolas, domepits (*sensu* Klimchouk 2007) and ceiling channels in particular display dissolution upward in the vertical sense. As the speleogens found in flank margin caves cannot be the result of fluid pressure forcing water upward through overlying confining layers, there must be another way to generate such geopetal speleogens. In both flank margin caves and in confined hypogenic caves, lateral flow is either non-existent or very slow. The lack of rapid lateral flow allows other flow regimes to express themselves. These flow regimes are not commonly found when exploring active epigenic stream caves.

In confined hypogenic caves, convection can be forced by the upward movement of water under pressure, to generate a partial return flow pathway. The return flow could be generated by the density difference of the water at the cave roof as it becomes saturated with solute, such that it is now denser than the ascending, less saturated flow. Given these caves are believed to form by upward dissolution (Klimchouk 2007), saturated water is constantly being created at the cave roof. Thermal gradients may also assist in creating density differences, and hence convection, in confined hypogenic caves. Ascending water will cool as it travels upward, increase in density, and sink. The initial force to create ascending water may be the result of the pressure of aquifer confinement, but once the water has moved upward, it will experience a lower temperature regime and thermal convection may express itself.

In flank margin caves, however, neither forced upward flow nor thermal gradients are likely. Convection can still be established by two possible mechanisms, both a result of the condition that at the margin of the fresh-water lens, the cave extends across most of the thickness of the lens (Fig. 2). One mechanism begins with vadose flow to the top of the lens. Mixing dissolution of vadose and phreatic waters can result in renewed dissolutional aggressivity in carbonates (Bögli 1980). Such mixing at the top of the fresh-water lens would create a fluid having more solute than either initial component, so in an isothermal environment, it would be denser than either initial fluid. As shown in the cartoon in Figure 3, the entry of this denser water into a flank margin cave causes the water to sink to the cave floor at the approximate position of the halocline (Fig. 2). This descending water displaces the bottom water of the cave, causing dissolution at the base of the cave as a result of the dissolutional aggressivity obtained by mixing this new fresh water with sea water (Plummer 1975). The descending water requires a return flow to the top of the chamber, where mixing with incoming vadose water generates cupolas and related ceiling topography. At the floor of the chamber, mixing dissolution creates slots, basins and other dissolutional floor topography. Once this topography becomes established on both the floor and the ceiling, it would tend to lock in the descending and ascending flows, to create a closed convection cell. Dissolution of this type has been suggested as a possible mechanism for the formation of a very specific type of cupola in flank margin caves, the bell hole (Birmingham, et al. in press).

A second possible mechanism for generating speleogens in flank margin caves involves the decay of organics. Organic material collects both at the top of the fresh-water lens, and at the base of the lens, as both locations are regions of density contrast. The geochemical effects of organic decay to promote carbonate dissolution has been well established for blue holes (e.g. Bottrell et al. 1991). Subsequent work demonstrated that similar dissolutional activity occurred in flank margin caves as a result of organic loading of the lens, and eventual decay (Bottrell et al. 1993). These studies showed that organic decay produces not only excess CO_2 that promotes additional carbonate dissolution, but that significant organic loading can drive the system into anoxic conditions, such that H_2S-mediated dissolutional activity occurs. The evolution of these gases from decay at the halocline can create bubbles and entrain water flow upward, and across cave roofs (Fig. 3). As a result, dissolution by both water mixing and by gas absorption can result at the cave ceiling. This activity can create ceiling notches or chains of cupolas if the lateral movement is significant, as shown in Figure 3. While the mechanisms presented here are merely speculative, they demonstrate that logical arguments can be applied to produce a selection of

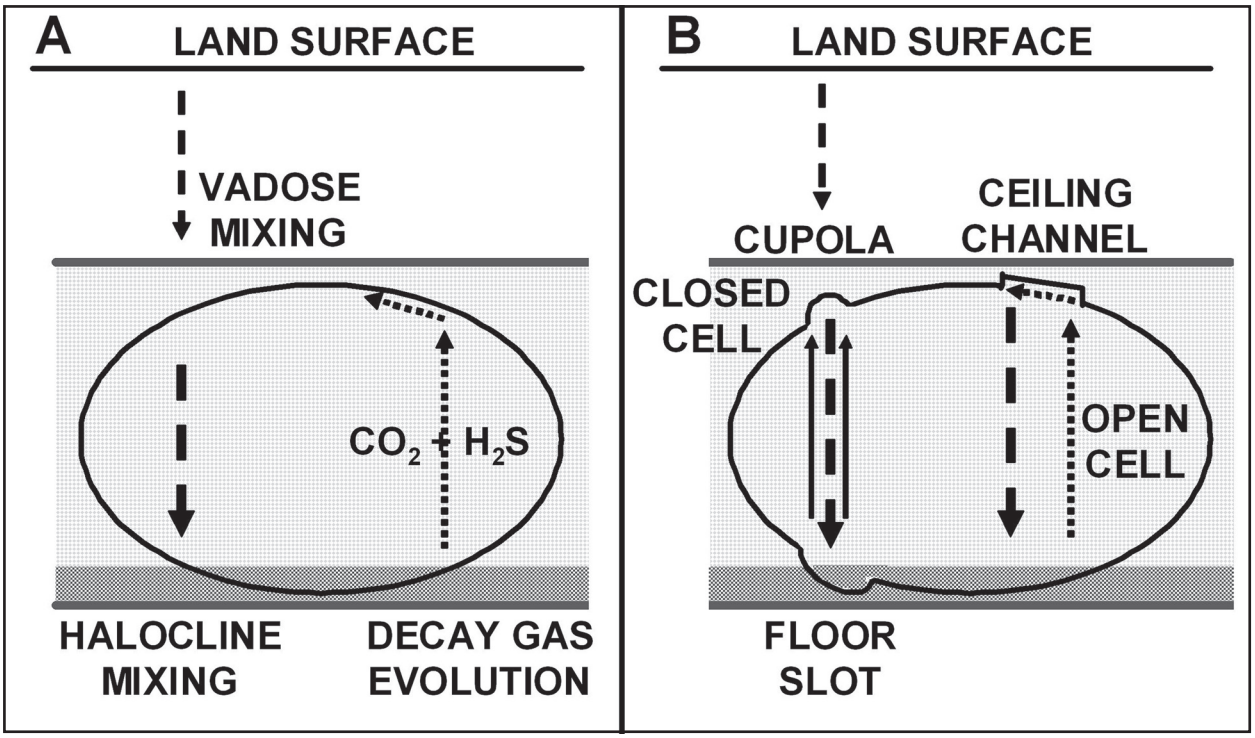

Figure 3: Diagrammatic representation of possible dissolutional processes within flank margin caves that can produce bedrock morphologies similar to those found in confined hypogenic caves. A) Mixing locations (left), and decay of organics trapped at the halocline to produce CO2 and H2S (right). B) Closed cell convection creates cupolas and floor dissolution (left), open cell convection creates ceiling channels and chains of cupolas (right). See text for a full discussion.

dissolutional ceiling morphologies that are extremely similar to those seen in confined hypogenic caves.

Flank margin caves form in the fresh-water lens by the enlargement of touching vug porosity into chambers, which subsequently intersect other enlarging chambers and groups of chambers to create the cave complexity seen in the field today (Labourdette, et al. 2007). One consequence of this cave development style is that it creates numerous thin bedrock partitions between chambers and passages, commonly with holes in them. Similar to the confined hypogenic cave model, the development of flank margin caves occurs with little or no competition between adjacent sites of speleogenesis. Passages and chambers intersect randomly, and this intersection does not change the overall hydrologic regime, as it would in epigenic stream caves.

3. The Case for Epigenic Stream Caves

The origin of the unique dissolutional morphologies found in both confined hypogenic caves and in flank margin caves can be explained as an outcome of slow flow, which allows other flow styles to be expressed. Vertical flow under pressure, or convective vertical flow, can explain much of what is seen in these two cave types. What of the similar dissolutional forms seen in epigenic caves? These dissolutional forms are abundant in epigenic caves, and Klimchouk (2007) argues that they represent inherited dissolutional forms from an earlier confined hypogenic origin. One could argue as well that these dissolutional forms have been inherited from an even earlier eogenetic origin, though we consider the successful transit of these voids from the eogenetic to the mesogenetic to the telogenetic environment highly unlikely. In epigenic caves, some of these forms have been ascribed to flood water conditions (Palmer 1991), a condition that at first seems quite different from the proposed slow flow environments discussed for flank margin caves and confined hypogenic caves.

Flood waters and epigenic caves need to be examined from two perspectives, *input flooding* and *output flooding* (Fig. 4). During input flooding, water input is of large magnitude, and passages may be unable to handle the high discharge, especially if passage constrictions or obstructions exist (Fig. 4A). Hydraulic heads are high, and water flow velocities are not only turbulent but commonly very fast. Output flooding occurs when base level rises, hydraulic heads decrease to zero for many cave passages, and flow velocities can drop significantly; the cave is hydraulically dammed (Fig. 4B). At this time, lateral flow is much decreased, and

vertical convective flow can be expressed. The same vadose-phreatic mixing hypothesized for flank margin caves can occur, to form cupolas and create solute-dense water near cave ceilings. During flood events, increased vadose flow can be expected from meteoric input, and mixing dissolution thusly increased. The presence of organic material, commonly introduced by the initial flood pulse, can decay to release CO_2 to both increase dissolutional aggressivity and to form bubbles to help drive vertical water flow. While the onset and end of output flood cycles may have high velocities, the middle stagnant phase does not.

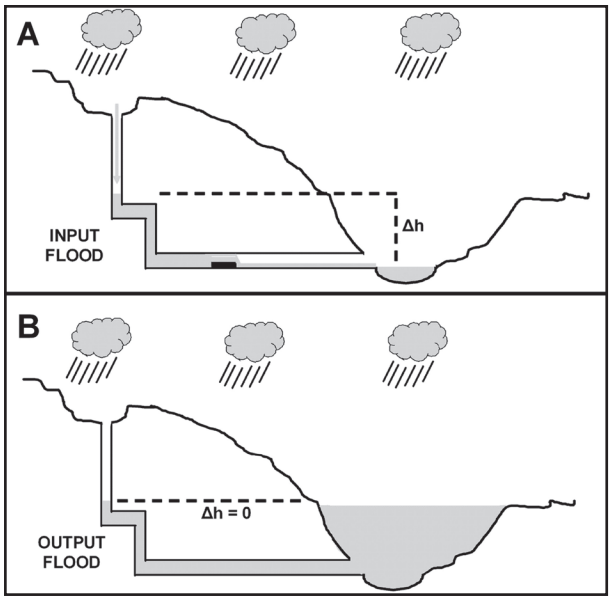

Figure 4: Comparison of input and output flooding. A) Input flooding can fill all or part of the cave, but high flow velocities may also be present because the hydraulic head (Δh) is large. B) Output flooding creates a zero head condition (Δh = 0), and stagnant flow conditions in much of the cave. This setting could allow slow vertical flow mechanisms to produce bedrock dissolutional morphologies similar to those seen in confined hypogenic caves.

The assumption that certain dissolutional passage configurations and orientations found in epigenic stream caves are the result of inherited confined hypogenic cave features is not necessarily true. It is certainly likely that confined hypogenic caves, as paleokarst features, have been intersected by epigenic cave systems. What is unlikely is that these intersected features play a significant role in epigenic cave genesis and function. Confined hypogenic caves form as caves that developed independent of each other, and connections are fortuitous and have no effect on aquifer flow. These criteria are a key point expressed by Klimchouk (2007) for confined hypogenic cave genesis. For such a cave to be configured so as to provide the most efficient and effective pathway for fast, turbulent epigenic flow is a low probability situation. Models that explain epigenic cave development, taking into account rock characteristics, structural features such as dip and strike, faulting, folding and jointing, and climatic history, do an excellent job (e.g. Palmer 1991). Output flooding is an alternative explanation for some of the dissolutional morphologies thought to be unique to confined hypogenic caves, especially for those caves where there seems to be a pattern of cave development and utilization of passage segments with these morphologies (e.g. Alexander 2008).

4. Conclusions

Confined hypogenic caves are an important aspect of cave development. That they are poorly understood, and poorly represented in the cave literature is also true. The explorational bias associated with hypogenic cave development in general has been discussed by Mylroie (2003) and Klimchouk (2007). Hypogenic caves are decoupled from surface processes; they appear in the epigenic realm as paleokarst. The typical evidence cavers use to find and explore epigenic caves does not work for hypogenic caves. Epigenic caves are coupled to the surface hydrology. Sinking streams, springs and karst windows are observable features that assist the cave explorer to locate and enter epigenic caves. Hypogenic caves interact with the surface in a random fashion. Access points are not intuitive. Furthermore, because hypogenic paleokarst caves are not coupled to surface hydrology, they are vulnerable to segmentation, overprinting, and most of all, they are sediment traps. Not only are hypogenic caves hard to find, most are blocked or plugged with sediment. It is almost a certainty that in humid environments, epigenic caves have intersected paloekarst hypogenic caves. Some unusual cave chambers and passage segments in epigenic caves could well be inherited from the hypogenic realm. However, widespread utilization of hypogenic paleokarst as a significant control of epigenic cave development does not appear to happen. The three large hypogenic caves of the American West (Lechiguilla, Wind and Jewel) are notable for their *lack* of interaction with current epigenic hydrology, which has been a significant factor in their survival and access for exploration.

Explorational bias not only distorts our understanding of the location, abundance and extent of hypogenic caves, it influences our understanding of how these caves form. It is nearly impossible to explore confined hypogenic caves in their environment of formation when they are actively developing. We must infer their mode of formation by examining evidence after these caves have become paleokarst

and have been intersected by surficial processes. Flank margin caves have similar problems; they form without entrances, the ultimate explorational barrier. Epigenic stream caves have an explorational bias as well, especially as concerns what happens within them during output flooding when cavers cannot directly view speleogenesis within the cave. Because output flooding is a repetitive event for epigenic stream caves, they can be visited between floods for an assessment of incremental change to dissolutional speleogens. Such change has been reported in some caves that flood repeatedly (Palmer 1972).

Utilization of dissolutional morphologies as obligatory proof of confined hypogenic origin is not valid. Flank margin caves contain a large number of identical dissolutional morphologies and have never been confined or deeply buried. Considering the flow regime similarities between confined hypogenic caves and flank margin caves, slow flow, perhaps assisted by convection of various types, seems the most likely cause of the diagnostic speleogens. While the slow flow dissolutional morphologies found in epigenic caves could be inherited from a mesogenetic (or even eogenetic) origin, it is also possible to demonstrate that slow flow can be a common occurrence in epigenic caves as a result of output flooding.

Confined hypogenic caves develop at depth under very slow conditions, in sedimentary basins of a scale that cover portions of continents, basins that form and are subsequently exposed on time frames of millions to tens of millions of years. This cave development is necessarily slow. Flank margin caves, on the other hand, develop in small islands in young rocks during brief sea-level highstands measured in thousands of years. They must develop very rapidly. Yet the same dissolutional morphologies are found. The geochemical mechanisms must be working at very different speeds, and the similarity of morphology indicates that the nature and style of the water flow is the critical control of cave morphology. Epigenic caves may also generate, as well as inherit, such dissolutional morphology. The confined hypogenic cave model of Klimchouk (2007) has opened investigation into a variety of other issues involving cave development. While we have been critical of some aspects of the confined hypogenic cave model and its interpretation (Mylroie 2008; Mylroie and Mylroie 2008; in press), the model represents a new and important frontier for cave research.

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KARST DEVELOPMENT IN THE CASTILE FORMATION OF EDDY COUNTY, NEW MEXICO, AND CULBERSON COUNTY, TEXAS: A STUDY OF MULTIPLE MODELS FOR REGIONAL SPELEOGENESIS

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The Castile Formation crops out over ~1,800 km^2 in Eddy County, New Mexico, and Culberson County, Texas. GIS-analysis has indicated that over 9,000 karst features are likely in this area. The majority of these features are epigenic in origin. However, hypogenic caves as well as caves with a mixed speleogenetic origin are found throughout the study area. The most common karst features in the study area are closed depressions or shallow caves, rarely extending further than 10 m. These caves formed in the vadose zone along well developed joints, though some have developed along bedding planes. Scallops in the walls and floors of these caves provide evidence of periodic flash flooding that continues to enlarge the caves in the vadose zone. Evidence of hypogene processes is widespread throughout the area. Dense clusters of hypogenic caves are typically associated with calcitized evaporites and selenite masses, suggesting a genetic relationship. Within these caves, specific morphologic forms (i.e., risers, cupolas, and half-tubes) provide evidence of their hypogenic origin. Blanket brecciation, breccia pipes, and subsidence troughs are common throughout the Castile Formation, indicating subsurface dissolution and collapse. Calcitized evaporites are extensive throughout the region and are frequently associated with zones of brecciation. Deposits of native sulfur have also been observed in association with zones of brecciation, calcitized evaporites, and selenite (tabular gypsum) masses. The close proximity of hypogene caves, breccias, native sulfur, selenite masses, and calcitization suggests that hypogene processes have dominated sulfate diagenesis in the Castile Formation.

1. Introduction

The Castile Formation crops out in the western edge of the Delaware Basin (Fig. 1). The Delaware Basin is part of the larger Permian Basin and lies at the boundary of the Basin and Range and the Great Plains provinces. The outcrop covers an area of ~1,800 km^2 in a band extending from Eddy County, New Mexico into Culberson County, Texas. The Castile Formation is a basin filling evaporate sequence encircled by the Capitan Reef (Hill 1996). The Castile is underlain by the clastic Bell Canyon and Cherry Canyon formations. After deposition, it was covered by Permian evaporites of the Salado and Rustler Formations (Hill 1996) (Fig. 2). Stratigraphically, it contains anhydrite, halite, and limestone beds. Most of the Castile Formation is varved anhydrite and halite or varved anhydrite and calcite (Anderson et al. 1978), resulting from seasonal salinity cycles in the shallow inland Permian Sea.

Regional uplift began with the Laramide, tipping the basin east/northeast at approximately 3-5° (Horak 1985). During the mid-Miocene, roughly 30–40 Ma, basin-and-range expansion resulted in the development of east-northeast trending faults. Hentz et al. (1989) described these faults extending into the Bell Canyon Formation and possibly deeper. Tectonic activity resulted in zones of west-east permeability that developed throughout the basin (Horak 1985). Grabens formed along these faults are evident throughout the western edge of the outcrop. Solution/subsidence valleys formed along the surface between these fractures through halite dissolution by waters rising from depth (Olive 1957). Horak (1985) described igneous activity that began during this period of basin-and-range expansion. According to Barker and Pawlewicz (1983), the Delaware Basin experienced high heat flow from 40-30 Ma related to igneous intrusions and from 23-0 Ma as a result of basin-and-range type block faulting. As a result, the basin has exhibited a higher than average thermal gradient (Hentz et al. 1989).

2. Epigenic Karst

Stafford (2008) described multiple solutional features formed by descending. He described karst features found in fifty randomly selected 1-km^2 areas, including blind valleys, pirated arroyos, closed depressions, sinkholes, karst windows, springs and cenotes. Epigenic caves described typically had large openings and closed rapidly. Scallops observed in these caves are evidence of seasonal flash flooding that continues to modify these caves.

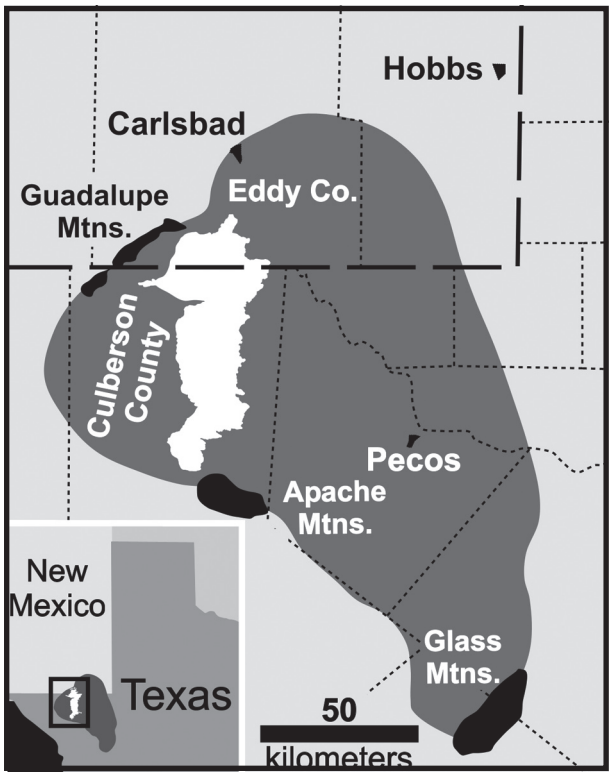

Figure 1. Location map showing location of Gypsum Plain including outcrop areas of the Castile Formation (solid white) and the Rustler Formation (solid black) within the Delaware Basin (dark gray), Eddy County, NM and Culberson County, Texas. Location of the Delaware Basin in relation to Texas and New Mexico is illustrated in bottom left corner, with the enlarged region outlined by the small black rectangle (adapted from Kelley, 1971, Dietrich et al., 1995 and Hill, 1996).

3. Hypogene Karst

Faulting during the mid-Miocene provided pathways for water from basinal aquifers to rise into overlying Castile and Salado formations. Anderson and Kirkland (1980) proposed two prerequisites for brine density flow: 1) Pressurized or artesian source of relatively fresh water and 2) permeable fracture systems and salt mass normally isolated from groundwater. They demonstrated that the upper 30 meters of the basin aquifer in the Bell Canyon formation has sufficient flow to remove the salt from 100 dissolution chambers of $1x10^6$ m^3 in a period of about 30,000 years. Calcitized evaporite masses are dominant karst features in the western Delaware Basin. During the past 30 Ma, hydrocarbons migrated updip to the west. Kirkland and Evans (1976) described the reaction between the hydrocarbons and anhydrite in which sulfate is altered to carbonate and H_2S is released:

$$CaSO_4 + CH_4 \rightarrow H_2S + H_2O + CaCO_3 + \text{energy}.$$

The resulting carbonate masses observed in the subsurface and on the surface form distinctive 'castiles' that give the formation its name. Stafford et al. (2008) demonstrated the linear nature of the carbonate masses. Kirkland and Evans (1976) cited isotope data indicating biogenic origin. Worden and Smalley (1996) indicated that bio-sulfate reduction (BSR) and thermal-sulfate reduction (TSR) fractionate carbon and sulfur isotopes to similar degrees. There does not appear to be definitive support for BSR over TSR based on isotopic data. The presence of local igneous intrusives and higher than normal thermal flux are sufficient to support thermogenesis of the carbonate deposits (Calzia and Hiss 1978).

The diagenesis of anhydrite to carbonate resulted in a volume decrease of 20% (Kirkland and Evans 1976). Hydrocarbons migrated through resulting permeability to a diagenetic boundary layer where dissolved anhydrite was immediately replaced by calcite (Kirkland and Evans 1976). Hydrogen sulfide oxidized in place, forming elemental sulfur (Smith 1978) or migrated back into the fracture where it continued to rise (Hentz et al. 1989). Hydration of anhydrite to gypsum sealed fractures, creating a trap for rising gases (Guilinger 1993).

Basinal breccia resulted from hypogene processes. Rising undersaturated waters would dissolve laterally into halite beds. Density circulation resulted in dissolution along the top of the bed with water descending along the bottom of the bed and returning to the aquifer below. Halite saturated water enhanced the solubility of anhydrite (Warren 2006). Anderson et al. (1978) correlated breccia beds observed in the west with halite beds found in the east. As breccia beds formed outward from fractures, water moving into the Castile from the west descended downdip, along breccias, to halite beds. As halite beds dissolved, anhydrite beds containing, or adjacent to, halite formed dissolution breccia beds (Anderson et al. 1978).

Smith (1978) described important factors for origin of elemental sulfur deposits: 1) presence of sulfate rocks, 2) presence of hydrocarbons, 3) fracturing or brecciation of rocks to facilitate fluid flow, 4) oxygenated groundwater or other agents capable of oxidizing hydrogen sulfide, 5) sealing to prevent loss of hydrogen sulfide gas, 6) absence of halite. Klimchouk (1997) noted factors 1-4 are also prerequisites for karst development and that karstification must occur for sulfur deposits to form. All known ore bodies in the Rustler Springs sulfur district are associated with zones of fractured evaporate strata (Hentz et al. 1989). All native sulfur observed by the authors was associated with calcitized

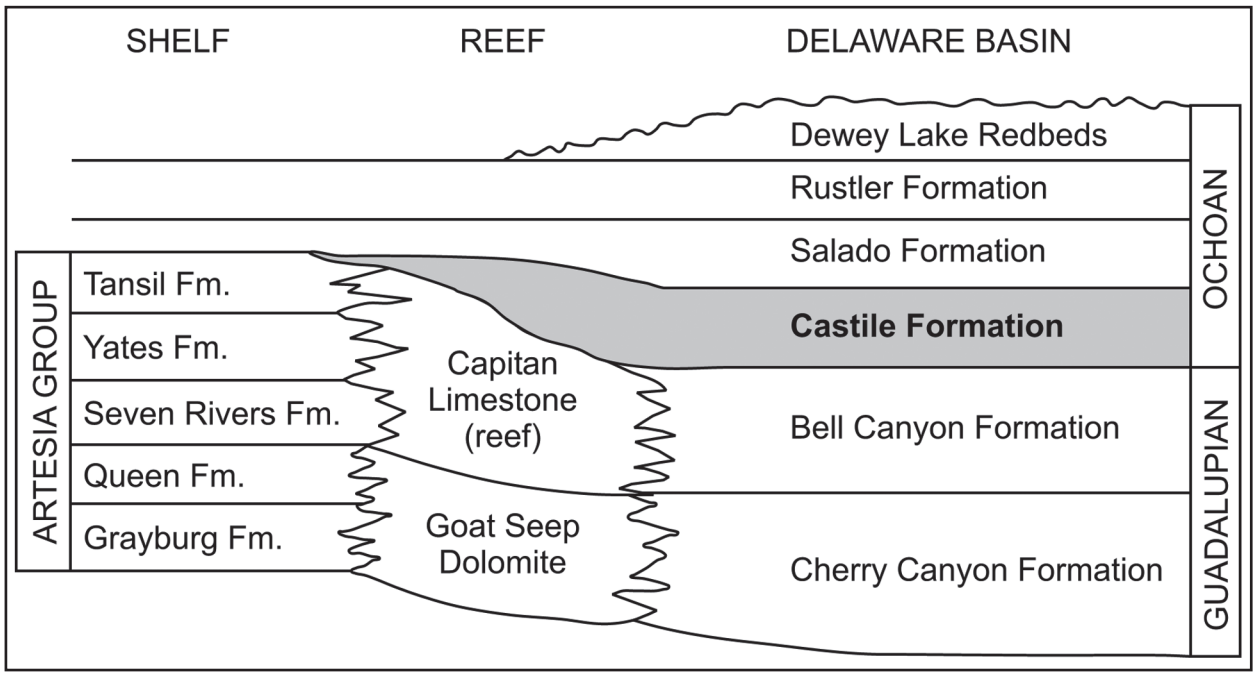

Figure 2. Diagrammatic representation of late Permian (Guadalupian and Ochoan) deposits associated with the Guadalupe Mountains (left) and Delaware Basin (right). Note that the Castile Formation fills in the basin and marks the beginning of the Ochoan (dashed white line) (adapted from Hill, 1996).

evaporites or large masses of tabular gypsum in fractured evaporate zones.

Hydrogen sulfide migration was laterally limited to breccia originating at the breccia pipe and upward by sealing of fractures. Breeching of seals resulted in movement of oxygenated meteoric water into hydrogen sulfide rich zones. Mixing with oxygenated water resulted in deposition of elemental sulfur. At the Grant Prospect, Smith (1978) described a 30 meter deep shaft lined with a four inch layer of crystalline sulfur. The authors have observed minor deposits of sulfur in calcite lined vugs at this site.

Most carbonate masses and sulfur ore bodies are surrounded by selenite (tabular gypsum) deposits. The authors have observed numerous tabular gypsum crystals in excess of two meters in length. In Crystal Cave, the lowest extent of the surveyed cave is in a relatively homogenous mass of tabular gypsum in excess of 20m tall. Mohammed (1988) suggested that sulfur was oxidized with the help of sulfur oxidizing bacteria to form sulfuric acid. This then reacted with limestone to produce carbon dioxide and gypsum. In a confined, limited flow system, calcium sulfate would recrystallize from this saturated solution in the form of tabular gypsum. Hill (1996) has suggested that the selenite formed concurrently with deposition of sulfur. The authors have observed native sulfur in association with selenite at several locations.

4. Recent Hypogene Processes

Several caves in the study area exhibit a diagnostic suite of hypogene features, indicating confined speleogenesis by rising waters (Klimchouk 2007). Dead Bunny Cave lies in the basal Castile Formation and is formed in varved gypsum and calcitized evaporites. Crystal Cave is the deepest gypsum cave in Texas. It has been surveyed to a depth of 90 meters and is formed along extensive selenite (tabular gypsum) deposits.

Dead Bunny Cave contains a suite of features indicative of hypogene speleogenesis. The upper portion of the cave is formed along the fold axis of several anticlines (Fig. 3). Throughout the cave, risers, wall channels, ceiling channels, and cupolas have been documented. A boneyard area, typical of deep phreatic flow, was also documented. A clay "dike" extends through the lower portion, indicating an earlier period of speleogenesis in which the passages were later filled with clays. The system was breeched in the updip area of the anticlines and epigenic overprinting continues to modify the pre-existing features.

Davis (1993) described a basal Castile aquifer located in the area of the Culberson sulfur mine. He described the aquifer as having good transmissivity and suggested it could

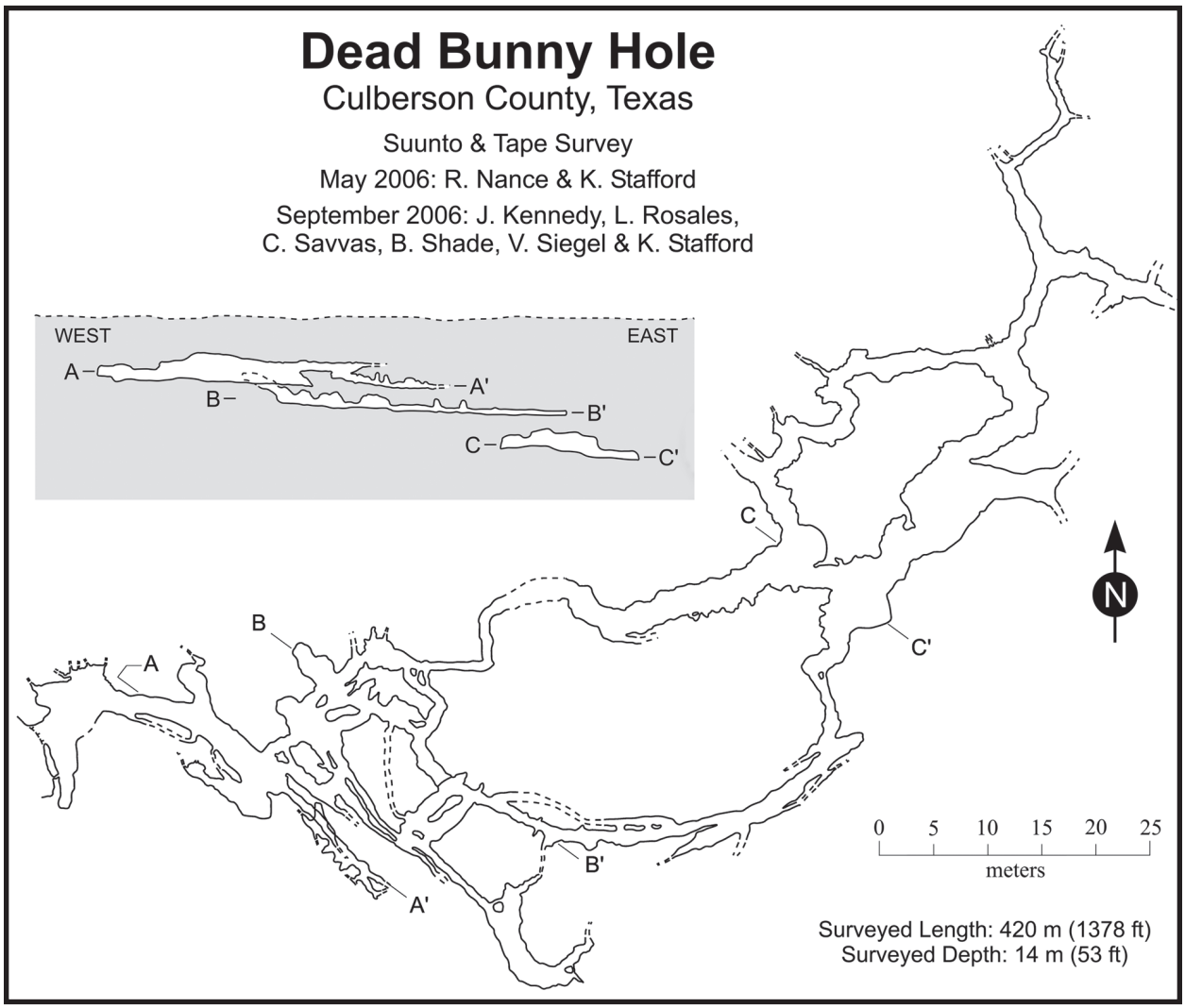

Figure 3. Dead Bunny Hole. Cave was formed by deep phreatic flow in the basal Castile Formation. Epigenic overprinting is currently an active process due to surface breaching in the vicinity of NW-SE trending anticlines.

extend further under the Castile. The contact between the Lamar Limestone and the Castile Formation was observed approximately .5 km west of Dead Bunny cave. The cave lies very close to the base of the Castile Formation and calcification observed is very similar to that described at the base of the Castile in the Philips Ranch sulfur deposit. Dead Bunny cave is assumed to have initially formed under deep phreatic conditions as part of a hypogene system.

Ford (2007) commented on the existence of simple, single conduit caves formed by rising water, noting they were rare. Crystal Cave is a single riser, hypogene cave that can be described in three sections (Fig. 4). The upper section is vadose entrenched passage that reaches a depth of 25m below surface level. In the area of Quarryman Pit, vadose entrenchment cut into the midsection passage. Quarryman pit is formed along a zone of minor faulting that predates deposition of selenite beds observed in the mid section of the cave. The cave mid-section is an epigenically modified passage that follows regional dip east/northeast at approximately 6°. It follows a vein of selenite that also lies along regional dip. Selenite is underlain by nodular gypsum in several locations and lies within breccia through much of its length, indicating formation along a dissolved halite bed. The caves lowest section is formed in homogeneous tabular gypsum (selenite). The passage drops approximately 10 meters through a vertical pit (Glacier Bay II) and then stair-steps to a terminal sump at a total depth of about 105 meters. Risers and cupolas were observed above the terminal sump, leading upward into the pit. The terminus of the mid-section of the cave lies directly above these riser features. At the lip of Glacier Bay II, slotting is minimal. In most caves, this is typically attributed to heterogeneous lithology, with a less soluble layer forming the lip of a pit. Without such a

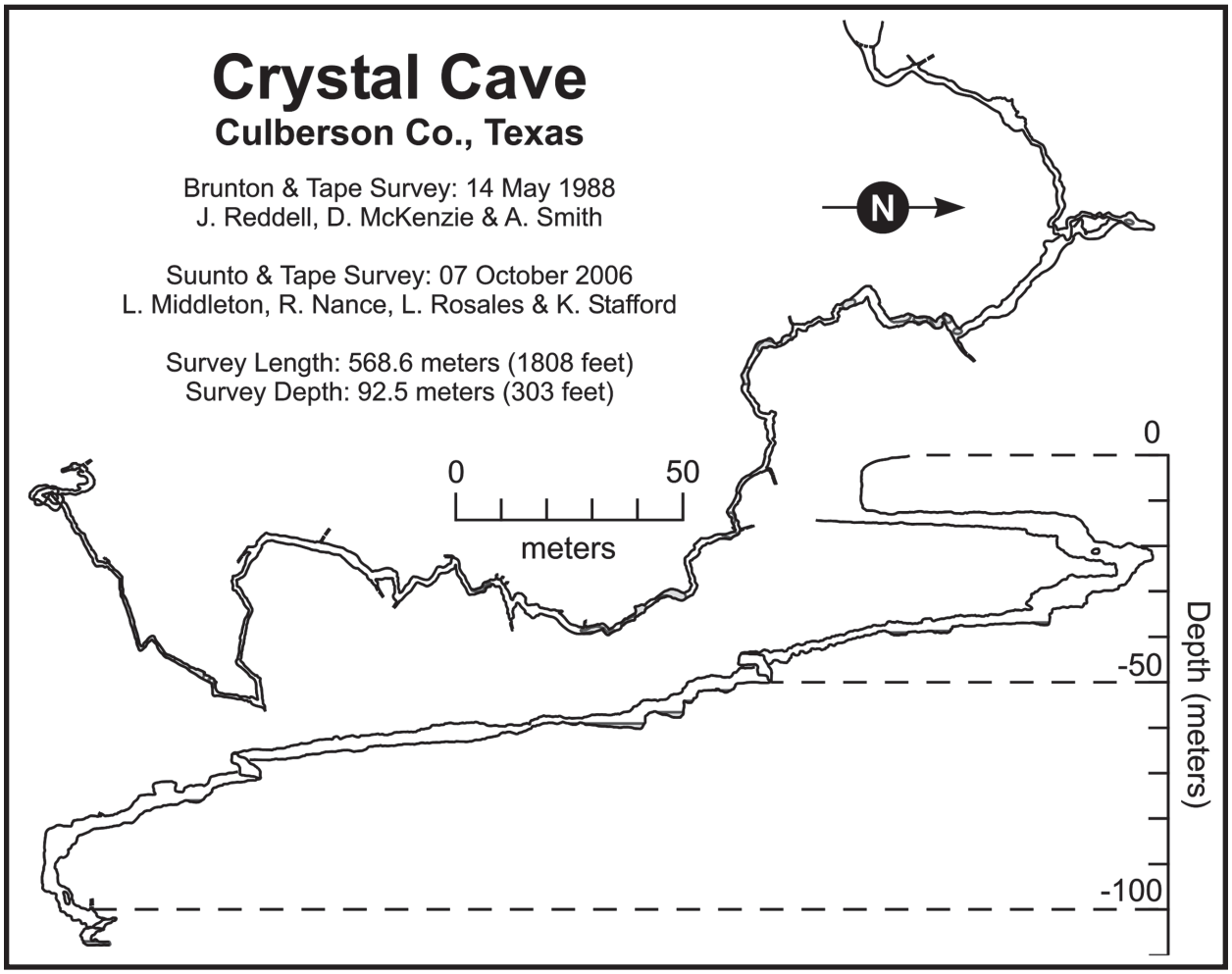

Figure 4. Crystal Cave. Upper section of the cave extends from the surface level to a depth of 25 meters. The mid-section of the cave extends from 25 meters to a depth of 80 meters below the surface. The lower section of the cave lies below 80 meters depth.

layer, epigenic water will entrench the edge of a pit, forming a stair step structure. If the pit was formed by epigenic processes, the floor should be slotted the full depth of the pit due to the homogeneous rock in which it is formed. Instead, a slot approximately 2 to 3 meters deep lies directly above a 10 meter tall riser feature. The vertical nature of Glacier Bay II and the minimal pit-edge slotting indicates a rising water origin with slight epigenic overprinting.

Stafford (2008) suggested episodic development of carbonates and sulfur deposits. Crystal Cave presents features supportive of the idea of episodic development. Early hypogene processes produced the riser void, later to be filled with selenite and become Glacier Bay II. A halite bed was dissolved and subsequent formation of breccias occurred. Hydration of anhydrite on either side of the breccias resulted in a selenitic rather than alabastrine texture in sulfate bedrock. Tabular gypsum began to precipitate from sulfate brines. Minor, possibly localized, tectonism produced minor faulting in the area of Quarryman's Pit. This breech allowed rising water to begin forming passages observed in the lower and mid-sections of Crystal Cave. Lowering of the potentiometric surface eventually lowered the water level in the cave. Epigenic processes enlarged fractures in the bedrock until they breeched the existing voids found in the area of Quarryman's Pit. Epigenic process became dominant, resulting in a mixture of speleogenic features.

5. Paleokarst Reactivation

Chosa Draw, in southern Eddy County, New Mexico, shows evidence of early deep phreatic development and later paleokarst development that is currently heavily overprinted by epigene processes. Most passages in the caves of Chosa Draw are formed along heavily overprinted elliptical tubes. Among these caves is the Parks Ranch Cave system, currently the second longest gypsum cave in the United States. Sares (1984) described regional

hydrologic and geomorphic development, but failed to recognize the importance of early phreatic flow in area karst development. Nance (1993) described denudation rates showing aggressive solutional development in cave portions exposed to meteoric waters during seasonal monsoonal rains. Some passages in Chosa Draw caves have developed along boundaries between gypsum bedrock and overlying sulfate cemented clastics. Numerous arroyos in the area cut perpendicularly across filled paleokarst features such as elliptical tubes, solutional incised arroyos, and collapsed fills.

6. Summary

In the Delaware Basin of southeastern New Mexico and west Texas, the study of sulfur deposits has yielded information on a suite of features indicative of hypogene processes. The conversion of anhydrite to carbonate and the resulting masses, associated breccias, large selenite deposits and associated deposits of elemental sulfur are all found together in the study area. These features resulted from aquifer fluids deeper in the Delaware Basin moving upward through fractures in the overlying evaporate beds. Hydrocarbons in the rising water reacted with anhydrite resulting in conversion to carbonate. This process was likely biogenic, but may have been thermogenic. The hydrogen sulfide produced as a result was later oxidized to produce deposits of elemental sulfur and tabular gypsum (selenite).

Caves in the study area exhibit characteristics of initial formation by hypogene or deep phreatic conditions. Hypogene caves studied appear to have formed along zones of permeability resulting from previous hypogene episodes. Overprinting by epigene processes has resulted in complex morphology in caves studied, making speleogenetic studies difficult. Numerous sulfide vents and sulfur springs in the area indicate ongoing processes at depth. Speleogenesis in the study area needs to be evaluated from its position within the overall evolution of the Delaware Basin. Processes at depths in excess of 300 meters, some of which may have been active as for as long as 30 Ma, have been critical in the development of karst features seen in the basin today. Karst processes in the basin have played a crucial role in the economy of the region by forming aquifers, hydrocarbon reservoirs and economic sulfur deposits.

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THE SPELEOGENESIS OF KANAAN CAVE, LEBANON: GEOMORPHOLOGICAL INTERPRETATION AND PALEOENVIRONMENT RECORDS OF ANTELIAS REGION

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Kanaan cave, 170 m long and 100 m above the Mediterranean sea, is composed of two different morphologic sections. The genetic analysis of the cave, based on the map study confirms that these sections were developed separately and were connected later in the cave development. The geological characteristics of each section and the different hydrogeologic regime in the gallery, as well as tectonic formation, these three facts affect, at a large scale, the karstic network system of the Antelias area. The detailed mapping, especially the determination of exact elevations, helped us to compare the processes that operated in different parts of the cave today as well as since the late Quaternary. The relative chronology based on this kind of cave mapping can reveal the main geological events and hydrological system development implicated in paleoenvironment conditions. This approach is necessary to understand speleothem dating records and to insert them in the geographical and geomorphological context of the study area.

1. Introduction

Suite à une étude menée sur la grotte de Kanaan, située dans la région d'Antelias, une nouvelle méthode a été utilisée aboutissant à la connaissance de la spéléogenèse de la grotte et du régime karstique de la région d'Antelias et révélant ainsi des événements paleoenvironnementaux de l'ensemble de la région. La méthodologie se base sur un relevé topographique à haute résolution du contenu de la cavité et sur une carte géomorphologique de la grotte Kanaan. L'analyse de cette dernière a révélé des processus morphogéniques relatifs à la formation de la grotte ayant joué un rôle important et a permis d'identifier les événements paleoenvironnementaux de la région d'Antelias.

2. Etude du Site

2.1. L'endokarst de Kanaan

Après une longue phase de sédimentation carbonatée mettant notamment en place l'épaisse formation des calcaires de Kesrouane, la région correspondant au Liban actuel émerge au Jurassique supérieur suite à un soulèvement. Les couches du Jurassique majeures se retrouvent exposées à l'action des agents atmosphériques. Les calcaires de Kesrouane ont été fortement fracturés et fissurés avant une phase d'activité volcanique. Les dépôts volcaniques et les sédiments continentaux résultant du volcanisme d'une part, et de l'érosion, d'autre part, ont rempli ces fractures préexistantes, accentuant à leur tour la paléotopographie du massif (Renouard, 1955; Nader et al., 2003). C'est à cette époque que se produit une première phase de karstification. Au Crétacé inferieur, les couches du Jurassique supérieur sont enfouies à nouveau, jusqu'à 3 km de profondeur, selon Nader et al., (2004). Le dernier soulèvement du Mont Liban s'est produit à l'Oligocène (Dubertret, 1975; Nader et Swennen, 2004). Depuis le Miocène, aucun changement tectonique majeur affectant la morphologie du Mont- Liban n'a eu lieu. La seconde phase de karstification des terrains carbonatés du Liban s'est mise en place à ce moment-là.

Le vallon d'Antélias, incisé perpendiculairement à l'escarpement bordier, résulte du creusement par un petit fleuve côtier dont l'écoulement est conditionné par le niveau de base, celui de la Méditerranée toute proche. Ainsi, le grand talus atteint 100 m de commandement au niveau du vallon. Le fleuve d'Antélias résulte en partie du ruissellement des précipitations et tombant en amont du plateau bordier. Mais il est aussi alimenté par un massif karstique, à travers la perte de Fouar Dara (haute vallée du Nahr Beyrouth) dont les eaux ressortent au niveau de la résurgence appelée Fouar Antélias (Karkabi et al., 1988).

La grotte de Mgharet Kanaan s'est développée dans les calcaires gris-bleu monotones caractéristiques de la Formation du Kesrouane (Dubertret, 1975; Walley, 1997). Sur l'extrait d'une carte hydro-géologique du secteur, réalisée par B. Hakim (1988), figure au Sud du site de la grotte de Mgharet Kanaan une bande de terrains gréseux néocomiens (C1), séparés des couches calcaires du Jurassique. Par une faille orientée NE-SO, l'observation de la relation

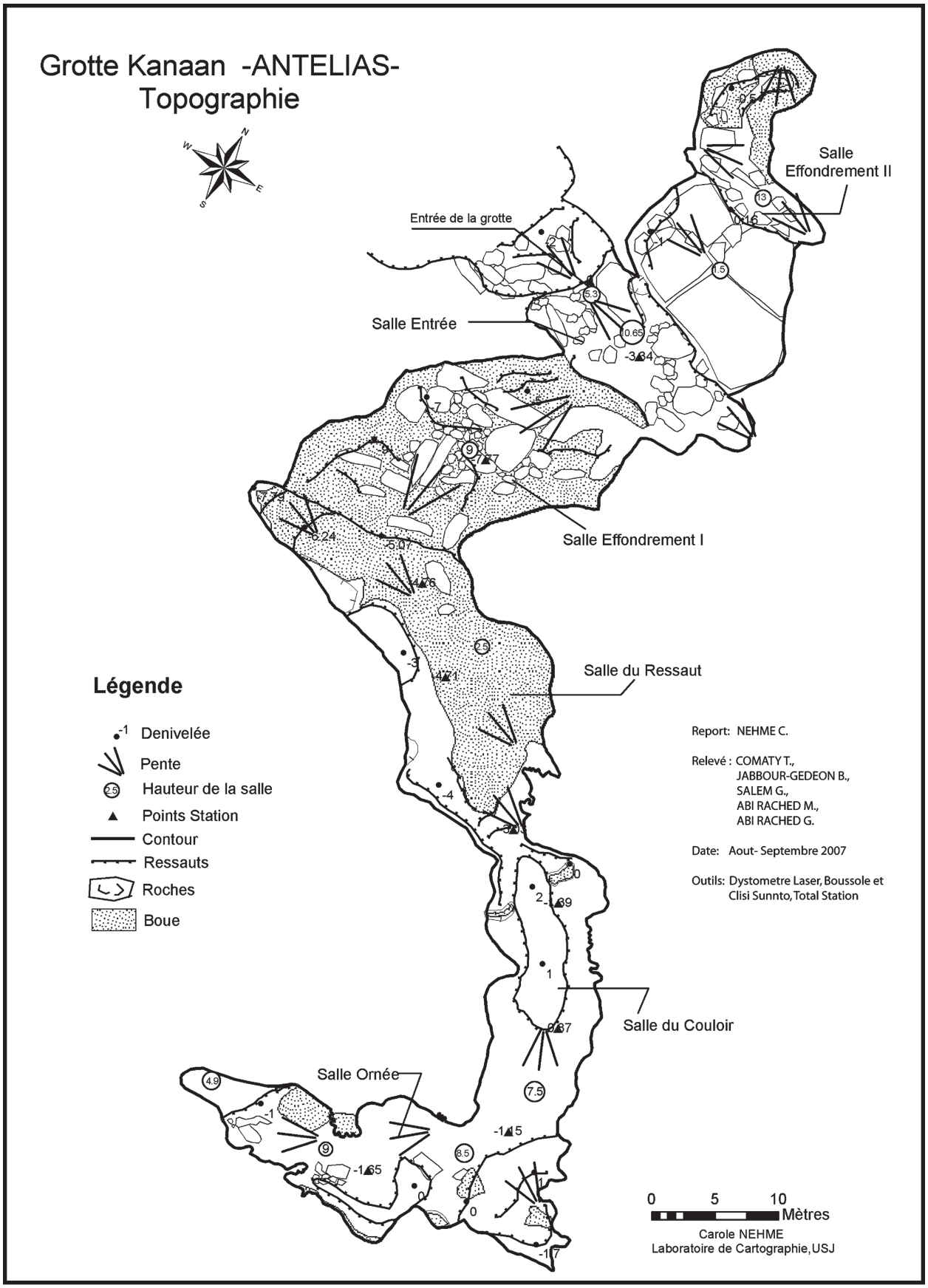


Figure 1: La carte topographique de la grotte.

entre topographie et substrat géologique montre que le compartiment où affleurent les grès du crétacé inferieur est tectoniquement affaissée par rapport au compartiment constitue des terrains Jurassique. On relève également la présence d'un réseau de petites failles locales, orientées NNE-SSO et E-O, qui ont certainement joue un rôle important dans la fracturation des couches affectées par la karstification.

2.2. Localisation de la zone d'etude

La grotte de Kanaan se situe approximativement à 6 km au NE de Beyrouth, en rive gauche de la vallée du Nahr Antélias. Elle a été découverte en 1996 par une équipe du B.T.D. (Bureau Technique pour le Développement), au sein de la carrière « Kanaan », d'où son nom. Les premières explorations menées en 1997 par le Spéléo Club du Liban (Nader, 1998) ont permis d'acquérir les premiers éléments d'information sur cette cavité. L'entrée en a été mise à jour lors de l'exploitation de celle-ci, qui a détruit en partie un réseau karstique caché. L'accès actuel à la grotte s'ouvre en arrière à 6 m du front de taille, au pied duquel un cône d'éboulis de quelques 10 m de haut, constitué de grands blocs de calcaire provenant de l'escarpement, livre quelques fragments de draperies et de coulées stalagmitiques, vestiges de la cavité partiellement détruite.

2.3. Les caractéristiques de la grotte de Kanaan

La grotte se trouve à 98 m au-dessus de la mer, elle est accessible par un talus rocheux s'élevant à 50 m au-dessus du sol de la carrière, elle fait 162 m de développement et sa température intérieure est de 19° C. La morphologie des salles de la cavité est sous une dominance d'orientation NO-SE. Les rapports antérieurs publiés par le Spéléo club du Liban (SCL) lors des premières exploitations de la cavité menées en 1997 montrent une subdivision de la grotte en trois sections, mais suite au relevé topographique effectué dans le cadre du mémoire de Master II, il s'est avéré qu'une subdivision de la cavité en 6 salles pouvait être faite. Les noms que nous leur avons donnés évoquent leurs caractéristiques dominantes (Fig. 1).

3. Méthodologie

3.1. La cartographie géomorphologique

Issue du croisement des expériences entre géomorphologues, karstologues et préhistoriens, la cartographie géomorphologique à haute résolution a été appliquée pour la première fois dans la grotte Chauvet, dans le but d'expliquer la disposition des ossements découverts, de détecter la chronologie des événements préhistoriques et de révéler les agents de remobilisation d'objets préhistoriques (Delannoy et al., 2004). Le relevé cartographique oblige à s'interroger sur les agents responsables de leur présence sous terre et sur leur chronologie. Cette méthodologie nécessité diverses étapes méthodologiques avant d'aboutir à la carte géomorphologique à haute résolution de la cavité.

3.2. La topographie à haute résolution

La réalisation d'une carte géomorphologique d'un système endokarstique comme celui de Mgharet Kanaan doit se baser sur un lever topographique exprimant le mieux possible la réalité du terrain. Ce lever doit donc être réalisé à très haute résolution (échelle du 1/100^{e} ou 1/200^{e}), afin de pouvoir relever le contenu de la cavité avec la plus grande précision, englobant toutes les formes et les formations, ainsi que les processus. Pour réaliser ce travail, il fallait donc disposer d'un relevé topographique à très grande échelle de la grotte Kanaan. Le lever topographique a nécessité deux méthodes différentes, mais complémentaires : le relevé électronique en utilisant la « Total Station » (Fig. 2) et un

Figure 2: La Total Station utilisée pour la topographie a haute résolution.

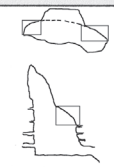
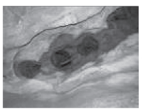
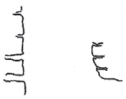
Nom	Formes endokarstiques	Type d'écoule-ment	Dimension/ position	Information paléoenvironne-mentale
Formes de dissolution				
Galerie syngéné-tique		Ecoule-ment en régime noyé	Section métrique à plurimétrique Position horizontale ou sub-horizontale	Creusement en régime noyé et écoulement rapide. Remodelage de la section par écoulement libre et relativement permanent
Cheminée		Ecoule-ment ascendant rapide et sous pression	Section metrique, a plurimetrique Position verticale ou sub-verticale	Creusement de la cheminée par dissolution de la roche calcaire : l'eau chargée de CO_2 dissous élargit les parois de la diaclase
Coupoles de dissolu-tion		Ecoule-ment ascendant rapide et sous pression	Sections métriques présentes au plafond	Dissolution par des écoulements rapides et ascen-dants (syngénétisme et paragénétisme) par effet de tourbil-lons engendrés sur une hétérogénéité de la roche
Remplissages chimiques				
Concré-tions	Stalagmites, stalactites, draperies	Ecoule-ment à surface libre	Formes centimétriques	
Coulées stalag-mitiques	Plaques disloquées	Ecoulement à surface libre	Dimensions metriques presents au sol	Formées par écoulement et ruissellement
Remplissages détritiques liés à des processus mécaniques				
Bancs calcaires disloqués		Pas d'écoule-ment	Section métrique a plurimétriques présents sur les parois	Dislocation des bancs due à des phénomènes tec toniques majeurs ou des ondes sismiques récentes
Eboulis de roches	ou	Pas d'écoule-ment	Section métrique a plurimétriques présents au sol	Effondrement du plafond par accident tectonique ou par fragilisation du cal-caire par les fissures

Figure 3: Inventaire des formes et des processus et les informations paléoenvironnementales associées.

relevé spéléologique en utilisant le clisimetre et boussole.

3.3. La légende de la carte géomorphologique

Apres avoir élaboré la carte topographique a haute résolution de la cavité, le remplissage du contenu de celle-ci a été reproduit à partir d'une légende créée par EDYTEM, Univ. De Savoie (France). Celle–ci représente les processus, les formes et les phénomènes géomorphologiques présents dans la cavité. Elle est étoffée à deux niveaux :

(i) au niveau des symboles, afin de couvrir l'ensemble des phénomènes observés ; et (ii) au niveau de la chronologie des événements : la plage de couleur utilisée est plus ou moins intense selon l'âge. Plus un phénomène est ancien, moins la couleur est intense (Fig. 3).

3.4. Le dessin de la carte

Le relevé géomorphologique de la grotte Kanaan a consisté à procéder sur le terrain par le dessin des formes et des formations présentes. En se basant sur les cartes d'inventaire produites à l'aide du SIG, le dessin du contenu des salles a été tracé sur un calque superposé : ces croquis représentent les minutes de terrain qui serviront à la réalisation des cartes géomorphologiques (Table 1).

4. Analyses: Interpretation géomorphologique

4.1. Identification des processus géomorphologiques par salle.

Le lever géomorphologique de chaque salle nous a permis de représenter les formes et les formations le plus proche possible à la réalité. Ce lever s'est basée sur un lever topographique exhaustif, une observation à haute résolution du chaque chambre, un relevé exhaustif avec localisation et mesure de chaque objet placé dans la chambre. Ce relevé nous a permis de mettre en place des tableaux d'inventaire de chaque chambre résumant les formes et les processus selon les phases spéléogéniques, les dimensions de ces formes, leur localisation et leur répartition ainsi que les informations paléoenvironnementales liées à ces formes (Fig. 4).

NOM	DEVELOPPEMENT (m)	AXE PREFERENTIEL	ORIENTATION DE LA SALLE (°)	ORIENTATION DES COUPOLES
Salle de l'Entrée	12.3	ONO- ESE	290° W	292° W
Salle d'Effondre-ment I	23.2	NE-SO	345° N	274° W
Salle d'Effondre-ment II	24.5	NNE-SSO	37° E	274° W
Salle du Ressaut	36.7	ONO-ESE	297° W	282° et 297° W
Salle du Couloir	24.3	NNO-SSE	333° N	340° N
Salle Ornée	33.5	ENE-OSO	83° E	275° et 285° W

Table 1: Les salles de la grotte Kanaan.

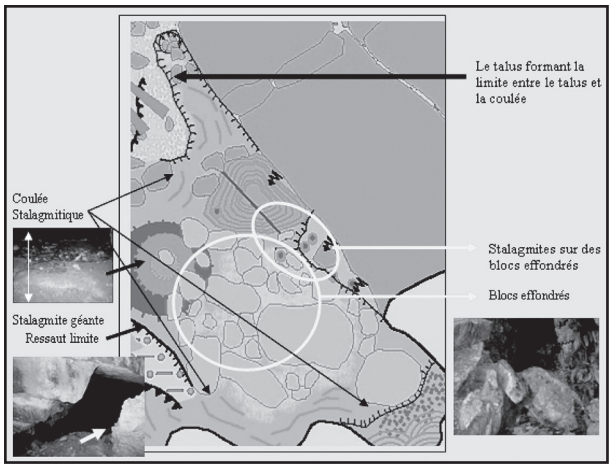


Figure 4: La cartographie géomorphologique de la salle de l'entrée.

4.2. Analyse spatiale de la grotte

La description des formes et formations présentées dans chaque chambre et l'analyse spatiale liée à leur localisation et leur répartition a été élaborée suivant les phases spéléogéniques d'une cavité : la phase syngenetique, la phase paragénétique, la phase vadose, la phase actuelle. L'analyse a permis de décrire l'évolution des formes et des processus géomorphologiques liées à la formation de la cavité après leur identification, par phase spéléogénique.

5. Résultats

5.1. La spéléogenèse de la grotte: inventaire spéléogénique de chaque chambre

L'analyse géomorphologique des formes et des formations a pu aboutir à la reconstitution de l'évolution spéléogénique de chaque chambre, depuis la phase syngénétique jusqu'à la phase vadose (Fig. 5). La comparaison des chambres par phases nous a permis de relever des phénomènes caractéristiques de la grotte Kanaan ayant contribué à sa formation, à savoir : l'effondrement récent en blocs,

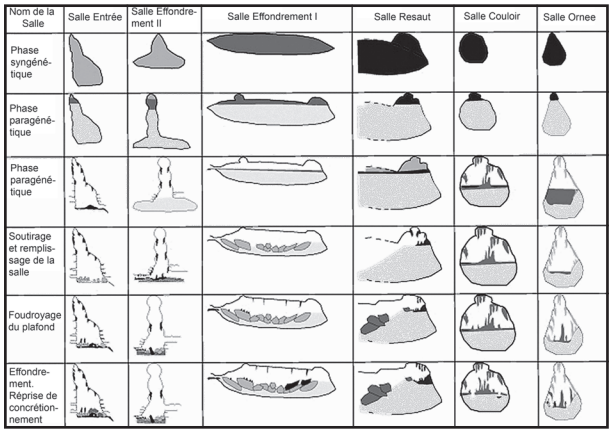


Figure 5: L'évolution spéléogénique de la grotte Kanaan.

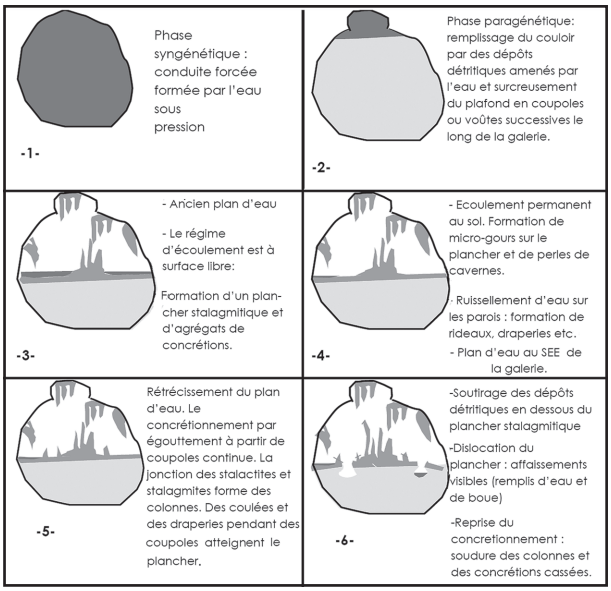


Figure 6: L'évolution spéléogénique de la salle du Couloir de la grotte Kanaan, Antelias, Liban.

le soutirage du matériel des planchers et le réseau d'alimentation de la grotte (Fig. 6).

5.2. Identification des informations paléoenvironnementales de la grotte et reliées au macro-environnement de la région d'Antelias.

Après avoir expliqué la spéléogenèse de chaque chambre, les grandes étapes du développement de la grotte ont été définies montrant ainsi l'évolution du système karstique de la grotte ainsi que celui de la région d'Antelias. En effet, le soutirage présentant deux types de fonctionnement dans la grotte de Kanaan assure l'évacuation du dépôt endokarstique vers un (des ?) réseau (x ?) sousjacent (s ?) et montre l'ampleur de la karstification dans cette région du Liban. Il est probable que ce phénomène est relié au type du système karstique binaire dans cette région, au creusement des réseaux lié au soulèvement tectonique du Mont-Liban, au changement du niveau eustatique, ou au taux de karstification reliée à l'agressivité de l'eau et de la structure de la roche encaissante.

6. Conclusion

Cette méthode d'appréhension du karst à partir de la cartographie géomorphologique nous a permis de définir les grandes phases paléoenvironnementales de la région et de les raccorder à d'autres analyses faites dans ce secteur. Cependant, cette approche, bien qu'elle soit utile à la compréhension plus profonde du contexte paléogéographique d'une région et du contexte géomorphologique d'un réseau karstique, doit être

complétée par des mesures de datations pour délimiter dans le temps les phases paléoenvironnementales identifiées. En conclusion, il est donc nécessaire de combiner les techniques de datations à la cartographie géomorphologique pour aboutir à une meilleure connaissance des événements paléoclimatiques et paleoenvironnementaux de cette région

7. Acknowledgment

Je tiens à remercier M. Jean Jacques Delannoy et l'équipe EDYTEM-Univ de Savoie- France, pour leur stage de Formation et leur suivi continuel, M Pierre-Charles et Mme Jocelyne Gérard pour avoir dirigé mon Master à l'Université Saint-Joseph. Enfin, une mention Spéciale pour l'Equipe de l'ALES pour leur soutien technique sur le terrain.

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THE GEOMORPHOLOGICAL MAPPING OF KANAAN CAVE, LEBANON: A NEW APPROACH IN THE SPELEOLOGENESIS OF A CAVE

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Geomorphic mapping has been applied in scientific fields since 1950s to represent landforms. This technique has been also applied in the mid-1990s to karst terrains, specifically in caves and sinkholes. In 2007 the application of this technique by the EDYTEM Laboratory (CNRS UMR5204, University of Savoie-France) on Kanaan Cave in Lebanon pointed to several scientific discoveries. A map legend adapted to Lebanese karstic terrains was developed by Nehme C., PhD researcher and speleologist at Saint-Joseph University (Lebanon) and applied to the 170-m-long cave in order to represent forms and geomorphic processes involved in the speleogenesis of this cave. A high-resolution map was the result of two months of topographic survey and analytical observation by the ALES team. Scientific analysis of this map has allowed the definition of 6 speleogenetic phases. Also, a karst-system model of the Antelias region was developed to understand the factors related to the cave origin and to examine the paleo-environmental conditions of the Antelias region.

1. Introduction

L'étude est un premier essai de ce genre sur une grotte libanaise. La grotte Kanaan (Antelias Liban) fait l'objet d'une étude géomorphologique aboutissant à la connaissance de la spéléogenèse de la grotte et de son système. Une méthode cartographique géomorphologique appliquée à cette grotte a été élaborée par le Laboratoire d'EDYTEM de l'université de Savoie (France). Grace à un travail de recherche mené dans le cadre d'un Master, les avantages de cette méthode ont été largement démontrés ainsi que la nécessité de l'adapter au contexte libanais.

2. Localisation du Site d'Étude

Situé en aval du Bassin Versant du Fleuve d'Antelias, au Nord de Beyrouth (Liban), la grotte Kanaan s'élève à 50 m au dessus du niveau de la mer méditerranée. Localisée dans la région des « Kessarat » (Kessarat: les carriers), elle a été découverte en 1997 suite à l'exploitation d'une carrière qui avait dégagé l'entrée de la grotte. Celle-ci se trouve perchée à 20 m de hauteur du sol de la carrière. Elle fait 170 m de développement (Fig. 1).

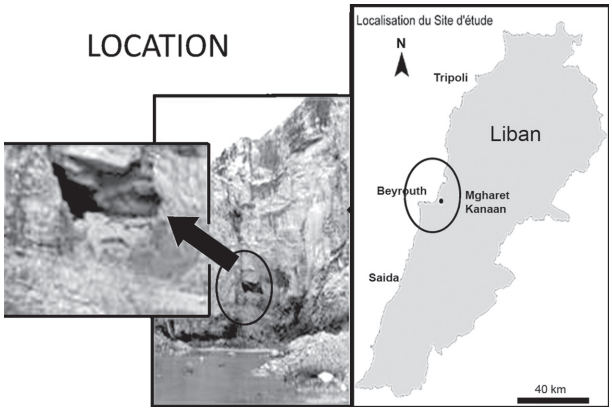

Figure 1: Situation de la grotte Kanaan, en aval du Bassin Versant du Fleuve d'Antelias, au Nord de Beyrouth (Liban).

3. La Géologie de la Zone d'Étude

La grotte Kanaan s'est développée dans les calcaires gris-bleu monotones caractéristiques de la Formation du Kesrouane (Dubertret, 1975 ; Walley, 1997). Sur l'extrait d'une carte hydrogéologique du secteur, réalisée par B. Hakim (1988), figure au Sud du site de la grotte une bande de terrains gréseux néocomiens (C1), séparés des couches calcaires du Jurassique. Par une faille orientée NE-SO, l'observation de la relation entre topographie et substrat géologique montre que le compartiment où affleurent les grès du crétacé inferieur est tectoniquement affaissée par rapport au compartiment constituée des terrains Jurassique.

4. La Méthodologie Appliquée

La méthodologie consiste à élaborer un relevé topographique à haute résolution du contour de la grotte, de ses parois et de ses remplissages. Ce relevé a permis, grâce à un système d'informations géographiques (GIS, ArcInfo) l'élaboration d'une carte topographique et d'une carte d'inventaire des formations karstiques. Grace à ces documents, il a été possible de déduire les processus qui ont généré les formes observées à Kanaan.

Ces cartes d'inventaire ont été validées sur le terrain par la cartographie géomorphologique basée sur la méthode

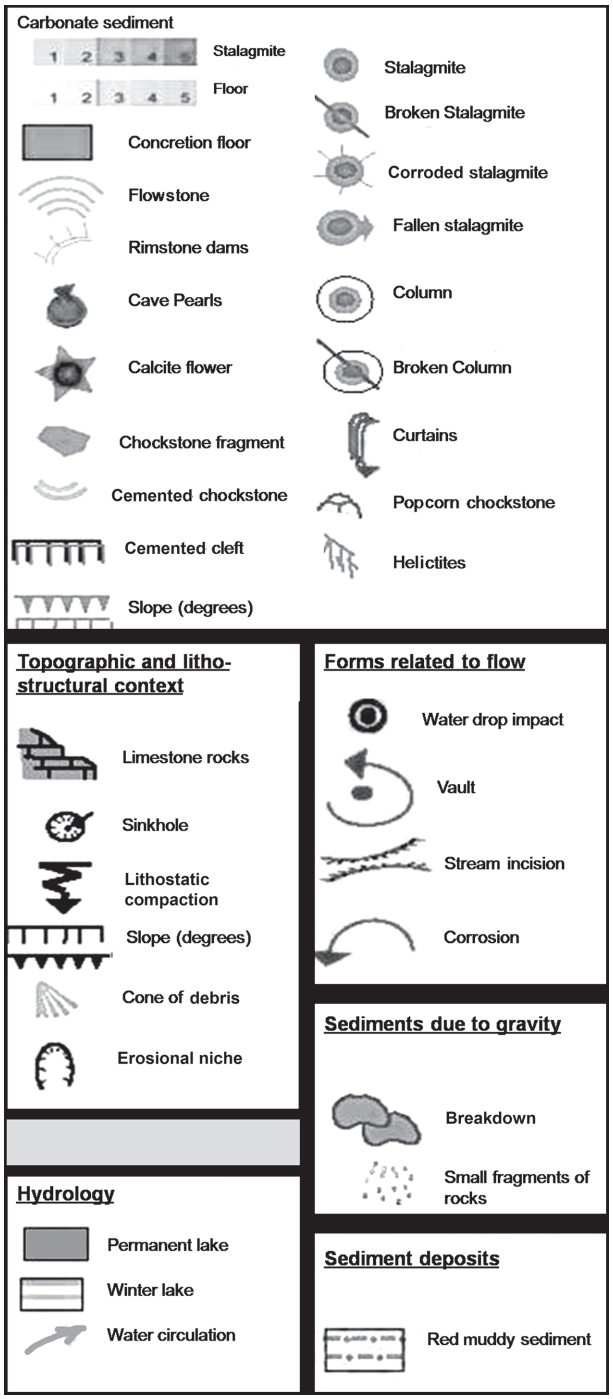

Figure 2: La méthode cartographique développée pour les formes observées aux processus géomorphologiques.

développée par le laboratoire EDYTEM.

5. Les Avantages de la Cartographie Géomorphologique

5.1. Les intérêts scientifiques

5.1.1. La relation entre formes et processus

La méthode cartographique développée relie les formes observées aux processus géomorphologiques présents actuellement dans la grotte, à savoir: (i) Les dépôts chimiques ou carbonatés ; (ii) Les formes liées au contexte topographique et litho-structural ; (iii) Les formes liées à l'écoulement ; (iv) Les formes liées à la gravité ou à l'appel au vide ; (v) Les formes liées à la circulation de l'eau ; et (vi) Les dépôts détritiques (Fig. 2).

5.1.2. La structure spatiale des remplissages endokarstiques

La carte géomorphologique a permis de définir trois zones morphologiques suivant le type de remplissage, à savoir : la partie d'effondrement, la partie boueuse et la partie concrétionnée. De plus, des analyses plus poussées du type de remplissage, du pendage des couches, de la variabilité du remplissage et du réseau d'alimentation en eau ainsi que de la circulation de l'air au sein de la grotte ont pu aboutir à l'identification de deux zones morphogéniques différentes, à savoir : les zones effondrée et boueuse qui constituent la première partie morphogénique, la zone concrétionnée qui forme la deuxième partie morphogénique (Fig. 3).

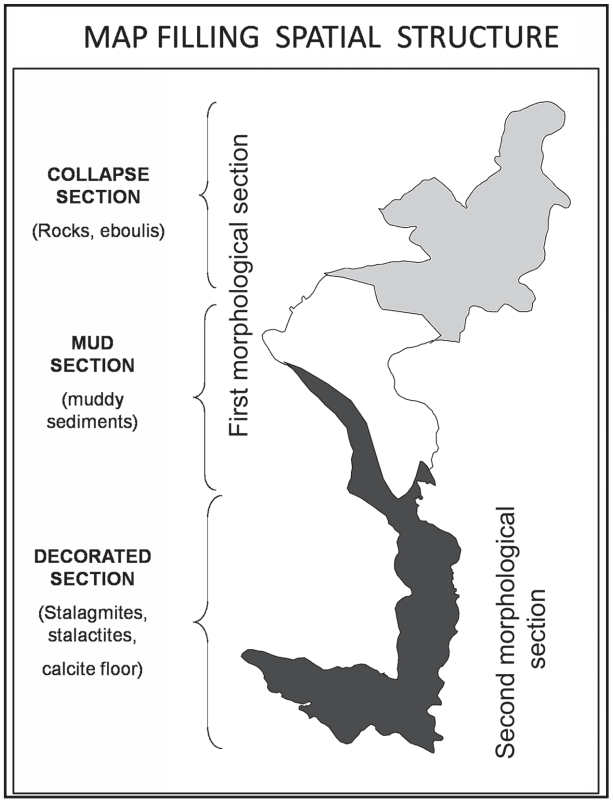

Figure 3: Les zones morphogéniques dans la grotte Kanaan.

c. Le système karstique

La connaissance du système karstique d'Antelias a permis d'identifier les facteurs qui ont affecté la genèse du système, les phases de formation des dépôts (les dépôts détritiques

paragénétiques de la salle centrale, les dépôts carbonatés post-paragénétiques qui se sont mises en place sur les dépôts détritiques, et les dépôts récents formés de graviers et de roches dans la salle d'Entrée) et les événements paleoenvironnementaux de la région qui ont contribué à l'évolution du système. Cependant, il faut souligner que les informations qui peuvent être exploitables a partir de cette technique n'apportent qu'une dimension spatiale dans l'étude paléoenvironnementale de la cavité et de la région. Par conséquent, une approche par datation s'avère nécessaire pour introduire la dimension temporelle à ce cadre paléoenvironnementale de la cavité.

5.2. Les intérêts spéléologiques

Le premier intérêt est que le relevé géomorphologique est une aide aux spéléologues. Ceux-ci procèdent à un relevé topographique exhaustif des formes et des formations pour mieux comprendre la spéléogenèse de la cavité. Par conséquent, une cartographie géomorphologique, telle que nous la proposons et basée sur une légende plus exhaustive en matière de formes représentées selon une chronologie relative permet de cerner les zones de formations anciennes et les zones de formation récente dans la cavité en question. Ajoutons à cela, l'intérêt informationnel de cette technique qui nous permet de cerner les zones actives et les zones non-actives de la cavité. Ces renseignements sont alors essentiels pour une exploitation scientifique du site.

Le deuxième intérêt qu'apporte cette technique est qu'elle contribue à un aménagement durable de la grotte dans le cadre de projets d'une mise en valeur patrimoniale. Un relevé à haute résolution pourrait cerner les zones à haute valeur touristique, les zones dangereuses auxquels il ne faut pas accéder et les zones fragiles qu'il faut protéger. Par conséquent, cet outil est une aide à la décision utile aux exploitants touristiques de la cavité.

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EARLY CARBONIFEROUS UNLITHIFIED CAVE SEDIMENTS: THEIR IMPLICATIONS

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Many geologists question whether unlithified sediments in open caves accessible to humans might date to 430 Ma (Early Carboniferous), assuming that such ancient caves would have collapsed close to the surface or been crushed during burial in a very much shorter time. Geomorphologists might expect that surface lowering would have removed the whole mass of rock, cave and clay included, in just a fraction of that time. K/Ar dating of clays, however, is sound, as is the evidence that they were precipitated in the caves. The deposits are in clear view of the public in Jenolan Caves; Australia's most-visited show caves. You might be tempted to think that this is just another quaint report from the land that brought science such curiosities as the echidna and platypus, but just as these discoveries were important to nineteenth century biology, Early Carboniferous cave sediments may be significant for twenty-first century cave science. Caves always held the *promise* of preserving geologic records that are not found elsewhere. Despite this, few deposits in open caves (as opposed to paleokarst deposits) have been found that are Mesozoic or older, and most dated cave deposits are younger than 2Ma. The relevance of cave deposits to geologic questions has thus been limited. While one discovery may not a summer make, it does hold out the prospect of more being made and of caves making a contribution to what one might called big geology.

1. Introduction

Located some 100 kilometers west of Sydney and developed in steeply dipping Silurian limestone, Jenolan Caves are Australia's best-known and most visited show caves. Remnant deposits of illite-bearing clay in Jenolan Caves were identified during a mineral survey and dated as Early Carboniferous in age by Osborne et al., (2006). The age indicated by the potassium-argon clay dates came as a surprise as the dated deposits were unlithified and looked not unlike any other cave sediment. Recent thinking about the age of the caves was that they were probably excavated during the Cretaceous perhaps 100 million years ago (Osborne, 1999), old for a cave one can walk around in, but nothing like the 340 million years indicated by the potassium -argon dating. Readers interested in the details of the materials and dating methods are referred to the original paper. A summary of the key points is provided below to support the discussion of the relevance of the findings.

These extremely old dates raised three significant problems: -

1. Were the deposits in the caves really 340 million years old or were the old clays reworked from a surface store?

2. What were the implications for the local and regional geology and geomorphology if the clays were really deposited in open caves 340 million years?

3. How could the deposits have survived for such a long time and how were they able to survive essentially unlithified? Why were they not destroyed by erosion and surface lowering or converted into solid rock?

2. Jenolan Caves and the clays in context

Before proceeding with discussion of the dates and the issues they raise, some contextual information is essential. Jenolan Caves lie within the Lachlan Fold Belt, a Paleozoic component of the north-south trending Tasman Fold Belt System that underlies eastern Australia (Fig, 1). The Paleozoic sequence at Jenolan Caves, including the cavernous limestone, was deformed twice, initially into tight folds during the Late Middle Devonian Tabberabberan Orogeny and later into sinusoidal folds during the Early Carboniferous Kanimblan Orogeny, which terminated deposition in the Lachlan Fold Belt (Cas, 1983). As a consequence of this folding, bedding in the limestone is in places near vertical, with local variation in dip on either side of vertical due to small-scale folds with horizontal axes. As with many karst areas in eastern Australia, the limestone at Jenolan crops out as a narrow north-south trending strike ridge (Fig, 2). The limestone has a faulted unconformable boundary with Ordovician radiolarian cherts to the west and is overlain partly unconformably by Early Devonian silicic volcaniclastics to the east.

The accessible caves, undeformed paleokarst deposits and

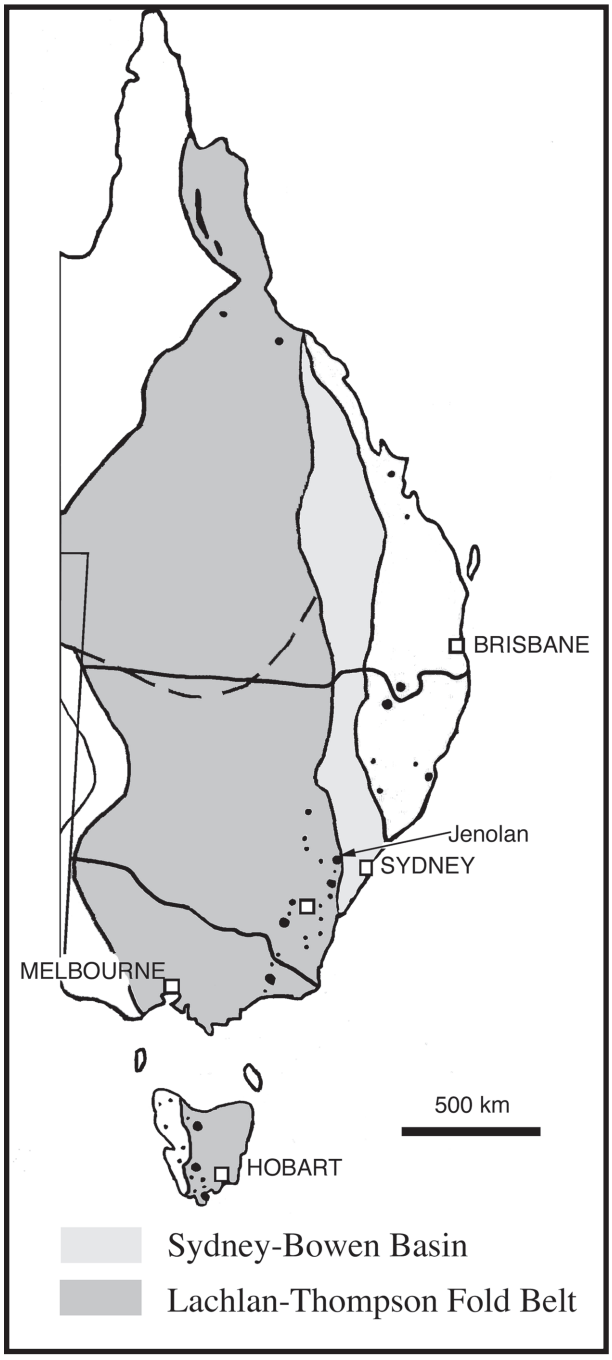

Figure 1: Eastern Australia showing Jenolan Caves, black dots are cavernous karsts. Note close proximity of Jenolan Caves to the western border of the Sydney Basin.

cave sediments such as the 340 million year old clays must be younger than the Kanimblan Orogeny and set a minimum age for the last folding in the Jenolan area. The Paleozoic sequence near Jenolan Caves is intruded by post-tectonic granites related to the Carboniferous Bathurst Batholith.

The Jenolan Caves are located at the western edge of the Permo-Triassic Sydney-Bowen Basin, composed of

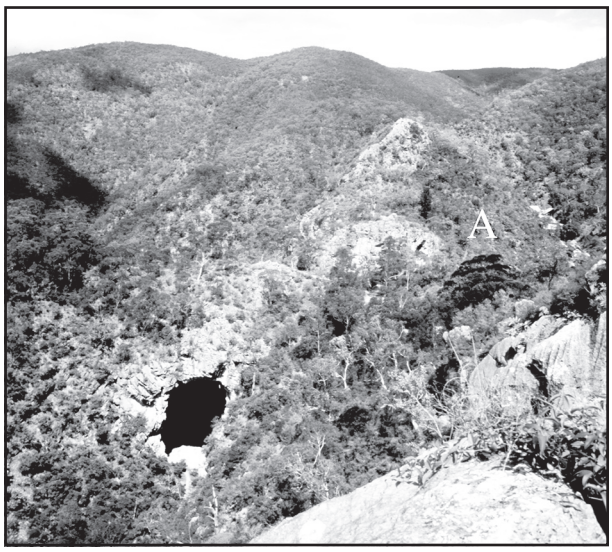

Figure 2: Looking south along limestone outcrop at Jenolan Caves, not narrow NE-SW trending limestone massif crossing right to left and plateau edge in distance. Many of the caves containing the Early Carboniferous clays are located below "A".

siliciclastic glacial marine, marginal marine, terrestrial fluvial sediments and Permian coal measures (Fig. 1). The Sydney Basin sequence unconformably overlies Paleozoic strata of the Lachlan Fold Belt. Small remnants of basal sediments of the Sydney Basin occur at different levels in the landscape near Jenolan Caves. These indicate that the pre-Sydney Basin paleolandscape in the Jenolan Caves area had relief of 1500m and that some of the valleys at Jenolan Caves are in part exhumed pre-Permian landforms (Osborne, 1995). During the Permian and most of the Mesozoic Jenolan Caves was probably under a thin cover of Sydney Basin sediments.

There are two generations of paleokarst in the limestone at Jenolan, both older than the Early Carboniferous. The oldest, found in the same study that recognized the 340 million year old clays consists of lithified sheared clay with a soapstone-like texture. Osborne et al., (2006) dated this clay at 398 Ma (Early Devonian) and interpreted it as volcaniclastic paleokarst related to the deposition of the volcanics overlying the limestone. The second generation of paleokarst are widespread deposits of caymanite (marine carbonate turbidites) filling an ancient cave system These deposits are horizontal or gently dipping (Osborne, 1995) so must postdate the Kanimblan Orogeny and predate the Early Carboniferous clays which in places disconformably overlie them.

Evolution of the present landscape probably began in the

Cretaceous with the uplift of the eastern Highlands and the opening of the Tasman Sea. The landscape at Jenolan today has a relief of 400 meters. The caves are developed in a prominent strike ridge of limestone, standing up in valleys in the incised eastern margin of the highlands plateau.

3. The Clays

Clays with components dating to the Early Carboniferous came from seven locations in Jenolan Caves. The sample locations consisted of two remnant deposits in cupola-shaped chambers (Fig. 3A), one deposit completely filling an ancient tube intersected by a more recent fluvial passage (Fig. 3B), one small remnant deposit projecting from a cave wall (Fig. 3C), one deposit within a crystal-lined vug intersected by a more recent cavity (Fig. 3D), one gossan-like deposit smeared on the wall of a cupola and one deposit taking the form of a remnant sediment bridge. There is no bedding or lamination in the clays and SEM images (Fig. 4A) show intact stacks of euhedral pesudohexagonal clay platelets, suggesting much of the clay was not transported but formed in situ.

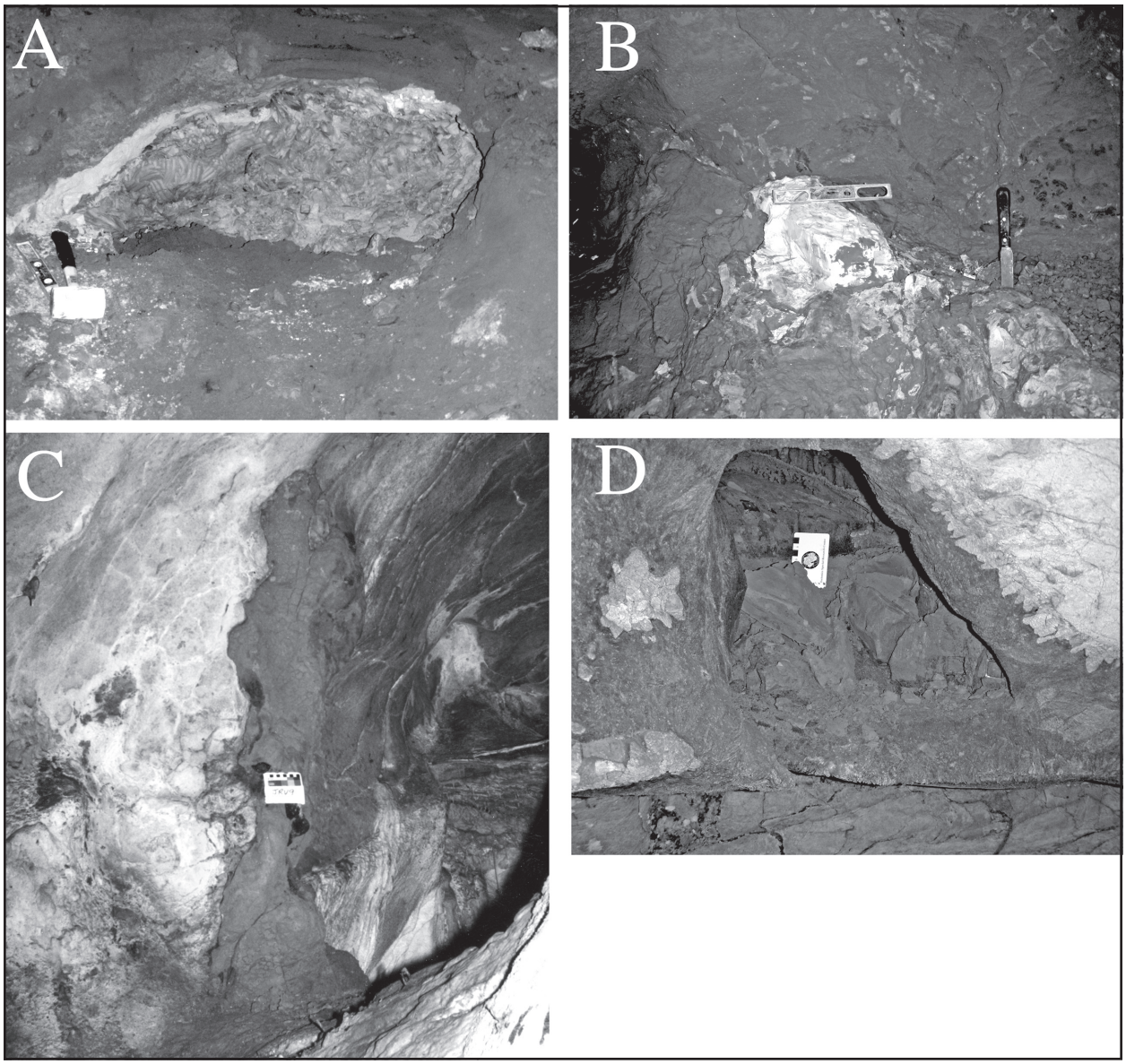

Figure 3: Clay Locations
A: Deposit in the Temple of Baal. Carboniferous clay is mottled material in center field.
B: Deposit filling fossil tube, River Lethe section River Cave. Carboniferous clay is white material in center field.
C: Deposit projecting from cave wall, The Junction, River Cave. Carboniferous clay is dark material behind scale bar.
D: Clay in crystal-lined vugh, Selina section, Imperial Cave. Carboniferous clay is blocky material behind scale bar.

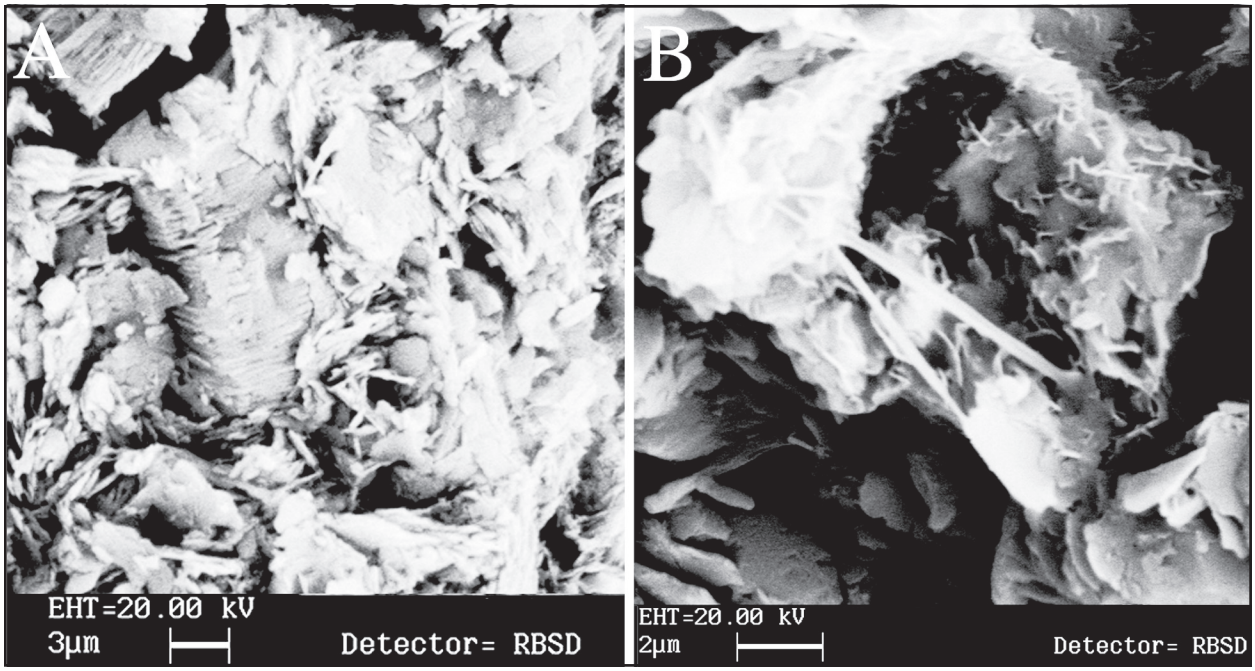

Figure 4: SEM Images
A: Detail from SEM image showing intact stack (book) of clay platelets, down and right from "A". This is unlikely to have remained intact if the clay was transported.
B: Detail from SEM image showing hairs of secondary illite growing from the surface of larger plates. These are thought to represent diagenetic growth during burial under the Sydney Basin.

Semi-quantitative X-ray diffraction indicated that the major components of the clays were quartz (73-27%), illite (53-7%), kaolinite (24-3%), with minor amounts of goethite and hematite. Calcite was only detected in one sample and then only as 0.4%. The coarse fractions were in the order of 10% by weight and consisted of a range of grains including tiny prismatic double terminated quartz crystals, spherical quartz grains with high surface polish, zircons, clinopyroxenes and small volcaniclastic rock fragments with illite pesudomorphs after feldspar. Osborne et al (2006) argued that the coarse fraction composition was consistent with the clays forming from the in-situ alteration of feldspars and glass in siliceous tephra entering the caves from the surface.

4. The Dates

K-Ar dating of clays often gives different ages for the different size fractions of the dated material. Dates for samples from the seven sites described above formed a group around a mean of 339Ma (Visean). Coarse (2-6µm) fractions from two sites gave dates of 394 and 391 Ma (Early Devonian); these were interpreted as clasts inherited from paleokarst related to the volcanics overlying the limestone. One young date, 259 Ma (Late Permian), was obtained from the fine (<0.4 µm) of the sample from the crystal-lined vugh. SEM of this sample showed the presence of fine illite hairs growing on the platelets (Fig. 4B). This date and the hairs were interpreted as secondary illite growing in response to burial of the filled caves under the Sydney Basin. The K/Ar dated clays from the caves and from the surface environment around Jenolan Caves are now being dated using paleomagnetic methods by P. Schmidt of the CSIRO. This has the advantage of providing a depositional rather than a mineral age.

5. Were the Dated Clays Formed In-Situ?

Given both the surprisingly old ages given by the dating and that K-Ar dating gives the age of mineral formation, not deposition it was essential to be sure that the clays were formed in-situ and not deposited in the caves at a later date from an external source. To this end clays in the surface environment around Jenolan Caves were sampled and their mineral composition was determined by X-ray diffraction. Five clay deposits were found in the surface environment with sufficient illite content for dating. Two were immediately ruled out due to their young ages (Middle Jurassic and Permian to Jurassic). Two were similar to the oldest dates, but material from these sources showed SEM evidence of transport not seen in the old dated cave clays. Two deposits had ages of 320 and 327 Ma, making them the most likely candidates as a surface source. These were

compared in SEM images, using peak height analysis, with the old cave clays. Both these surface deposits showed distinct evidence for transport with broken plate edges and no intact pates stack occurring. The clay crystals in these surface sources were distinctly less ordered than those in the cave clays, ruling them out as sources.

6. Implications for Regional Geology

The presence of 340 million year old clays in Jenolan Cave has significant implications for the regional geological history of the area. The clays and the caves containing them must be younger than the last folding event in the area, the Kanimblan Orogeny. This event was considered to have occurred in Early Carboniferous (early Visean) times by Cas (1983) and in a range from 350-340Ma by Scheibner and Veevers (2000). For the clays to have formed in-situ by 340Ma, than after the folding the caves have to have formed, been exposed to the surface and the tephra enter between the folding and 340 Ma. By itself this would suggest that the Kanimblan folding at Jenolan must have been earlier than has been generally accepted. The paleokarst record at Jenolan however contains undeformed, strongly lithified, caymanites, which are overlain by the dated clays. This means that before the clays were deposited and after the folding there was cave development, a marine transgression, filling of caves with marine mud and lithification. These

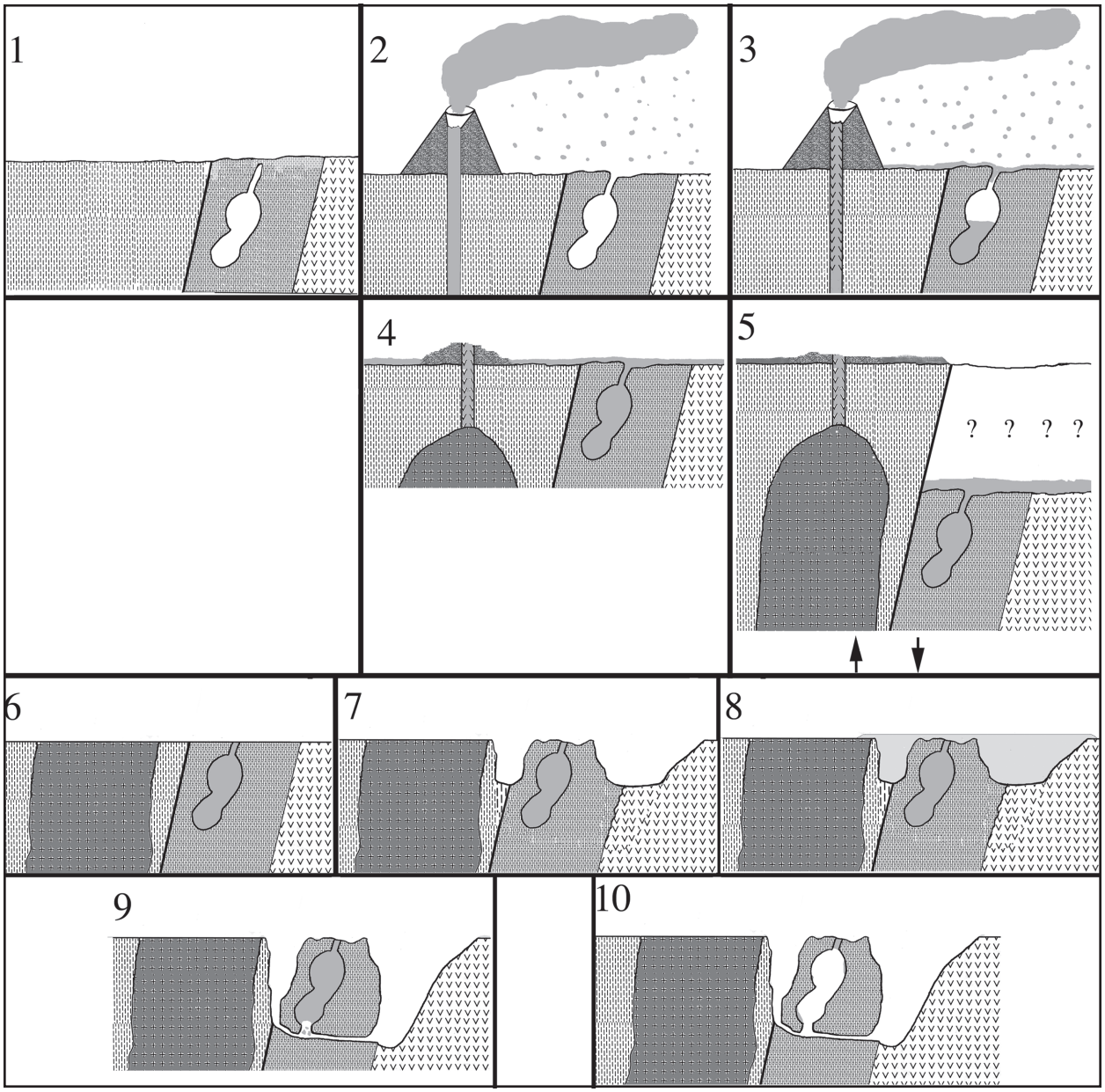

Figure 5: Cartoon illustrating the history of clay survival and the "Fault block shuffle" expanded after OSBORNE (2007).

events must push the timing of the last folding at Jenolan back into the earliest Carboniferous or perhaps even back into the latest Devonian.

7. How Did the Clays and the Caves Containing Them Survive?

While low rates of surface lowering are a characteristic of the Australian land surface in general, including that of the area around Jenolan Caves as Gale (1992) pointed out, low erosion rates by themselves cannot account for the survival of extremely old landforms such as 340 million year old caves. Burial under the Sydney Basin can account for preservation during the Permian and Mesozoic, but it cannot account for some of the other geological/landscape relationships at Jenolan Caves. The plateau surface adjacent to Jenolan Caves intersects Carboniferous plutons, assumed to be approximately 320 Ma. For the caves to form and the tephra to enter them about 340Ma, the mass of limestone containing the caves must have been close to the surface in the Early Carboniferous. This is incompatible with the present relationship with the plutons unless there has been differential vertical movement between the mass of rock containing the caves and that containing the eroded plutons. The limestone body at Jenolan has a thrust fault at its' western boundary making differential movement possible. Osborne (2007) described this process as the "Fault Block Shuffle" and illustrated it with a cartoon; this has been expanded to form Figure 5, showing the history of the clay and its survival.

8. Caves, Landscape and Climate

Osborne (2007) discussed many of the issues surrounding the survival of very ancient caves and their implications for geology and geomorphology. Some new issues, however, that have emerged since 2007, the most important being the relationship, or lack of relationship, between caves, landscape and climate.

Many geomorphologists have regarded caves as an underground extension of the surface landscape and an expression of the present or recent climate. Thus it is common as a default to consider caves a product of recent geomorphic processes and to classify both karst landforms *and* caves according to the climatic zone in which they are now located Even in a continent like Australia with many ancient landscapes (Gale, 1992), caves formed more than 100 million years ago are clearly not related to the origin of the present landsurface above and around them. If we take plate tectonics and climate change into account then in many parts of the world caves that formed more than a few tens of millions of years ago did not form under the present climatic conditions. In the Australian case, much of the present landscape originated at high latitudes in the supercontinent Gondwana.

Recognition of very old caves, coupled with the recent increase in the identification of hypogene caves (Klimchouk, 2007) means that it will be increasingly necessary to recognize that many caves and sections of complex caves are the products of internal and/or ancient processes and are thus genetically unrelated to both the present landform and the present climate.

We should expect similarities to emerge between old and/or hypogene caves currently located in dramatically different climatic zones and landscapes. Recent work with A. Tyc in Poland has revealed surprising morphological similarities between caves at Mt Etna located on the Tropic of Capricorn in Queensland and developed in Devonian limestone with caves in the residual limestone hills of the Katowice-Czestochowa Upland near Krakow located at just over 50 degrees North in Poland and developed in Jurassic limestone.

9. Caves as G*eological* Repositories

During the 19th Century caves were important to geologists because they contained vertebrate fossils, crucial evidence in then current arguments about The Flood, extinction, Ice Ages and evolution. Recent interest in caves has been largely concerned with their significance as a repository for a relatively recent climatic record. While paleokarst has frequently been an important source of geological information, caves, often seen as young, transient, surface-related features have tended to be ignored by mainstream geology.

Ongoing work in central Europe by P. Bosák and colleagues has shown that open caves there may be as old as 35 Ma (Zupan Hajna et al., 2008), while absolutely much younger than the Jenolan dates, relatively a similar result. Increasing recognition of caves as old and hypogene has the potential to make caves just as, or perhaps more interesting to geologists in the 21st century as they were in the 19th, we just need to go, look hard and date.

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GEOLOGIC HISTORY OF THE BLACK HILLS CAVES, SOUTH DAKOTA, USA

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Caves of the Black Hills, South Dakota, have a complex geologic history that spans about 340 million years. They include Wind Cave and Jewel Cave, which are among the world's four longest mapped caves. Prior interpretations of their origin have varied greatly. Recent petrographic evidence and U/Pb dating support their strong relationship to the regional geologic history: Early Carboniferous (Mississippian) voids and breccias were produced by interaction between primary carbonates and sulfates. Mid-Carboniferous (Mississippian-Pennsylvanian) karst developed, including surface depressions and caves. Burial by 1-2 km of mainly clastic sediment took place, and voids were lined by calcite during deep burial. The main dissolutional cave enlargement was in the late Eocene, late in the uplift history of the Black Hills, with caves closely following older voids and breccias. Temporary draining of the caves was followed by re-flooding when springs were blocked by Oligocene-Miocene sediments; calcite crusts up to 15-20 cm thick were deposited in the caves. The caves have since drained as the sediments were removed by erosion. This sequence is now being clarified by U/Pb dating of cave calcites. The latest calcite wall coatings in Jewel Cave range from 25 ± 4 Ma to 14.7 Ma ± 1.1 Ma. Preliminary analysis of calcite breccia matrix gives model ages that support an old age, but they await calibration. Low U concentrations in the supposed deep-burial calcite has so far prevented obtaining valid dates. The polygenetic history of Wind and Jewel Caves relates strongly to the geologic history of the entire region, and U/Pb dating can provide an absolute chronology for many of these regional events.

1. Introduction

The Black Hills of South Dakota and Wyoming (Fig.1) contain some of the most important caves, karst, and paleokarst in the USA. Jewel Cave (232 km mapped length) and Wind Cave (209 km) are complex multi-tier networks that developed in several phases since the early Carboniferous (Fig. 2). Three or more stages of calcite deposition allow U/Th dating of these events. There are still many diverse interpretations of the cave origin, and the dates are helping to resolve the controversy.

2. Geologic Setting

The Black Hills consist of a structural dome of early Cenozoic age. Erosion has exposed Precambrian crystalline rocks in the center, surrounded by the eroded edges of Paleozoic and Mesozoic sedimentary rocks that dip away in all directions. Carbonates of the Mississippian (early Carboniferous) Madison Formation contain the major caves (Fig. 3). The Madison is 100–180 m thick. Only 10–30 m of limestone and sandstone separate it from the underlying Precambrian rocks. The Madison is overlain by the Minnelusa Formation, 100–250 m of interbedded sandstone, shale, carbonates, and anhydrite of Pennsylvanian (late Carboniferous) to Permian age. The contact is a major paleokarst horizon. The Minnelusa is overlain by thousands of meters of sedimentary rocks of Permian through Cretaceous age. By the end of the Mesozoic, the paleokarst was buried to depths of 1–2 km.

Black Hills uplift and erosion took place mainly during the Paleocene-Eocene. Most cave enlargement took place near the end of that episode. By the end of the Eocene (about 37 Ma) the landscape was very similar to that of today. Drying of the climate during the Oligocene-Miocene allowed several hundred meters of detrital sediment to accumulate on the outskirts of the Black Hills and over the surrounding plains. Much of the dissected late Eocene terrain was buried and preserved by these deposits. Since then, most of the sediment has been removed by erosion, exhuming the Eocene topography. Remnants of the sediment persist at elevations higher than Wind and Jewel Caves.

Surface streams that cross the exposed Madison lose most or all of their water underground. This is a major source of recharge to the semi-confined Madison aquifer, which extends beneath the surrounding plains. Much of its flow is lost to springs around the perimeter of the Black Hills, where water rises through overlying strata along fractures.

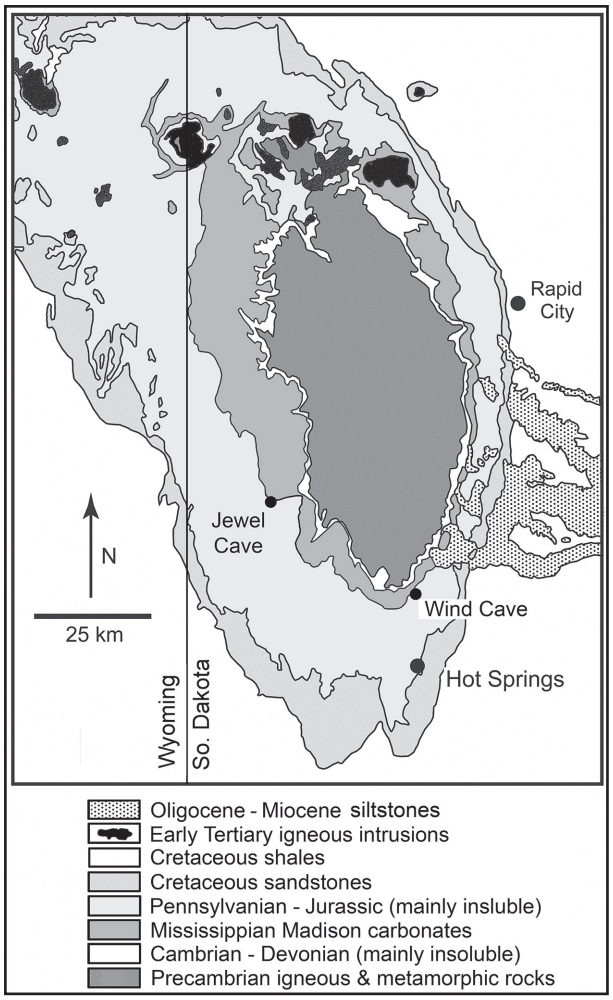

Figure 1: Map of the Black Hills, South Dakota and Wyoming, showing the geologic setting and location of caves.

Wind and Jewel Caves are almost totally dry today, except for vadose seepage and minor trickles. The lowest few passages in Wind Cave intersect the water table, but no traversable openings have been found that lead farther into the phreatic zone. No known parts of Jewel Cave reach the water table.

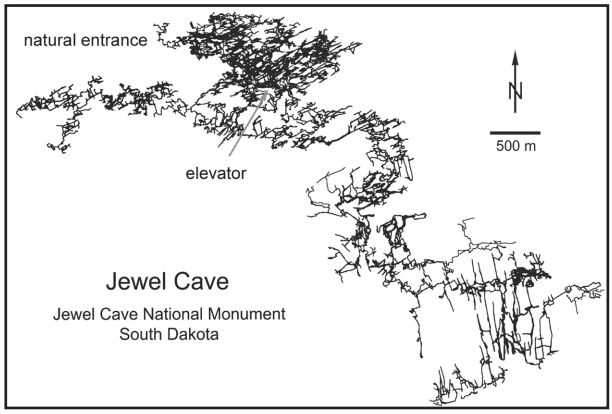

Figure 2: Map of Jewel Cave showing the dense network pattern typical of most large caves in the Black Hills (courtesy of Jewel Cave National Monument).

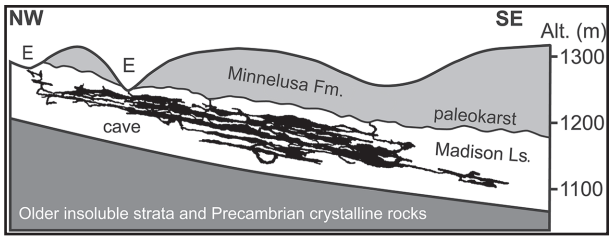

Figure 3: Geologic profile through Wind Cave. E = entrance.

The caves seem to have little relation to the local topography or hydrology. Many passages intersect paleokarst features such as breccia, boxwork, and Mississippian solution pockets, both sediment-filled and open (Figs. 4–6). Many (or most) of the cave passages of Cenozoic age appear to be enlargements of Carboniferous precursors. Most boxwork fins project into the caves about 10–20 cm. In the opposite direction the veins extend into the bedrock only a few tens of centimeters. Boxwork and caves are clearly related. The present cave walls are lined in many places by a calcite crust up to 20 cm thick. It is very extensive in Jewel Cave. It has been removed by subaerial weathering in most upper levels. Many of the paleokarst voids are also lined with calcite.

There is a great debate about the cave origin. Some attributed it to slow confined flow (Tullis and Gries, 1938;

Figure 4: Mississippian sulfate-related breccia with calcite matrix, Jewel Cave.

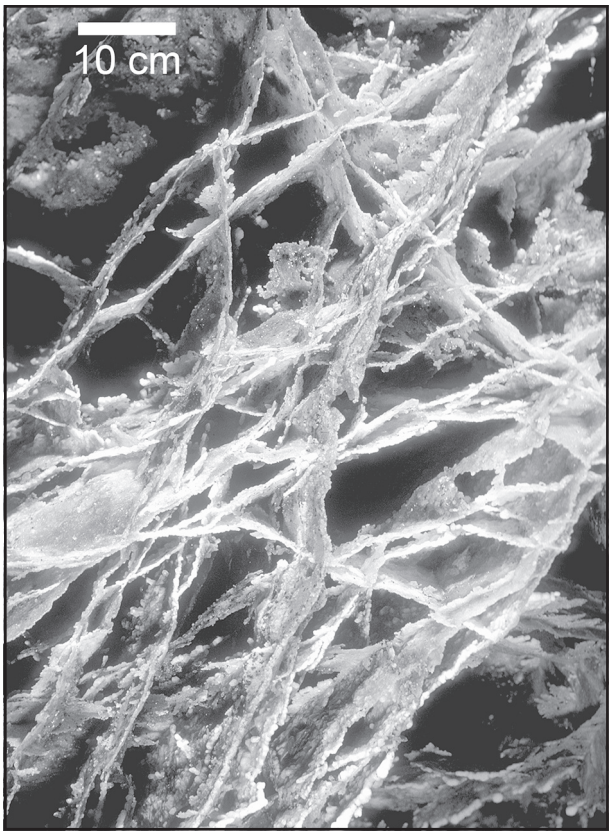

Figure 5: Boxwork in Wind Cave, composed of thin calcite veins with deeply altered intervening bedrock.

Deal, 1962; Howard, 1964); but the cave patterns and wall crusts resemble those of thermal caves (Bakalowicz et al., 1987; Ford, 1989). A third alternative attributes the major enlargement phase to mixing between the through-flowing Madison water and at least one other water type, including diffuse infiltration (Palmer and Palmer, 1989). All three models are discussed below. Note, however, that the cave is clearly polygenetic, with several contrasting phases.

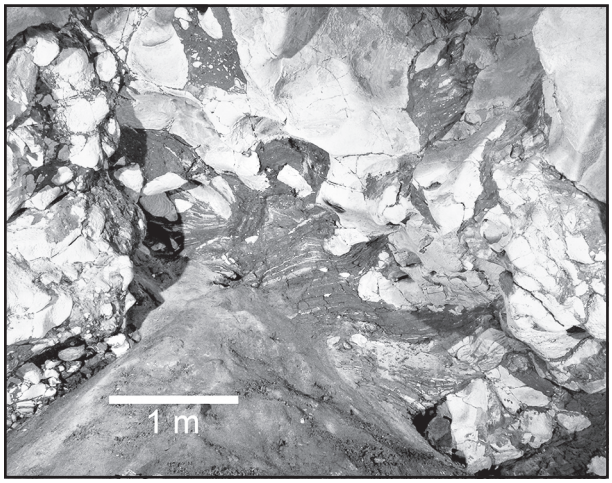

Figure 6: Ceiling pockets in Wind Cave along Carboniferous paleokarst pockets, breccia, and sand fill.

3. Stages of Cave Development

a. The Madison carbonates were deposited in shallow evaporative seawater ca. 355-345 Ma (early Mississippian), with much interbedded anhydrite (Sando, 1988). Soon after deposition, reduction of the sulfates produced hydrogen sulfide and pyrite, as shown by petrographic analysis.

b. Gradual exposure of the limestone above sea level admitted fresh water during the late Mississippian and early Pennsylvanian (ca. 330-300 Ma). Hydration and dissolution of anhydrite caused chaotic fracturing of surrounding carbonates, with effects ranging from thin fissures to widespread brecciation and collapse. Sulfuric acid dissolution of carbonates produced secondary gypsum and solution pockets up to 2 m in diameter. The acid was produced by oxidation of pyrite and H_2S. Bleaching and etching of the carbonate bedrock produced a sandy-textured weathering rind, but fracture fillings of gypsum or anhydrite were largely unaffected by the acid.

c. As the influx of meteoric water increased, calcite replaced the remaining sulfates by the common-ion effect (Palmer and Palmer, 2004). Petrographic evidence includes calcite pseudomorphs after pyrite and anhydrite, residual bits of anhydrite, lobate dissolution fronts, and yellow-brown calcite veins and breccia matrix. This calcite contains iron oxide grains and fossil filaments of iron-oxidizing bacteria. It is non-laminated, unlike typical cave deposits. Boxwork is a relic of these processes, and it is clear why the fragile calcite veins protrude while the surrounding bedrock is weathered: they were gypsum/anhydrite during sulfuric acid dissolution.

d. With further uplift, surface sinkholes and fissures developed at the top of the Madison, and shallow caves formed within the top few tens of meters (ca. 330–300 Ma). Cave patterns resemble those formed by mixing of waters of contrasting water chemistry, as in seacoast aquifers, or by modification of voids formed by sulfuric acid.

e. Surface karst was buried by the mainly detrital Minnelusa Formation, and most caves were partly or completely filled. The area was covered by additional sediments to depths of 1–2 km through the end of the Cretaceous. During deep burial a layer of white calcite was deposited on the walls of solution pockets that survived from stages 2–4. The calcite averages about 1 cm thick and has pointed scalenohedral terminations ("dogtooth spar").

f. Paleocene–Eocene uplift of the Black Hills, accompanied by rapid erosion in a humid climate, exposed the Madison Formation to increased groundwater flow. New caves were formed and old ones enlarged, guided by solution features from stages 2-4.

g. By the end of the Eocene (ca. 37 Ma), the topography over the present caves had reached essentially the form seen today, and it stabilized in a drying climate. The caves became air-filled and bedrock surfaces weathered.

h. In the dry climate of the Oligocene to early Miocene, sediments eroded from the Black Hills and Rocky Mountains were deposited on the plains and buried the foothills of the Black Hills. Remnants of this sediment can be seen as high as 1,800 m today, higher than any major caves in the Madison. Springs around the Black Hills, which originally drained the Madison aquifer, were clogged with sediment, which reduced their flow or blocked them completely, forcing most of the water to follow surface paths. Caves filled with relatively static water that was probably warm from geothermal heating. The thick calcite wall crust seen in many caves was deposited at that time. Most crystal terminations are blunt ("nailhead spar").

i. Erosion since then has exhumed the springs. Groundwater now follows approximately its original Eocene flow pattern. The caves have become aerated again. Evaporative speleothems and sparse dripstone have accumulated.

This sequence has been verified by field mapping, rock analysis, and geochemical evidence (Palmer and Palmer, 2008), and by preliminary U/Pb dating. The caves are so complex because the traces from all of these events have been superposed on one another. Evidence for each stage is visible in the caves today.

4. U/Pb Dating of Calcite Deposits in the Caves

Until recently the lengthy history of the Black Hills caves was interpreted mainly from correlation with the regional geologic history, and on geochemical principles. In 2008, uranium-lead dating of calcite samples was begun, with laboratory analyses by Victor Polyak of University of New Mexico. Results so far are: (1) The outermost calcite crusts on the cave walls (Fig. 7) range from range from 25 ± 4 Ma (single model age on the earliest phase of the spar lining) to 14.7 ± 1.1 Ma (3D linear isochron age on the tips of the spar lining). As predicted, these dates correlate with the thickest accumulations of sediment that buried the cave areas during the late Oligocene to early Miocene. (2) The yellow-brown calcite matrix of the early breccias and in the boxwork veins has given preliminary results that suggest great age, but they cannot be reported without proper calibration. (3) The uranium content of the assumed deep-seated calcite (dogtooth spar) is very low, and U/Pb dating may not be possible.

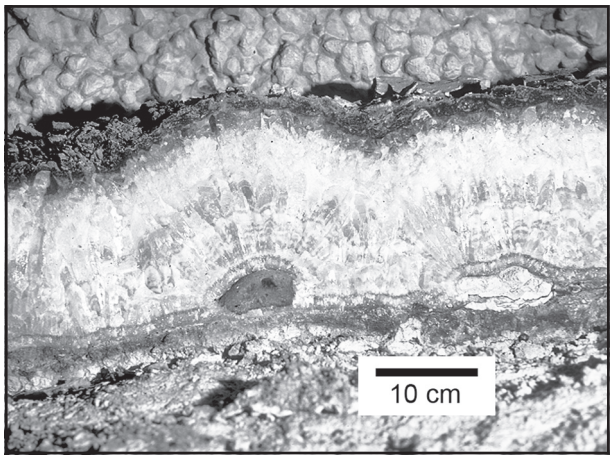

Figure 7: Late-stage calcite crust in Jewel Cave, overlying weathered dolomite and exposed by natural fracturing.

5. Debates About Cave Origin

The exact origin of the caves, i.e., the last great phase of cave enlargement, is a topic of debate. Most researchers invoke either artesian flow or rising thermal water. The complex network pattern is considered diagnostic of either origin, and the calcite crusts are commonly ascribed to thermal cave development. Breccias, boxwork, light oxygen isotopic ratios in calcite deposits, and the presence of nearby hot springs add weight to the thermal interpretation.

But the cave distribution does not favor either interpretation. Caves are concentrated in the upper-middle parts of the Madison Formation. At Wind Cave only a few passages extend into the lower third of the formation, and Jewel Cave does not extend below the middle of the formation. Likewise, only a few cupolas extend to the top of the formation, and because nearly all of them terminate in clay-rich paleofill, they are apparently exhumed Mississippian relics (Fig. 6). The caves also do not extend indefinitely below the water table, as they would if formed by confined flow. The water table is accessible at only a few points in Wind Cave, and nowhere (yet) in Jewel Cave.

Nearly all passages in both Wind and Jewel are overlain by thin beds of basal Minnelusa Formation (mainly sandstone, dolomite, and shale), but they terminate where the Minnelusa becomes thicker in the down-dip direction

(Fig. 3). The caves also die out farther up-dip, and just a few narrow passages extend into the area where carbonates are exposed at the surface. Instead, the greatest extension of the caves, and the direction of most new discoveries, is along the strike of the beds. The caves are essentially isolated from all of the most likely water sources and outlets.

Rising thermal water would tend to produce caves that span the entire thickness of the aquifer. Cupolas and domes in the cave ceilings are common, and these are often attributed to rising thermal water. Here, however, they were formed (or at least enlarged) by condensation of rising warm, humid air, rather than phreatic water (Palmer and Palmer, 1989). Breccias and boxwork are Mississippian relics that merely guided the Tertiary cave development.

In light of these limitations, a more feasible mode of cave enlargement involves mixing of two or more waters of contrasting chemistry, where the inputs are already saturated with respect to carbonates. Possible sources include

(1) the semi-confined flow in the Madison, (2) high-CO_2 water rising from depth, and (3) infiltration through the Minnelusa caprock. The most abundant flow in the Madison today, and apparently for a long time in the past, is delivered through the exposed edges of the formation. Rising water could have joined it, and there is some evidence for this kind of source around the perimeter of the Black Hills where the groundwater rises to springs (Rahn and Gries, 1973); but most of it is from the Madison, not from deeper sources.

Infiltration through the overlying Minnelusa, mixing with the ambient artesian water, fits the cave distribution best. This may seem like a poor possibility, because the infiltrating water is expected to be saturated with both calcite and dolomite. But where overlying insoluble strata shield the water from soil CO_2 much dissolution of the carbonates takes place in conditions that are essentially closed to further uptake of CO_2. CO_2 drops to very low levels. This has been documented in the field and by geochemical modeling (Palmer, 2007). Mixing of this water with artesian water (already near saturation with calcite, and at moderately high CO_2) would have concentrated along the most permeable paths—i.e., the zones of Mississippian paleokarst—and cave enlargement would have been greatest there.

Infiltration through the Minnelusa is relatively small in today's dry climate. But measurements by Wiles (1992) show infiltration rates of nearly 12,000 m^3/year per km^2 of surface area through the thin lower Minnelusa beds. Typical groundwater has a CO_2 partial pressure of about 0.01 atm. The CO_2 of infiltrating water is difficult to measure, because it changes as soon as the water is exposed to air; but geochemical modeling suggests values of about 0.0002 atm, less than that of the surface atmosphere. Mixing of the two waters could dissolve a maximum of about 0.5 $m^3/yr/km^2$ of limestone, and it would be localized specifically within the cavernous zone. Even in today's dry climate, this water could enlarge the caves to their present size within a couple of million years. This mode of recharge can also account for the network pattern of the caves, where each opening experiences comparable rates of enlargement. The pattern of moisture that infiltrates into the Madison today correlates well with the zones of intense bedrock weathering in the caves. Except in very few places, this water does not deposit calcite. During the more humid Eocene, cave development would have been considerably faster. Rising thermal water could also have contributed to the mixture, but it was unlikely at that late stage of Black Hills development, when the discharge areas had already been established farther down-dip around the margins of the hills.

Zones of sulfate-related paleokarst are abundant throughout the caves but are rare in surface outcrops. Surface canyons contain very little evidence for caves except for sparse paleo-pockets. Nor is there evidence in the caves for widespread collapse or fill where they approach canyons. The early sulfate-related paleokarst features guided the development of the later Mississippian-Pennsylvanian paleokarst, and both appear to have influenced the major phase of Cenozoic cave enlargement. The present caves therefore cluster where early sulfates were present in the Madison. This may explain why passages are so concentrated in some areas and sparse in others.

6. Conclusions

The three types of calcite in the Black Hills caves are petrographically and isotopically distinct from one another and clearly represent different episodes. U/Pb dating of the latest calcite in Jewel Cave of 25-14.7 Ma alone shows that these caves are among the oldest in the country. But this represents only the last stage in a complex history more than 20 times longer. The match between predicted dates and the measured U/Pb dates (so far) is encouraging. See Palmer and Palmer (2008) for details of the interpretation outlined in parts **3** and **5** above.

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GEOLOGIC SETTING, STRUCTURE, TECTONIC HISTORY, AND PALEOKARST AS FACTORS IN SPELEOGENESIS IN THE GUADALUPE MOUNTAINS, NEW MEXICO AND TEXAS, USA

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Middle Permian (Guadalupian) rocks of the Guadalupe Mountains, southeastern New Mexico and West Texas, contain over 400 caves, including Carlsbad Cavern and Lechuguilla Cave. The rocks of the mountains have been dissolved during at least six generations of secondary porosity, later collapse and infilling with minerals and sediments. Understanding this history helps shed light on the diagenetic and speleogenetic evolution of the region: (1) Dissolution associated with early exposure to localized fresh water lenses beneath islands and tidal flats and associated mixing zones, resulting in moldic pores, spongework, and small, irregular caves. (2) Syndepositional dissolution in polygonal elevated areas in the tidal-flat facies, called "teepees," with disrupted axial zones. Teepee caves were not very large but helped influence flow regimes in later cave-forming episodes. (3) Mid-late Permian dissolution accompanied lower sea levels. Broader exposure led to larger freshwater lenses and to down-to-basin growth faults, which localized significant early dissolution and collapse. Stage 3 tectonic and dissolutional features controlled development of significant parts of Carlsbad Cavern and other caves. (4) Late Permo-Triassic clastic sediments in some caves suggest uplift and possible cave development at that time. (5) Major caves formed as the Laramide uplift was eroded to form a low-relief surface. This resulted in a missing stratigraphic section, which cut most deeply into the section in the southwest, exposing mid-Guadalupian rocks, and least deeply in the northeast, where the surface lies atop Permo-Triassic rocks. Carbonates exposed beneath this surface are extensively stylolitized, consistent with the removal of a substantial rock column from above the surface. This suggests the high point of Laramide uplift lay west of the boundary fault that defines the western margin of Basin and Range uplift in the region. Following Laramide uplift and deformation, which produced open folds parallel to the shelf edge that contain most of the major caves of the region, a "proto-Capitan Aquifer" developed in the shelf-edge carbonate rocks, forming caves in mixing zones. Some hydrothermal flow may have been driven by local igneous intrusions. (6) Major caves resulted from the Basin and Range uplift, as the Capitan Aquifer developed in the shelf-edge strata, again forming caves by brine-fresh water mixing. Spar lined or filled caves formed in stages 1, 2, 3, 5, and 6, driven by degassing of H_2S and CO_2 from groundwater pools in the caves. Early pores are commonly cut across by later ones, but are rarely filled with later crystals or sediments. It seems likely that where flow rates decrease away from principal flow paths, deviations of solutions from equilibrium and consequent reaction rates are reduced. Clastic sandstones and pebbly sandstones are found in place in the upper Guadalupian section as well as in fractures and paleokarst. Where these have been eroded on the surface the sands were dispersed and the pebbles scattered across the erosional surface, where they are commonly mistaken for Ogallala deposits.

1. Introduction

The caves of the Guadalupe Mountains are neither the largest nor deepest in the world, but they are amongst the most beautiful, complex and scientifically significant. It is a measure of the significance of the region that its origins are still debated after decades of study. This study is presented in three parts, following the natural division of studies into considerations of bedrock geology, including stratigraphy, structure and paleokarst (Part I – this paper), pre-drainage history of the present caves (Part II) and post-drainage modification of the caves (Part III). Rather than duplicating figures they are referred to by Part and figure number. If only a figure number is given it refers to that part.

2. Location, Paleogeography and Stratigraphy

The Guadalupe Mountains are located in southeastern New Mexico and West Texas, in the arid southwestern United States (Fig. 1). They are composed of carbonate and terrigenous clastic sedimentary rocks deposited as a progradational, shoaling upwards sequence in shelf and

shelf-edge environments in the upper middle Permian, adjacent to the deep interior Delaware Basin (King 1948, Dunham 1972). The quality of exposures is so good that the region has been designated as the international stratotype for rocks of this age, which is called the Guadalupian Stage of the Permian Period (International Stratigraphy Commission 1994). The shelf edge was characterized by a complex facies mosaic, including normal marine reefs, biostromes, shoals and channel environments, in which limestones accumulated. These include the world famous Capitan Reef Complex (Newell et al. 1953; Dunham 1972; Prey 1977). Shoreward of the shelf edge was a shelf-crest facies mosaic with beach, tidal flats, pond and channel environments. This separated an interior restricted lagoon from the unrestricted nearshore marine facies. Sediments deposited here are generally preserved as dolostones (Fig. 2). During intermittent periods of lower sea level the shelf and shelf-edge was exposed, allowing the transport of clastic sands across the shelf to the basin beyond. During these times of exposure failure of the shelf edge led to massive debris flows into the basin (Dunham 1972), and to the development of growth faults (Hunt and Kosa 2003; Kosa et al. 2004), and extensive fractures along which secondary dolomitization occurred (Melim 1991). This represents one of the best-studied carbonate shelf complexes in the world. However, superior exposures in the caves are still providing valuable insight into the nature and interrelationship of facies. Following the Guadalupian Stage, circulation of seawater between the Delaware Basin and the Permian Ocean to the west was restricted. This resulted in increased salinity and to the basin being filled with a thick sequence of evaporites, including the Castile, Salado and Rustler Formations (Hill 1996).

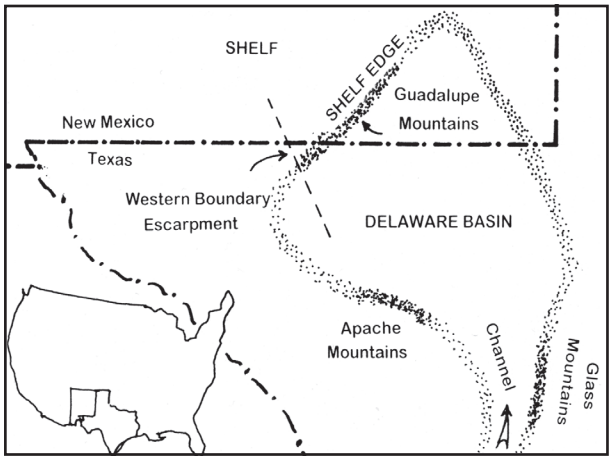

Figure 1: Paleogeography of the mid-Permian in southeastern New Mexico and west Texas. Inset shows the Texas New Mexico area covered by figure.

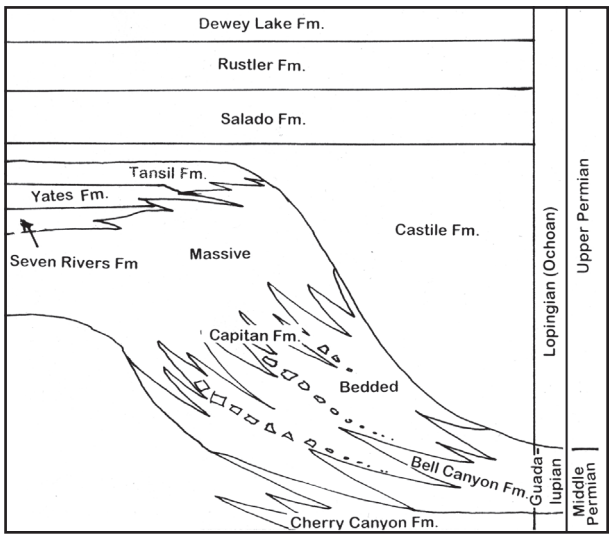

Figure 2: Stratigraphy of the Delaware Basin shelf margin (modified from King, 1948).

3. Physiographic Setting

The Guadalupes lie at the junction of three great physiographic provinces – the Basin and Range to the west, the Rocky Mountains to the north and the Great Plains to the east (McKnight 1988). It is not surprising that the region was affected by tectonic and sedimentary processes associated with each province. What is surprising is that most studies of the caves have focused only on the Basin and Range history of the region. Laramide uplift in the early Cenozoic was followed by regional erosion, which formed a low-relief surface with mature drainage patterns (Fig. 3a). This surface exposes middle Guadalupian sediments in the southwest, where uplift and erosion were greatest, and Permo-Triassic sediments in the northeast, where erosion was least (Kelley 1971). Basin and Range uplift of the area began in the late Miocene (Hawley 1993) with extensive normal faulting along the Western Boundary Escarpment (Fig. 3b; King 1948) This tilted the Laramide erosional surface toward the northeast, creating the wedge of rocks that form the present Guadalupe Mountains. The mountains can be divided into three distinct physiographic zones (DuChene and Martinet 2000). In the south the Guadalupes are highest (approx. 2600 m) and most deeply incised by canyons that run largely perpendicular to the shelf edge. In the northeast, where Basin and Range and Laramide uplift has been uplifted least (elev.1000 m), the shallow canyons largely run parallel to the mountain front. East of the town of Carlsbad the Guadalupian shelf edge is buried beneath basin-filling sediments.

4. Structure

The structure of the area results from the superposition of Basin and Range features over those developed in the

Laramide Orogeny. The region is dominated by gently dipping rocks that fall away from the high-angle normal Western Boundary Escarpment that defines the western edge of the Guadalupes. King (1948) and Pray (personal communication) report that the northeast dip becomes steeper as the boundary fault is approached. This is the opposite of the expected deformation caused by drag along the boundary fault. It suggests that the high point of Laramide uplift lay west of the boundary fault. The northeast dip of the mountains is steeper in the middle area, where the Huapache Monocline cuts the shelf edge. The monocline results from deformation along a zone that has been intermittently active since even before the Guadalupian sediments were deposited (Kelley 1971). It coincides with the transition zone between the deeply incised canyons to the southwest and the shallowly incised canyons to the northeast. Although the area has commonly been portrayed as being minimally deformed, several structures are important to regional hydrology and speleogenesis. A broad band of open folds parallels the shelf edge (Part II, Fig. 3). These include the Shelf-edge Anticline, Walnut Canyon Syncline, Guadalupe Ridge Anticline, and the Waterhole Anticlinorium. Most of the major caves of the region lie beneath the anticlinal structures (Jagnow 1977), which are thought to have formed in the Laramide uplift (Kelley 1971). These anticlines and associated thrust faults (exposed on Lonesome Ridge and Camp Wilderness Ridge) are the site of localized mineralization by iron pyrite and copper minerals. High-angle fractures running roughly parallel and perpendicular to the shelf edge have had a pronounced influence on many of the caves of the area (Bretz 1949; Jagnow 1977). These have been thought to result from Guadalupian slumping into the basin and from Basin and Range faulting since the mid-Tertiary (Bretz 1949; Hill 1987). Recently, Kosa , et al (2004) and Hunt and Kosa (2003) described common syndepositional growth faults in the Guadalupian shelf edge. The trend of Laramide fractures is roughly the same as in both sydepositional failure of the shelf edge and as fracturing associated with Basin and Range deformation, so that determining the timing of particular fractures is difficult.

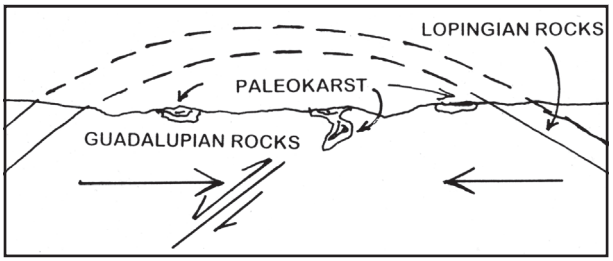

Figure 3a: Cenozoic structural evolution of the Guadalupe Mountains. Early to mid Cenozoic Laramide compression results in regional uplift, followed by the formation, collapse and infilling of caves and their unroofing by erosion.

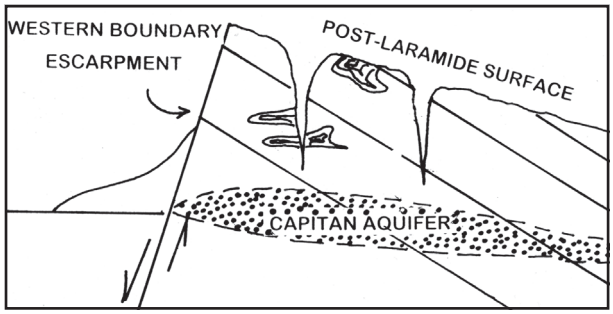

Figure 3b: In the late Miocene to Recent, normal faulting along the Rio Grande Rift elevates the earlier formed erosional surface, resulting in the development of a fresh water lens beneath the mountains.

5. Karst and Paleokarst

Although evidence of surface karst in the Guadalupes is rare, careful examination of the rocks and caves reveals that at least six generations of caves have formed in the area. Each generation of karst is associated with subsurface dissolution, collapse, and infilling with mineral precipitates. and sediments Three generations date to syndepositional or early post-depositional times. **Stage I** features comprise extremely irregular pores, which seem to express subtle differences in the initial fabric and early cementation of the sediments. These are similar to pore systems formed in incompletely cemented and stabilized calcarenites in Bermuda (Land et al. 1967; Queen 1994b). By analogy with these Bermudian examples, Stage I pores are interpreted to have formed from brine-fresh water mixing associated with localized fresh water lenses beneath exposed areas on the shelf-crest during sea-level high-stands in the Guadalupian. Stage I pores may have internal sediments similar to the sediments, of which the bedrock itself is composed, and which exhibit no sign of having been previously cemented. **Stage II** also formed syndeposionally beneath polygonal disrupted zones in the shelf-crest environments, which created ponds between them. Disrupted zones, called tepees, exhibit a complex of broken strata associated with both dissolution and precipitation of early marine cements (Dunham 1972). At any given time the relief associated with tepees was less than a meter or so, but the disrupted zones themselves may extend over vertical distances up to 30 m. Internal sediments in Stage II pores are generally terrigenous clastic sands identical to those interbedded with the shelf-crest and shelf-interior carbonates. Early pores associated with tepees are rarely large enough for a person to enter, but in places have localized later cave development (Spider Cave, Yellow Jacket Cave, Chocolate High). **Stage III** caves formed during times

of lower sea level, which allowed extensive fresh water lenses to develop beneath the exposed shelf edge. Failure of the shelf edge formed extensive growth faults largely parallel to the shelf edge. (Kosa, et al, (2003). Like the major caves of Bermuda, with which they are considered analogous, these formed after significant cementation allowed major fractures to form and concentrate water flow and mixing (Palmer et al. 1977; Queen 1994a). These caves collapsed before the end of the Guadalupian and filled first with fine grained, gray and black laminated geopetal sediments, and later with clastic sands and spar (Dunham's Iceberg in Walnut Canyon is an example: Dunham 1972; Queen 1981, 1994a, b). The gray, laminated geopetal sediments are commonly associated with complex moldic pores, which resulted from the dissolution of metastable skeletal material. These pores are commonly lined with isopachous carbonate cements, described by Given and Lohmann (1986) as the first fresh water cement to form in the shelf edge strata. Stage III moldic pores are found scattered throughout the carbonate section, but Stage III collapse breccias with clastic fill are commonly localized along trends parallel to the shelf edge. In Carlsbad Cavern two of these may be traced through the Bat Cave, Main Corridor, and /Left Hand Tunnel and the Guadalupe Room/ and New Mexico Room. These may also be found on the surface above these areas, where they resemble the growth faults described by Hunt and Kosa (2003).

Stage IV caves are exposed as filled paleokarst near Jurnigan's Draw and Ogle Cave. They are characterized by abundant cemented terrigenous clastic fill. Similar sediments are found on the mountain front northeast of Rainbow Cave in high-angle fractures, which in places preserve slickensides showing strike slip movement. Unlike the generally fine-grained and well sorted clastics found in the Guadalupian section, clastic fills in Stage IV caves include coarse-grained, ferruginous pebbly sands. The only sedimentary rocks historically documented on the surface that could have sourced these internal sediments are Permo-Triassic beds exposed east of the Pecos River (Kelley 1971), which have been eroded from above the Guadalupian uplift. King (1948) believed these features to be Cretaceous. An alternative possible source is provided by apparently in-place beds of course pebbly sands between ¼ - 1 km down Bat Cave Draw from the Bat Cave entrance of the Carlsbad Cavern. These bear further study, because if there are pebbly terrigenous clastics in the upper Guadalupian section, their erosion could provide the rounded quartzite and chert pebbles, which have been described as Ogallala (Hill 1987, 1996). An Ogallala date for the scattered pebbles found across the Guadalupian uplift is problematic if the timing of Guadalupian uplift is late Miocene, since the Ogallala spread eastward from the Rocky Mountains about this time (Hawley 1993). **Stage V** caves formed following Laramide uplift. Collapsed and infilled remnants of these caves are exposed beneath the inclined upper surface of the Guadalupes, where they must have formed before this surface was eroded and before subsequent uplift. These caves are characterized by the dark chocolate-brown flowstones that filled them, and by extensive spar-filled collapse breccias. These and Stage III breccias have in places been misinterpreted as fore-reef breccias (Jagnow 1977). Caves in the southern Guadalupes associated with sulfide mineralization are here considered to be Stage V. Brown flowstones associated with Stage V karst is found from the top of the Guadalupian uplift to near the bottom of the deep canyons and from near the shelf edge to near Sitting Bull Falls, suggesting the hydrologic base level at this time (graded to the ancestral Pecos River) was quite low. Some stage V caves remain open and have been intersected by, and may have controlled development of Stage VI caves. **Stage VI** represents the latest generation of caves.

Although later generations of porosity commonly cut across earlier ones, it is rare for the later sediments or mineral precipitates, to fill significant parts of the earlier-formed porous systems. It seems likely that the degree of porosity development, as well as the degree to which pores are subsequently filled with sediments or precipitates, is related to the flow rate of fluids through these pores. Away from the dominant flow-paths the speed of flow decreases, which lowers the degree of undersaturation or supersaturation of the fluids and reduces the resulting reaction rates. Nowhere is this more apparent than where later-formed passages cut across earlier formed ones with crystalline linings, in which the fine-scale structure of the earlier linings is commonly preserved even though they are adjacent to zones of massive dissolution.

6. Calcite Spar

Calcite spar has been found in fractures and karstic voids associated with stages I, II, III, V and VI. Stage IV caves are less well understood, but may also be associated with dogtooth spar. In Stage V and VI caves some calcite crystals may exceed 1 m in length. This spar has commonly been corroded by later atmospheric condensation (see Part III of this paper), except where it is preserved in small fractures and voids off the main cave, or as peculiar three-pointed marks resembling a Mercedes logo, which apparently represent the slightly denser trace of the coins of the growing spar crystals (as for instance in the Mystery Room of Carlsbad Cavern and Virgin Cave). The great vertical and

horizontal distribution of these five generations of calcite spar begs for a detailed microstratigraphic description of trace-element geochemistry, cathodoluminescence, and fluid inclusions. Lacking this, it is impossible to know to which generation a particular generation of spar belongs, unless its relationship to local geology is well documented. When Lundberg et al. (2000) collected and dated samples from a spar-lined cave, it was expected that the dates would help constrain the age of the last generation of caves. However, the age determined for this material (91.3 +/- 7.8 Ma), clearly indicates that it had lined voids formed in Stage III or IV, and not Stage V or VI.

7. Conclusions

Caves in the Guadalupe Mountains have formed in a number of generations associated with changes in hydrologic base level resulting from fluctuations in sea level and with later tectonic and erosional events. Dissolution in mixing zones is suggested as the dominant origin for generations I, III, V and VI due to the regional stratigraphy and tectonic history, which led to the repeated juxtaposition of fresh and saline groundwaters. Understanding these karst features and generations will require a detailed analysis of cave-filling precipitates and sediments.

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PRE-DRAINAGE DEVELOPMENT OF THE CAVES OF THE GUADALUPE MOUNTAINS, NEW MEXICO AND TEXAS, USA

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Major caves of the Guadalupe Mountains formed after the Laramide Orogeny in the early-mid Tertiary and after the Basin and Range Orogeny in the late Tertiary-Recent. Caves formed in mixing zones between oxidized fresh waters and the reduced brines on which they floated, which were in equilibrium with basin-filling evaporites. However, phreatic sulfide oxidation played only a minor role in bedrock dissolution because only in the freshest parts of the mixing zone was there enough oxygen to oxidize the sulfide. Critical to all speleogenetic models here is the source of sulfide and its mode of transport in the phreatic zone. Evaluation of field and theoretical data indicate that the massive gypsum deposits, for which the caves are known, formed after drainage. Basinal waters are highly undersaturated in H_2S, which argues against any significant transport as a gas. H_2S supply in compaction waters was probably insignificant since the basin contained few compactable sediments. Likewise, concentration gradients of H_2S are sufficiently low that little passive diffusion into shelf-edge environments would have resulted. If H_2S had been transported in solution, it would have lost its original isotopic signature. Also, since even the evaporite beds have common carbonate components, sulfidic water moving into the shelf edge would have been saturated in carbonate, so that no additional bedrock dissolution would result. H_2S is widespread in basinal waters, which suggests a diffuse source, probably from the bacterial reduction of sulfate in brines. Because the shelf-edge strata that hosted the aquifer were buried beneath a blanket of impermeable evaporites, resurgence from the aquifer was focused where the northeast end of the outcrop of shelf-edge carbonates plunged beneath the evaporite cover. Fresh water presently continues in the aquifer to a depth of over 300m. Leakage from the aquifer in the deep phreatic focused mixing, which increased local porosity and further focused flow. This created steeply inclined conduits, which later connected horizontal levels of the caves, reflecting localized discharge at different levels as uplift and erosion continued. Where leakage occurred above the deeply buried aquifer, evaporite dissolution resulted in localized breccia pipes. In the southwestern part of the Guadalupes caves are principally controlled by joint sets perpendicular to the shelf edge. In the northeast the caves are principally controlled by joint sets that parallel the shelf-edge. This may reflect the increased dominance through time of flow down the axis of the aquifer, perhaps resulting from a lower permeability of Castile evaporites compared to that of higher strata. Mixing was greatest where flow was focused in fractures, faults, paleokarst and along bedding planes that transected the fresh water-brine contact, where topography, etc., allowed discharge. Some hydrothermal flow may have resulted from local igneous intrusions in the early-mid Tertiary. The ubiquitous presence of carbonate bedrock in phreatic environments guaranteed that phreatic pH was buffered and every where near neutral. Consequently, acidophilic minerals found in the caves could not have been precipitated prior to drainage. Degassing of H_2S and CO_2 from groundwater pools in the cave lowered carbonate solubility, resulting in a succession of precipitates including spar, mammillaries and rafts reflecting increased supersaturation.

1. Introduction

This is the second of three papers considering the origins of caves and karst in the Guadalupe Mountains. The first part deals with bedrock geology and paleokarst. The last part deals with post drainage modification of the caves. Both appear in this volume. Where figures from the other parts are referenced they are noted as "Part__, Fig.__". Where only a figure number is given it applies to the part in which it is cited.

The Guadalupe Mountains of southeastern New Mexico and West Texas (Part I, Fig. 1) expose a thick sequence of carbonates and minor terrigenous sandstones deposited in shelf-edge setting in the middle Permian (Part I, Fig. 2), that have been uplifted and deformed during the Laramide and Basin and Range Orogenies of the middle and upper Cenozoic. Because of the regional stratigraphy and tectonic history, fresh water lenses formed beneath the shelf-edge

sediments were in contact with saline groundwaters in equilibrium with basin-filling evaporates. Six generations of karst have formed here, of which the first three were Permian. These are analogous of early and later stages of cave development in Bermuda, which also formed from mixing (Fig. 1-a, b) (Palmer, et al. 1977; Queen 1994b). Part II of the paper considers the pre-drainage origins of the last two stages, which have formed most of the major, enterable caves of the mountains. Part III considers the surprisingly complex post-drainage history of the caves.

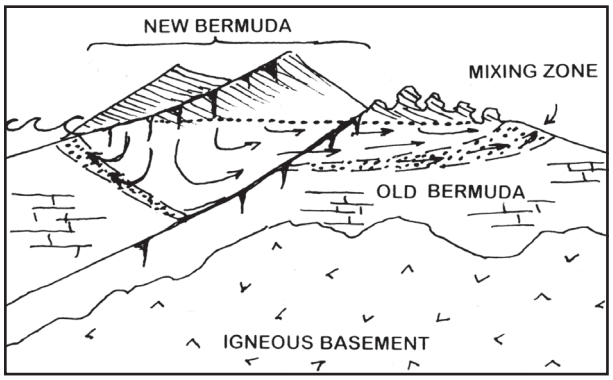

Figure 1a: Hydrology of Bermuda. In the older rocks that mantle the igneous basement, joints and paleokarst lead to high regional transmissivity, low residence times, a thin fresh water lens and thicker mixing zone. In younger rocks jointing and paleokarst are not as well developed, leading to thicker lenses and thinner mixing zones.

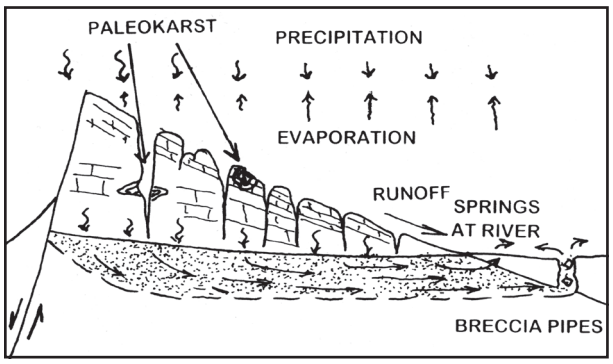

Figure 1b: Hydrology of the Guadalupe Mountains. The Capitan is everywhere lower than the canyon bottoms, forcing water to resurge along the river.

2. Characteristics of Guadalupian Caves

The Guadalupe Mountains contain over four hundred caves. The caves are significantly different from most caves of the world, which formed in epikarstic environments from the concentrated input of surface waters charged with CO_2 (Good 1957; Davis 1980; Queen 1981; Palmer 1991). Foremost amongst these is the lack of passage integration in the Guadalupian caves (small passages joining to form larger ones), the lack of evidence of flowing water, the lack of relationship between cave size and location to surface catchment areas or recognized recharge or discharge sites, and the abundance of massive gypsum blocks and crusts, odd carbonate precipitates (popcorn), and the relatively common occurrence of native sulfur, halloysite and other usually rare minerals.

3. Past Studies

The caves of the region were first formally studied by Bretz (1949), who concluded that they had formed from classical karst processes (Davies 1930). Bretz concluded that the gypsum blocks and crusts and popcorn were related to later flooding of the caves by waters derived from the surface. However, the dramatic differences in cave morphology, mineralogy and relation to surface hydrology and topography have led most subsequent researchers to conclude that other hydrochemical mechanisms had played an important role in regional speleogenesis. Although many new and exciting models have been proposed for the caves of the area, it is this author's opinion that there is still more to be said, which is a measure of how significant the caves here are – and of how complex they are. These complexities involve both the timing and hydrochemical origins of the caves, and allow much room for further research.

Bretz's interpretation began to be challenged when Egemeier (unpublished memo 1971) commented on similarities between Carlsbad Cavern and the Kane Caves of Wyoming, Queen (1973, 1981) recognized that some of the gypsum blocks and crusts had replaced dolomitic bedrock, and were early and not late, and proposed that the bedrock had been replaced by gypsum and later dissolved to form the caves. Queen et al. (1977) proposed that this replacement had taken place in the mixing zone between reduced basinal brines and oxidized fresh meteoric waters, in which sulfuric acid was formed and dissolved the bedrock while precipitating gypsum. Jagnow (1977) suggested that the source of sulfuric acid was the vadose oxidation of iron pyrites scattered through the section. Hill (1987, 1993, 2000, 2001), citing the similarities between sulfur isotopic distributions in the gypsum blocks in the caves and that that of H_2S from basinal hydrocarbon accumulations, proposed that the caves had been formed from sulfuric acid from the oxidation of H_2S derived as a gas from basinal hydrocarbon sources. This model has been widely accepted (Palmer 1991, 2000, 2007; Palmer and Palmer 2000; Klimchouk 2007). However, as data accumulated, weaknesses in the Hill model became harder to ignore.

4. Evidence Against the Phreatic Sulfuric Acid Model

The phreatic sulfide oxidation model must be abandoned based on a number of relationships. Basinal waters are undersaturated with H_2S below about 1 m (Palmer 2000, using data from Wiggins et al. (1993), which means that gaseous transport of H_2S out of the deep basin is unlikely. Even if H_2S were saturated in basinal waters, rising bubbles from basinal hydrocarbon accumulations would equilibrate with dissolved H_2S in the fluid through which it was moving, destroying the isotopic signature, upon which the Hill model depends entirely. Transport by passive diffusion is unlikely, due to the low concentration gradients of H_2S (Palmer and Palmer 2000, using data from Wiggins et al. 1993). Aqueous transport driven by compaction is unlikely because the basin contains few fine-grained compactable sediments (Dunham 1972). Furthermore, any model that involves aqueous transport of H_2S would result in the loss of the isotopic signature upon which the Hill model was based. Palmer (2000) pointed out that H_2S was itself an acid, which could dissolve limestone. The first dissociation constant of H_2S is only somewhat lower than that of H_2SO_4. The second dissociation constant is significantly lower, but at intermediate and high pH dissolution should still occur (Weast and Astel 1981). However, even aqueous transport of H_2S could not result in significant carbonate dissolution in the shelf edge since the basinal evaporates from which the H_2S bearing fluids might be sourced contained fine-grained carbonate components. Consequently, aqueous solutions would have been already saturated in limestone as they moved into the carbonate shelf edge. Furthermore, a recalculation of mineral solution chemistry by this author based on these data determined that no combination of sulfidic basinal fluids and fresh meteoric waters of the compositions reported by Palmer (2000) would result in gypsum supersaturation and calcite dissolution, since the amount of oxygenated fresh water necessary to oxidize the sulfide in the brine would result in the dilution of the mixed fluid below the level of saturation. With brines containing 600-750 ppm H_2S and fresh water containing 8-12 ppm O_2 it is only in the freshest 1% of the mixing zone that the mixed fluids will be oxidized. The phreatic sulfuric acid model must be abandoned, and a new mechanism must be found to generate the high negative $\delta^{34}S$ values reported by Hill for gypsum in the caves.

5. An Alternative Model

An alternative speleogenetic model is proposed, which involves a mechanism for bedrock dissolution, an expanded time range over which dissolution took place, and a new mechanism for the generation of high negative $\delta^{34}S$ values. I propose that: (a) the major caves of the Guadalupes formed after the Laramide and Basin and Range orogenies from traditional mixing processes, in which sulfide oxidation played only a minor role; (b) the gypsum blocks and crusts are vadose and not phreatic; and that (c) sulfur isotopic fractionation took place through a three or four part process beginning in the phreatic and finishing in the vadose environments. The latter part of this will be discussed in Part III of this paper. Traditional brine-fresh water mixing (Bögli 1980; Plummer 1975) is capable of producing Guadalupian-sized caves in relatively short periods of time (Palmer et al. 1977; Queen 1994b; Mylroie and Carew 1995). In this model, fresh water accumulated beneath the Guadalupe Mountains as they were erosionally freed from the basin-filling evaporates that had buried them in the late Permian (Part I, Fig. 3b), This would have happened following uplift of the region, first following the Laramide Orogeny and subsequently following the Basin and Range Orogeny. Following the model developed for Bermuda (Queen 1994b), mixing would have been greatest in fractures and faults, along bedding planes and formation contacts, and in zones of paleokarst, even where these had collapsed and been partially infilled with sediments and precipitates. The Capitan Aquifer runs the length of the Guadalupe Mountains. Mixing would have been greatest where flow was concentrated around discharge sites. Presently, springs along the mountain front are associated with perched aquifers. The Capitan Aquifer is presently significantly deeper than the perched aquifers which discharge at Rattlesnake Springs (Bowen 1998). Consequently, no discharge of the Capitan Aquifer is expected in these settings. It does discharge from springs along the Pecos River near the town of Carlsbad, where the shelf-edge carbonate strata plunge beneath the uneroded evaporates that fill the basin to the east. Additionally, fresh water continues in the shelf-edge strata eastward to depths of over 300 m (Anderson 1981). Leakage of fresh water upwards from the aquifer through vertical zones of weakness has caused the formation of breccia pipes in the overlying evaporates (Bjorklund and Motts 1959). This would have promoted mixing of fresh water and brines in the shelf-edge strata, and would have created the steeply inclined conduits observed by Palmer (1991, 2000, 2007), Palmer and Palmer (2000), and Klimchouk (2007). As erosion progressed, the flow of water would have been through more horizontal conduits. Presently, flow in the aquifer between White's City and the springs at Carlsbad is through near-horizontal conduits (Hiss 1975) (Fig. 2).

Thrailkill (1987) observed that most of the caves in the southern Guadalupes formed along joints perpendicular to the shelf edge, while most of the caves in the north were

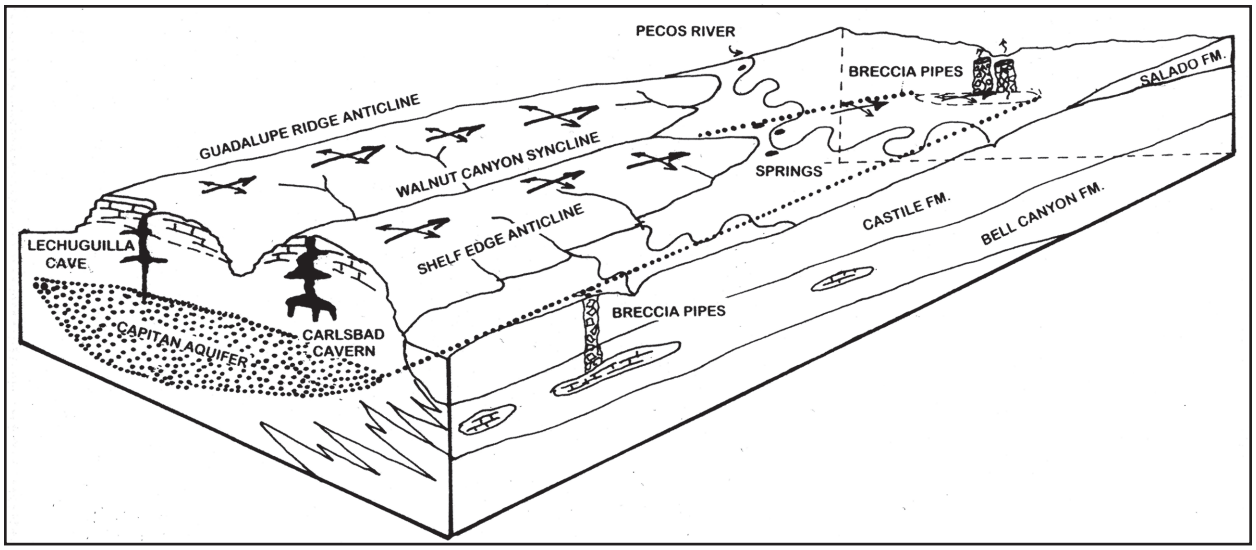

Figure 2: Relationship of regional structure to the aquifer and location of major caves. The erosion of the Basin and Range uplift has progressed more slowly than the development and integration of the Capitan Aquifer, which is everywhere below the level of the mountain front, forcing all flow through the springs and breccia pipes in the Pecos River Valley.

developed along joints parallel to the mountain front. This pattern is similar to that of the surface canyons observed by DuChene and Martinez (2000). It may reflect changes in the discharge patterns from the post-Laramide and post-Basin and Range discharge points. In the Delaware Basin near Rattlesnake Springs low mounds of Cretaceous (Commanchian) carbonate debris have been interpreted as remnants of breccia pipes developed through the Permian evaporates (Kelley 1971). The breccia pipes may have formed from the upwards movement of fresh waters from the proto-Capitan Aquifer, moving basin-ward through tongues of carbonate debris flows,

Although the origin and significance of gypsum blocks and crusts will be discussed in Part III, the fractionation of sulfur must be mentioned here as an alternative to the Hill model. I propose a four part fractionation process: (I) isotopically lighter gypsum is dissolved from the bedded Castile Gypsum that filled the basin in the upper Permian; (II) widespread bacterial reduction of sulfate in anoxic brines results in substantial fractionation; (III) lighter sulfur is preferentially degassed from cave pools into the caves; (IV) heavier H_2S preferentially dissolves in seepage waters first, leaving lighter sulfur to circulate in convective cells in the cave.

6. Final Evolution of Pre-Drainage Fluids

As the transmissivity of a karst aquifer increases through time the residence time of waters in the aquifer decreases, This will result in the thinning of the lens and with cave passages that had formed in mixing zones being invaded by brines. If this is occurring as uplift progresses, recently drained caves will overlie water table pools filled with brines. If there is no exchange of the cave atmosphere with the outside atmosphere the cave atmosphere will be in equilibrium with the dissolved gasses in the pools. In the Guadalupes this suggests that early cave atmospheres were high in CO_2 and H_2S. Erosion led to greater exchange of gasses with the atmosphere outside. This promoted degassing of CO_2 and H_2S from ground water pools in the caves. The rate of degassing was greatest just below the pool surface and decreased downwards. Degassing resulted in increased pH's and the decreased solubility of carbonate minerals. Where rates of gas loss were less the degree of supersaturation was less and the rates of mineral precipitation lowest, which led to low nucleation rates and the precipitation of fewer, larger and better formed crystals. Where degassing rates were higher, the rates of nucleation and mineral precipitation were higher, leading to the precipitation of more crystals showing greater disorder. As uplift proceeded this led to a succession of carbonate precipitates from few, large and well formed dogtooth crystals followed by more, smaller spar crystals, followed by radial fibrous carbonates in mammallary crusts ("clouds") covered by accumulations of cave rafts. Not all crystal morphologies are necessarily found at each locale, but where these late pre-drainage precipitates are found the order of succession conforms to this general model. Because of the ubiquitous presence of soluble carbonate bedrock, the pH of pool deposits should have been generally near neutral. Even in caves pools with high H_2S, as for instance in the active H_2S caves of Mexico , Wyoming and Italy (discussed in Part III) the pH of cave pools is not strongly acidic, and no

acidophilic minerals are found to precipitate in subaqueous environments.

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POST-DRAINAGE EVOLUTION OF THE CAVES OF THE GUADALUPE MOUNTAINS, SOUTHEASTERN NEW MEXICO AND WEST TEXAS, USA

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The Guadalupe Mountains were uplifted, caves that had formed in mixing zones were drained, and modified during three-stages, which depended on: the rates of supply of H_2S and CO_2 from the groundwater; the supply rate of O_2 from vadose seepage, through the permeable rocks above the cave and through entrances; and rates of exchange of the cave atmosphere with that outside. The caves first formed without entrances, and it was only after significant uplift and erosion that some entrances opened. In **Stage I**, O_2 input was minor or lacking, H_2S and CO_2 input from groundwater was high, and cave atmospheres were everywhere at or near saturation with water. Atmospheric circulation in Stage I was driven by thermal (Rayleigh-Benard) convection, in which rising air loses heat to the bedrock and cools, and descending air picks up heat from the bedrock and warms. Rising air may reach its dew point, after which condensation will occur. H_2S dissolved in films of condensate, decreasing pH. Where these waters seeped downward into descending, warming, evaporitic air flow, minerals precipitated and H_2S and CO_2 were released back into the cave atmosphere to circulate again. In **Stage II**, erosion thinned the rock cover above the caves, so that O_2 input > 2 x H_2S input. At this point almost all the H_2S was oxidized, increasing the deposition of primary and replacement gypsum, but decreasing the overall efficiency of the sulfur-related modification of the cave. Relative humidity was high in Stage II, resulting in the widespread distribution of zones of condensation and evaporation. In **Stage III**, continued erosion increased atmospheric exchange between the caves and surface, drying them out. This limited the distribution of convectively driven condensation and resulting evaporation. Where saturated seepage films are exposed to evaporation, they are subject to varying degrees of evaporative concentration depending on the relative humidity, the thickness of the seepage film, and the rate of flow along a particular flow path. These processes result in closely spaced, chemically distinct microenvironments, in which a succession of crystal forms and minerals may develop, in places facing into the convective flow. Condensation is greatest where heat loss to the wall rock is highest, which results in the accentuation of surface topography, forming scallops, arches, pendants, cupolas, and domes. In large passages the amount of vadose dissolution is generally minor, but where air is forced between rooms by barometric pumping, significant enlargement and integration of passages may occur. Gypsum deposits formed only after the caves had drained, since the effects of dilution during mixing outweighed those of increasing [$SO_4^{=}$] through sulfide oxidation. Rather extreme negative $\delta^{34}S$ observed in some cave gypsum is interpreted as the product of fractionation resulting from dissolution of bedded gypsum, bacterial reduction of dissolved sulfate, degassing of H_2S from groundwater pools, and dissolution of H_2S in seepage films.

1. Introduction

This is the last of three papers on the geology of the caves of the Guadalupe Mountains, which appear in this volume. The first paper "Geology of the Caves of the Guadalupe Mountains: Bedrock Geology, Tectonics, Structure and Paleokarst" discusses the geologic setting and evolution of this important area, and draws attention to the six generations of karst that have shaped it. The second, "Pre-drainage History of the Caves of the Guadalupe Mountains" briefly summarizes past speleogenetic models, details reasons why the prevalent current model, which relies on the phreatic generation of sulfuric acid by oxidation of H_2S derived as a gas from the adjacent basin, does not work, and proposes an origin for the caves that involves freshwater-brine mixing. The last paper focuses on post-drainage modification of the caves as it is related to regional hydrology, and erosional history. This proves to be an amazingly complex and interesting aspect of regional speleogenesis, which involves aspects of vadose sulfuric acid-related processes but goes significantly beyond traditional models and interpretations. Many of the figures needed to explain these relationships would normally appear in more than one of these papers: in order to save valuable space, figures presented in the first two papers are referred to as

"Part___, Fig.___". If a figure is referred to just as "Fig.___", it refers to the paper in which it is cited.

2. Gypsum Blocks, Crusts, and Popcorn Lines Point to New Models of Post-Drainage Passage Modification

The Guadalupe Mountains, located in southeastern New Mexico and West Texas in the southwestern United States (Part I, Fig. 1) expose a thick sequence of upper middle Permian (Guadalupian) strata (Part I, Fig. 2) in which over 400 caves have been discovered, including Lechuguilla Cave and Carlsbad Cavern. The caves are known for their size and beauty, and for the diversity and complexity of the minerals and speleothems they contain, including massive blocks and crusts of gypsum and deposits of native sulfur (Bretz 1949; Good 1957; Davis 1980). The unusual morphology and mineralogy of the caves has given rise to a large number of speleogenetic models (Bretz 1949; Queen et al. 1977; Jagnow 1977; Davis 1980; Queen 1981, 1994a; Hill 1987, 1996, 2000; Palmer 1991, 2000, 2007; Klimchouk 2007). Most of these have focused on the pre-drainage development of the cave, and have treated the massive gypsum blocks and crusts as products of phreatic processes (Buck et al. 2000). This interpretation is unsustainable, given the composition of brine and fresh meteoric groundwaters (see Part II), and field relationships involving the gypsum blocks and crusts are inconsistent with a phreatic origin, particularly where the gypsum overlies sediments and mineral precipitates interpreted to be vadose. But it was clear that gypsum was an integral part of the caves history. The distribution of gypsum blocks and crusts is also related to that of popcorn, morphologically and mineralogically complex precipitates with a commonly lumpy texture. Many deposits of popcorn occur beneath well-defined levels, which have been called "popcorn lines," above which the passage walls were commonly corroded. Bretz (1948) proposed that the gypsum blocks formed after the cave had formed, drained and been reflooded by sulfate-bearing fluids derived from dissolution of evaporite strata on the surface. He proposed that the popcorn lines had formed around the top of these flooded pools. The most extensive popcorn line is in the Big Room of Carlsbad Cavern, and extends eastward over a kilometer in the Left Hand Tunnel. Jagnow (1977) determined that the western part of the popcorn line was slightly higher than the eastern end, which he attributed to regional uplift.. Queen (1981), paid attention to the details of popcorn deposition, and realized that these deposits were commonly preferentially developed on surfaces that faced towards the upper parts of the cave. This seemed unlikely to have occurred in a phreatic environment. Field observations revealed that, in particular passages, the top of gypsum blocks and many crusts were at the same general level as the popcorn line (Fig. 1). Several other aspects of popcorn development are inconsistent with it having formed at a water table: popcorn deposits were not associated with other deposits formed in a pool-surface environment , as for instance cave rafts, shelf stone, or the typical mammillary deposits observed beneath rafts and shelf stone; popcorn lines commonly do not continue across walls where the floor descends to lower levels; popcorn lines are commonly inclined where the passage they occur in is inclined; collapse blocks on the floor of a passage may not have any popcorn, even though the passage walls are covered with it. Taken together, these observations argued against an origin having anything to do with reflooding or pool levels, and supported an entirely vadose origin related to thermal (Rayleigh-Benard) convection in the cave atmosphere. These observations, as well as work in Wyoming, USA (Egemeier 1973, 1987), Mexico (Hose and Pisarowicz 1999; Palmer 2001), and Italy (Cigna and Forti 1986; Galdenzi and Manichetti 1995; Galdenzi and Maruoka 2003), allow a new model for popcorn, gypsum and passage development to be proposed. In all these cases, certain similarities were apparent: gypsum precipitation and replacement of carbonate bedrock was limited to the vadose; pH of pool waters from which H_2S degassed was always near neutral, although condensation films on vadose rock surfaces encrusted with gypsum could be quite low. The following model for vadose cave modification focuses principally on five aspects of vadose cave modification: 1) redistribution of heat, moisture and atmospheric gasses as a function of thermal convection in caves; 2) evolution of cave atmospheres as a function of the degree of exchange with the surface atmosphere; 3) evolution of cave walls as a function of local variations in heat flow; 4) evolution of the chemistry of seepage films as a function of their thickness and the amount of evaporation to which they are exposed; and 5) evolution of sulfur isotopes in Guadalupian settings (discussed in Part II).

3. Thermal Convection in Cave Atmospheres

Because caves are three dimensional voids, they cut across the regional thermal gradients in the bedrock. The bedrock at depth is generally warmer that that at lesser depths. Because the deeper parts of the cave are more likely to be flooded, atmospheres in the deeper caves are more likely to be warmer and more humid than those in the shallow cave, which results in thermal convection (Cigna and Forti 1986). Where circulation is confined to within the cave it may be considered as a form of Rayleigh-Benard convection (Flaschka and Busse 1994; Fig, 2). Warm, humid air from the deeper parts of a room will rise, loosing heat to the wall

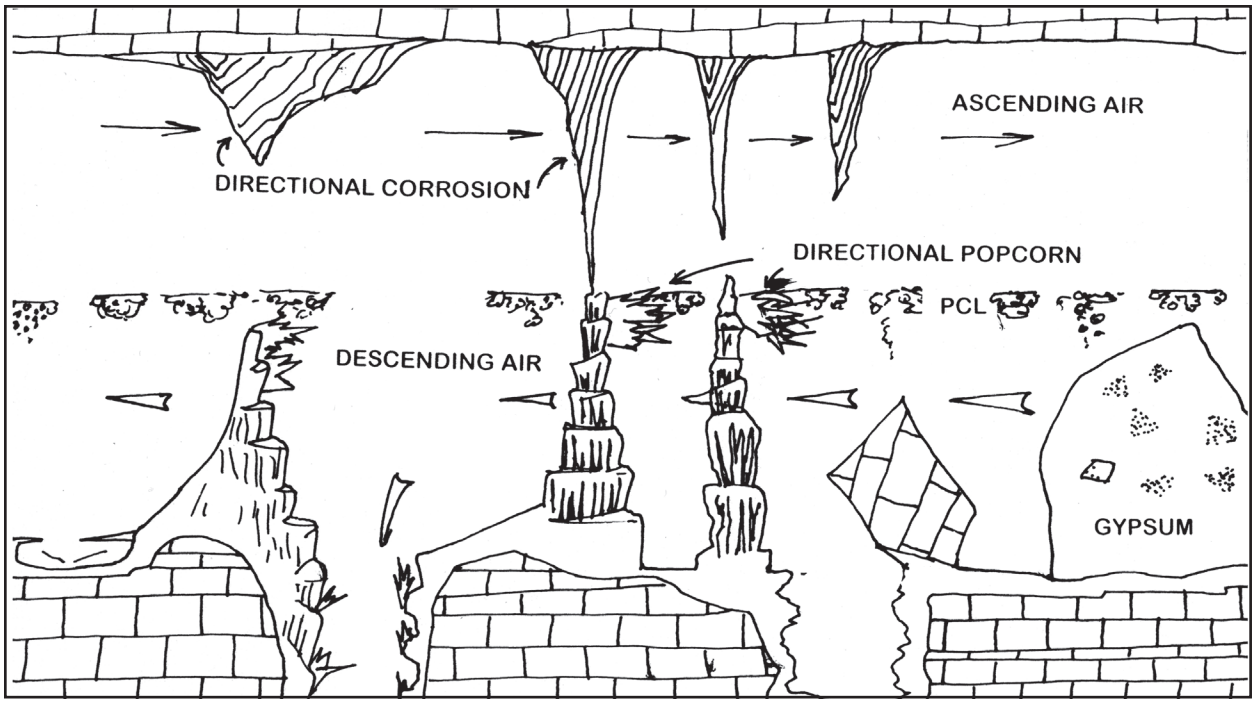

Figure 1: Diagram of typical post-drainage relationships, showing convective airflow resulting in corrosion of areas above the popcorn line (PCL) and evaporation below. Gypsum blocks generally confined to evaporative areas. Popcorn line is discontinuous over open pits in floor and lacking from surfaces without a source of saturated seepage.

rocks. If it starts near saturation, heat loss will result in condensation as an aerosol and on exposed surfaces, from which heat may be conducted. Descending air warms as it absorbs heat from wall rocks and due to adiabatic processes, becoming less saturated and evaporating water from moist surfaces. If circulation within a particular convective cell is rapid, the temperature of the entire cell may converge on an intermediate value between that of the shallowest and deepest wall rock. As such, the system may appear static, but if the heat content of a unit volume of cave atmosphere, converted to a standard pressure is determined, a systematic gain and loss of heat within the cell may be computed. Unless the bedrock can conduct heat away from a surface faster than it is supplied by condensation and conduction the rock will warm until it reaches equilibrium and heat flow stops (a point recognized by Michie 1997). Variations in the thickness of lithic cover over a cave, in distances separating passages, and reversing airflow driven by barometric variations may result in continued heat-flow. This circulation is responsible for the orientation of popcorn into descending air-flow and of dissolutional surfaces into ascending airflows. Where ascending and descending limbs of a convective cell occupy the same passage the interface may be marked above by greater condensation due to mixing condensation and below by increased mineral precipitation to form the popcorn lines first observed in the caves of the Guadalupes. Although ascending air will approach and

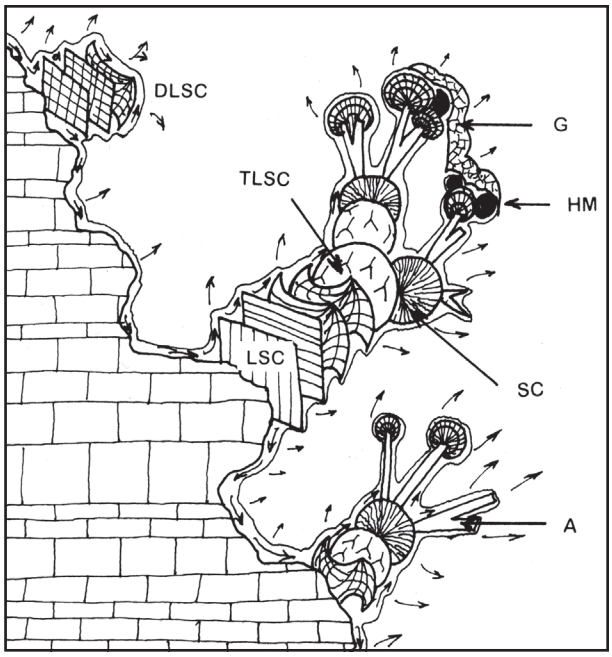

Figure 2: Diagram showing cross section of wall rock with saturated seepage film, which thins outward. The effect of evaporation is greatest on thin films with little through flow, creating a series of closely spaced microenvironments in which a succession of minerals and crystal morphologies evolve: length-slow calcite (LSC), deformed length-slow calcite (DLSC), twinned and deformed ball of length-slow calcite, balls of calcite showing split-crystal growth (SC), aragonite prisms (A), hydromagnesite (H) and gypsum (G).

remain at 100% relative humidity, descending air may fall considerably below saturation if the wall rocks are dry. Where this drier air comes in contact with seepage waters it may result in a greater degree of evaporation than where it is close to saturation, allowing the precipitation of more soluble minerals (Skipwith 1966). Selective etching of passage walls has created extensive and complex outcrops on which depositional and diagenetic textures are far better developed than on most surface outcrops.

4. Evolution of Seepage Water Chemistry as a Function of the Thickness of the Seepage Film

The "popcorn" deposits associated with subaerial evaporation of seepage films commonly show a consistent outward progression of mineralogy and crystal morphology (Fig. 3). In the Guadalupes this typically entails (outward from the rock surface): length-slow calcite (nailhead spar) with planar crystal faces; length-slow calcite with deformed (saddle-shaped) crystal faces; balls of length-slow calcite showing twinned and split-crystal growth; aragonite prisms; balls of palisades calcite crystals; irregular masses of hydromagnesite; crusts of gypsum. These reflect fluids that have been progressively concentrated by evaporation, as the seepage film thins over slight protrusions in the substrate due to the meniscus effect. The rate and degree of evaporative concentration at a particular point depends on: (1) the relative humidity of the air; (2) the thickness of the water film; (3) the flow-rate of water across any cross-section perpendicular to flow; and (4) the ionic strength of the solution. In this way, chemically distinct microenvironments may be generated and maintained from the same parent solution, leading to the contemporary precipitation of different mineral species and morphologies.

5. Evolution of Passage Morphology

If passage walls act as sites of heat exchange, then recessed areas may allow greater heat exchange than areas that protrude into the passage (Fig. 4). If this leads to greater rates of condensation the recessed areas will be preferentially dissolved, becoming more recessed. Protruding areas will be the site of less heat flow and will experience less condensation and evaporation. Consequently, topographic relief of cave walls exposed to thermal convection will be accentuated to form scallops, cupolas, arches, pendants, boneyard, etc. Where condensation takes place around the periphery of a highly porous zone, through which cooling air flows, the central parts of the zone will experience less condensation than the margins, and may collapse, forming a breccia as the margins continue to dissolve.

6. Evolution of Cave Atmospheres

In the Guadalupes where caves formed deep below the surface and initially without entrances, cave atmospheres evolved through three stages, In Stage 1 no exchange of the cave air with that outside took place. The early atmospheres were in equilibrium with the groundwater in the deeper caves, and were everywhere near saturation with water. Even small amounts of upward movement in areas where heat could be lost to the wall rock resulted in supersaturation and extensive areas wall-rock dissolution and areas of saturated seepage. These seepage films provided a source from which descending air might evaporate water, causing widespread and well-developed precipitates (popcorn). Where rising and falling convective flow occupied separate passages, depending on the pre-drainage morphology, a passage with no seepage waters and a descending airflow might remain effectively unchanged from its predrainage morphology. In Stage 1, caves had no or small entrances, O_2 input was low and humidity was high. H_2S and CO_2 dissolved in seepage and condensation films and etched the bedrock. Where these waters were evaporated the CO_2 and H_2S were given back off into the atmosphere and the

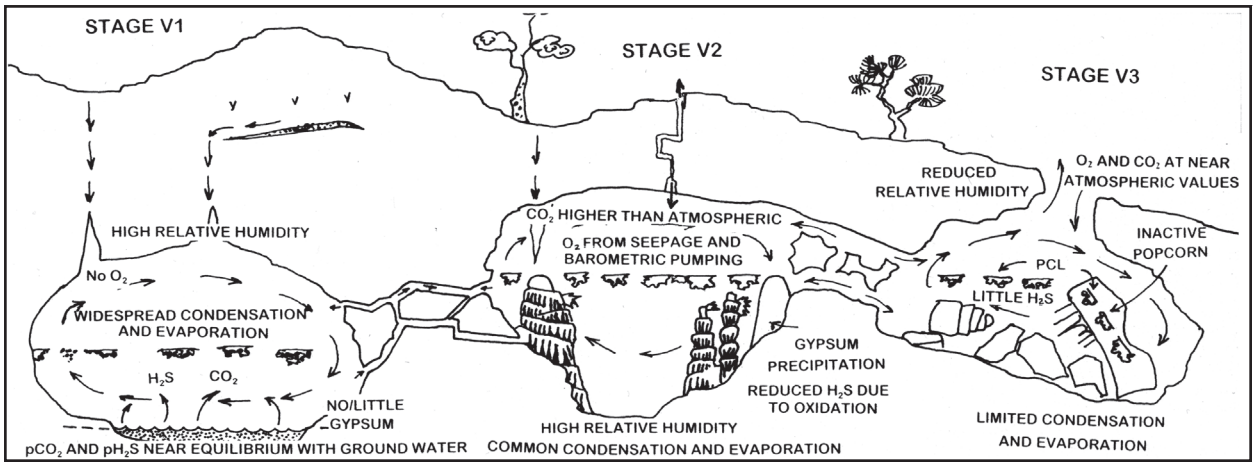

Figure 3: Diagram showing three stages of vadose cave modification accompanying the opening of a cave by erosion.

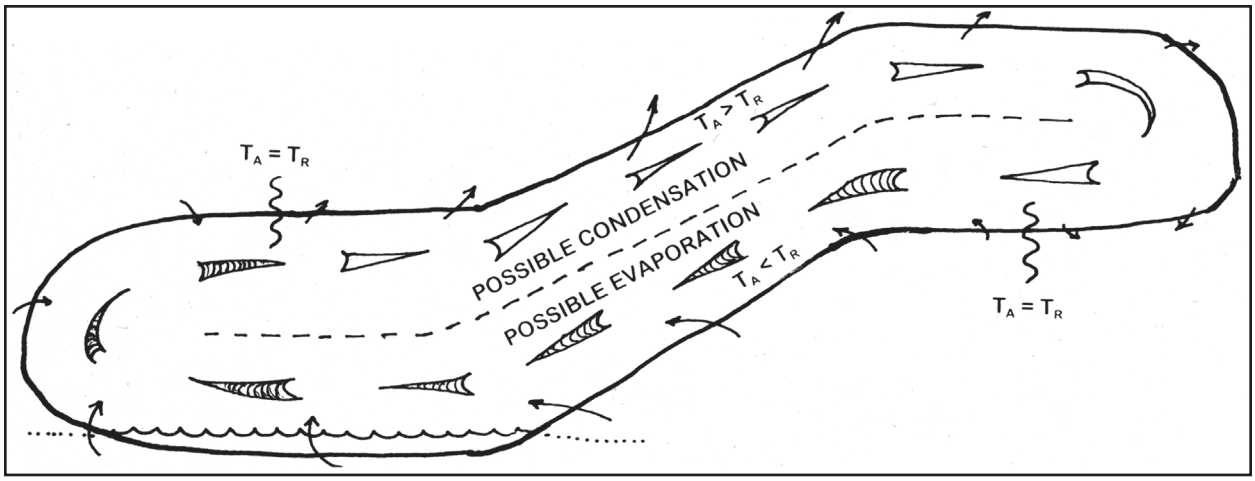

Figure 4: Rayleigh-Benard convection in a closed cave. The degree of heat exchange depends on the difference between the temperature of the cave air (TA) and that of the bedrock away from the passage wall (TR).

dissolved constituents reprecipitated (Fig. 5). In Stage 2 erosion of the surface thinned the lithic cover, allowing increased input of O_2, although humidity remained high. H_2S was oxidized to H_2SO_4, and when the seepage films evaporated gypsum precipitated in blocks and crusts. Areas of condensation were still widespread, as were areas of mineral precipitation. As the lithic cover above the caves thinned more, allowing greater exchange with the atmosphere outside (and if the outside atmosphere was less humid than that in the cave), then areas of condensation in the cave would have become more limited. This in turn would have limited the distribution of saturated seepage waters, from which evaporation mineral precipitates might have formed. In Stage 3, continued erosion of the lithic cover created and enlarged entrances, leading to drying of the caves and reducing the extent of condensation. Deprived of seepage films, the extent and rate of mineral precipitation was limited. Consequently, the most active system (Stage i) produced little gypsum, while the less active system (Stage 2) produced the significant gypsum deposits by which the process was recognized. Consequently, it may be misleading to refer to these caves as "sulfuric acid" caves. Since H_2S can dissolve cave walls even without oxygen, and since all H_2SO_4 depends on the oxidation of H_2S, it seems appropriate to refer to the caves as H_2S-related.

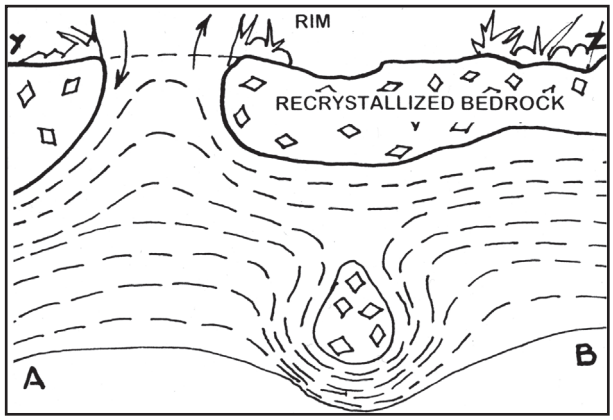

Figure 5: Wall rock retreat due to condensation. If two rock surfaces, A-B and Y-Z are at different temperatures, the amount of heat flow will depend on the temperature gradient (DT/d). Small variations in thickness may result in locally higher rates of heat flow, resulting the progressive accentuation of surface topography.

7. Evolution of Sulfur Isotopes

In this model isotopically light sulfur results from a four part fractionation process involving: (1) initial preferential dissolution of isotopically light sulfate from marine gypsum; (2) preferential bacterial reduction of lighter sulfate; (3) preferential degassing of lighter hydrogen sulfide from pools in the lower cave; and (4) the preferential solution of heavier hydrogen sulfide in the first seepage films encountered, allowing lighter sulfide to travel farther.

8. Assessing the Degree of Post-Drainage Modification: Weathering and Passage Integration

In Spider Cave (and others) corrosion residues are common on the walls, and were originally thought to have resulted from the original phreatic dissolution of the cave. However, they have been removed from the wall rocks and redeposited on the passage floors following a recent flood, which has created a prominent line marking the high-water line. This demonstrates that the residues could not have been developed in a phreatic environment, but must be vadose. Above the flood-line the in-place residues are up to 2 to 3 cm thick over dolomitic bedrock but are of negligible thickness over veins filled with calcite spar.

These veins protrude from the wall 2 to 3 cm, which gives a clear indication of the extent of the passage wall before condensation corrosion. This indicates that only a small proportion of the cave was enlarged after drainage. Consequently, although vadose condensation, augmented by bacterial chemolithotrophic processes (Northup et al. 2003), is important in understanding the evolution of the caves, it was generally volumetrically minor within any single convective cell, compared to phreatic dissolution. However, where barometric pumping forces air in and out of passage constrictions between rooms, in which circulation in convective cells prevails, dissolution will generally exceed precipitation because some water will flow into the rock surface and be removed from the system. Repeated wetting and evaporation may cause recrystalization of the bedrock. Air flow is progressively captured by larger, better connected pores forming boneyard between rooms. These connections have been interpreted as the products of paleokarst systems intersected by the later rooms (Hill 1987, 1996, 2000), but the boneyard is an integral part of the in-cave atmospheric circulation system.

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REGIONAL GEOLOGIC EVOLUTIONARY EFFECTS ON SPELEOGENESIS AT VILLA LUZ PARK, TABASCO, MEXICO

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Abstract

The understanding of speleogenesis is enriched by the study of its contextual regional geologic evolution. Here we present an initial evaluation of the relationship between regional evolution and the genesis of the caves in the Villa Luz park area, Tabasco State, in southern Mexico. Evaporite rocks composed of halite and anhydrite were deposited in grabens associated with the opening of the Gulf of Mexico during middle to Upper Jurassic time. Springs rich in sulfate and chloride (up to 2,900 mg/L of SO_4^{2-} and 4,700 mg/L Cl^-) constitute the present evidence for dissolution of these materials. An analysis of the δD-$\delta^{18}O$ values that follow the meteoric water line argues against a brine or hydrothermal source for these salt concentrations. These evaporite deposits were unconformably covered by Cretaceous carbonates ranging from dolostone with interbedded anhydrite to limestone, ranging from supratidal to reef and pelagic sedimentary environments. Most caves in the area are formed in these Cretaceous carbonates, including Cueva de Villa Luz (aka Cueva de las Sardinas) and Cueva de Luna Azufre. Paleocene compressional and extensional tectonic events created basins in which carbonates and terrigenous sediments were deposited. These less-permeable beds probably act as an aquiclude that isolates the older rocks from the influence of surface water, and therefore generate hypogenic conditions. During the Miocene, platform carbonates were deposited parts of the area. In the middle Neogene (late Miocene to early Pliocene), the Chiapas Fold and Thrust Belt formed by decollement over the Jurassic salt. This event is expressed in the area as narrow anticlines offset along their flanks by reverse faults that generally overthrust the preexisting synclines. Box-shaped folds (detachment folds) and non-vergent asymmetric anticlines (fault propagation folds) are also present. The uplift associated with the last tectonic event has increased the extent of erosion and helped to define the present geomorphology of the area. This event also formed the anticline that contains the caves in the Cretaceous block. This deformation helped to concentrate the dissolution at the Cretaceous-Paleocene contact. This focus probably created, or at least enlarged, the cave passages of Villa Luz that follow the folded bedding plane with a ramiform to spongework pattern. Assuming a hypogene origin, the Luna Azufre network passages were the first to develop in a partially dolomitized limestone. Progressive uplift and subsequent erosion during the Paleocene exposed hypogenic springs in the caves and at the surface. Proximity to the source (the evaporitic beds) is suggested by an increase of TDS (up to 4,000 mg/L) in the spring water at Luna Azufre Cave relative to other springs in the area (TDS of 2,000 to 1,000 mg/L).

Today, Pliocene or younger fresh-water carbonates lie horizontally over the inclined Paleocene sequence. Small caves with dendritic to linear passages have developed in this limestone following the contact. The water composition in these caves fluctuates from brackish to fresh, probably responding to fluctuations in the water table.

GEOLOGICAL EVOLUTION OF THE COBLESKILL PLATEAU, NEW YORK STATE, USA

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The geological evolution of the Cobleskill Plateau, in eastern New York State, USA, is interpreted from geologic field investigations. The Cobleskill Plateau contains four of the State's longest caves (Secret-Bensons, Howe Caverns, McFail's, Barrack Zourie). Major caves in Upper Silurian-Lower Devonian Helderberg Group carbonates, some with strike-oriented segments, developed progressively from east to west, coincident with headward incision of the Cobleskill Plateau by Cobleskill Creek. Recognition of Guenther Resurgence Cave as the relict outlet of Howe Caverns permits an estimate of initial plateau cave development on the order of 1.5 to 5 my. The interaction between karst and multiple glaciations, as interpreted based on the superposition of cave deposits, is significant. The morphology and superposition of cave passages, sediment deposits, flowstone, and breakdown enable interpretation of late Cenozoic geomorphology and climatic change. Regional geologic history is recorded by fills in plateau caves and is especially well preserved in Howe Caverns. A moderately rounded, chert-rich, pebble melt-out till present as canyon fill, on ledges, in braided anastomotic tubes, and in two phreatic conduits, provides evidence of one of the oldest glacial advances or retreats in New York State. They indicate rapid infilling of till via sinkhole and joint inputs beneath warm-based glacial ice. Deeply weathered chert pebbles indicate an age of more than 1 my. This is further supported by younger cave fills and massive flowstone over this till. Some fill removal required large flows of water, probably glacial meltwater. Floodwater dissolution of speleothems and canyon walls provide evidence that repeated long-term influx of glacial meltwater increased Plateau cave dimensions. Many Plateau caves were later twice inundated by Glacial Lake Schoharie which, in places, left behind thick rhythmites. Pebble till and breakdown-rich horizons within glaciolacustrine sediments provide evidence of a ~ 87 m lake level change around the Middleburgh readvance. Around 14 ka, an ice tongue impounding this lake thinned sufficiently that Plateau caves drained.

1. Introduction

Cobleskill Plateau caves have repeatedly been covered by continental scale ice sheets. While researchers have recognized and determined that these and other area caves predate Wisconsinan glaciations (Lauritzen and Mylroie 2000), we have, to only a limited degree, been able to elucidate earlier regional landscape and climatic conditions. Surficial erosion and valley filling by sediments have served to remove and mask the geologic record. However, in-cave sediments and material have faithfully preserved portions of New York State's geologic history. Glaciologists believe that the Pleistocene Laurentide ice sheet made four major advances into New York State (Isachsen et al. 2000). Some had multiple advances and retreats, as indicated by moraines and marine oxygen isotope data. In New York State almost all sediments not associated with the most recent glacial advance (i.e., Woodfordian Substage of the Wisconsinan Stage) were removed, leaving few clues as to sediment type and climatic conditions associated with pre-Wisconsinan advances and interstades. Sediments preserved in Howe Caverns, isolated from typical terrestrial erosive processes, provide a window into New York State's Cenozoic history. The trunk passage is ideal for the preservation of sediments because of its location near a valley flank and a number of sinkhole inputs that deposited sediments downstream of a major passage collapse area. Here, a first approximation of the interaction between caves and glacial processes in the late Cenozoic Era is presented.

2. Geologic Setting

Caves and karst features in the Cobleskill Plateau have developed in approximately 40–50 m of the Helderberg Group carbonates. A gentle south-southwesterly bedrock dip controls vadose cave development. Many sinkholes drain low-permeability glacial soils into preglacial caves, sometimes around drumlins. McFail's Cave, the longest and deepest surveyed cave in the plateau (7 km, 96 m; Palmer 1976), has high canyon passages and a 2^{+} m high phreatic passage. Other Plateau caves have similar conduits, and domes to heights of 33 m. Howe Caverns and Secret

Caverns are the only caves in the area open to the public. A number of caves and a mine in the Cobleskill Plateau reveal faulting. The importance of faulting and its impact on cave development has been debated by researchers. All downstream Howe Caverns and the transition zone between phreatic levels follow a thrust fault zone. In places, fault planes are displaced some 2 m and beds are repeated. Laterally continuous, slickensided, white calcitic horizons commonly mark multiple bedding thrusts. Widely different slickenside orientations revealed on opposite sides of a single thick calcite bed provide evidence for at least two distinct faulting episodes probably associated with the Acadian Orogeny (400–380 mya). A series of offset extension veins in downstream Howe Caverns reveals rotational motion along multiple fault planes. Examination of fault planes relative to cave development reveals that it is only in the transition zone between the cave's two phreatic levels that influence of the fault zone has been significant (Mylroie 1977; this author).

3. Development and Age of Cobleskill Plateau Caves

Cave development in Helderberg Group carbonates has adjusted to multiple regional base-levels coincident with the westward incision of the plateau by the Cobleskill Creek and valley aggradation via glacial sediments. Initial cave development progressed in a down-dip direction until reaching a former water table elevation graded to the Cobleskill Creek (Fig. 1). Here, a large phreatic conduit connected McFails Cave with Howe Caverns prior to occlusion by glacial sediments (e.g., Egemeier 1969; Palmer 1976; Mylroie 1977; Palmer et al. 1991; Dumont 1995; Palmer and Rubin 2007). Subsequent vadose entrenchment of McFails Cave occurred as Cobleskill Creek downcutting continued. McFail's Cave now resurges upward through glacial sediments at Doc Shauls Spring. Howe Caverns, a beheaded relict portion of McFails NW-SE passage, documents regional history and climate change spanning multiple glaciations. A 12-m-diameter phreatic conduit that formerly conducted groundwater through Howe Caverns to Guenther Resurgence Cave (Palmer and Rubin 2007) is now 45 m above the invert elevation of Cobleskill Creek. The large size of this conduit documents a long-term stable regional base level. Measurements of chemical equilibria in McFails Cave by Palmer (2007) permit a possible extrapolation of a cave age of 1.5 to 5 my based on his estimated entrenchment rate of 0.001-0.003 cm/yr. Vadose conduits in the Plateau, including a Howe Caverns canyon passage graded to this higher phreatic tube (Winding Way, Fig. 2), provide evidence of flow from both active and now-abandoned sources. A drop in regional base level of 6 m is documented in a lower strike-oriented phreatic conduit, representing a second stable base level in the region. Later vadose canyon incision followed base-level lowering. Cave deposits provide material that can be used to further refine age and geologic events.

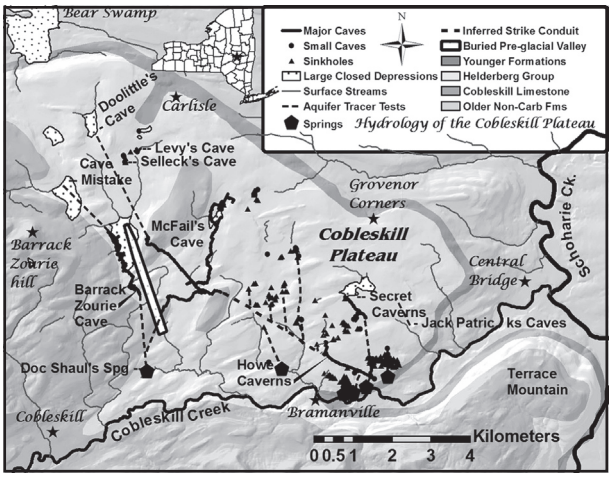

Figure 1: Cobleskill Plateau and major caves.

4. Chronology of Late Cenozoic Events Interpreted from Howe Caverns

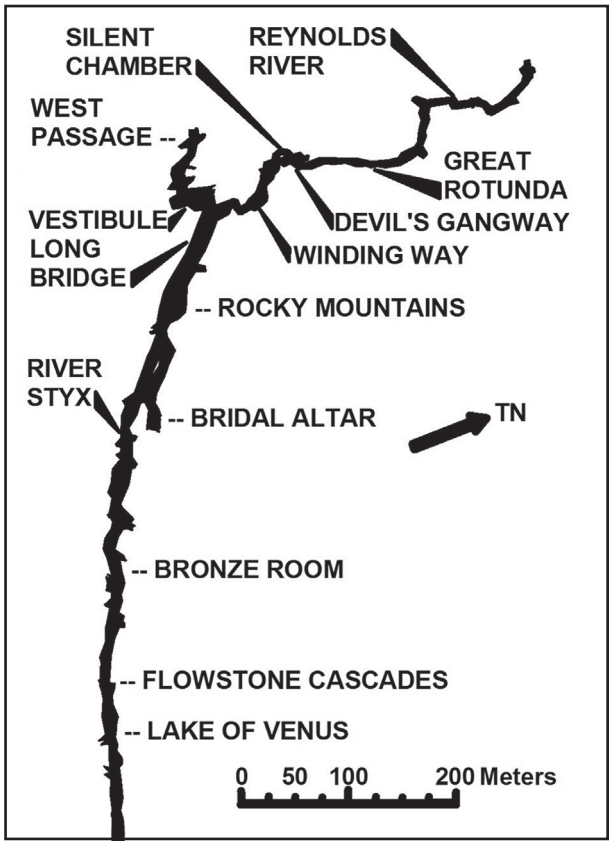

Figure 2: Key place names in Howe Caverns.

The relative superposition of cave sediments and materials, and their subsequent alteration, allow a first interpretation of glaciogenic sequences, events, associated climatic conditions, and hydrologic conditions. Absolute dating of these events via uranium-series disequilibrium dating and other methods has not been conducted. For ease of reference, the geologic sequence has been broken into chronologic intervals based on superposition and relative age, sometimes grouping several events together. Future research may help refine this working model and may add to these geologic intervals. Furthermore, age dating of speleothems and sediment deposits may identify depositional gaps.

Interval 1: Flowstone and small stalagmites were deposited over small wavelength scallops on exposed bedrock walls of the highest level phreatic tube. These small stalagmites may be some of the oldest speleothems in the northeastern United States. Formation precipitation is interpreted as having occurred during interstadial, ice-free, conditions some 1-5 mya.

Interval 2: A subglacial, pebble-rich (~50%), melt-out till (Fig. 3) flowed into Howe Caverns primarily through a large open joint near the Vestibule and via several sinkhole inputs. The ~ 1m wide joint trending N14°E is located near a valley wall. Melt-out till formation and flowage occurs commonly at the margins of glaciers and ice sheets, where ice is nearly stagnant (Hambrey 1994; Sugden and John 1976) and where thick unfrozen subglacial till exists beneath temperate ice (Boulton 1972). Unstable, saturated, till (yellowish brown sandy clay loam to clay), injected under pressurized conditions, was squeezed throughout the cave. It is assumed that the cave outlet was open in an unconfined hydrologic setting in order for the till to flow completely through the cave. Whether or not melt-out till exited the cave subaerially or under glacial ice is not clear. Till filled the cave's vadose canyon to unknown depths, as well as much of both phreatic conduit levels. Its hard-packed, over-consolidated, form indicates drying in-situ vs. after emplacement by fluvial action. Till also fills much of a high-level phreatic conduit exposed in a quarry wall near the cave's original downstream outlet at Guenther Resurgence Cave, situated above the new Cave House Museum (Palmer and Rubin 2007). Nearby, excavation of the quarry floor within a de-roofed portion of Howe Caverns produced massive quantities of this melt-out till. The vertical distribution of this deposit, emplaced throughout all levels of the cave under subglacial conditions, documents that the cave was open and actively functioning as a zone of low hydraulic head. Therefore, at least locally, it is likely that preglacial conduits served to control the potentiometric surface beneath continental or wasting ice. Moderately well-rounded chert pebbles in this deposit suggest subglacial transport from beyond the small watershed present today. The deeply weathered condition of insoluble pebbles indicates an age in excess of one million years (pers. comm. with Campbell, in Palmer 2007). This interpretation is further supported by deep weathering rinds within chert pebbles (Flint 1957). The melt-out till is interpreted as evidence of glacial recession. (Alternately, if this till was not emplaced under pressure, it would reflect deposition coincident with either the earliest phreatic cave level or at a time of valley filling and related rise in the regional base level.) If indeed the age of this pebble till exceeds 1 million years, it would provide evidence based on marine oxygen isotope stage dates that Cobleskill Plateau caves may have survived more than 10 glacial advances. This till may represent the oldest documented terrestrial Pleistocene or Pliocene deposit in New York State.

Figure 3: Melt-out till exposure near Winding Way steps. Note small stalagmite amidst till.

Interval 3: Following emplacement, the melt-out pebble till was deeply excavated throughout much of the cave. Remnants of this deposit occur on ledges, in canyon exposures, in infeeders, and in floodwater tubes. The over-consolidated nature of this till probably required considerable time and water quantity to excavate, likely substantially more than that measured during a March 2007 flood (6 cms). Interval timing is somewhat constrained by Interval 7 flowstone deposits that would have substantially reduced stream power and caused back flooding in the main cave conduit had they been present. This would have precluded till excavation. It is interpreted here that till excavation occurred via invasion of subglacial meltwater during glacier thinning and retreat (i.e., warm-based ice under either polar tundra or microthermal climatic conditions). The Cobleskill Creek valley may have been partially or wholly ice-free at this time. It is likely that

Interval 3 represents many hundreds of thousands of years and multiple glaciations, with little or no remaining sedimentary evidence.

Interval 4: Climatic conditions were warm during this time interval. Surface water infiltration into the cave slowly began to increase, resulting in significant formation development in the Winding Way, near the Vestibule area, above the Long Bridge, and elsewhere. Saturated cave pool conditions and related calcite growth occurred in natural cave segments on both ends of the Manmade Tunnel. Sediments in the Silent Chamber area were cemented together. Also, calcite wall coatings were precipitated in conduits that, during wet climatic conditions, conduct floodwater (e.g., Fat Mans Misery/Devils Gangway). In the absence of age dating, speleothems in this interval are interpreted as pre-dating massive flowstone growth discussed in Interval 7. Formations developed in this time interval were subjected to floodwater dissolution, whereas the massive flowstone cascades of Interval 7 remain largely intact.

Interval 5: Under ice-margin conditions, a second melt-out till flowed into Howe Caverns. This flow was less massive than that in Interval 2 and is predominantly pebble-free brown clay. This till includes cobble and boulder (25^{+} cm) sized rocks probably derived from in-cave breakdown, indicating that it flowed in rapidly in a saturated state. Remnants of this till occlude side passages in the Winding Way and several large side conduits along the up-dip side of the Howe Caverns master conduit upstream of the Lake of Venus. The relative timing of this till interval is inferred to be after removal of the Interval 2 pebble till and before massive invading subglacial flows (Interval 6) removed most of this deposit from the Winding Way. The location of sediment exposures provides evidence that this clay-rich till formerly filled much of the Winding Way and part of the main cave. Its limited exposures in lower cave levels outside of the Winding Way suggest that the cave served as an open conduit drain to a wholly or partially ice-free Cobleskill Valley. Thus, flowage into the cave probably occurred at or near a wasting ice margin. A small sediment exposure in the Lake of Venus depicts a basal contact with the Interval 2 melt-out till and overlying glaciolacustrine rhythmites (Interval 9).

Interval 6: This interval was marked by the influx of vast quantities of subglacial meltwater that far exceeded historic floods. This required a watershed larger than that of today, indicating a far-reaching subglacial source area (Rubin 1991). During this stage, almost all Interval 5 melt-out till was removed from the Winding Way and lower levels of Howe Caverns. In addition, short wavelength wall scallops attest to aggressive, high flows in the Winding Way that continued to expand canyon width. Concurrently, flood water dissolution partially dissolved Interval 4 flowstone formations in the Winding Way and elsewhere, leaving small wavelength scallops behind as evidence. During this interval, meltwater continued to expand the main cave and furthered development and enlargement of tap-off passages extending down-dip toward the Cobleskill Creek. Today, some of these tap-off passages are active while others remain as small relict caves.

Interval 7: A continental glacier again advanced over the region. Massive flowstone cascades and formations developed in area caves over time. The partial cross-section of a Lake of Venus cascade (Fig. 4) exposes 2 m of thinly-layered flowstone. If van Beynen et al.'s (2004) minimum annual speleothem growth rate of 0.019 mm/yr is assumed, a growth time of about 100,000 years is possible. Other flowstone deposits are more than twice as thick, indicating that quiescent climatic conditions may have persisted for at least 250,000 years (Fig.5). Slow growth is likely because massive flowstone extends downward into what are today active stream passages (e.g., River Styx, Reynolds River). U/Th dating of this flowstone may be possible. Lauritzen and Mylroie (2000) correlated U/Th terrestrial-based dates obtained from speleothems with marine oxygen-isotope stages, thus documenting that many regional caves survived multiple glacial advances. Sample ages analyzed by Lauritzen and Mylroie (2000) and Smart (see Dumont 1995) from Barrack Zourie and Caboose Caves reveal flowstone growth in marine oxygen isotope stages 6 and 8, indicating speleothem growth during glacial conditions. It is possible that U/Th dating of Interval 7 flowstone cascades may reveal formation coincident with oxygen isotope stages 6 to 8 (130-300 Ka). Pebbles from the Interval 2 melt-out till are cemented in the base of some of these deposits. Similarly, a large formation in the center of a nearby Barton Hill stream passage (Schoharie Caverns above waterfall) also indicates long-term quiescent regional conditions, possibly during the same time period. Alternately, Interval 7 flowstone may predate oxygen isotope stages 6-8 (e.g., a speleothem in Schoharie Caverns yielded a date greater than 350 Ka; Lauritzen and Mylroie 2000). Massive flowstone growth throughout the main stem of Howe Caverns is interpreted as having initiated beneath a continental glacier, with partial growth under warmer conditions. U/Th dating is warranted.

Interval 8: This long-term interval is characterized by the break out of large and small bedrock blocks from conduit ceilings and walls. Stream erosion continued and new

Figure 4: Cross-section of a Lake of Venus flowstone cascade.

formations developed. This interval may include one or more glacial advances and retreats. Additional field work may find that this interval predates Interval 7.

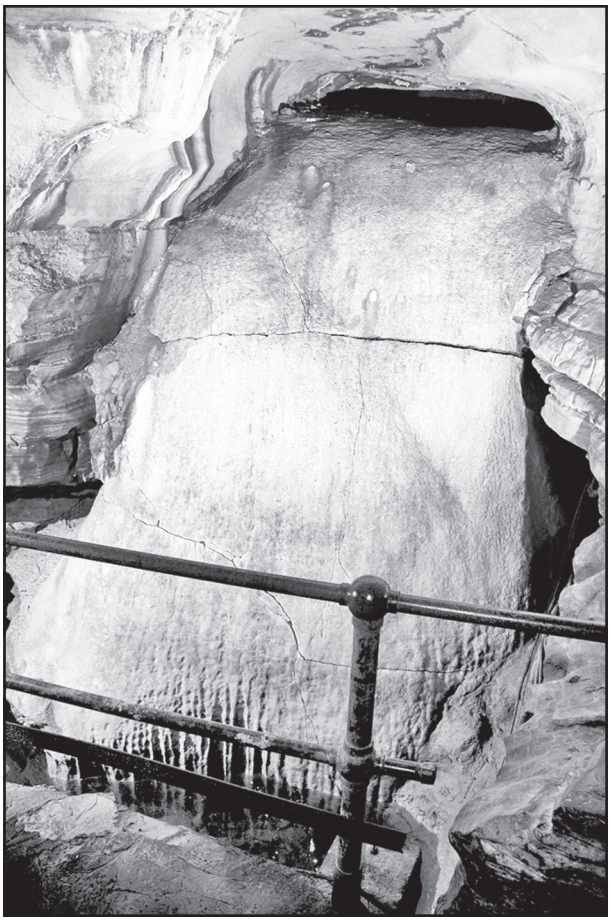

Figure 5: Flowstone cascade nearly occludes cave passage near Lake of Venus.

Interval 9: Glacial striations in bedrock provide evidence that the direction of most recent glacial advance (Woodfordian) was toward the west-southwest. Sediments from this advance buried many Plateau sinkholes, some with gleyed lodgement till to depths of 7 meters or more. With the retreat of the Laurentide ice sheet starting 21,750 years ago (Isachsen et al. 2000), Glacial Lake Schoharie formed behind an ice tongue blocking northward flow from the Cobleskill and Schoharie Creeks to the Mohawk River (i.e., Mohawk Sublobe). The first outlet of Glacial Lake Schoharie routed surface water flow south-southeast into Catskill Creek at an elevation of 357 m amsl via the Franklinton channel. Locally, hilltops projected above the lake as islands. As the glacier receded northward, Glacial Lake Schoharie expanded until a lower outlet was reached at Delanson. This outlet elevation of about 262 m is well represented in Howe Caverns. Sediment exposures beneath the Long Bridge and in the Haunted Castle (downstream of the Lake of Venus) reveal one significant and several thin horizons of pebble till (Fig. 6; ~ 270 m amsl) and breakdown (Fig. 7) within a thick glaciolacustrine sequence. These horizons indicate fluvial emplacement when the surface of Glacial Lake Schoharie was lowered to that of the Delanson outlet. Rhythmitic layers above these horizons document the subsequent rise in glacial lake level back to the Franklinton channel elevation as a result of the Middleburgh readvance. This investigation reveals that Howe Caverns and many other Cobleskill Plateau caves were twice inundated by deep lake waters and, thus, provides

Figure 6: Stream-borne melt-out till between varved clays indicates lake lowering before Middleburgh readvance.

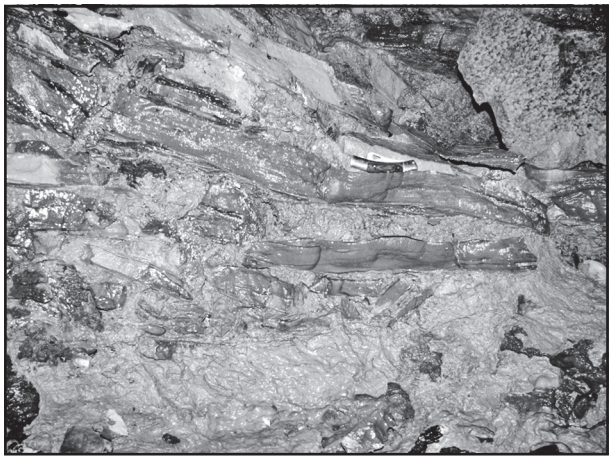

Figure 7: Breakdown and sediments within glaciolacustrine sequence.

evidence of ice margin positions. Annual rhythmites were deposited (Fig. 8), sometimes completely filling cave passages. Palmer (1976) reports rhythmites in McFails Cave to an elevation of 345 m, 58m above the highest varved clays in Howe Caverns (Vestibule area, ~287 m amsl). Dumont (1995) reports paleomagnetic dates for two samples from a varved clay in Barrack Zourie Cave of late Pleistocene age. The gray color of the lowest Howe Caverns' rhythmites, as well as buried till excavated from a nearby sinkhole, reveal that lake-bottom sediments accumulated in a reducing environment (~264 m amsl downstream of Bridal Altar). A far downstream Howe Caverns' conduit exposed during quarry operations revealed glaciolacustrine deposits over the Interval 2 melt-out till at nearly the highest phreatic level in the cave (Palmer and Rubin 2007).

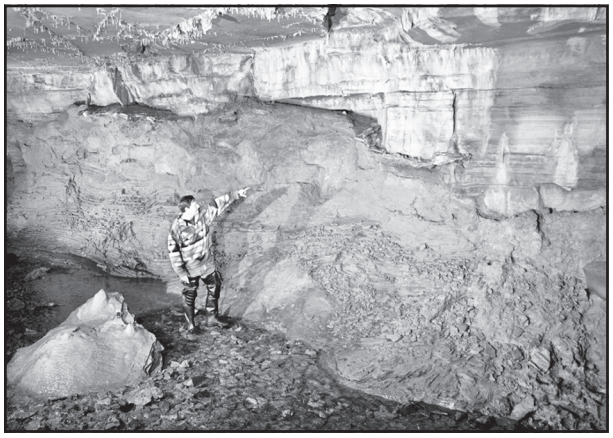

Figure 8: Glaciolacustrine deposit in River Styx of Howe Caverns.

Interval 10: The Wisconsinan glacial ice margin retreated northward by about 14 Ka, Glacial Lake Schoharie drained, and the northward flow of Schoharie Creek was restored. Surficial till deposits remain behind, covering and occluding many pre-glacial sinkholes. Upland pre-glacial drainage patterns are altered but, to a large extent, runoff still drains into pre-glacial conduits. Inside Howe Caverns, flowstone deposits formed atop glaciolacustrine clays. Preglacial drainage was restored in Plateau caves, sometimes to artesian springs (i.e., Doc Shauls Spring). Stream flow continues to excavate cave sediment deposits, albeit at a much slower rate after the McFails Cave strike passage was beheaded from Howe Caverns.

5. Conclusion

Caves in the Cobleskill Plateau contain important clues to glacial and interglacial events and climatic conditions that cannot be recognized at the surface. Clues are preserved in cave sediments, flowstone, breakdown, and post-depositional dissolution and scalloping of flowstone. Sediment deposits near relict inputs are particularly useful in delineating surficial conditions. Conduit morphology of Cobleskill Plateau caves has been used by researchers to interpret former hydrologic conditions and regional base-level adjustment. With few exceptions, the northeastern United States terrestrial record of pre-Wisconsinan sediments has been removed by successive glaciations. Cobleskill Plateau caves reveal a long history of growth and enlargement under both ice-free and ice-cover conditions during Pliocene and Pleistocene Epochs. Considering the large number of glacial advances indicated by marine oxygen isotopes, as well as in-cave evidence of repeated sediment excavation, it is possible that glacial meltwater significantly contributed to cave enlargement. The interpretation presented here provides a framework for additional research and age dating. This will improve our understanding of regional glacial, interglacial, and climatic conditions and help to fill a major gap in our knowledge of the region's late Cenozoic history.

Acknowledgments

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CAVE SEDIMENTS AS RECORDS OF LANDSCAPE EVOLUTION IN THE EASTERN ALPS

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Abstract

Landscape evolution in the European Alps has been a major topic of research for Earth scientists during the past several decades. The effects of landscape modeling processes are quantified using estimated sediment budgets, fission track analysis, and the dating of geomorphic markers like fluvial terraces, glacial moraines and erosion surfaces. Caves can provide additional clues for understanding landscape development because the position of phreatic cave passages, which form close to the local water table, is linked to the position of springs and valley bottoms. Lowering of the valley floor by erosion leads to the development of progressively younger phreatic passages at lower elevations. Therefore, valley incision rates can be obtained, provided that the age of a cave is known with reasonable accuracy. The minimum age of a cave can be determined by dating the sediments it contains, which are younger than the cave itself. The available techniques are U-Th dating, paleomagnetic analysis, and burial age dating based on the differential decay of the $^{26}Al/^{10}Be$ isotope pair in quartz.

The Northern Calcareous Alps (NCA) of Austria provide an ideal application for landscape evolution studies based on cave sediments because caves, which developed in thick limestone sequences, show a clear vertical distribution. Attempts have been made to empirically link this distribution pattern to the geomorphic history of the Alps, but numerical ages for the caves have yet to be determined. In the high karst plateaus of the central and eastern NCA (Dachstein, Tennengebirge, Totes Gebirge) speleogenesis probably started in the Miocene. The oldest known caves are currently located at altitudes of more than 1800 m asl. Progressive valley incision led to the development of a second level of caves at altitudes of 1400–1800 m asl. The third and youngest level is situated close to modern valley floors and is still active today. In the largest cave systems of the NCA (Hirlatzhöhle, Schönbergsystem, Dachstein-Mammuthöhle), distinct levels of horizontal passages which developed during times of relative tectonic calm, are connected by series of vertical shafts which formed during times of rapid valley incision, when the development of underground systems was forced to keep up with rapid geomorphic changes at the surface.

A project funded by the Austrian Science Foundation is currently underway, with the goal of investigating cave sediments from the NCA and the Slovenian Alps using the $^{26}Al/^{10}Be$ dating method. The goal of this study is to answer questions regarding the timing of speleogenesis in the NCA and to compare the pace of landscape modeling processes along a N-S transect of the Eastern Alps, as well as other available records from the alpine region.

SPELEOGENESIS AS A COMPONENT OF CORROSION OF THE EARTH SURFACE, WITH AN EXAMPLE FROM THE BIG LEVELS OF THE APPALACHIAN PLATEAU, USA

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The development of meteoric karst features is part of the process of corrosion (*sensu lato*) of the Earth surface. In the context of meteoric karst development, structural discontinuities such as bedding planes and joints serve to deepen the effect of weathering, in essence carrying regolith-producing processes deeper in to the crust. On the temporal and spatial scales of a landscape, most caves are relatively shallow and short-lived features, and probably little more than a blip in regional landscape evolution. In the deformed Appalachian Plateau of Greenbrier and Monroe Counties, West Virginia, USA, an extensive karst upland, the Big Levels, is present. Limestones of Carboniferous age host thousands of caves here, including several of the longest in North America. The Big Levels are developed within a complex anticlinorium on the order of 10 km wide, and the present surface can be considered to result from the unroofing of the primarily carbonate core of the anticlinorium. Most of the caves found in the area are hydrologically active. The caves conduct recharge from an average elevation of 650 m to the regional base-level stream, the Greenbrier River, at an elevation of 500 m. The depth of caves below the surface (i.e., roof thickness) varies, with the major conduits tending to be near base level, even though far from the river (e.g. Mystic River in Scott Hollow Cave). A few caves found high in the landscape and/or close to the river are relatively dry and shallow (e.g. Haynes and Windy Mouth Caves). The system of conduits is effective at removing surface drainage, and in this sense the Levels may be considered to be retarding the lowering of the land surface, or at least transferring mass removal to lower positions within the rock mass. Without the deeply incised river valley, the karst would probably be shallower, and more similar to that of the limestone valleys of central Pennsylvania. The margins of the Levels are mountains of clastic rock. Competition between scarp retreat rates and upland denudation will determine the future configuration of the landscape.

1. Introduction

The development of meteoric (epigene) karst features is part of the process of corrosion (*sensu lato*) of the Earth surface. If the near-surface were composed solely of homogeneous, continuous materials, the only variations in surface erosional form would be caused by spatial variation in weathering intensity. In reality, the heterogeneity of materials, presence of discontinuities, and variation in weathering intensity all work in concert to produce varied landforms. Biotic processes intertwine with these mechanical factors. In the context of meteoric karst development, structural discontinuities such as bedding planes and joints serve to focus dissolution in certain areas, forming, for example, linear rows of sinkholes. The discontinuities also deepen the effect of weathering, in essence extending regolith-producing processes deeper into the crust. Specific features develop as a result of system details – mainly the position and styles of recharge to the carbonate mass, percolating porosity distribution, and time. On the temporal and spatial scales of a landscape, however, most caves are relatively shallow and short-lived features, and probably little more than a blip in regional landscape evolution.

The present paper examines these relations in a portion of the deformed Appalachian Plateau of Greenbrier and Monroe Counties, West Virginia, USA (Fig.1). In this region an extensive karst upland, the Big Levels, is present. Limestones of Carboniferous age host thousands of caves here, including several of the longest in North America. Significant deformation of the bedrock ceased with the termination of the Alleghenian orogeny (300 Ma), when rifting of the present-day Atlantic Ocean basin was initiated. The local land surface configuration from that time is unknown, but the present day Big Levels are developed within a complex anticlinorium on the order of 10 km wide. The surface can be considered to result from the unroofing of the primarily carbonate core of the anticlinorium.

2. Observations

Most of the caves found in the area are hydrologically active.

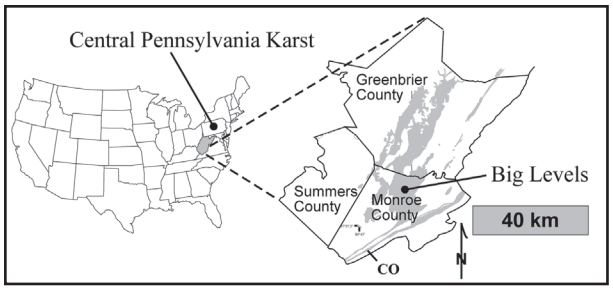

Figure 1: Index map showing location of Big Levels, West Virginia and Central Pennsylvania Karst in USA. Expanded view shows limestone outcrop in 3 county area of interest (modified with permission from an original figure by Greg Springer).

The caves conduct recharge from an average elevation of 650 m to the regional base stream, the Greenbrier River, at an elevation of 480 m. Depth of caves below the surface (i.e. roof thickness) varies, with the major conduits tending to be near base level, even though far from the river (e.g. Mystic River in Scott Hollow Cave). A few caves found high in the landscape and/or close to the river tend to be dry and shallow (e.g. Haynes and Windy Mouth Caves). The system of conduits is effective at removing surface drainage, and in this sense the Levels may be considered to be retarding the lowering of the land surface, or at least transferring mass removal to lower position within the rock mass.

Scott Hollow Cave is one of the extensive conduit systems developed beneath the Big Levels. It has a current mapped length of 44 km, and is 175 m deep. Numerous swallets feed the cave from the east, through tributaries that flow down dip. These tributaries join a north-trending master conduit known as Mystic River, which roughly follows regional strike. This conduit has a remarkably low gradient, with the result being that the cave has a roof thickness of greater than 100 meters through much of its length.

3. Discussion & Conclusions

In any landscape the form of the surface is the result of initial structure, erosive processes, and time elapsed. In a karst landscape the possibility of subsurface drainage frequently results in decreased stream incision because stream order is kept low. In the case of the Big Levels the Greenbrier River has incised a deep gorge, and a substantial limestone upland remains along the structural valley (Fig. 2). This incision appears to have allowed relatively deep

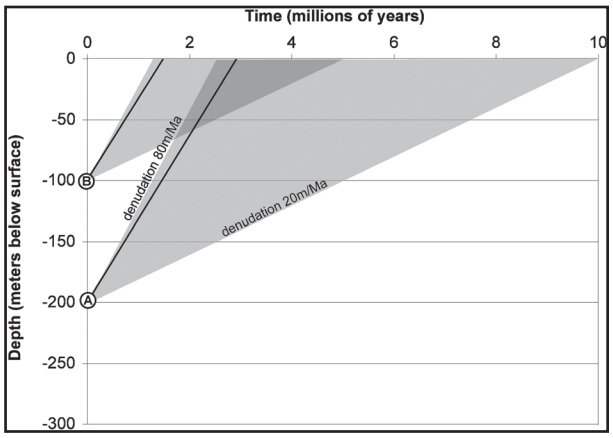

Figure 3: Theoretical persistence of caves in an erosional environment. The length of time that a given cave will exist depends upon the initial depth of formation (position on y-axis) and the denudation rate (slope of line). Gray regions envelope a range of reasonable denudation pathways for two examples. In case A, a cave formed at 200 m depth, the expected lifetime is 2.5 to 10 Ma. For a cave formed at 100 m depth (case B), the lifetime is reduced to 1.25 to 5 Ma. Solid sloping lines are the average denudation rate, 69 m/Ma, for 33 major drainage basins (calculated from data in Summerfield and Hulton, 1994).

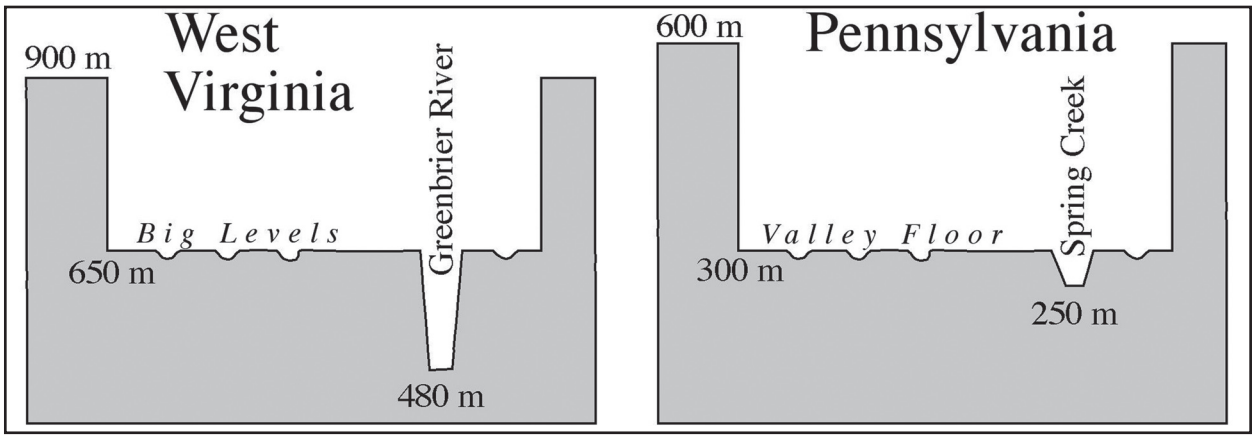

Figure 2: Diagrams showing generalized landscape elements for the Big Levels of West Virginia and the limestone valleys of central Pennsylvania. Vertical scales are the same, although the absolute elevation values are offset in order to aid comparison. No horizontal scale.

karstification by providing a high hydraulic gradient. The master conduits are developed along strike, but make use of, at least in part, other structural elements such as fault planes.

Without the deeply incised river valley, the karst would be shallower, and more similar to that of the limestone valleys of central Pennsylvania (Fig. 2). The margins of the Levels are clastic mountains. Competition between scarp retreat rates and upland denudation will determine the future configuration of the landscape. Considering a worldwide average denudation rate of 69 m/Ma, prior removal of tens of kilometers of overlying material is possible, and likely (Fig. 3). This means that in the overall scheme of landscape evolution, the development of caves is really only a minor interlude, and caves are not expected to persist in the landscape for long. In the case of Scott Hollow, a lifetime of less than 6 Ma is likely.

Reference

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HYPOGENE PROCESSES IN THE BALCONES FAULT ZONE EDWARDS AQUIFER, SOUTH-CENTRAL TEXAS USA

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Abstract

The Balcones Fault Zone Edwards Aquifer (Edwards Aquifer) is one of the most important karst aquifer systems in the United States. It provides water to more than 1.7 million people and is used for agricultural, municipal, industrial, and recreational purposes. The Edwards Aquifer in south-central Texas extends 400 km from the Rio Grande River near Del Rio, eastward to San Antonio and then northeastward through Austin. The aquifer ranges from 10 to 60 km wide and extends to a depth of 1200 m. The aquifer is contained in the limestones of the Cretaceous Edwards Group and is 150 to 300 m thick.

Most existing aquifer models assume epigenic conditions and implicitly or explicitly assume that circulating meteoric waters formed the Edwards Aquifer. The initial karstification is assumed to have occurred along paleokarst features that originated during an initial subaerial exposure. Such paleokarst features created zones of enhanced permeability that allowed the deep circulation of waters and the formation of the present aquifer.

However, epigenic processes do not adequately explain many features in the Edwards Aquifer. For example, large voids that are isolated from epigenetic processes formed deep in the aquifer by mixing corrosion. Acidic water is generated by oxidation of sulfides and intrusion of CO_2 from below, and possibly from hydrocarbon sources. In addition, the Edwards Aquifer displays characteristics that are difficult to accommodate in epigenic models. Examples include the wide distribution of high permeabilities, extreme depth of circulation, and the extremely high yields of most wells.

Recent data and new interpretations suggest that hypogenic processes have contributed to the formation of the Edwards Aquifer. Klimchouk concludes that waters rising from depth are important agents of karst development, and this model explains many hitherto cryptic features in the Edwards Aquifer.

GEOMORPHIC AND HYDROGEOLOGIC EVOLUTION OF KARST IN THE BURNSVILLE COVE, VIRGINIA, USA: NEW EVIDENCE AND PERSPECTIVES

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The Burnsville Cove in Bath County, Virginia, hosts an extensive karst system (>100 km of mapped passages) developed under a complex synclinal valley in the Silurian-Devonian Keyser Limestone of the Helderberg Group. Observable patterns of cave development are the result of hydrogeologic controls on paleo-conduit formation, landscape evolution, and several episodes of conduit modification as the subterranean drainage system adjusted to changes in surface drainage and morphology. Currently, most of the mapped caves contain vadose free-surface streams that drain north-northeast toward the Bullpasture River, which flows south into the James River. However, many passages are dominated by solutional and sedimentary features indicative of former phreatic conditions and substantially different paleo-drainage characteristics. Widespread evidence of deep phreatic development under low-velocity conditions exists throughout the Burnsville Cove in cave passages between 0 and >230 m above modern spring elevations. Mineralogical and geological evidence of hydrothermal fluid migration and volcanism in the area has recently been recognized and may have contributed to the formation of proto-conduits which influenced early stages of karstification.

Observations of surface topography and cave passage morphologies indicate at least two stages of phreatic passage development in the Burnsville Cove. The first was low-velocity deep circulation and dissolution that predates all modern landscape controls and karst drainage features. Prior to the development of the current surface drainage pattern, groundwater (and surface water) may have flowed to the south toward what is now Dry Run Gorge. This early stage of development was likely disrupted by the incision of the Bullpasture River Gorge, which pirated the river to the east near what is now Williamsville. After the initial piracy and lowering of the water table, the second stage of phreatic development was related to a stable period during incision of the Bullpasture River Gorge. Incision redirected drainage toward a paleo-spring in the incipient Bullpasture River Gorge and initiated development of a large, nearly horizontal phreatic trunk. Most recently, renewed and rapid incision of the Gorge lowered the water table again, rearranging drainage patterns and dissecting what may originally have been one larger drainage basin into the four smaller basins which exist today.

1. Introduction and Background

The Burnsville Cove is located in Bath County, Virginia (Fig. 1). This region is in the center of the Appalachian Mountains, which are part of the Valley and Ridge physiographic province. Speleology in the Burnsville Cove has a long history of integrated exploration and scientific observation, particularly from the early 1950s through 1970s. In 1982, the Burnsville Cove Symposium volume of the NSS Bulletin (Davis et al. 1982) was published and represented, at that time, the current state of understanding with respect to several areas of scientific investigation in the Butler-Sinking Creek Cave System and the Burnsville Cove (the Cove). Since then, tremendous advances have been made in the Cove, primarily with respect to exploration. In some ways, scientific examination and interpretation of the more recently discovered caves has lagged behind exploration because of their difficult nature and resulting inaccessibility to most people (Clemmer 1988a; Clemmer 1988b; Clemmer 1992, 1993; Schwartz 1994-95, 1999; Shifflett 2003). In this paper we present a new model for the speleogenetic and geomorphic evolution of the Cove. It is based both on new evidence and re-interpretations of old observations. While this paper is not meant to be the final word on the evolution of this large and complex karst region, we believe that an abundance of new physical evidence requires new interpretation and explanation.

When the Burnsville Cove Symposium was published, the Butler Sinking Creek Cave system was the longest cave in Virginia at around 27 km in length. Breathing Cave was the only other major cave in the region and contained approximately 7 km of mapped passages. Since 1982,

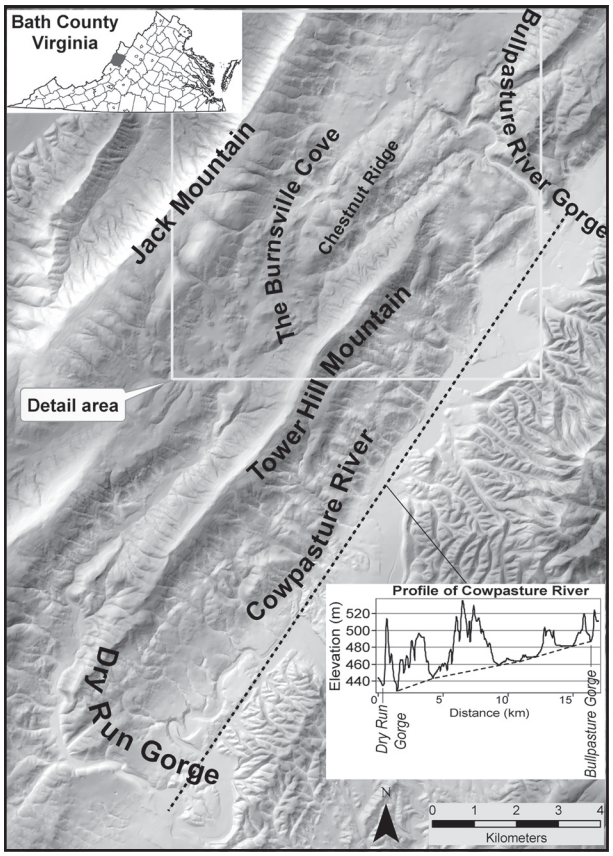

Figure 1: Map showing topography and major features in the study area. Box denotes area of detail in Figure 3.

many significant caves have been discovered including the Chestnut Ridge Cave System (>33 km and composed of Bobcat (Chestnut ridge Blowing), Blarney Stone, and Burns Chestnut Ridge Caves), Barberry Cave (>6 km), Helictite Cave (>12 km), and many other caves between 0.5 and 3 km in length. Not only have there been many new discoveries since 1982, but most of these discoveries have been under the flanks and nose of the Chestnut Ridge Anticline; an area where no significant caves were known prior to the early 1980s.

2. Hydrogeologic Setting

The Burnsville Cove is formed in a large northeasterly plunging synclinal structure which is complicated by the smaller Chestnut Ridge anticline in its center. This anticline also plunges gently to the northeast and divides the region into three structural regions. From northwest to southeast they are the adjacent Sinking Creek syncline, Chestnut Ridge anticline and White Oak Draft syncline. These three structural features are the dominant hydrogeologic controls on the modern karst system. Many other structural features both large and small (faults and folds at a variety of scales) have significantly influenced karst development in the area.

The majority of caves in the Cove are formed in the middle unit of the ~100-m-thick Devonian-age limestone of the Keyser Formation, which is locally divided by at least two thin and probably discontinuous sandstones (Fig. 2). One exception to this is in the northeastern nose of Chestnut Ridge, where most of the known caves are formed in the upper portion of the Helderberg Group.

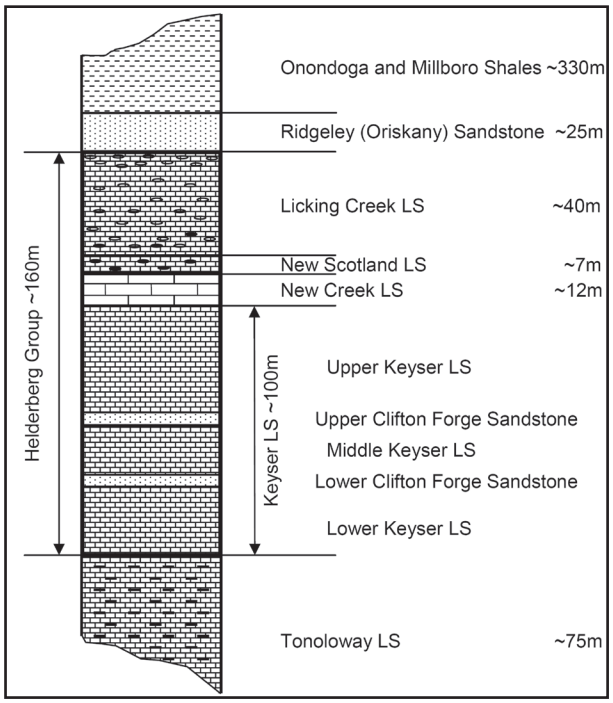

Figure 2: Stratigraphic section of the Helderberg Group. Modified from Davis et al. (1982).

The Chestnut Ridge Cave System (CRCS) is formed around the nose and on the northwestern and southeastern flanks of the northeasterly plunging anticlinal Chestnut Ridge. The ridge lies between the Sinking Creek syncline (containing the Butler-Sinking Creek System) and the White Oak Draft syncline (containing much of the Cathedral drainage and a portion of CRCS) (Fig. 3). The hydrogeology of the Burnsville Cove is dominated by the structural geology: primarily the Sinking Creek syncline and the Chestnut Ridge anticline. Four adjacent karstic drainage basins carry water generally towards the east and northeast toward the local base level defined by the Bullpasture River. Springs along the Bullpasture River associated with these basins, from the farthest upstream to the farthest downstream, are: Emory Spring, Aqua Spring, Cathedral Spring and Blue Spring (Fig. 3). Numerous dye traces in the past 40 years have defined the drainage divides between each of these basins (Davis et al. 1982). These traces and other hydrologic evidence indicate that residence times for conduit flow in Aqua Spring and Cathedral Spring basins are relatively

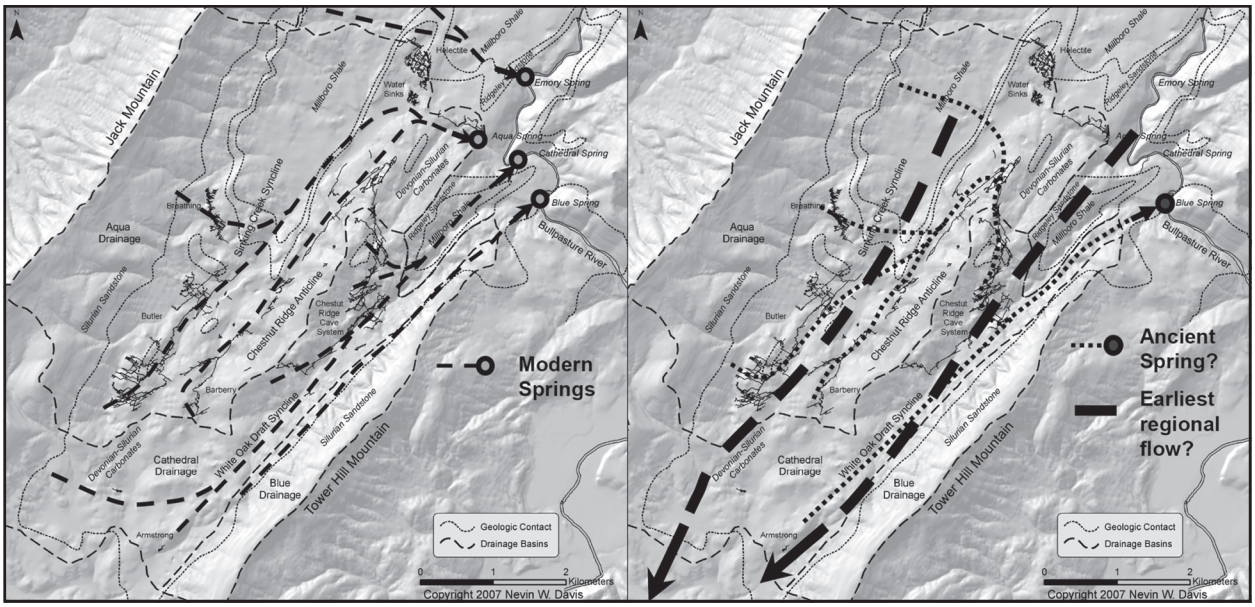

Figure 3: Shaded relief detail map of the Burnsville Cove showing major caves, modern drainage basins, geologic contacts, modern springs and flowpaths (left), and hypothesized ancient spring and earliest regional flowpath (right).

short (usually less than 2 weeks) while Emory Spring and possibly Blue Spring have somewhat longer residence times due to larger phreatic conduit volumes. With the possible exception of Blue Spring, all these springs discharge from strata in the upper one-third of the ~160m thick Helderberg Group.

3. Old Ideas and Problems

3.1. Paleo-flow direction prior to most recent incision of the Bullpasture River

Some of the most prominent karst features in the Cove are the four major springs which collectively drain the karst and discharge at or near river level in the Bullpasture River Gorge. Surveyed cave passages containing active streams all drain towards these springs and carry water generally from the southwest to the northeast. However, there are several pieces of evidence which indicate that a similar drainage arrangement in the past is unlikely.

First, the elevation of a regionally extensive abandoned phreatic trunk passage in CRCS is inconsistent with its current position within the hydrogeologic setting of the Cove. For such large-scale phreatic development to have occurred in Chestnut Ridge, the water table must have been at least as high as the uppermost portions of this passage: currently ~120 m higher than both the sumps in the cave system and the corresponding spring elevations. Therefore, the regional base level was at least 120m higher than at present, which means that the Bullpasture River's channel was also ~120 m higher. If this were the case, what is now the Bullpasture River Gorge would have been largely or entirely covered by substantial amounts of Ridgeley Sandstone (~25 m) and impermeable Millboro Shale (~330 m).

In a similar geologic setting, a breccia body associated with volcanic rocks near Monterey, Virginia, in Highland County, contains chips of the now-eroded overlying Millboro shale. This has been interpreted to represent a history of at least 330 m of erosion since Eocene volcanism (Tso and Surber 2006). Although erosion rates remain unconstrained in the Burnsville Cove, such a cap of siliciclastic rocks would have prevented the formation of large springs in locations similar to the modern Emory, Aqua and Cathedral Springs. It would not, however, have prevented deep circulation and dissolution from occurring. With no outlet available near the location of modern springs, water would have been forced to find the most hydraulically efficient discharge point. There is no concrete evidence indicating exactly where the paleo spring may have been, but there is evidence in CRCS which indicates that the most probable location is in the vicinity of Blue Spring. Blue Spring currently drains a long narrow strip of steeply dipping limestone which is bounded on the southeast by the Silurian siliciclastics which form Tower Hill Mountain. This strip of nearly vertical carbonates may have been the only outcrop exposed in the early Bullpasture River channel and may also have been the most efficient discharge point. In CRCS, a large horizontal trunk passage has been explored to a sediment fill just east of the axis of the White

Oak Draft Syncline (Fig. 3). This trunk passage extends for approximately 3 km along strike from the nose of Chestnut Ridge to White Oak Draft where further exploration has been stopped by a sediment plug. It seems probable that this passage curves to the north beyond this obstacle and continues along the strike toward a paleo-resurgence near the modern Blue Spring (Fig. 3).

Unfortunately, scallops indicating the paleo-flow direction have not been found in the large phreatic horizontal trunk passage in CRCS. This is probably due to the combined effect of two factors: extremely low flow velocities and highly deformed and thin-bedded limestone interbedded with sub-mm to mm-scale shale beds. The first definitive evidence of a flow direction was recently discovered in an area of CRCS known as Leprechaun Forest. Here, the large trunk passage diminishes in size to a crawlway for ~30 m, likely owing to sediment fill in a descending loop in the passage. On the southeastern side of this restriction, a large mound of sediment was identified as a deposit caused by flow and transport from generally north to south, which is away from the modern springs. As water moves through a restriction it is able to transport sediment. When the passage volume increases and flow velocities decrease, this sediment load drops out (Fig. 4). The morphology of the sediment pile and a small excavation in the side of it confirmed the direction of flow.

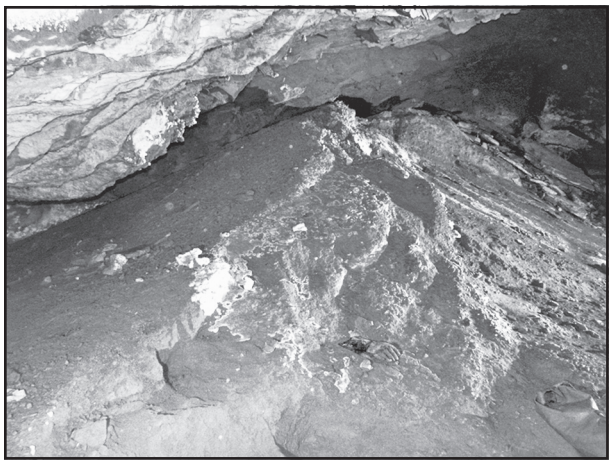

Figure 4: The sediment pile in CRCS which provided the first evidence of paleo flow to the southeast in the abandoned phreatic trunk passage. Flow was from left to right in the picture. Photo by: Benjamin Schwartz.

3.2. Questions about the earliest phreatic development

One of the most interesting characteristics of Breathing Cave and much of the upstream portion of Butler Cave is that many of the passages clearly formed under phreatic conditions, perhaps even with ascending water. Such a phreatic hypothesis was previously put forth for Breathing Cave (Deike 1960). Upper wall and ceiling morphologies in both caves preserve records of phreatic conditions with very low velocities. From the evidence in Butler Cave, we know that these passages are at least 230 m higher than current spring elevations. Upper-level passages in Butler Cave show a strong dependence on geologic structure for their development, both along strike-oriented bedding planes and folds, and along dip-oriented joints. The lack of horizontal levels of passages that cut across the structural planes of weakness provides no indication that these passages were formed near the water table. In fact, passages formed along joints that parallel the dip on the western flank of the syncline exhibit morphologies that indicate water once flowed upward against the dip (Fig. 5).

Figure 5: A set of rising cupolas in Butler Cave. These features formed along a dip-oriented joint in the Daves Gallery passage and indicate phreatic flow upwards along the dip. Boulder chockstone is approximately 0.5m in width. Photo by: Dan Doctor.

This is a distinctly different setting from the one that currently exists, which is an extensive network of abandoned dry passages with a few active vadose infeeder passages carrying water down toward the axis of the Sinking Creek Syncline. In Butler Cave, a large trunk passage roughly

follows the axis of the syncline. Water flows to the northeast in this trunk, alternately following the trunk passage and disappearing into inaccessible parallel passages below and to the southeast of the main trunk. Ultimately, all streams sump at the northeastern terminus of the explored cave. A small stream in Breathing Cave also sumps as it drains towards the axis of the syncline. Both Breathing and Butler caves contain abundant evidence of more recent modification by vadose action, including directional scallops and erosional features at floor level. Many passages that were once completely filled with clastic material derived from Jack Mountain have been and continue to be re-excavated by vadose stream action.

In addition to evidence for early deep-phreatic flow and passage development, other geologic evidence in the region indicates that hydrothermal fluid migration affected the rocks that host caves in Burnsville Cove. Numerous Eocene igneous intrusions occur in northern Highland County, about 20 km north of the Burnsville Cove (Tso et al. 2004). Breccia bodies associated with some of these volcanic intrusions are interpreted as having formed via a mechanism of hydrovolcanic diatreme emplacement in which dikes propagated upward along joints, encounter groundwater, and explosively form diatremes (Tso and Surber 2006).

Recently, an igneous intrusion was found in a cave in southern Bullpasture Mountain (Schwartz 2003). This is a considerable southern extension to the known range of igneous intrusions in Highland County, and places confirmed igneous activity within 13km of Butler Cave. Additionally, a lithium-bearing manganese oxide mineral [Lithiophorite (Al, Li)Mn4+O2(OH2)] has recently been identified in Butler Cave (Schwartz et al. 2008). This mineral is most commonly associated with hydrothermal deposits. Herkimer Diamonds and milky quartz veins are also associated with hydrothermal fluid migration and are abundant in the highly deformed Keyser Limestone. The link between karstification and the hydrothermal activity that affected the carbonate rocks is as yet unclear.

If extensive networks of passages that are now >230 m above base level were clearly developed under phreatic conditions, then this is evidence of a karst system which developed under conditions which were much different than those we observe today. This idea was put forth earlier by Deike (1960) regarding the development of Breathing Cave. Since that time, several pieces of new evidence support this hypothesis of deep-phreatic flow. The first is that explored conduits in Aqua and Cathedral Springs rise from depths of at least 85m and 50m, respectively (Simmons 1991; Simmons 2000). In both cases, the conduits continue and exploration was halted due to diving logistics. The second piece of evidence is from a karst system which lies adjacent to and north of the Emory Spring drainage. Here, the Chestnut Ridge anticline plunges to the north and probably flattens out into the much larger Bullpasture Valley syncline. This syncline exposes the Helderberg Group carbonates on the flanks of Jack Mountain to the west and Bullpasture Mountain to the east. The Bullpasture Valley is floored with the stratigraphically higher Millboro Shale. Dye tracing from high on the flank of Jack Mountain revealed that water sinking there flows under the Bullpasture Valley, rises at a large karst spring on the eastern flank of the valley before flowing back to the west and into the Bullpasture River (Davis 1991). A third piece of evidence is discharge observations at Emory Spring, which has no explored cave passages associated with it. Emory Spring responds differently than Aqua and Cathedral Springs to flood events. Although discharge increases significantly after a rain event, large volumes of clear water discharge before muddy water arrives at the spring. In contrast, Aqua and Cathedral Spring begin discharging muddy water much more rapidly. Combined, these pieces of evidence tell us that not only is it probable that deep-phreatic development occurred in the region, but that these conditions still exist.

Based on geomorphic patterns (Fig. 1) and evidence found in the caves, we believe that the system may have originally drained towards an outlet farther to the south near Dry Run. Deike (1960) noted that, "Breathing Cave, as explored, does tend to parallel the local strike southward, and this may reflect a tendency for the water to go around the structures, parallel to the strike and hence to the structure contours, rather than directly beneath the anticlines and synclines." Currently, the southern end of the Burnsville Cove karst system is bounded by the erosive exposure of underlying sandstones that prevent karst development. However, this exposure creates a relatively narrow divide between two karst systems: the Burnsville Cove and the Dry Run karst system to the south. Dry Run, as its name implies, is dry for most of the year downstream from where the streambed encounters carbonates. Below this point, a deeply incised gorge carries floodwaters to the Cowpasture River while the karst system discharges from one or more springs to the west of the Cowpasture River. While we are still in the initial stages of investigation, a basin-size vs. gorge depth analysis suggests that the Dry Run Gorge is oversized and over-incised for its current size. The Dry Run basin drains ~80 km^2 through its gorge while the Bullpasture River basin drains ~340 km^2 through its gorge. In essence, the Dry Run basin contains <25% of the drainage area in the Bullpasture River basin,

yet it has a developed a gorge of similar dimensions and in a similar geologic setting. Both topographic features and an elevation profile along the Cowpasture River valley (Fig. 3) show that the Cowpasture River has a steeper channel gradient and is incising a gorge near its confluence with Dry Run Gorge. While this is still speculative, it may indicate that this portion of the Cowpasture River has experienced a relatively recent increase in erosion – perhaps because of an increase in erosive power after capturing the Bullpasture River.

4. Conclusions

We hypothesize that ancient drainage of both the early karst system and the Bullpasture River was toward the southwest where the nearly abandoned Dry Run Gorge intersects the Cowpasture River ~17 km SW of the Burnsville Cove. During the time of maximum cave enlargement, widespread deep-phreatic development occurred along structural features, and possibly along preexisting hydrothermally-formed proto-conduits, under low-velocity conditions. Mineralogical and geological evidence of hydrothermal fluid migration and volcanism in the area has recently been recognized and deep (>100 m) phreatic pathways still exist in the northern portion of the Cove's drainage, as well as farther to the north in the Bullpasture River Valley where water sinks high on the western flank of the valley and follows deep flow paths to discharge at a spring on the east side of the valley. Incision of the Bullpasture River Gorge, which continues today, significantly rearranged regional surface and subsurface drainage. As the gorge incised, it created new and more efficient discharge points along the ancestral Bullpasture Gorge, which drained phreatic passage networks and induced free-surface stream flow and sediment transport in many of the caves. There may have been an extended period of relative stability in the Cove during which time a large phreatic trunk passage formed along strike around the Chestnut Ridge anticline. Drainage rearranged again as the gorge probably experienced a second episode of rapid incision. This second period of incision may have been related to either climate variability or the erosive removal of geologic controls (i.e., resistant sandstone beds in the river channel). Much of the karst system as it exists today is in a state of disequilibrium as streams in the cave modify and/or abandon earlier passages in favor of newer vadose flow paths.

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ASCENDING WATER OF THE DELAWARE BASIN, SOUTHEASTERN NEW MEXICO, AND FAR WEST TEXAS

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The Delaware Basin of west Texas and southeastern New Mexico is a deep, enclosed basin that formed during the Permian as a result of the final assembly of Pangaea. The Delaware Basin is defined by the Capitan Reef, which forms a nearly continuous carbonate reef complex that encloses a thick sequence of evaporite deposits in the basin interior. Inland of the Capitan Reef, interbedded gypsum / dolomite facies indicate Permian deposition in shallow, restricted shelf environments.

All of the Permian facies of the Delaware Basin region show evidence of speleogenesis associated with ascending fluids. Much of this hypogene karst appears to be related to the genetic evolution of the Pecos River, which has been a significant potentiometric low driving the upward migration of fluids throughout the Cenozoic. North of the Capitan Reef, karst development proximal to the Pecos River in the San Andres, Seven Rivers and Rustler Formations shows morphological evidence of dissolution within a sluggish flow regime exhibiting mixed convection. Within the Delaware Basin, large subsidence features and intrastratal breccia occur in the Castile, Salado and Rustler Formations which attest to ascending fluid paths, many of which appear associated with the migration of the Pecos River.

In the western Delaware Basin, complex hypogene caves and evaporite calcitization within the Castile Formation indicate the updip migration of hydrocarbon-rich fluids, which likely mixed with shallow surface waters. The world famous hypogene caves of the Guadalupe Mountains appear to be related to the eastward migration of the Pecos River in the Cenozoic, which provided the potentiometric low for ascending fluids rich in hydrogen sulfide. The source of hydrogen sulfide, which formed aggressive sulfuric acid-rich waters when mixed with oxygenated fluids at shallow depths, was originally attributed to evaporite calcitization in the Castile Formation. However, recent work suggests that this is not a geologically feasible source for significant amounts of hydrogen sulfide to be delivered to the Capitan Reef. Epigenic processes are currently overprinting evidence for hypogene origins for much of the karst development within the Delaware Basin region. However, enough evidence exists in both the carbonate and evaporite facies of the region to attest to the importance of ascending fluids in the speleogenetic evolution of the region.

1. Introduction

Recent advances in karst science have made us rethink the speleogenesis of long-studied regions. Caves and karst regions that previously required complex and often creative theories to explain their speleogenetic origin are now being viewed through much simpler process that can be explained through conventional hydrologic models. Cave systems and karst regions that were originally attributed to unique fluid chemistries can be explained by confined hydrologic models where fluid chemistry simply increases or decreases fluid aggressivity but does not drive speleogenesis. The recent recognition of a diagnostic suite of solutional morphogenic features (i.e. inlet risers, half tubes, ceiling channels and outlet cupolas) has been used to provide evidence of dissolution within confined or semi-confined environments, where sluggish flow is driven by mixed convection, including components of both free and forced convection (Klimchouk, 2007). However, caution must still be taken in interpreting speleogenesis based on these morphogenic features, because each individual morphogenic feature can be explained by alternate theories, but it is difficult to explain the complete suite of morphogenic features by processes other than hypogene speleogenesis.

The Delaware Basin (Fig. 1), located in southeastern New Mexico and west Texas, is a classic example of how we are beginning to reevaluate karst provinces in light of new emerging theories. Carlsbad Cavern and the caves

of the Guadalupe Mountains have for several decades been associated with sulfuric acid speleogenesis, with a possible thermal component that often involved complex models of base-level lowering to form "levels" of cave development (Hose and Pisarowicz, 2000). However, these caves have recently been explained by hypogenic processes (Klimchouk, 2007), where thermal and sulfuric acid components simply made hypogene waters more aggressive. Complex gypsum caves in the shelf and basin-filling deposits of the Delaware Basin were long attributed to only epigene processes, but recent investigations have shown that many of the caves are the result of ascending, hypogene processes (Stafford et al., 2008b). Based on recent advances in karst science, it appears that most of the karst development within the greater Delaware Basin region is associated with hypogene processes, which are either directly associated with porosity development or at least provided the initial permeable flow paths for later epigene processes to modify. The greater Delaware Basin can be subdivided into three basic hypogene karst regions: (1) Northwestern Shelf; (2) Capitan Reef; and (3) Basin Interior.

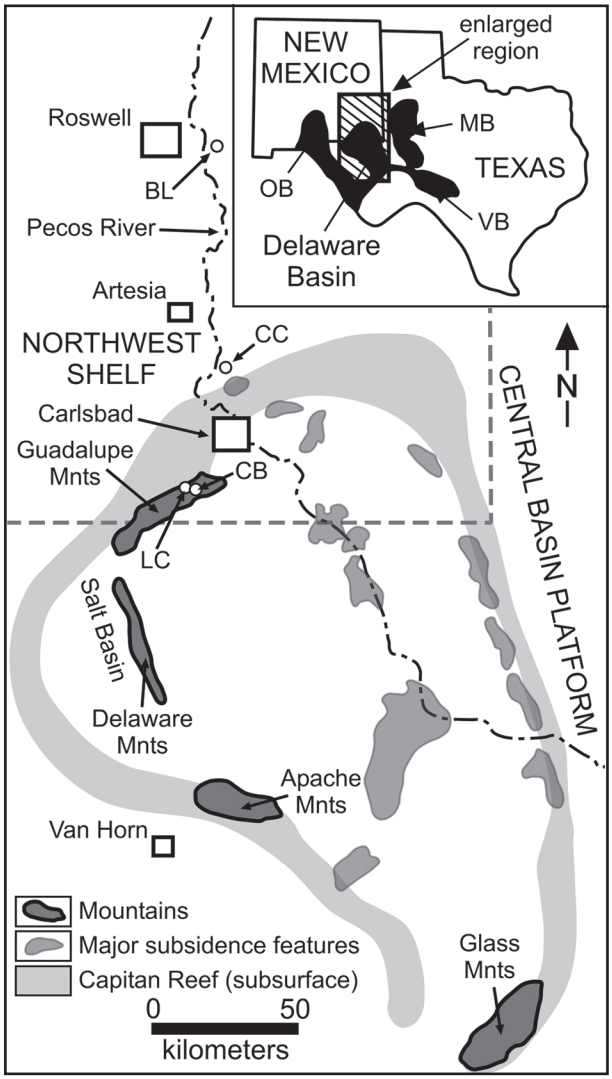

Figure 1: Map of Delaware Basin showing the geographic relationships between the Capitan Reef, major subsidence features and the Pecos River. BL = Bottomless Lakes State Park, CC = Coffee Cave, CB = Carlsbad Cavern, LC = Lechuguilla Cave, OB = Orogrande Basin, MB = Midland Basin, VB = Valverde Basin (adapted from Klimchouk, 2007).

2. Delaware Basin

The Delaware Basin covers an area of ~33,500 km^2 (Fig. 1) and represents one of the deepest intracratonic basins within the United States (Hill, 1996). Permian strata comprise 95% of the units exposed within the Delaware Basin, including both carbonate and evaporite facies (Fig. 2) (Kelley, 1971). The basin is delineated by the Permian Capitan Reef complex, which forms a narrow carbonate belt 600 to 700 km long around the periphery of the basin (Fig. 1). The Capitan Reef crops out in the Guadalupe, Apache and Glass Mountains. The Northwestern Shelf bounds the north and western portion of the Delaware Basin where interbedded carbonates, evaporites and siliciclastics were deposited in a shallow, shelf environment inland of the Capitan Reef. The basin interior is filled largely with evaporite facies. At the time of deposition, the Delaware Basin was located within 5 to 10° of the equator on the western edge of Pangea (Scholle et al., 2004).

The Delaware Basin was part of the larger Tobosa Basin from the latest Precambrian through the Late Mississippian, with continuous deposition and tectonic quiescence (Hill, 1996). During the Pennsylvanian, collision of Laurasia and Gondwana produced the Ouachita Orogeny coupled with block faulting in the Tobosa Basin, which separated it into the Delaware Basin, Central Basin Platform and the Midland Basin (Horak, 1985). Collision continued through the early Permian, but had effectively ceased by the middle Permian, as the Delaware Basin once again entered a period of tectonic stability.

During the middle Permian, the Delaware Basin was connected to the Panthalassa Ocean via the Hovey Channel, which maintained open marine circulation enabling the prolific growth of the Capitan Reef (Scholle et al., 2004). During the late Permian, the Hovey Channel closed and the interior of the Delaware Basin became hypersaline, resulting in a shift from carbonate dominated deposition to evaporite dominated deposition in the late Permian. By the end of the Permian, evaporite strata had completely filled the interior of the Delaware Basin and had extended across the Capitan Reef and onto the Northwestern Shelf (Scholle et al., 2004).

In the Triassic, the Delaware Basin region was uplifted above sea level and throughout the Mesozoic the region was dominated by erosion and fluvial entrenchment (Kelley, 1971). During the middle Cretaceous, a period of marine transgression flooded the region resulting in a brief period of clastic and carbonate deposition. By the end of the Cretaceous, the Laramide Orogeny began, which resulted in an additional 1.2 km of uplift, regional tilting to the east and the development of broad anticlinal flexures (Horak, 1985). In the early Neogene, Laramide Orogeny shifted to Basin and Range extension with associated higher geothermal gradients (Barker and Pawlewicz, 1987), but by the late Neogene the region was effectively tectonically stable once again. Throughout the Cenozoic, the Pecos River persisted within the Delaware Basin, as it migrated laterally in response to uplift, and surface denudation.

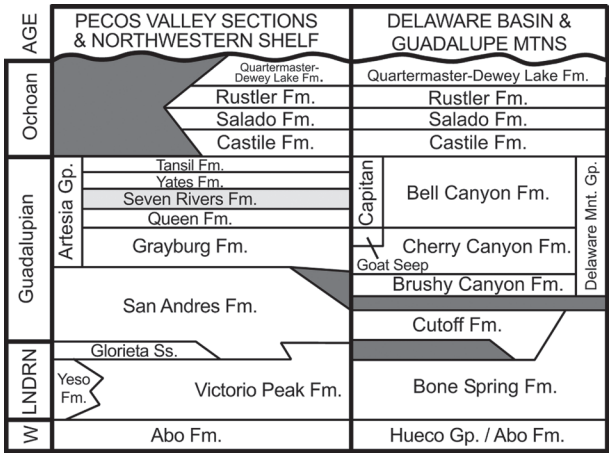

Figure 2: Stratigraphic chart of Permian facies in southeastern New Mexico with comparison of stratigraphic units within the Pecos Valley / Northwestern Shelf and the northern Delaware Basin / Guadalupe Mountains. Coffee Cave is developed in the Seven Rivers Formation (highlighted in gray). W = Wolfcampian; LNDRN = Leonardian (from Stafford et al., 2008a).

3. Hypogene Karst of the Capitan Reef

Cavernous porosity within the Capitan Reef has been associated largely with sulfuric acid processes based on secondary minerals (e.g. gypsum, native sulfur) found in caves throughout the Guadalupe Mountains (Hose and Pisarowicz, 2000). Many of the caves in the Guadalupe Mountains (e.g. Carlsbad Cavern, Lechuguilla Cave) consist of large isolated chambers, maze sections and multiple levels (Fig. 3), suggestive of dissolution in a confined or semi-confined setting involving sluggish flow. Cave development is found throughout the reef and forereef facies of the Capitan Reef and extends into the near-backreef equivalents of the Artesia Group (Fig. 2). Abundant suites of morphometric features, including cupolas, ceiling channels, half tubes and risers, are found throughout the Capitan Reef caves providing further evidence for solutional origins within a hypogene system. Caves similar to those found in the Guadalupe Mountains, although much smaller and less developed, are rumored to exist within the Apache and Glass Mountains.

Massive accumulations of secondary gypsum attest to a significant role of sulfuric acid in the development of solutional porosity throughout the Capitan Reef (Hose and Pisarowicz, 2000). Hose and Pisarowicz, (2000) reported that sulfuric acid-rich fluids were derived from hydrogen sulfide produced as a byproduct of evaporite calcitization

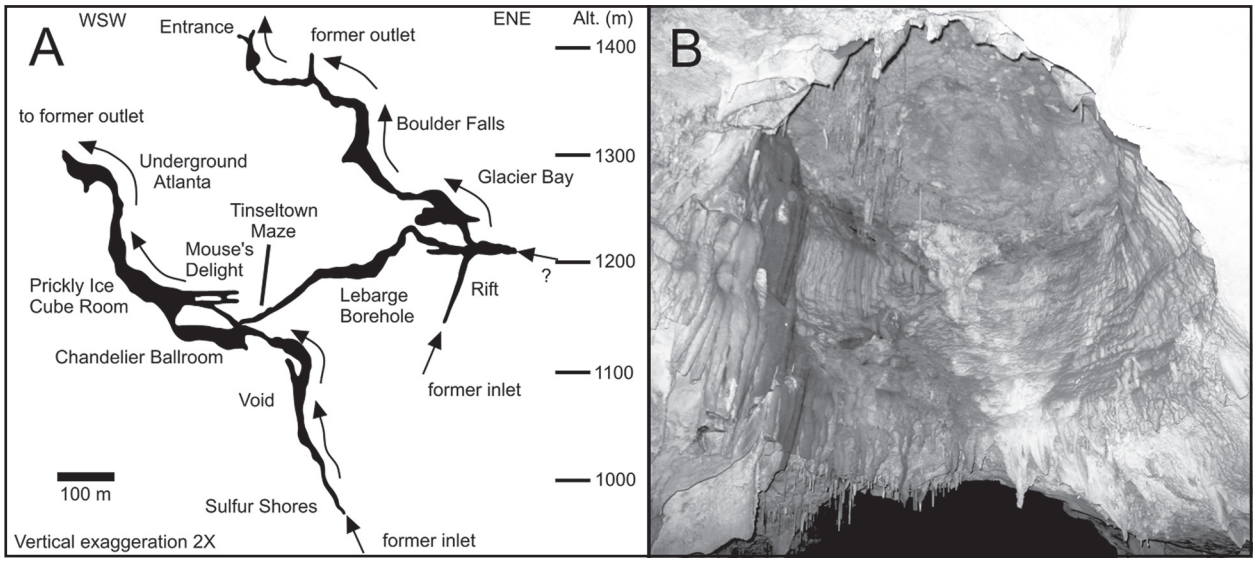

Figure 3: Guadalupe Mountains. A) Simplified profile view through part of Lechuguilla Cave in the Guadalupe Mountains shows the flow paths of ascending fluids (from Palmer and Palmer, 2000); b) typical cupola (~4 m in diameter) in a Guadalupe Mountains hypogene cave.

within the Castile Formation of the Basin Interior, which then migrated laterally into the Capitan Reef. However, Duchene and Cunningham (2006) suggested that the hydrogen sulfide originated from the Artesia Group and the interior platform, which has been further supported by recent studies of regional evaporite calcitization (Stafford et al., 2008c). Regional tectonic studies have shown that geothermal gradients were as high as 40 to 50°C/km in the Neogene (Barker and Pawlewicz, 1987). This would have increased the solutional aggressivity of rising fluids within the Capitan Reef. While thermal and sulfuric acid components increased the solutional aggressivity, Klimchouk (2007) suggests that the migration of the Pecos River across the Guadalupe Mountains provided the regional potentiometric low for the upward migration of fluids. Terrace levels throughout the Guadalupe Mountains record the eastward migration of the Pecos River throughout the Cenozoic (Klimchouk, 2007). Therefore, the mixed convection system that formed the hypogene caves of the Guadalupe Mountains is likely the result of forced convection directed towards the potentiometric low created by the eastward migration of the Pecos River and density convection associated with increased solute loads and cooling fluids as ascending aggressive fluids become cooler and saturated.

Along the eastern edge of the Delaware Basin (Fig. 1), additional manifestations of karst development within the Capitan Reef occur as a series of large subsidence features (Hill, 1996). Focused discharge from the Capitan Reef has produced large, vertical stoping features through the overlying evaporites (Hill, 1996). It is likely that extensive hypogene cave systems exist within this buried section of the Capitan Reef. These large subsidence features have developed because fluids rising out of the Capitan Reef are expected to be undersaturated with respect to gypsum and halite, which would make them solutionally aggressive as the ascending fluids passed from the carbonate facies of the Capitan Reef into the overlying evaporite facies. Further research needs to be conducted on the extent of karst development in the Capitan Formation outside of the Guadalupe Mountains.

4. Hypogene Karst of the Northwestern Shelf

The Northwestern Shelf is composed of interbedded carbonates, evaporites and siliciclastics, the inland shelf equivalent of the Capitan Reef. Cave development is widespread throughout the Northwestern Shelf, specifically in the San Andres, Seven Rivers and Rustler Formations (Fig. 2). In the near back reef, cave development in the Guadalupe Mountains merges with back reef karst development as massive limestones of the reef complex merge into flat lying, bedded carbonates. Further inland, bedded limestones become interbedded carbonates and sulfates indicating deposition in shallow waters that were restricted and even subaerialy exposed at times. Even more distal to the reef complex, strata is interbedded with siliciclastics recording the transition from shallow marine deposition to terrestrial environments in the Permian.

In the near backreef facies of the Northwestern Shelf, extensive maze caves have developed Seven Rivers and Yates Formations. Caves in this region (e.g. McKittrick Hill Caves) show multiple levels of development that forms complex three dimensional network mazes. The caves commonly contain abundant secondary gypsum deposits as well as other secondary minerals (e.g. endellite, alunite) indicative of solutional fluids with a sulfuric acid component. Throughout the cave, morphogenic hypogene features are abundant (Klimchouk, 2007). These caves clearly show evidence of hypogene origins, illustrating how minor heterogeneities in bedrock produce complex hypogene systems in bedded carbonates, similar to that which has been long-documented in the great gypsum maze caves of the western Ukraine (Klimchouk, 2007)

More distally inland from the Capitan Reef, karst development is well-developed in the carbonate / sulfate interbedded facies of the Seven Rivers Formation. This region is well known for its artesian wells, as evidenced by the town named Artesia, which attests to the importance of rising fluids within the region today. Both large vertically stoping collapse features (Fig. 4a), reminiscent of cenotes, and complex three dimensional maze caves (Fig. 4b) occur along the Pecos River (Stafford et al., 2008a). Here, waters that were recharged to San Andres Formation on the Pecos Slope to the west are semi-confined beneath overlying evaporite rocks (Fig. 4c). The Pecos River has acted as a potentiometric low within this area since at least the mid-Neogene and continues today (Stafford et al., 2008a). Therefore, semi-confined fluids have risen towards the Pecos River through the forced convection induced by the potentiometric low, while free convection has enabled the solution of complex hypogene cave networks in the Seven Rivers evaporites.

Additional hypogene karst development is found throughout the shelf facies, including widespread intrastratal dissolution and brecciation (Stafford et al., 2008a). East of the modern Pecos River, clusters of hypogene caves are common in the Rustler Formation, possibly representing paleo-discharge features associated to the ancestral Pecos

River as it has migrated laterally across southeastern New Mexico. Many of the caves throughout the Delaware Basin shelf facies have been traditionally associated with paleo-epigene processes that invoked significantly different climate regimes in the past (Kelley, 1971); however, many of the caves show clear evidence of having formed by ascending, hypogene fluids which does not require significantly different climatic regimes.

5. Hypogene Karst of the Basin Interior

Within the interior of the Delaware Basin, hypogene karst falls largely within three varieties: 1) hypogene karst associated with the Pecos River; 2) intrastratal brecciation; and 3) sulfate diagenesis of the western Delaware Basin. Cave development within the basin interior occurs throughout late Permian, basin-filling evaporites including those of the Castile, Salado and Rustler Formations (Hill, 1996). The Castile Formation fills the entire Delaware Basin, while the Salado and Rustler Formation cover the basin interior, as well as the Capitan Reef and the shelf margins in locations where these units have not been removed through regional uplift and surface denudation (Kelley, 1971).

The Pecos River currently flows through the eastern half of the Delaware Basin. Along this route several large subsidence troughs have formed, which have been largely filled with Quaternary fluvial deposits (Hill, 1996). These subsidence troughs have been attributed to intrastratal dissolution and upward stoping. In this model, fluids originating in the underlying clastic units of the Delaware Mountain Group have migrated upwards through the overlying evaporites, resulting in vertical collapse structures

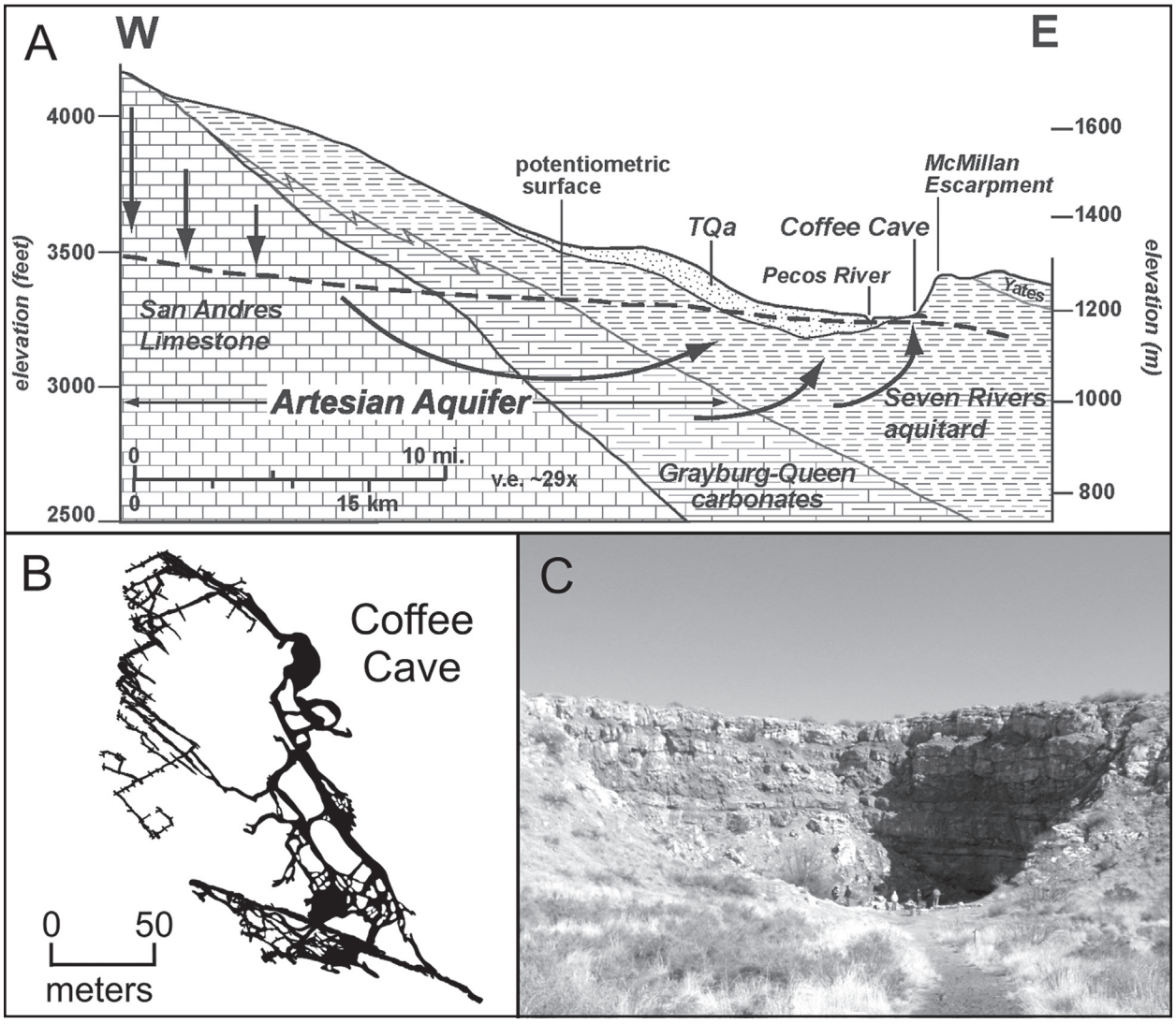

Figure 4: Northwestern Shelf. (A) Hydrostatrigaphic section showing relationship between Coffee Cave and the underlying Artesian Aquifer (from Stafford et al., 2008a); (B) Plan view outline map of Coffee Cave showing maze pattern (from Stafford et al., 2008a); (C) Large collapse structure near Roswell, New Mexico. Note people in middle of photo for scale.

(Hill, 1996). The location of these hypogene voids was likely driven by the potentiometric low created by the Pecos River, while ascending solutionally aggressive fluids were constantly replenished at the dissolution front through brine density convection.

In the western Delaware Basin, extensive evaporite karst development occurs in the Castile and Rustler Formations. Caves are highly clustered throughout the outcrop area of the Castile and Rustler Formations suggesting focused, upward migration of fluids (Stafford et al., 2008b). Caves range from simple steeply rising structures to complex three dimensional maze-like caves (Fig. 5a). Complete suites of morphogenic features indicative of hypogene fluids are commonly found in these caves. In addition, evaporite calcitization is widespread throughout the Castile Formation (Fig. 5b), where ascending light hydrocarbons have fueled sulfate reduction (Stafford et al., 2008c). Commonly, clusters of calcitized evaporites and caves exhibiting evidence of hypogene origins are found in high densities, suggesting the two are genetically related. These clusters of intense hypogene diagenesis result from the combination of: 1) waters ascending from the Delaware Mountain Group that have migrated downdip from their recharge region in the Delaware Mountains to the west; and 2) upward migration of light hydrocarbons, likely methane, from deeper within the strata of the Delaware Basin. In association with both caves and zones of calcitization, intrastratal brecciation is common (Stafford et al., 2008b,c).

Throughout the Delaware Basin interior intrastratal dissolution is widespread. Anderson and Kirkland (1980) recognized vertical breccia pipes that cut across the late Permian evaporite deposits, including the Castile, Salado and Rustler Formations. They attributed these features to deep subsurface dissolution at the contact with underlying transmissive clastics, which then stoped upwards and continued to enlarge as more aggressive waters were supplied from the underlying clastic units. Similarly, Anderson et al. (1978) identified widespread blanket brecciation within these same late Permian evaporites. The blanket breccias are the result of intrastratal dissolution of halite interbeds, which are more soluble than the surrounding sulfate units. As a result of halite dissolution, overlying sulfates collapsed producing widespread brecciation. While blanket breccias and breccia pipes are not hypogene caves, they formed through the same process involving sluggish, mixed flow regimes in a confined or semi-confined setting.

6. Conclusions

Throughout the greater Delaware Basin region, karst is extremely well developed with abundant evidence of hypogene origins found in individual caves and other karst features. However, these features are now exposed at the Earth surface, where they are currently being overprinted by epigene processes. While some features show minimal overprinting, others show extensive overprinting, making it difficult to positively identify them as having originally formed in a hypogene setting. While many features in the region were originally attributed to special fluid chemistries, current advances are showing that these features are actually the result of hypogene processes where solutional aggressivity was simply enhanced by fluid chemistry and / or temperature. As karst science continues to evolve, better models will undoubtedly be developed for karst development throughout the Delaware Basin.

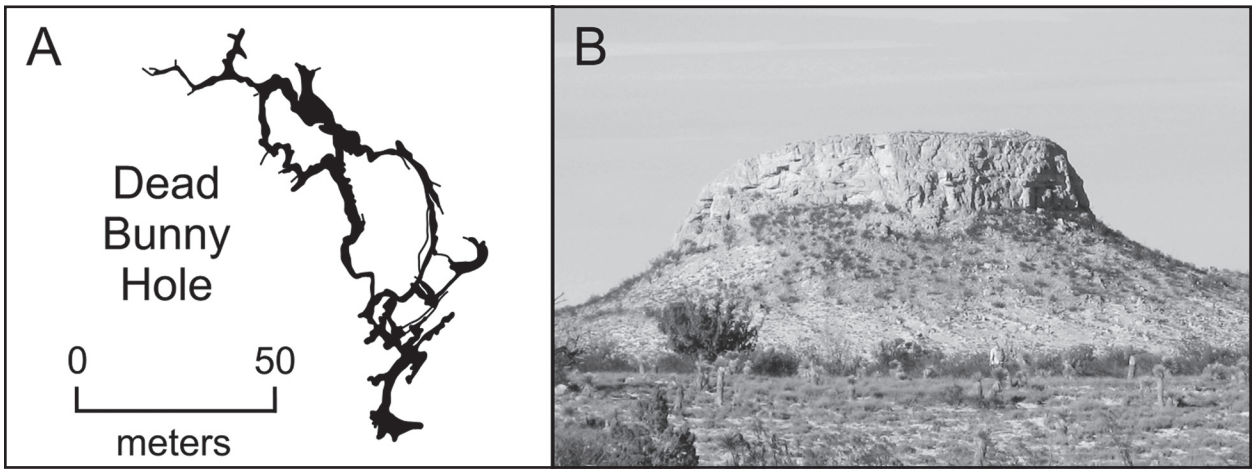

Figure 5: Basin Interior. (A) Plan view map outline of Dead Bunny Cave showing maze cave development in the Castile Formation (from Stafford et al., 2008b); (B) Typical calcitized mass in the Castile Formation, forming a resistant mass as unaltered gypsum continues to erode away around it. Note person in foreground for scale.

However, recent studies are pointing towards a basin-scale speleogenetic province that is dominated by hypogene processes related to regional tectonic history coupled with evolution of the Pecos River, which has been persistent in southeastern New Mexico and west Texas since the late Cretaceous.

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TYPOLOGY, GENESIS, AND EVOLUTION OF TUNNEL-CAVES IN SOUTHWESTERN CHINA

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A tunnel-cave is a system involving a sinkhole, a large underground river (several m^3/s), and a resurgence. Three main types occur: natural bridges, single-tunnels, and tunnel-cave levels, including eclipse (blind) valleys. Their genesis requires: 1/ a large catchment area in impervious rocks upstream, 2/ limestone rocks downstream, 3/ a subtropical climate with abundant rainfall. Tunnel-caves are able to evolve over millions of years provided they have a sufficient limestone thickness. Tunnel-cave levels are caused by the combination of strong uplift and underground piracy.

1. Typology of Tunnel-Caves

The typology of tunnel-caves is based on the work of Maire et al. (2004).

Natural bridge is the translation of *tian sheng qiao*, introduced by the chinese geographer Xu Xiake in the 17th century (Xu Xiake translation, 1993). It corresponds to a short gallery, less than 100 m long. Two geneses can be considered: most frequently the ceiling of a cave has collapsed except for a short expanse which is more resistant. The bridge is then the relict of an underground passage, which was considerably larger (fossil or active tunnel-cave) and is now almost completely unroofed by erosion and collapse. Tianshenqiao-Gedahe (Panxian, Guizhou) is a residual piece of a tunnel-cave. It is 50 m high below the ceiling, which is only 20 m thick (Fig. 1).

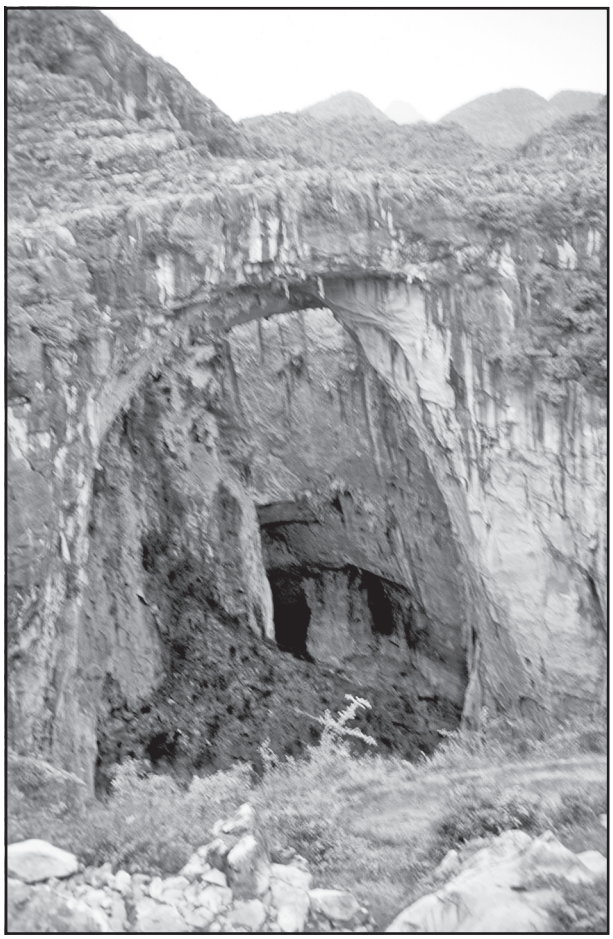

Figure 1: Natural bridge of Tianshengqiao related to the old Gedahe through cave (Panxian County, Guizhou); N. Vanara, 2000.

Travertine buildups are less common. Near the Lunan stone forest (Shilin, Yunnan), a river (20 m^3/s max.) flows

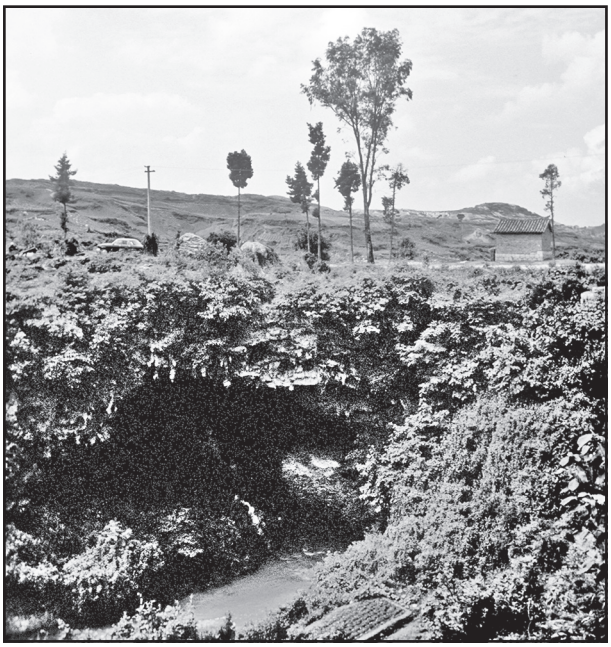

Figure 2: Travertine natural bridge in the stone forest area (Shilin, Yunnan); JP Barbary, 1988.

through a fossil travertine dam (arch ~ 20 m high, 50 m wide, roof 10 m thick; Fig. 2).

Tunnel-bridge is a transition between natural bridge and tunnel-cave. They are between 100 to 300 m long. The daylight is sufficient to allow exploration without artificial lighting. Residual parts remain between collapsed galleries. The tunnel-bridge of Yijie (Zhijin, Guizhou; Fig. 3) is 100 m long with a 120 m high gallery and a roof thickness of 70 m. The passage segments occur where the river is diverted through ridges of limestone or where meander cutoffs occur, which could be either phreatic or vadose. Dongshuandong (Lemin, Guizhou; Fig. 4) crosses a Permian limestone barrier in a gallery 60 m long, 25 m wide and 30 m high.

Figure 3: The natural-bridge of Daxiaocoakou 120 m high is located on the way of the Yijiehe through cave (Zhijin County, Guizhou); Guizhou Expedition 1986.

Tunnel-caves are more than 300 m long**. Single-tunnel** is the simplest form. The Yanfengdong sinkhole, underground river and resurgence (Ganhedong) are located in the south-east part of the Yunnan plateau (Shizong). The entrance, 190 m high, was formed at the contact between impervious rocks and a Triassic limestone outcrop, which is 1200 m wide. After a flood in August 1996 (120 mm rainfall in 26 hours), the middle passage of the through-cave, which is at the greatest depth, was filled with pebbles. Cave exploration could also be stopped by flooded sections**: flooded single-tunnel** or **flooded tunnels** if several galleries are present. Dadong is a 100 m-high porch opening at the end of a blind

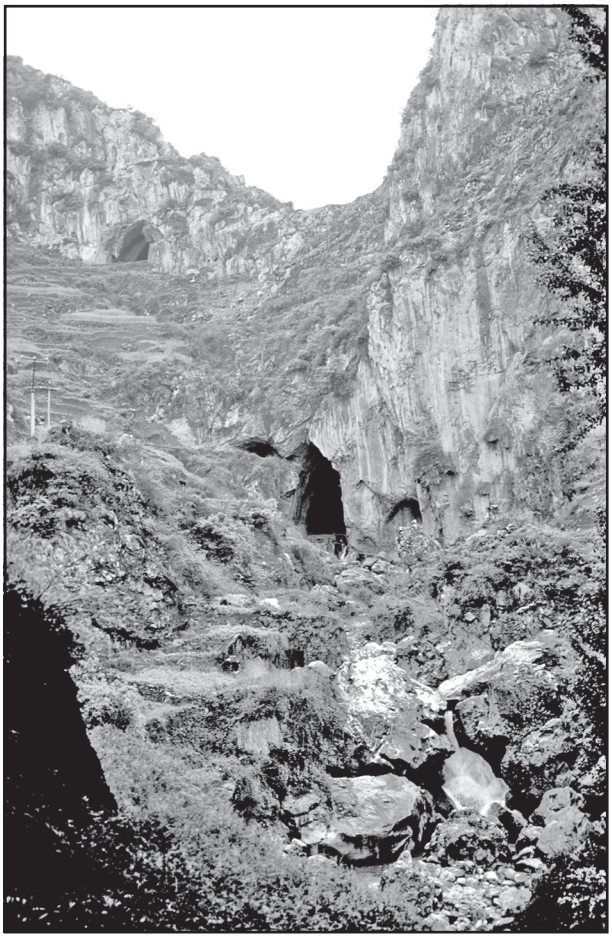

Figure 4: Lower entrance of the Dongshuangdong tunnel-bridge. Here the river crosses a big fault (Lemin, Panxian County, Guizhou); N. Vanara, 2000.

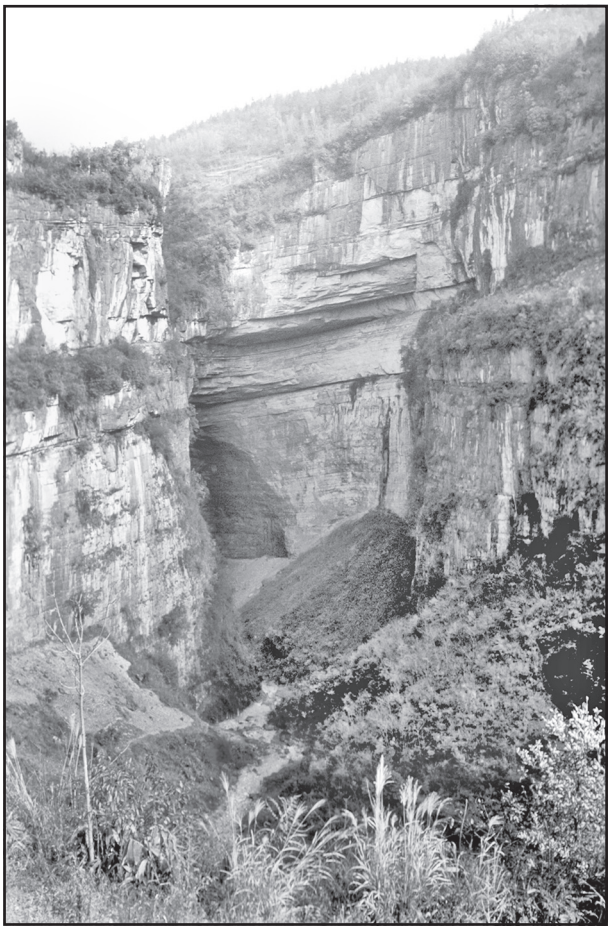

Figure 5: The entrance porch of Dadong tunnel-cave (Wufeng County, Hubei), 100 m high, is located at the end of a blind canyon; R. Maire, 1992.

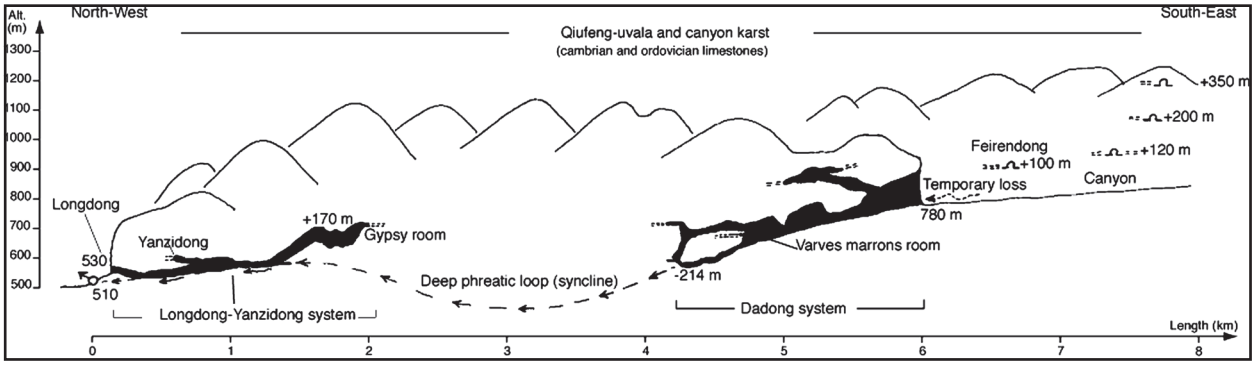

Figure 6: Synthetic section of the Dadong-Longdong tunnel-cave (Wufeng County, Hubei). We notice a saturated level in the syncline part.

canyon (Fig. 5). The huge entrance (50 m wide, 100 m high) splits into several "smaller" passages. The deepest one ends at -556 m and is clogged by pebbles, trunks, and branches. After a deep phreatic loop beneath the syncline, the river reappears 3 km downstream (-560 m) in the Longdong resurgence (Fig. 6). Flooding of the downstream part is caused by the tiny gradient of the river, by the head losses, and by the deltaic organization of the passages. Depending on geomorphological conditions, these basic types can have either a vertical (Waltham, 2005), or a horizontal pattern.

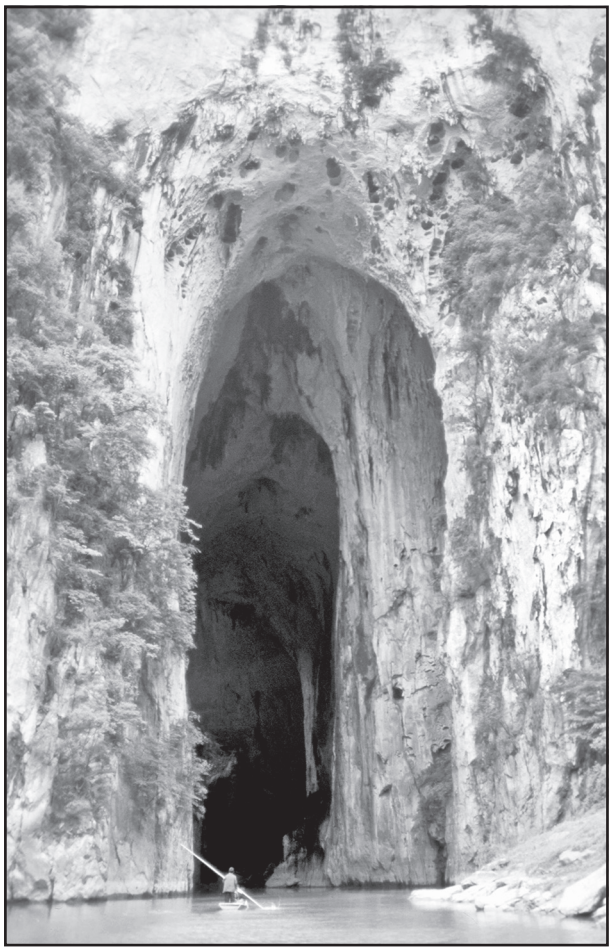

Figure 7: The Gebihe sinkhole entrance is 116 m high (Ziyun County, Guizhou); R. Maire, 1999.

Tiers of tunnel-caves extend vertically. The Gebihe (Zihun, Guizhou) has five levels. An active sinkhole and gallery at base level (Fig. 7); fossil gallery at level 2 (+100 m); tunnel bridge at level 3 (+226 m); porch at level 4 (+350 m); collapsed porch at level 5 (+370 m) (Fig. 8). The Himalayan uplift stages of the Neogene are recorded by the successive lowering of sinkholes and by vertical connections (370 and 210 m-deep shafts). Collapsed ceilings clearly show the limestone denudation and lowering of the topography.

Eclipse ("blind") valleys extend horizontally, with a succession of surface flow and underground passages, such as Wutuhe (Panxian, Guizhou). This system includes: 1/ Yunihe tunnel-cave with a resurgence located 3 km downstream; 2/ a 2 km-long canyon; 3/ Gedahe tunnel cave (1340 m surveyed) with a resurgence located 2.3 km downstream; 4/ a 1.5 km-long canyon; 5/ Liuchehe tunnel with a resurgence located 1.8 km downstream; 6/ Wutuhe, a deep-entrenched pocket-valley (Fig. 9). Eclipse valleys can also be the result of an original single-tunnel becoming canyon due to successive collapses such as Yijiehe (Zhijin, Guizhou; Fig. 10). Abundant boulders in the talweg clearly show that all the canyons are caused by a recent collapse of the ceiling.

2. Origin, Evolution, and Destruction of Tunnel-Caves

Such a diversity of karst features results in diverse scenarios, including genesis, evolution, and destruction. Nevertheless, a general scenario appears. The first condition is a surface river. For instance, the Gesohe tunnel-cave (Panxian, Guizhou) develops beneath a 3.5 km-long dry valley, perched 100 m above the resurgence (Fig. 11). Entrenchment ended after the underground capture,

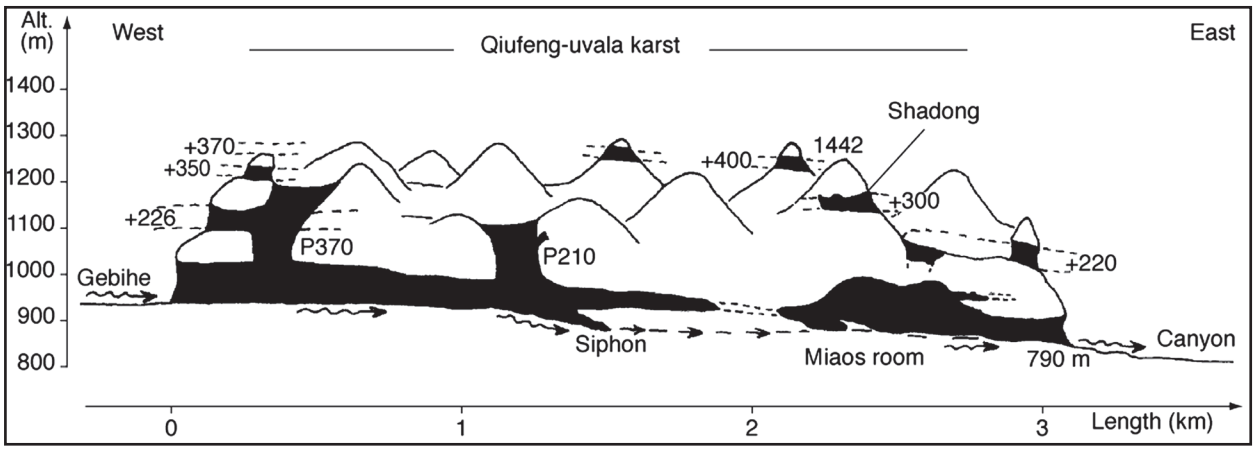

Figure 8: Synthetic section of the Gebihe staged tunnel-cave (Ziyun County, Guizhou).

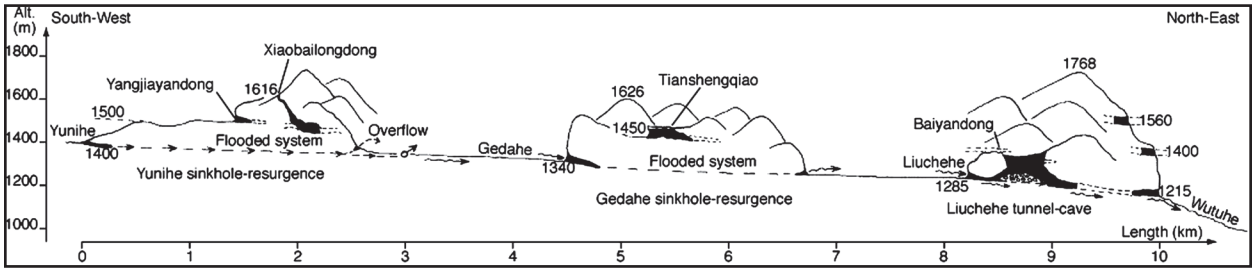

Figure 9: Synthetic section of the tunnel-caves system of Wutuhe (Panxian, Guizhou).

Figure 10: Sinkhole of the Yijiehe tunnel-cave (Zhijin County, Guizhou); R. Maire, 1989.

caused by the continuous uplift. The tunnel appears when the impervious covers are breached, causing a sinkhole to develop (binary karst). Huangguoshu, a Beipanjiang affluent, has sinkholes along the riverbed, especially near a 250 m –long limestone outcrop. During high water, about 100 m^3/s sinks into an incipient tunnel-bridge. Above this threshold, the river overflows onto the surface. Considerable pressure and steep gradients produce strong mechanical erosion and a rapid evolution. A tunnel survives by giving life to other tunnels. The three necessary conditions required for tiered tunnels are found in Southwestern China: 1/ limestone thickness (Yangtze plateau limestones are 1,000 m thick), 2/ considerable uplift; the motion of the Indian plate toward the Asian continent caused a general uplift of South China from Middle Tertiary onward; and 3/ active karst development. Subtropical climate causes large river discharges. Due to the lag between uplift and karst development, surface runoff first prevails, while groundwater flow is incipient. Thereafter, when underground flow develops, capture occurs, with a piracy of the flow from the oldest sinkhole to the youngest one. The transition phase is characterized by a complete absorption in low water and temporary runoff in the highest level only during high water, which acts as an overflow. A senile tunnel is characterized by residual galleries: above the 32 km-long Tenlongdong-tunnel (Masschelein and Zhang, 1988), the older level has wide cave segments (Fig. 12).

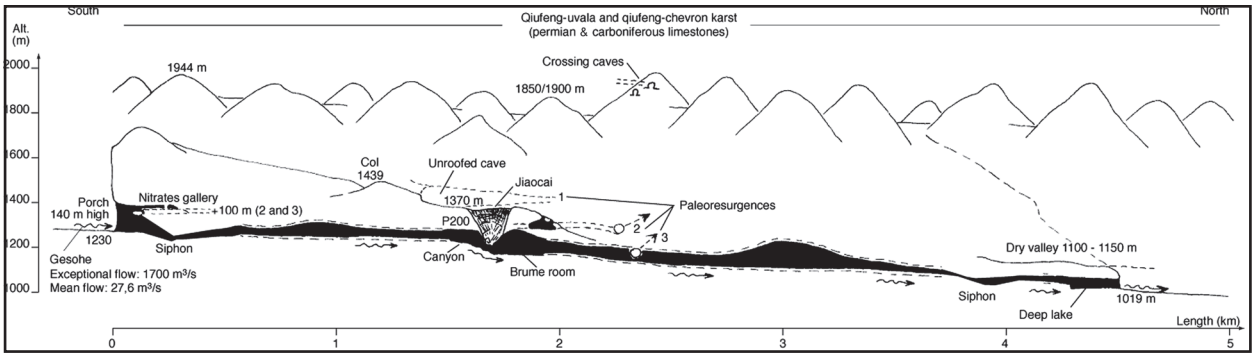

Figure 11: Synthetic section of the Gesohe tunnel-cave (Panxian, Guizhou).

Figure 12: *Above Tenglongdong Cave, eroded tunnel without roof looking like a dry valley (Lichuan County, Hubei).*

The debate is still open between two possible geodynamic inputs:
- discontinuous uplifts, where cave level records stability periods;
- continuous uplifting, where cave level records the delayed response of cave development (hysteresis).

Based on numerous field studies (Gebihe), it appears that cave levels are most frequently a combination of both hypothesis. Southwestern China offers to cavers and karst scientist a huge field of investigation, with both fossil and living karst.

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MESSINIAN KARST IN MONFERRATO GYPSUM AREAS (NORTH ITALY)

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An important more or less continuous Messinian evaporite sequence crops out in the Tertiary Basin of Piedmont (North Italy). The entire thickness of the evaporite sequence ranges between a few metres to over 70 m, due to an important Messinian post-evaporitic erosional event followed by a thick silty-argillaceous sequence of Upper Messinian age. Deep karst was believed to be rare in this poorly exposed gypsum formation until a large natural cavity was intercepted in an underground quarry near Moncalvo causing a catastrophic collapse at the surface. Here, these active phreatic conduits are developed for more than 1 km, with voids of 10 meters in diameter, developed mostly below the level of present thalwegs. Similar large phreatic voids have been found in several boreholes in other nearby areas where gypsum is quarried underground.

Combined observations of cave morphology and hydrology show that at least part of the water responsible for the dissolution of gypsum comes from an extremely karstified thin limestone bed at the bottom of the Messinian evaporite sequence. The presence of cave morphologies such as feeders in several parts of the karst galleries confirms this hypothesis. The water flowing in this limestone bed is of surface origin, as the high nitrate contents and the positive Eh clearly demonstrate, and has fast recharge. It probably derives from a combination of fast recharge of the limestone aquifer by open fractures in the overlying gypsum and marl formations and small amounts of slowly infiltrating waters having negative Eh and very low nitrate contents, coming from the dense but tight fissure network in the gypsum.

Observations lead to the hypothesis of an intra-Messinian epigenic karst cycle that started cave development, followed by a hypogenic stage still active today: 1) in many parts of the area gypsum beds have been extensively karstified although outcropping in very small areas and at present being sandwiched between Pre-Messinian and Upper Messinian-Pliocene impermeable clay- and siltstones; 2) the partially remobilised Burdigalian-Lower Pliocene fauna associations in cave sediments agree with a Messinian age of the voids they occupy. Their mobilisation with the Pliocene impermeable cover in place is highly improbable; 3) most karst conduits in gypsum have been discovered well below the present valley bottoms, and their genesis is difficult to explain in a phreatic situation between two impermeable beds. It is likely these voids at least started forming during the intra-Messinian uplift periods, when they were above local base level and not yet covered by impermeable Messinian post-evaporitic and Pliocene sediments.

1. Introduction

In the Monferrato area North of Asti (Piedmont Region) (Fig. 1) gypsum belonging to the *Formazione Gessoso Solfifera* (also called *Complesso Caotico della Valle Versa*) of Messinian age (Dela Pierre et al*.,* 2006) is quarried underground by Fassa Bortolo S.p.A.. This evaporite sequence crops out in a discontinuous manner for 35 km. The general stratigraphy of the study area is characterized, from bottom to top, by marly clayey deposits of Tortonian age capped by a thin bed (less than 1 m thick) of evaporitic limestone, followed by a succession of gypsum beds separated by marly layers of 0.3 to 3.0 m thick of Messinian age. These marl-gypsum sequences correspond to subsequent evaporite cycles with initial deposition of fine material (marls) followed by gypsum deposited in an increasingly salty brine, generally showing macrocrystals in the lower part and, due to increasing supersaturation, microcrystals at the end of the cycle (Vai and Ricchi Lucchi, 1977). The entire thickness of the evaporite sequence ranges between a few meters to over 70 m, due to an important Messinian post-evaporitic erosion surface that separates this succession from an overlying thick silty-argillaceous sequence of Upper Messinian-Pliocene age. While small caves have been exposed in quarries in the upper gypsum layers, close to

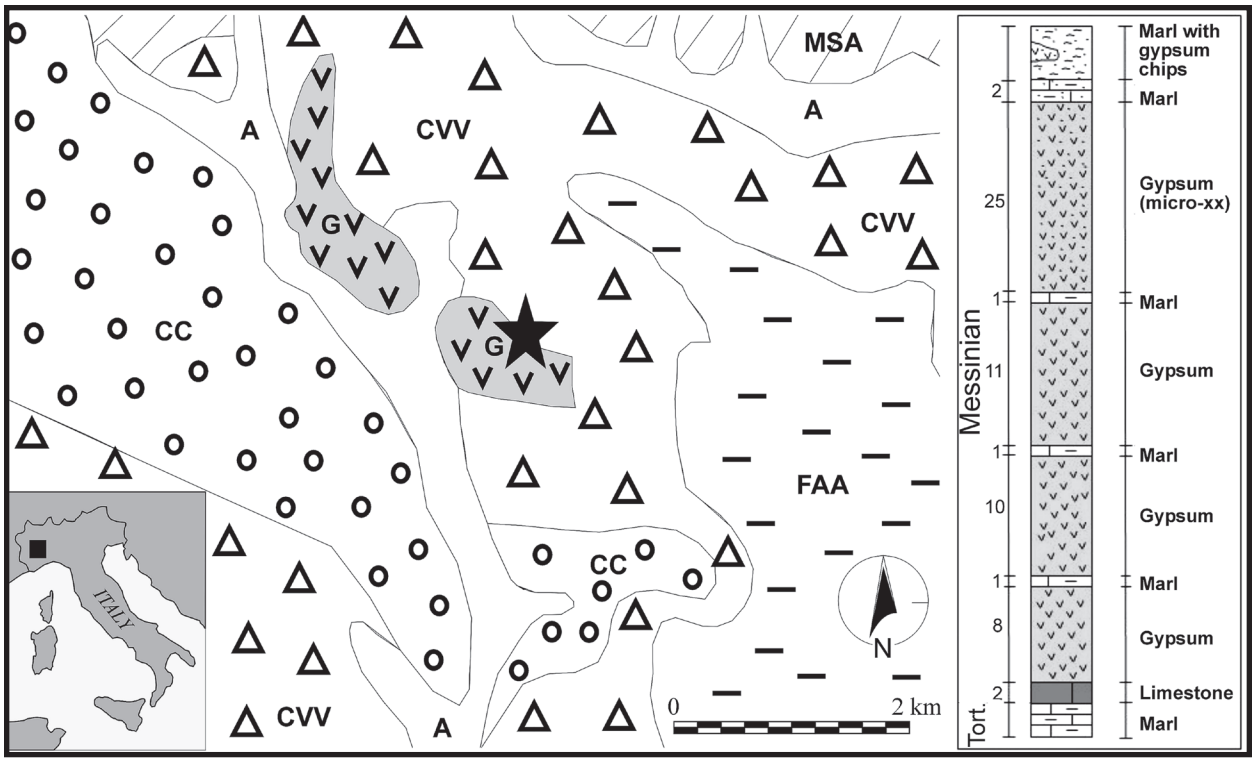

Figure 1: Simplified geological map and stratigraphic column of the study area.

the surface (Fig. 2A), deep karst was believed to be weakly developed in this poorly exposed gypsum formation until a large natural cavity was intercepted in an underground quarry near Moncalvo causing a catastrophic collapse at the surface on February 15, 2005 (Fig. 2B) (Vigna et al., 2009). Here, these active phreatic conduits are more than 1 km long, with voids of 10 m in diameter, developed mostly below the level of present thalwegs. Similar large phreatic voids have been found in several boreholes in other nearby areas where gypsum is quarried underground. A detailed geomorphological and hydrogeological study has been carried out in many quarries of the area to try and understand the genesis and the evolution of these voids.

2. Geological and Geomorphological Observations

The exploited gypsum deposit is generally massive macro- and microcrystalline beds 10-15 meters thick separated by marly interstrata of varying thickness between a few decimeters and a few meters thick (Fig. 2A). This evaporite sequence is sandwiched between lower and upper more or less impervious sediments (marls and clays of Tortonian and Messinian-Pliocene age respectively). This confined stratigraphic situation, typical of many gypsum deposits in the world, can lead to the development of an intrastratal karst (Klimchouk and Ford, 2000), where water is delivered from the adjacent sediments both from above (epigenic) and from below (hypogenic). In the case of Moncalvo, since entrenchment of the surface drainage system has not completely dissected the gypsum formations, the karst system can be defined as subjacent and/or deep-seated (Klimchouk, 1996). Before the end of Messinian age these gypsum beds were exposed for a more or less short time to meteoric agents in a continental setting, before being submerged again in the Late-Messinian sea getting covered with the above mentioned impermeable clayey sediments. Evidence of gypsum dissolution, especially in the uppermost evaporite beds, has been found in the underground quarries, where small karst cavities have been cut by the drifts. These caves are rarely accessible by man and, if they are, show modest development. The same sort of cavities can be seen in the open air quarry of Moncalvo at an altitude of 190 m asl (Fig. 2A) and also in the northwestern part of the nearby underground excavations, at 150 m asl. All of these caves do not penetrate deep into the gypsum sequence and seem to be confined to the uppermost layers, generally above or not far below the water table (Fioraso et al., 2004). Along the over 12 km of drifts in the Moncalvo underground quarry fractures are rarely encountered, and these sometimes carry small quantities of water (Figs. 2C-D-E). Most of these water-bearing fractures are located in the southeastern part of the quarry between altitudes of 129 and 150 m asl. Only two major caves have been discovered during mining operations. In general the caves are characterized by phreatic

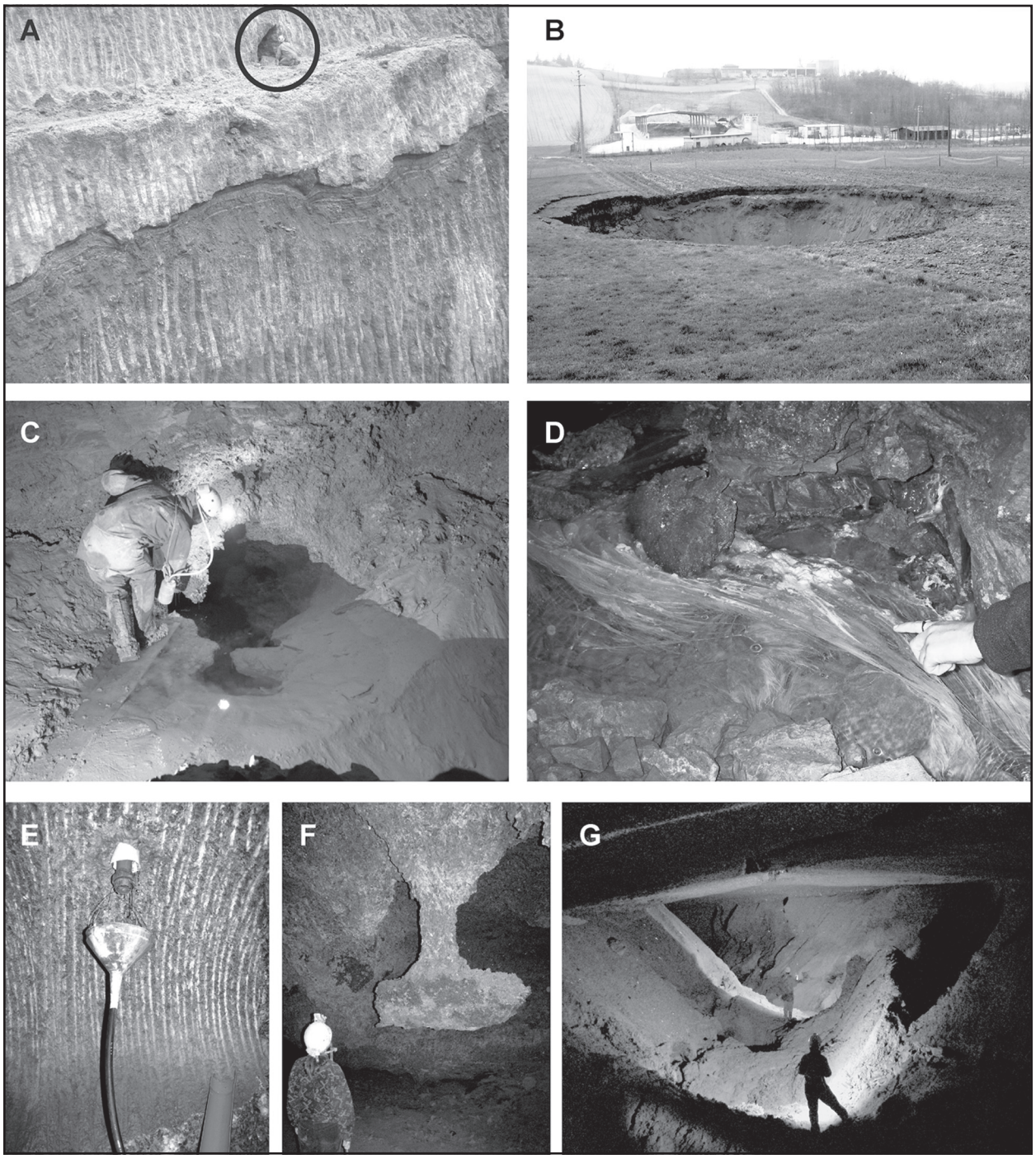

Figure 2: Moncalvo: (A) open air gypsum quarry with small intercepted caves (circle); (B) sinkhole at Moncalvo, caused by interception of a karstic cave on February 15th 2005 and consequent collapse into the underground quarry; (C) water upwelling from karstic conduits in the cave (VS); (D) water rising from fissures with bacterial colonies (VB); (E) water intercepted in fissures in the quarry drifts (VC-VF); (F) gypsum pendant in the Moncalvo cave; (G) corrosion bevel in one of the caves.

morphologies and their development has entirely occurred in underwater conditions. There are no traces of speleothems and the roof has a smooth surface with occasional cupolas, megascallop-like morphs, ceiling pendants (Fig. 2F) and corrosion bevels (Fig. 2G). The floor is covered with fine sediments deriving from the marly interbeds except in the final room in one of the caves where material has come from the surface (cover-collapse sinkhole). In several parts of both

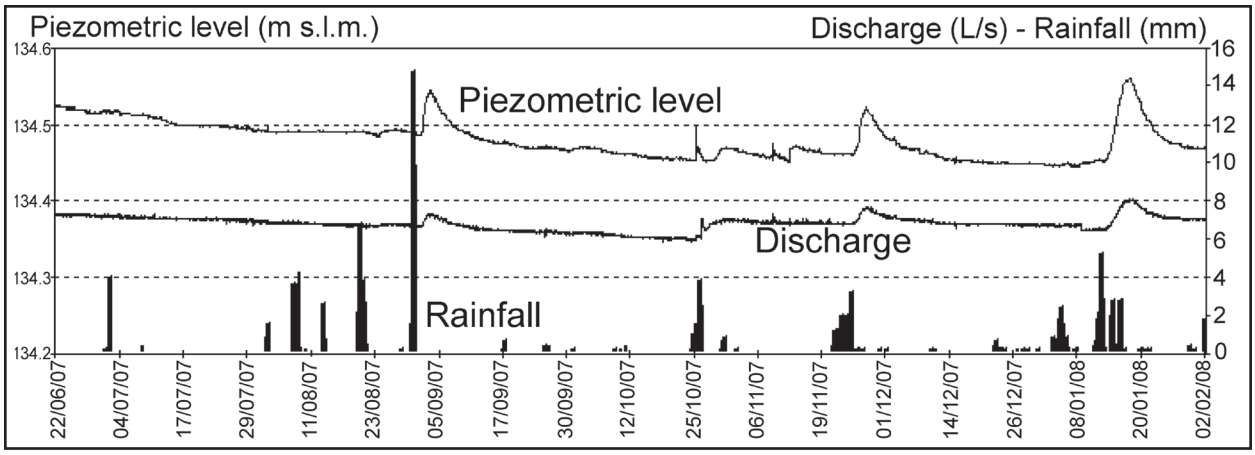

Figure 3: Flow rate, water levels and rainfall in the period June 22, 2007 – February 2, 2008 (piezometer S4).

caves, although mostly masked by clayey sediments, several feeders can be recognized in the form of descending passages showing where rising water entered the cave (Fig. 2C). Outlets are located in some parts of the caves, closest to the upper marl sequences, and are not easy to recognize because of breakdown (Vigna et al.,., 2009).

3. Hydrogeological Investigations

Before the interception of the karstic voids and sinkhole formation at Moncalvo on February 15, 2005, the hydrogeology of the underground quarry was contrantly monitored by several piezometers. Besides many small springs (usually less than 1 L/s), encountered along the drifts especially in the SE sector between 129 and 176 m asl, two boreholes located in the drifts intercepted larger water inlets with hydraulic pressures respectively of 100,000 and 300,000 Pa (1–3 bar). Repeated hydrological measurments have shown that the water table before the catastrophic sinkhole event was stable at around 170 m asl Hydraulic pressure at the time of cave interception must have been close to 360,000 Pa. After the event the water table dropped to 139 m asl in 14 hours, then because of continuous pumping reached less than 134 m asl by the end of 2005. The flow rate in the first months after the event was around 20 L/s, while discharge decreased continuously reaching a little bit less than 10 L/s in the summer of 2005, since then remaining relatively stable with only minor fluctuations (1-2 L/s) after heavy rainfalls.

The hydrodynamic behavior of the aquifer in response to rain events was investigated measuring discharge from the intercepted cave, water levels in piezometers installed in the gypsum beds and rainfall measured in a pluviometer placed near the quarry. This monitoring started in 2005, but in this paper only data sampled in the interval June 2007-February 2008 are considered, since they are representative of the hydrodynamics of the aquifer for both dry periods and intense rain events. The hydrograph of Figure 3 shows good agreement between water levels and flow rates, demonstrating that all data are relative to the same aquifer. Constant base flow is disturbed only by the most significant rain events, causing moderate and temporary changes. During the dry months modest rainfall does not influence water levels, due to high evapotranspiration, and only an important event at the end of August caused the water level to rise after 30 hours reaching its maximum height approximately 3 days after the rain fall peak. The flow rates changed from 6.6 to 7.2 L/s while water level rose 5 cm. Base flow conditions were re-established after 10 days. This hydrodynamic behavior of the aquifer did not change during the following months, except for January, when snow melt water was not immediately absorbed giving a retarded response.

A series of samples have been taken in various parts of the aquifer for chemical analysis to determine the origin of the waters. These have the chemical characteristics of infiltrating surface water (samples EM4 and EM6). Inside the gypsum bedrock the following samples were analyzed: 1) two water veins inside the underground quarry (SH and GS) that discharge after abundant rainfall and, since they are located 20-30 m from the surface, are representative of the direct infiltration water; 2) perennial water flow from fractures in the gypsum bedrock (VC and VF) located at greater depth and representing slow flow in the fissure network coming from infiltrating surface waters (VC2, VC3, VC4, VC6, VF2, VF3, VF4 and VF6); 3) water coming from fractures in the gypsum bedrock, with constant flow, different from the above mentioned because of the presence of bacterial filaments (VB and VBB), representing slow flow in the fissure network but with much longer transit times in the aquifer (VB2, VB3, VBB2, VBB3, VBB4 and VBB6); 4)

Sample	Eh	pH	T [°C]	EC a 20°C [µS/cm]	Hardn. [°f]	Na^+ [mg/l]	K^+ [mg/l]	Ca^{2+} [mg/l]	Mg^{2+} [mg/l]	F^- [mg/l]	Cl^- [mg/l]	NO_3^- [mg/l]	SO_4^{2-} [mg/l]	HCO_3^- [mg/l]	TDS [mg/l]
EM4	170	8.26	16.5	773	37.36	13.9	2.0	114.4	21.4	< 0.1	32.1	39.7	113.8	242.7	580.1
EM6	178	8.43	10.9	977	44.01	15.2	10.8	134.8	25.1	0.3	35.4	40.6	113.6	332.1	708.0
SH5	nd	7.03	nd	2534	166.15	9.1	1.8	649.0	10.0	1.4	20.5	35.0	1338.1	300.9	2365.8
GS5	nd	7.03	nd	2713	177.39	22.2	1.0	674.6	21.7	0.5	28.7	19.0	1396.1	380.2	2544.1
VC2	156	7.24	14.0	2610	176.66	19.1	2.5	654.1	32.4	0.7	31.7	30.2	1398.6	345.4	2514.6
VC3	24	7.44	13.5	2590	165.45	17.6	3.3	613.7	29.7	0.6	30.2	26.3	1334.9	348.7	2404.9
VC4	196	7.15	13.8	2600	184.08	18.4	2.9	683.3	32.7	0.6	28.9	26.7	1318.2	344.5	2456.1
VC6	120	7.37	13.6	2233	175.09	18.8	2.8	648.0	32.3	0.9	30.5	29.0	1346.2	339.6	2447.9
VF2	155	6.93	13.6	2620	180.24	19.5	4.5	674.2	28.9	0.7	35.4	31.1	1345.7	354.2	2494.2
VF3	193	6.81	13.7	2620	165.55	22.0	3.2	609.0	32.8	0.5	30.1	26.7	1313.5	353.5	2391.2
VF4	197	7.10	14.5	2610	167.77	20.1	3.4	623.2	29.5	0.6	31.5	27.5	1323.5	355.7	2415.0
VF6	88	7.19	13.4	2244	171.69	22.6	2.8	637.4	30.4	0.8	31.0	26.8	1328.2	350.0	2430.1
VB2	-196	6.77	13.7	3180	189.85	109.2	3.5	648.9	67.6	1.3	153.8	0.1	1557.1	364.1	2905.5
VB3	-186	6.78	13.5	3210	184.46	102.7	4.7	623.9	69.7	1.0	174.4	< 0.1	1467.4	369.7	2813.4
VBB2	-232	6.99	13.7	3190	200.90	104.2	4.7	670.1	81.6	1.6	150.6	< 0.1	1658.7	365.0	3036.6
VBB3	-253	6.86	13.8	3170	179.77	101.0	4.9	593.4	76.8	1.2	159.4	< 0.1	1479.0	368.6	2784.3
VBB4	-253	7.14	15.0	3070	181.90	87.9	6.7	590.2	83.9	1.3	134.5	< 0.1	1469.1	378.3	2751.8
VBB6	-201	7.16	13.7	3080	189.65	86.7	4.4	628.9	79.2	1.7	134.5	0.4	1525.0	370.1	2830.9
VS2	115	6.66	13.3	2700	185.84	37.2	3.6	670.5	44.7	0.7	50.1	11.5	1482.1	387.8	2688.3
VS3	180	6.68	13.3	2820	179.99	32.7	3.6	653.4	40.9	0.6	40.4	9.2	1428.8	391.4	2600.9

Table 1: Results of the chemical analysis of water samples in different environments. In Europe the comma (,) is typically used in numerical values instead of the decimal point (.).

Sample	SI-Cal	SI-Gyp	$\frac{Mg^{2+}}{CA^{2+}}$	$\frac{HCO_3^-}{SO_4^{2-}}$	$\frac{Na^+ + K^-}{Cl^-}$	Sample	SI-Cal	SI-Gyp	$\frac{Mg^{2+}}{CA^{2+}}$	$\frac{HCO_3^-}{SO_4^{2-}}$	$\frac{Na^+ + K^-}{Cl^-}$
EM4	1.256	-1.261	0.308	1.679	0.724	**VF4**	0.795	0.196	0.078	0.212	1.082
EM6	1.617	-1.218	0.308	2.302	0.941	**VF6**	0.885	0.204	0.079	0.207	1.205
SH5	0.671	0.222	0.025	0.177	0.759	**VB2**	0.465	0.237	0.172	0.184	1.115
GS5	0.780	0.240	0.053	0.214	1.226	**VB3**	0.470	0.204	0.184	0.198	0.933
VC2	0.935	0.229	0.082	0.194	1.000	**VBB2**	0.692	0.264	0.201	0.173	1.096
VC3	1.120	0.195	0.080	0.206	0.997	**VBB3**	0.529	0.189	0.213	0.196	1.005
VC4	0.864	0.223	0.079	0.206	1.069	**VBB4**	0.818	0.185	0.234	0.203	1.054
VC6	1.057	0.214	0.082	0.199	1.032	**VBB6**	0.851	0.219	0.208	0.191	1.025
VF2	0.650	0.226	0.071	0.207	0.965	**VS2**	0.407	0.248	0.110	0.206	1.211
VF3	0.493	0.186	0.089	0.212	1.227	**VS3**	0.425	0.230	0.103	0.216	1.327

Table 2: *Saturation indexes for Calcite (Cal) and Gypsum (Gyp) and characteristic chemical proportions. In this case, SI =log(IAP/K), so SI=0,0 = saturation.*

water coming from karst conduits in gypsum with variable flow rate (VS), resulting from the mixing of waters with different origins (VS2 and VS3). The most representative results of the chemical and physical analysis are reported in Tables 1 and 2 and in the Schoeller diagrams of Figure 4.

The surface waters EM4 and EM6 are characterized by a relatively low mineralization caused by the poor soil type and the marly deposits on which they flow. They are undersaturated with respect to gypsum and supersaturated with respect to calcite and very rich in nitrates. Of the

infiltration waters sampled in the underground quarry (SH and GS) mineralization rises after rainfall making them supersaturated with respect to both calcite and gypsum, while nitrate content is high although different between the two points. The waters coming from fractures, both without (VC-VF) and with bacterial filaments (VB-VBB), and that coming from karst conduits in gypsum (VS) are always supersaturated respect to calcite and gypsum. Nitrate is high in waters coming from the surface (VC-VF) and almost null in slowly flowing waters of an unknown deep origin (VB-VBB). The water of the karst conduits that drains the entire rock mass has intermediate nitrate contents, being the result of mixing of the different waters. Also the magnesium, alkali and chloride concentrations show differences according to the origin of the waters: those coming from dense fissure networks at slow flow (VB-VBB) show high values, while waters coming directly or indirectly from the surface show much lower values. From the karst conduits (VS) water with intermediate Na, K, Mg, and Cl contents is discharged, being a mixture of deep and surface waters. But the most significant parameter that identifies the different types of circulation waters is the redox potential (Eh). From the data it is clear that surface waters (EM) or those with short residence times in fissures (VC and VF) show positive Eh. On the other hand, waters from deep and slow circulation in fissure networks (VB and VBB) which are isolated much longer from the atmosphere have negative Eh. During the hydrogeological investigations several boreholes penetrated the entire Messinian evaporate sequence and reached the base level composed of Tortonian marls and the thin Messinian limestone bed. It is important to note that all boreholes that have reached this limestone bed at the base of the gypsum sequence have intercepted phreatic karst conduits of decimeter size that seem to occupy this level almost completely. It is probably this carbonate aquifer that feeds the gypsum karst from below.

4. Discussion

There was little evidence for deep karst before the collapse event in the Moncalvo underground quarry (Fioraso et al*.,* 2004). In fact, while some caves were reported in other gypsum areas of Piedmont region (Badino et al*.,* 2003), the gypsum outcrops of the Monferrato area, including Moncalvo, had never been thoroughly investigated by speleologists who were convinced there were only faint possibilities of finding interesting karst systems. Also the landscape around Moncalvo does not have many typical gypsum karst features, such as dolines, blind valleys and other surface karst morphologies. Gypsum rarely crops out and is mostly covered by a couple of meters of solutional residuum and the overlying marly formations. Combined observations from cave morphology and hydrology showed that at least part of the water flowing in the gypsum caves comes from below (Vigna et al*.,* 2009). The Moncalvo karst can be defined as a hypogenic karst (Klimchouk, 2007). The presence of the extremely karstified thin Messinian limestone bed at the bottom of the evaporite sequence is the major aquifer that recharges the gypsum formation from below. The presence of cave morphologies such as feeders in several parts of the karst galleries confirms this hypothesis. The water flowing in this limestone bed comes from the surface as clearly shown by the high nitrate contents, medium mineralization and the positive Eh, and has fast recharge shown by the rapid rise of water levels and discharges shortly after rain events. It probably derives from a combination of fast recharge of the limestone aquifer by open fractures in the overlying gypsum and marl formations and small amounts of slowly infiltrating waters coming from the dense but tight fissure network in the gypsum. Water flow is very slow in the gypsum since marks of fast flow (scallops) have not been observed and morphologies such as cupolas and ceiling pendants are compatible with low velocity flows. Also where the marl interbeds are encountered the water does not seem to have eroded these softer sediments in a differential way, again indicating slow moving water. Where fractures convey slowly moving undersaturated water from the surface into the uppermost gypsum beds, a corrosion bevel and 45° sloping facets develop close to the water table level. Such a morphology, spreading over tens of meters, is present in the western part of one of the largest explored caves, closest to the surface. The dimension of the voids, however, is hard to explain by present-day active karst processes. It is very probable that the cave systems started developing in the short period in which the gypsum beds were exposed to surface processes during the Messinian. In fact, all the analyzed waters that circulate in the gypsum are supersaturated respect to calcite and gypsum, and are thus at present not able to dissolve significant quantities of gypsum or limestone. The surface waters that infiltrate from above into the gypsum formation are undersaturated only with respect to gypsum. These waters are thus capable of dissolving gypsum on outcrops or at the contact between overlying clays and gypsum. The deeper cave systems, however, must have been formed in completely different conditions, when undersaturated waters circulated in the gypsum bedrock. This might have happened during the intra Messinian continental phase. It cannot be excluded, however, at this stage of the research, that the slowly circulating hypogean waters can have an active speleogenetic role at the base of the gypsum sequence, since their provenance is not yet completely clear. Clearly they become supersaturated very fast, after few meters of

distance inside the gypsum rocks.

5. Conclusions

A series of observations lead to the hypothesis of an intra-Messinian epigenic karst cycle that started the cave development, probably followed by a hypogenic stage still active today: 1) in many sectors of the area gypsum beds have been extensively karstified although their outcrops are small and at present are sandwiched between Pre-Messinian and Upper Messinian-Pliocene impermeable clay- and siltstones; 2) the partially remobilized Burdigalian-Lower Pliocene fauna associations in cave sediments agree with a Messinian age of the voids they occupy. Their mobilization with the Pliocene impermeable cover in place is highly improbable; 3) most karst conduits in gypsum have been discovered well below the present valley bottoms, and their genesis is difficult to explain in a phreatic situation between two impermeable beds; 4) at present all investigated waters, except for those at the surface, are supersaturated with respect to both calcite and gypsum, and cannot dissolve any gypsum. It is likely that these voids have at least started forming during the intra-Messinian uplift periods, when they were above local base level and not yet covered by impermeable Messinian post-evaporitic and Pliocene sediments.

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BULLITA CAVE, GREGORY KARST, N.T. AUSTRALIA: A MAZE CAVE IN PROTEROZOIC DOLOMITE

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The Bullita System is the largest cave of a number of maze caves in the Proterozoic Supplejack Member of the Skull Creek Formation in the Victoria River area of the Northern Territory, Australia. The area is in the monsoonal wet tropics and the cave is affected by seasonally flooding. Since the early 1990's systematic exploration has resulted in detailed understanding of the extent of the main system, but there is much still to be explored in detail.

The main cave is an extensive, horizontal, multi-entrance, multi-level, joint-controlled, maze system of over 100 km of surveyed passages and passage densities of up to 45km/sq.km. Unlike many other large maze caves elsewhere in the world it is a shallow, 'epikarstic' system with a surface karrenfield. This cave and others are restricted to the thicker lenses of dolostone (Supplejack Dolomite) compared to the thinner dolostone, dolomitic siltstone and chert bands, of the main Skull Creek Formation.

The system appears to be predominantly vadose with stream ways and canyons being the dominant passage type. The direct, vertical influx of water plays an important role, and the cave occurs exclusively where the surficial karst morphology is well developed. Discussions on the speleogenesis of the Bullita System are still occurring. The distinctively epikarstic morphological form and position in the landscape make it unlikely to be of hypogene origin.

This paper will describe the major characteristics of the cave and discuss its speleogenesis in the context of the Proterozoic dolomite karst of northern Australia.

1. Introduction

The Bullita System is the largest cave of a number of maze caves in the Proterozoic Supplejack Member of the Skull Creek Formation in the Gregory National Park in the Victoria River area of the Northern Territory, Australia (Fig. 1). The caves were first reported in 1991 (Storm and Smith 1991), as prior to this the area was very inaccessible. Top End Speleological Society explored several caves in the area in the late 1980s and early 1990s, and since 1992 an annual expedition has systematically explored and documented the karst. The exploration and documentation is currently carried out by the Gregory Special Interest Group of the Australian Speleological Federation, with the support and permission of the Northern Territory Parks and Wildlife Service.

The area is in the monsoonal wet tropics and the caves are affected by seasonal flooding. The monsoon period is from October to March; 650mm annual average rainfall which falls in concentrated events and temperature ranging between 24 and 38°C. The vegetation is open savanna with large baobab trees and thicker vegetation along the rivers.

2. Geological Setting

The area is underlain by the widespread Mid Proterozoic Skull Creek Formation of the Bullita Group (Sweet et al 1974, Beier et al. 2002). This is a clastic dolostone and dolomitic siltstone with minor shale beds, of maximum thickness of 162m, characterised by moderate relief and benched topography and is preserved in many places by a duricrust. The Supplejack Dolostone (Dolomite) Member is a conformable, thickly bedded stromatolitic dolostone between 10m and 17m thick within the Skull Creek Formation. It is regarded as indicative of a regional transgressive event and was probably deposited in a shallow marine environment (Beier et al. 2002). In the area where the cave system is developed, the strata dip at 1-5° to a direction varying from south of east in the North to north of east in the South, and there is prominent three directional jointing. It is intensely karstified in some areas in particular where the Upper Skull Creek Formation has been removed, and contains the maze caves including the large Bullita

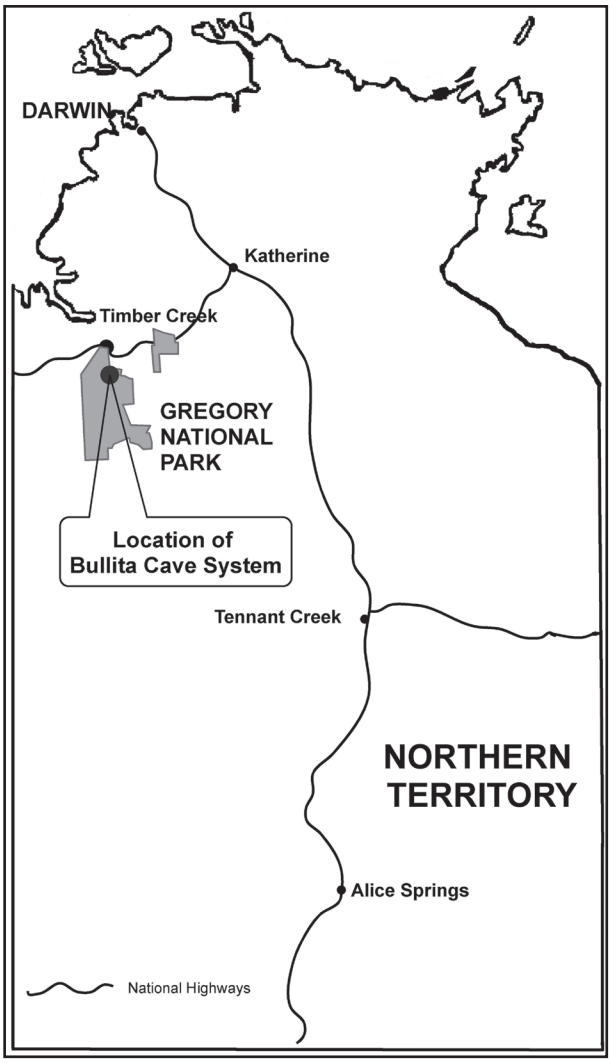

Figure 1: Location (after R. Kershaw, 2009).

System. Dome and conical stromatolites occur at the top of the member.

The main karst area known is in the tributaries of the East Baines River, a tributary of the major Victoria River, where the Supplejack Member outcrops. These tributaries, especially Limestone Creek contain extensive active and relic tufa deposits, including large tufa dams across the stream channel. However other dolomite karst areas probably exist and new areas have become known across northern Northern Territory over the past 5 years.

The geological and topographical setting of the Bullita System consists of a thin lens of dolostone gently dipping to the east, outcropping on the slope of a N-S oriented valley. The base level is the East Baines River and its tributaries, Limestone and Spring creeks. Where the Supplejack Formation is more intensely folded or horizontal, there is no known cave development.

3. Karst Characteristics

Karst morphology is well developed only on the Supplejack Member. The exposed surface is a rugged karren field with pinnacles, karren, kamenitzas and solution pits (Fig. 2). Where most of the Supplejack dolostone has been dissolved, the karst is characterised by isolated pinnacles and blocks resting on the Lower Skull Creek Formation. These blocks are often tilted and have sometimes slid down the slopes. The karst fields are crossed by deep joint controlled grikes; some of which have become very wide, up to 10m across. Other karst features such as dolines are missing. The karst field hosting the Bullita System forms a contorted and irregular band, 4 km long and roughly oriented North-South; its width varying from 100m to 900m (Fig. 3).

Figure 2: Karrenfield, Bullita (S. White 2004).

The major cave is the Bullita System, an extensive horizontal multi-level, multi-entrance joint-controlled maze system with a current total passage length 115km (2008) over 4 to 5 km north to south (Fig. 3) and at a maximum depth of about 35m. Passage densities are up to 45km/sq.km. This major system is in the main block of Supplejack Formation about 5 km long and up to 1 km wide. The cave can be divided into sectors, which are often connected by a single tight passage. Much of the cave is at a single level at the base of the Supplejack Dolostone and the underlying shale bed, but lower level entrenchment occurs at the northern and southern ends. Towards the eastern edge, beneath the contact with the overlying Skull Creek Formation, the passages become small and impassible. Remnants of high-level phreatic tubes can be seen above the present main passages. The main passage forms are narrow fissures and "tented" (inverted T) passages that have an upper fissure in the dolostone and a broad undercut into the Lower Skull Creek shale. Broad flat

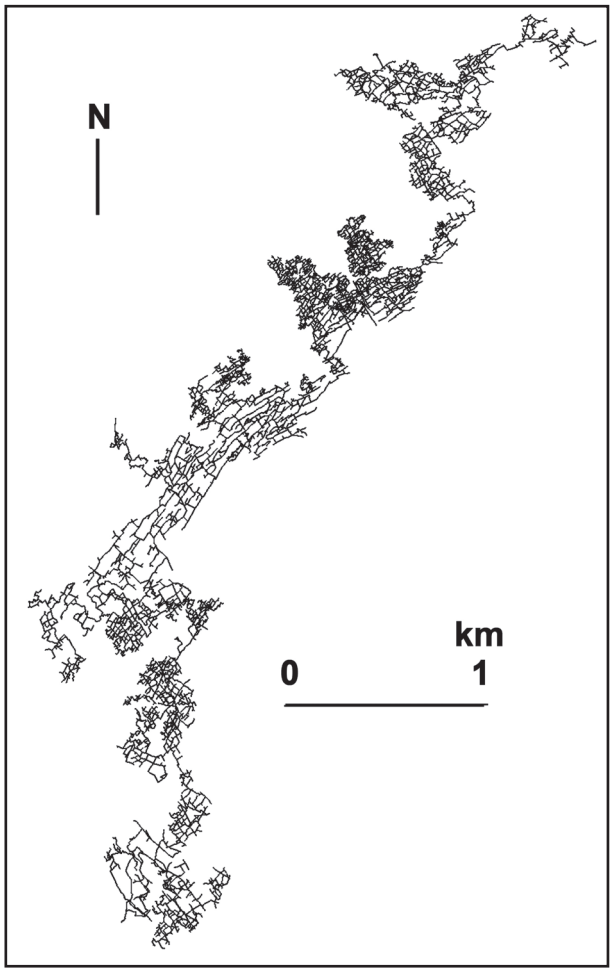

Figure 3: Outline map of Bullita System 2003 (R. Kershaw, 2003).

roofed chambers up to 3 m high have isolated pillars of the flaggy shale unit supporting the roof (Fig. 4). The passages are generally easy walking size with intersection spacing at 8-15m intervals. Pits occur in several areas. Speleothems are not common and are mainly cave coral. Tree roots from the surface fig trees occur throughout the cave. There are numerous daylight holes in the roof that vary from small holes at joint intersections through narrow discontinuous fissures to fully open giant grikes. At the western edge the cave breaks up into a system of open grikes and isolated remnant passages. Leaf litter accumulates beneath the daylight holes.

Other smaller maze caves are not connected to the main Bullita System. These have similar morphology: horizontal joint-controlled mazes, multi-entrances. The passages are similar shape but often smaller and there are fewer cave levels. These smaller caves are usually in blocks of exposed Supplejack Formation, which are separated from each other and the main block. Wide erosional valleys cut into the

Figure 4: Tent passage shape and undercut (photo S. White 2004).

Lower Skull Creek Formation shale and siltstone separate these blocks from each other.

4. Cave Hydrology

Although the system has always been dry when seen by cavers, there is abundant evidence, e.g. sediments covering older survey markers, that during the wet season flooding, underground stream flow occurs. Water levels can certainly reach a height of several meters in the cave. Many of the narrow passages receiving large volumes of water appear to be temporarily flooded up to the roof for short periods of time. The water enters the Bullita System in two ways: diffusely and allogenically (Bannink et al. 1995). The diffuse way is by direct infiltration from karren fissures and crevasses. The allogenic source is from the surface runoff on the Upper Skull Creek Formation, the water entering the cave system when reaching the karren field; the drainage is through the large number of karren fissures. As rainfall occurs in intense monsoonal storms the infiltration into the regolith on the Upper Skull Creek Formation may be limited. The bare karren fields on the other hand would allow virtually all the rainfall to sink underground into the cave. There is only one known resurgence at the southern end of the Bullita System, the Effux, which is entrenched 20 to 25m into to underlying shale. This shows evidence of flooding during the wet season and sediment deposition as the system drains slowly after the close of the monsoon season. Several resurgences drain into Limestone Creek at the northern end of the system. However a large number of minor, resurgences drain the system during the monsoon season and evidence of these are found throughout the caves. Similar hydrology occurs in the caves on the other blocks of Supplejack dolostone.

Speleogenesis

Undertanding the formation of the Bullita System is still very much under discussion. Dunkley (1993) and Bannick, et al (1995) have published different interpretations of the formation of the caves. However Bannick et al. (1995) discussed the caves on the north side of Limestone Creek rather than the main larger Bullita System and Dunkley (1993) discussed cave formation in the area before most of the main system had been either discovered or explored. The past 10 years has shown how extensive the system is, that there is one very large cave and many medium sized and smaller maze caves of similar morphology and that the cave processes must be dominated by the seasonal intense rainfall events, at least at present times.

Three important factors act as controls on speleogenesis:

(1)The development of the cave has probably occurred over a very long period of time. The host rock dolostone is Mid Proterozoic in age (1.6 Ga). A series of depositional environments occur from the mid Proterozoic through to the Middle Cambrian. A large time gap occurs from the Cambrian to an isolated outcrop of massive limestone of Tertiary age, only found well to the south of the Bullita area (Sweet 1973). The only other Cenozoic deposits are laterite and other regolith material. Early phases of speleogenesis may therefore have been removed over long periods of erosion.

(2) Cave development has occurred where the Supplejack Formation has been exposed by the removal of the overlying Upper Skull Creek Formation. The karstification is concentrated in the Supplejack dolostone, even though the Skull Creek Formation has significant carbonate.

(3) The most extensive cave development has been where the Supplejack is gently dipping (between 1° and 5°) away from the base level in the rivers or streams (Dunkley 1993). Where the Supplejack is more intensely folded, flat lying or dipping towards the incised streams there is little cave development.

The caves have limited phreatic passage shape present. In the Bullita System, remnant phreatic tubes are to be found relatively high in the passage walls. This is consistent with reported cave development and subjacent doline and limited cave development under the laterite capping further north (Newcastle Range area). Most of the cave passages are vadose development from surface runoff into the cave. The maze is therefore developed as a joint controlled epiphreatic and/or vadose system over a long period of time in a monsoonal climate. The alternating winter dry, summer wet tropical conditions maximize the solutional processes of the dolostone and the removal of the dissolved material.

The Bullita System does not show any evidence of hypogene development, although if this did occur in the past it may have been so long ago that most evidence has been removed. The cave is a large relatively shallow maze cave that appears to have been developed primarily under epiphreatic/vadose conditions. The smaller caves do not present any opposing evidence for this. However this is still very much work in progress.

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Symposium 12

UNEARTHING SECRETS OF THE PAST FROM SPELEOTHEM STUDIES

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EVOLUTION OF KARST SYSTEM FROM U-SERIES DATING AND FABRIC ANALYSIS: A CASE-STUDY FROM ROMANIA

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Abstract

Deciphering the evolution and "age" of cave systems was one of the major reasons for the development of U-series speleothem dating techniques, back in the 1980s. However, it soon became clear that this goal would be hard to reach for a number of reasons such as the random initiation of speleothem growth, the wildly different growth rates of coeval speleothems, and the necessity of a statistically significant population of samples that is hard to attain for conservation reasons. Consequently, the main interest of speleothem dating has turned towards the provision of an accurate time scale for the paleoclimatically significant isotope records.

There are, however, cases where a sufficiently large number of dated speleothem samples exists, and they can be used for speleogenetic studies. In this paper, we discuss the case of the Closani Cave (SW Carpathians, Romania), where more than 70 speleothem samples have been dated beginning with 1999. The oldest speleothems in Romania were dated here at ~1.3 Ma using the Regional Uranium Best Estimate method validated by independent alpha-spectrometry and TIMS measurements on replicates. These ages allowed the calculation of the maximum incision rate of the nearby Motru River at ~0.06 m/ka.

Several "generations" of speleothems have been recognized in the Closani Cave, each of them attesting for different stages in the evolution of the cave. U-series datings coupled with fabric analysis on speleothems allowed deciphering of different phases in evolution of the cave system, such as the separation between different sectors due to massive speleothem deposition and the transition to a stable meroclimate regime at ~270-300 ka. Overall, except for the Last Glacial Maximum, the dates show no evidence for any cessation of calcite deposition during the last 500 ka indicating that at this latitude and altitude, the climate during major glacials / interglacials was mild enough to allow continuous speleothem growth that can yield long climate records.

TEMPORAL VARIABILITY OF CAVE-AIR CO_2 IN CENTRAL TEXAS

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The growth rate and elemental and isotopic composition of cave calcite deposits (speleothems) are important proxies for past environmental and hydrologic changes. Understanding the timing and driving mechanisms of calcite growth is therefore important for interpreting such proxies. The deposition of speleothem calcite in two central Texas tourist caves 130 km apart is known to vary seasonally in response to fluctuations in cave-air CO_2. Calcite deposition is highest in the late fall through spring when cave-air CO_2 is lowest, likely due to density driven ventilation. In the warmer summer months, when cave air becomes stagnant and high CO_2 concentrations develop, calcite deposition decreases to near zero. To determine if this phenomenon is unique to tourist caves, which have been modified from their natural state (e.g., modified entrances, high numbers of visitors), CO_2 was measured along transects in three undeveloped caves in the central Texas.

Multiple transects of each cave showed that cave-air CO_2 varies seasonally in all caves, with peak concentrations in late August to early October and lower concentrations in December through late March. The monitored caves occur in six distinct stratigraphic units and range widely in volume (100 m^3 to >100,000 m^3), and geometry; however, the timing of seasonal CO_2 fluctuations is consistent in all caves monitored. The magnitude of seasonal cave-air CO_2 fluctuations in the undeveloped caves varied greatly (420–31,000 ppm CO_2), whereas the magnitude of seasonal CO_2 fluctuations in two of the three tourist caves monitored was much smaller (370–9,500 ppm CO_2). Cave-air CO_2 also shows significant diurnal fluctuations that are well correlated with changes in surface air temperature and barometric pressure. Diurnal fluctuations greater than 10,000 ppm CO_2 were routinely measured in the undeveloped caves whereas typical diurnal fluctuations in two of the three tourist caves monitored (Inner Space Cavern and Natural Bridge Caverns-North Cave) were only 500–1,000 ppm CO_2. The magnitude of seasonal CO_2 fluctuations in one tourist cave (Natural Bridge Caverns-South Cave) was similar to that of the undeveloped caves monitored (470–38,000 ppm CO_2). These results indicate that 1) the seasonality of calcite deposition observed in the tourist caves (as controlled by the concentration of cave-air CO_2) does not appear to be due to human alteration of the caves, 2) the concentration of cave-air CO_2 varies significantly on multiple timescales (i.e. daily to seasonally), 3) the seasonal fluctuation of cave-air CO_2 is regional in extent, 4) geometry, volume and the hosting stratigraphic unit do not exert a significant control on seasonal fluctuations of cave-air CO_2. These results suggest that speleothems records may be biased toward seasons with increased cave ventilation and calcite deposition rate.

1. Introduction

Speleothems provide important terrestrial records of regional and global climate variability in the late Quaternary. However, recent studies have raised the concern that speleothem paleoclimate records might be seasonally biased by changes in the deposition rate of calcite due to seasonally fluctuating cave-air CO_2 concentrations (BOUGRES et al., 2001). Other studies have shown that fluctuations of CO_2 in cave air can lead to disequilibrium precipitation (HENDY, 1971; MICKLER et al., 2004, 2006) or significant seasonal variability of calcite deposition rate (BANNER et al., 2007). Thus, it is important for paleoclimate studies to consider seasonal ventilation when using speleothem paleoclimate proxies.

Cave ventilation has received increasing attention in recent years and several researchers have reported significant seasonal fluctuations in cave-air CO_2 concentrations (TROESTER AND WHITE, 1984; VILLAR, 1985; HOYOS, et al., 1998; BUECHER, 1999; BOUGRES et al., 2001; SPOTL et al., 2005; BALDINI et al., 2006; BOUGRES et al., 2006; BALDINI et al., 2008). A recent study by BANNER et al. (2007) demonstrated that calcite growth rates in two tourist caves were inversely correlated with cave-air CO_2 concentrations, emphasizing

the importance of cave ventilation as a primary control of speleothem deposition. Consistent with previous research, the authors attributed fluctuations of cave-air CO_2 concentrations to seasonal temperature and pressure gradients forcing cave ventilation.

The two caves studied by BANNER et al. (2007), Natural Bridge Caverns and Inner Space Cavern, are located approximately 130 km apart on the Edwards Plateau in central Texas, and both caves reveal a first-order control of seasonal fluctuations in cave-air CO_2 concentrations on calcite deposition rates. In the cooler months, calcite deposition rates are at a maximum, while in the summer, prolonged periods of elevated cave-air CO_2 concentrations appear to inhibit dripwater degassing, resulting in a significant decrease or even complete cessation of calcite deposition. These results indicate that the potential for a regionally extensive seasonal bias in speleothem proxy data exists, and prompt the question: are seasonal fluctuations in CO_2 unique to tourist caves that have been modified from their natural state by modified entrances and visitation?

We test the hypothesis that the seasonal variations in cave-air CO_2 concentrations observed by BANNER et al. (2007) are regional in extent across central Texas and are not unique to tourist caves. We compare the timing and magnitude of CO_2 fluctuations within three undeveloped caves, District Park, Whirlpool, and Maple Run (hereafter denoted as DP, WP and MR respectively) with those measured in Natural Bridge Caverns North Cave (NBN), Natural Bridge Caverns South Cave (NBS) and Inner Space Cavern (IS). The undeveloped caves chosen for this study are ideal for comparison with the tourist caves as they are centrally located, they are formed in similar geologic units, are overlain by similar soil and vegetation, receive similar rainfall amounts, but by contrast they receive little visitation outside of our monitoring trips.

2. Previous Observations Concerning Cave-Air CO_2 Variability

The concentration of CO_2 in cave air is a function of the rate of CO_2 input into the cave and the rate of exchange between the cave air and the outside air (hereafter referred to as ventilation). Known sources of cave-air CO_2 include soil microbial respiration, in-situ decomposition of organic matter within the cave, diffusion from deep magmatic sources, respiration of animals and degassing from CO_2-rich groundwaters (TROESTER AND WHITE, 1984; BALDINI et al., 2006; BOURGES, et al., 2001, BATIOT-GUILHE, et al., 2007). These sources can vary by cave, region and on multiple timescales. In our study area, soil microbial respiration is likely the most significant source of CO_2.

Soil microbial respiration is the primary source of CO_2 in most caves. The concentration of CO_2 in vadose water is primarily controlled by the concentration of CO_2 in the soil. Vadose waters become enriched in CO_2 as they flow through the soil zone and when that water comes into contact with a lower pCO_2 environment (e.g. a cave), CO_2 degassing occurs. Diffusion of soil microbe respired CO_2 through fractures, cracks and dissolution cavities is also a mechanism by which CO_2 may be transported to the cave atmosphere (BALDINI et al., 2006).

Cave ventilation occurs on several timescales including seasonal and diurnal, and is caused by density driven exchange between cave air and the atmosphere (e.g., BOURGES, et al., 2001; SPOTL et al., 2005, BALDINI et al., 2008; JAMES AND BANNER, 2008). Regional patterns of air temperature and pressure variability exert a first order control on the seasonal ventilation of caves within a region. In the study area, cave air temperature varies by only a few degrees, thus ventilation is likely controlled by atmospheric temperature and pressure variability. During the warmer months, cave air temperatures remain below atmospheric temperature, causing cave air to stagnate and CO_2 concentrations to increase. During this time, the concentration of CO_2 in the cave air will continue to rise until ventilation occurs. When cave air temperatures are warmer than outside temperatures, a density-driven imbalance occurs and cave ventilation begins. Outside air flows down into the cave, mixing with and displacing the CO_2-rich cave air causing CO_2 levels to decrease.

3. Study Area

The caves monitored are located near Austin, Texas (Fig. 1) on the Edwards Plateau, which is composed of karstified lower Cretaceous marine carbonates overlain by a thin calcareous clay soil that supports oak and juniper savannah (BANNER et al., 2007). All study caves, with the exception of Natural Bridge Caverns, are located within the Edwards limestone; a Lower Cretaceous marine limestone unit with interbedded dolomitic layers. NBS and NBN are located within the interbedded limestone and dolomitic units of the upper Glen Rose and lower Walnut formation, which are also Lower Cretaceous. The two caves are separated by a large collapse, and have separate entrances. A more detailed description of the hydrology and morphology of IS, NBN, and NBS is given by MUSGROVE AND BANNER (2004) and BANNER et al. (2007).

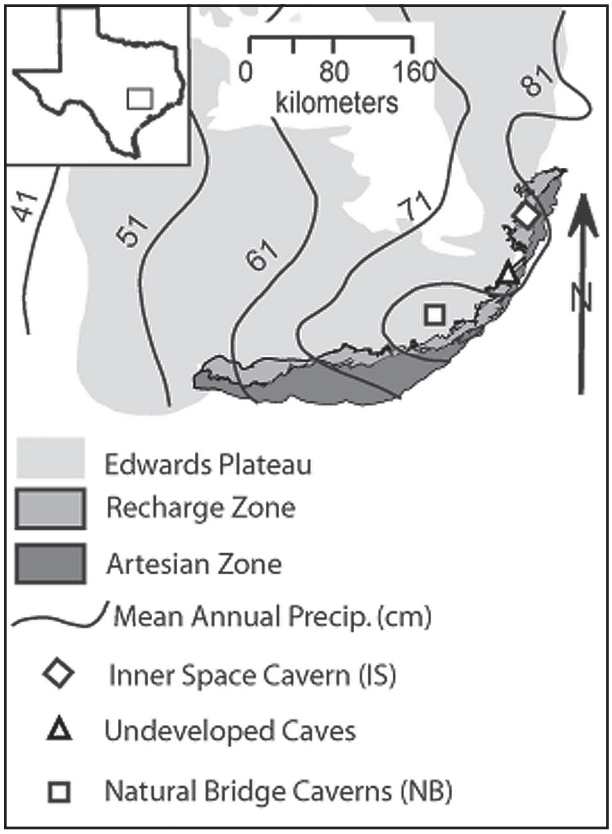

Figure 1: Map of the Edwards Plateau located in central Texas and the location of caves monitored for this study.

4. Methods

CO_2 concentrations were measured along transects of varying distance from the entrance of each cave using a portable Telaire 7001 CO_2 meter. Although all caves were monitored with varying frequency, we completed several transects throughout all seasons to capture seasonal variability. For this study we use CO_2 concentrations measured at sites within IS, NBN and NBS on a monthly basis from 2001 to present. MR and WP were each visited 17 times between July, 2006 and October, 2007 and DP was visited a total of 14 times during the same time period. No transects were taken in these caves from November 2007 to July 2008. Monitoring resumed in all three undeveloped caves in August 2008 and continued up to the time of publication. Logging CO_2 meters were placed at two monitoring stations within IS: ISST and ISLM. ISST is located approximately 260 meters from the cave entrance and ISLM is located approximately 460 meters from the cave entrance. A logging meter was also placed in MR at a site located approximately 20 meters from the cave entrance. Daily average surface temperature and total precipitation measured at a National Climate Data Center weather station (COOP ID: 410428) located in Austin, Texas.

5. Results

To allow for comparison of the overall CO_2 concentration of each cave over the duration of this study, the weighted mean of the measured cave-air CO_2 concentrations within each cave was calculated for each visit. The concentration of CO_2 in the tourist and undeveloped caves shows strong seasonal variability. In general, CO_2 concentrations remained low during the cooler season (November through April) and elevated throughout the warm season (May through October) with peak concentrations measured from August to September.

Correlations between the mean CO_2 concentration at each monitoring station and distance from the cave entrance are summarized in Table 1. All caves showed a positive correlation between mean CO_2 concentration and distance from the cave entrance except at DP and MR. Limited stations in DP prevent a statistical correlation to be calculated, though during every visit to the cave, CO_2 concentrations were highest at the station deepest within the cave. At MR, no significant correlation was found between mean CO_2 concentration and distance from the cave entrance (r^2=0.05), however, when mean CO_2 concentration is compared to monitoring station depth a stronger correlation is exhibited (r^2 = 0.29). This is likely due to the ease with which air can circulate through the rock unit in which the cave is formed. Much of the cave is formed in a collapsed rubble pile with interconnected void spaces and the main chamber of the cave is a collapse dome.

The data revealed that cave-air CO_2 is highly variable. At ISST CO_2 ranged from 450 to 920 ppm and was lower than concentrations at ISLM, with a few brief exceptions (Fig. 2). Typical diurnal fluctuations at ISST were approximately 200 ppm. CO_2 concentrations at ISLM ranged from 480 to

Table 1: r^2 values for correlations between CO_2 temperature and pressure.

Monitoring Station	CO_2 and Temperature	CO_2 and Pressure	Distance From Entrance (m)
ISST	0.57	0.29	260
ISLM	0.72	0.07	460
MR	0.01	0.38	29

1,600 ppm and several diurnal fluctuations of over 700 ppm were recorded. The largest CO_2 fluctuations were recorded at MR, ranging from 550 to 18,000 ppm with diurnal fluctuations exceeding 10,000 ppm.

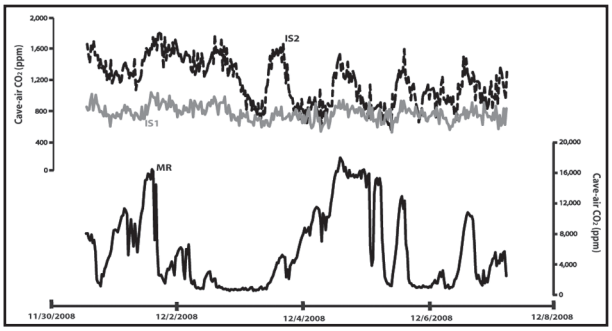

Figure 2: A representative sample wintertime CO2 fluctuations in Inner Space Cavern and Maple Run Cave. Distance of loggers from the cave entrance and r2 values for correlations between CO2 and surface temperature and pressure are given in Table 1.

6. Discussion

In all caves monitored, surface temperature fluctuations were inversely correlated with seasonal CO_2 fluctuations. Seasonal trends of lower winter CO_2 and higher summer CO_2 are similar in all caves, regardless of visitation, implying that the seasonal cave-air CO_2 fluctuations observed by BANNER et al. (2007) in the tourist caves are indeed regional in extent and not due to visitation or modification of the caves.

Frequent monitoring of these caves shows significant variability in the magnitude of cave-air CO_2 fluctuations within the region. Seasonal weather patterns alone cannot explain inter-cave variability, as all caves monitored for this study are located within 120 kilometers of one another and experience similar seasonal weather patterns. Additionally, the three undeveloped caves are located within 5 kilometers from each other and experience nearly identical seasonal and storm scale surface atmospheric forcing. The magnitude and exact timing of CO_2 fluctuations within the undeveloped caves are not identical, suggesting that important site-specific parameters play a significant role in cave ventilation.

Our observations suggest that the total volume of cave passage is an important control on CO_2 variability. With the notable exception of NBS, larger caves tended to have lower maximum CO_2 concentrations and experience fluctuations (seasonal and diurnal) that are smaller in magnitude than the smaller caves. This can be explained by considering the relationship between cave volume and dripwater infiltration. As the volume of a cave increases, the surface area to volume ratio decreases. Caves with larger volume will require a greater flux of CO_2 into the cave in order to reach the same CO_2 concentration as smaller caves. The larger magnitude seasonal and diurnal CO_2 fluctuations in the smaller, undeveloped caves further supports this observation, as the volume of these caves is much less than the volume of the tourist caves studied (Table 2, Fig. 2). Seasonal fluctuations are smoother and smaller in amplitude in the larger caves studied (e.g., IS, NBS and NBN). However, this may also be a bias reflecting the frequency with which caves were monitored.

The logging monitors revealed significant diurnal CO_2 fluctuations (Fig. 2). Like the seasonal fluctuations, diurnal CO_2 fluctuations in the undeveloped caves are much greater in magnitude than those in the tourist caves. Wintertime diurnal CO_2 fluctuations in the tourist caves typically range from a few 100's to 1,000 ppm, while diurnal fluctuations greater than 10,000 ppm are not uncommon in the undeveloped caves. This suggests that cave volume has a significant control on the magnitude of CO_2 fluctuations on a seasonal and diurnal timescale. Higher CO_2 concentrations are recorded at loggers stationed furthest from the cave entrances, which is consistent with the seasonal CO_2 measurements. However, on five

Table 2: r^2 values for correlations between CO_2 and distance from the cave entrance.

Cave Name	r^2 Value	Minimum CO_2 (ppm)	Maximum CO_2 (ppm)	Transect Length (m)
Inner Space Cavern	0.87	400	7,600	460
Natural Bridge North Cavern	0.79	370	9,500	200
Natural Bridge South Cavern	0.25	470	38,000	400
Whirlpool Cave	0.84	420	22,000	130
Maple Run Cave*	0.29	570	23,000	42
District Park Cave**	n/a	520	31,000	5

*No significant correlation was found between mean CO_2 concentration and distance from the cave entrance at Maple Run Cave. r^2 value for Maple Run Cave is for CO_2 and depth.
**Only two stations in District Park Cave.

occasions, the CO_2 concentration at ISLM decreased to similar values as ISST. This suggests that cave ventilation became sufficiently strong to ventilate ISLM at the same rate as ISST despite ISLM being nearly 200 meters further from the entrance than ISST. This is consistent with ventilation patterns reported by BOUGRES et al. (2001).

The current entrances at IS, NBN, and NBS have been modified from their natural state. These modifications have likely modified modern ventilation patterns as compared with ventilation patterns of the past (BANNER et al., 2007). However, the presence of active and ancient speleothem growth in both caves suggests that ventilation must have occurred in the ancient system. Additionally, Late Pleistocene fossils found in IS indicates that the cave was open to the surface in the past. This observation again highlights the importance for a greater understanding of how connectivity to the surface controls ventilation, which in turn is a primary control on speleothem deposition.

7. Conclusions

A common line of evidence for demonstrating equilibrium calcite precipitation is reproducibility from multiple records within a cave and between spatially separated caves in a given region (e.g., JOHNSON AND INGRAM 2007). When trends in proxies are similar among multiple records, it is less likely that site-specific parameters (e.g., dripwater flowpath, temperature, relative humidity) are exerting dominant controls at multiple drip sites in different caves. Reproducibility among spatially distributed records however, does not necessarily exclude regional effects biasing multiple records. In caves that experience CO_2 fluctuations large enough to slow or halt the deposition of calcite, the composition of speleothem calcite deposited by drips whose residence time is sub-seasonal may only reflect the dripwater composition in the cooler months when cave-air CO_2 concentrations are lower and calcite deposition is not inhibited.

While our results demonstrate some site-specific variability of ventilation patterns, all of the caves across our region show elevated levels of cave-air CO_2 during warmer seasons, and depleted levels during cooler seasons. This observation implies that even in regions where proxies are regionally reproducible among disparate records, seasonal fluctuations of cave-air CO_2 may also be regional in extent, and therefore these proxies potentially exhibit a seasonal bias. It is important to note that such seasonal fluctuations in CO_2 are likely more pronounced in regions that undergo temperature fluctuations that are significant enough to cause extended alternating periods (i.e. seasonal or diurnal) of cave air stagnation and cave ventilation (James and Banner, 2008).

In addition to this seasonal bias, our results also have implications for paleoclimate-speleothem sampling protocols. Paleoclimate reconstructions are generally concerned with atmospheric variability on geologic time scales. We observe lower mean CO_2 concentrations at sites located closest to the cave entrances, as well the magnitude of CO_2 fluctuations at these stations is generally less than at stations located further from the entrances. For theses reasons, in our study area it may be preferable to collect speleothems from localities closer to cave entrances as they may have undergone fewer hiatuses in growth.

Acknowledgements

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AGE ~ DEPTH MODEL CONSTRUCTION USING FULL INFORMATION FROM SAMPLES AGE AND DEPTH DISTRIBUTIONS BASING ON ^{230}TH/U, RADIOCARBON AND ^{210}PB DATING RESULTS

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Abstract

One of main isotopic dating purpose is time scale construction. Reliable age – depth relationship is a base for correct time scale construction. Two main problems are necessary to solve with this subject.

The first one is taking account uncertainties of both modeled parameters: age and depth. The second problem is correct decision of fitting function choosing.

The first problem can be solved using "randomization" as a analyze method. "Randomisation," the kind of Monte Carlo (MC) method, is a computer-based statistical method used to determine the accuracy of a statistics from experimental data with their uncertainties. As a first step of calculation algorithm for ^{230}Th/U and ^{210}Pb methods, sub-samples (sub-data set) coming from the original data set (activities and depth with uncertainties) are produced. Such sub-data set is produced using a random number generator of normal distribution with an expected value equal to the activity or depth measured and dispersion equal to the measured error of the activity or depth respectively. The second step of the procedure is calculation of the ages using adequate method. For ^{14}C method sub-samples of ages are selected from distributions of calibrated ages.

For every sub-data set age~depth model is constructed. It is possible to use linear model (GLM) or non-linear models as Splines, General Additive Model (GAM) or Local Polynomial Regression Fitting (LOESS) for age-depth relation fitting. Selection of the best function, the second problem solution, must take account any information of problem nature. Usually for time-scale construction the best solution seems be LOESS method.

Finally, basing on great number of age-depth model realizations, a time scale with confidence interval calculation is performed.

FACTORS PROMOTING PRESERVATION BIAS IN SPELEOTHEM GROWTH

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Abstract

Speleothems are important carriers of paleoclimatic and paleohydrologic information, as recorded by calcite growth rate, and isotopic and elemental variations. The implicit assumption in most speleothem proxy studies is that calcite deposition has occurred year-round at a constant rate. This assumption requires scrutiny. Variations in growth rates can be caused by interannual and seasonal environmental changes, including: (1) changes in cave temperature, (2) variation in water supply and water chemistry, (3) changes in CO_2 supply to the cave environment and, (4) seasonal and diurnal cave CO_2 ventilation.

Although cave temperatures are typically near the mean annual surface temperature, seasonal swings of a few degrees are common. Calcite growth rate changes driven by temperature are small, on the order of 1% per °C, although shallow and well-ventilated caves and cave entrances may be coupled to the surface sufficiently to be noticeably influenced.

Drips that feed speleothem growth may vary seasonally in drip rate. In arid to semiarid climates it is common for some cave drips to cease in the summer. At high latitudes or high altitudes freezing can curtail water supply in the winter. Drip water Ca concentrations influence growth rate dramatically. A 10% change in drip water Ca concentration can yield a 14% change in calcite growth rate. Seasonal water chemistry is related to variations in soil CO_2, water availability and aquifer flow path.

The difference between cave air CO_2 levels and the CO_2 levels of vadose water entering the cave influences growth rate. Models indicate that calcite growth rates from 80 ppm Ca drip waters at 20° C are halved by an increase in ambient CO_2 from atmospheric to ~2000 ppm and reduced to zero above ~7500 ppm. Field measurements of calcite growth in Texas caves suggest a lower, ~5000 ppm, CO_2 threshold for growth. These changes are seasonal, with high CO_2 and no calcite growth in summer. The balance of supply and loss accounts for seasonal changes in cave-air CO_2. Supply is typically derived from soil CO_2. Increasing soil temperature and moderate moisture increases biological production of CO_2. Cold, dry or very wet conditions retard microbial respiration. CO_2 supply is typically highest in the spring and summer. This soil CO_2 moves to the cave environment through the dissolution of epikarst carbonate rock and degassing of CO_2 and redeposition of calcite in the cave and connected fractures. In mid and high latitudes, seasonal build-up and loss of this cave CO_2 is commonly a response to density contrasts with surface air. When surface temperatures are above those in the cave, surface air density is lower than that in the cave and CO_2 can accumulate above the level where calcite deposition stops. When surface temperature is below that in the cave, accumulated CO_2-rich cave air is displaced by denser outside air at ~380 ppm CO_2, allowing faster speleothem growth. This yearly swing in cave CO_2 is a function of parallel soil CO_2 production and cave CO_2 accumulation. Typically, speleothem growth in mid latitudes favors preservation of proxies grown in the winter. Under-representation of the summer record may bias records developed from interannual composite samples.

GLACIAL CAVE ICE AS THE CAUSE OF WIDE-SPREAD DESTRUCTION OF INTERGLACIAL AND INTERSTADIAL SPELEOTHEM GENERATIONS IN CENTRAL EUROPE

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Here we present evidence, collected in four caves, explaining the, in Central Europe, wide-spread occurrence of naturally broken speleothems. We suggest that they belong to a specific facies caused by cave ice during glacial times when permafrost spread throughout the area. We strongly oppose the often published view that such damage was caused by paleo-earthquakes. The so far presented evidence for paleo-earthquake damages is, at best, inconclusive.

1. Introduction

The first reliable depiction of natural speleothem damage is seen on the sketches of Postojnska jama (Adelsberger Grotte) by Alois Schaffenrath from the 1820s. Hohenwart (1830, 1832a,b) discussed these damages, clearly excluding rock fall or earthquakes as a cause. Most striking are several leaning columns in Postojnska jama, still standing on or next to their bases. If broken by an earthquake, they would have received enough kinetic energy toppling them to the ground. Leaning them to the wall must have involved a much slower process, such as associated with freezing and thawing of ice.

During the Last Glacial Maximum (LGM) temperatures dropped by about 17° C in Central Europe, much more than in other temperate areas of the globe. Before permafrost closed pore spaces, caves filled with sub-freezing air causing seepage water to form wide-spread ice (but not necessarily filling them completely). During permafrost times, this ice would be cooled further, causing minute movements of the ice body possibly capable of breaking speleothems. When the permafrost towards the end of the LGM vanished, the cave ice melted. Then large ice masses could slide also breaking speleothems firmly surrounded by them. The slowly melting ice could also provide the possibility that large columns would slowly tilt until leaning at the wall.

To document all sorts of speleothems damage that may be caused by cave ice and not by other causes (such as rockfall, erosive undercutting, sediment compaction, anthropogenic damage or others) we searched and surveyed sections of caves in a north-south profile in Central Europe. Specific attention was paid to the Baumann Cave in the Harz, the newly discovered and completely undisturbed Herbstlabyrinth in Northern Hesse, the well preserved Geisloch in the Frankonian Alb and the non-touristic sections of Postojnska jama. One of the most compelling evidence for ice as an agent to break speleothems are fragments of flowstone that rest precariously at places where they could not have fallen to. In many passages the pre-Holocene generation of speleothems is substantially damaged. Stalactites and draperies have been sheared off the ceiling and deposited on the floor. Stalagmites have been broken and moved to the side of the passages or have been broken and moved a few cm off their original bases where they were re-fixed by postglacial flowstone. If accepting speleothem damage as a consequence of glacial cave ice, then its extent is yet another paleo-temperature marker, dividing Europe into areas were substantial cave ice formed and where not.

2. Overview of Processes Causing Speleothem Damages

The possible causes of speleothem damage are manifold and were discussed by many authors (e.g., Spöcker, 1933; Schillat, 1965; Moser & Geyer, 1981; Knolle, 1982; Kempe, 1989; Pielsticker, 1998), they can be grouped as follows (Kempe & Henschel, 2004):

In some caves damaged speleothems outnumber intact formations. As Table 1 shows, the question why speleothems broke has to be answered individually for every site. When focussing on cave ice as a reason for sinter damage, its formation has to be explained. It cannot form during

Site-limited processes	Processes of local impact	Processes of regional impact
Incasion	Frost in entrances, caves in high altitude and in cold air traps	Ice in caves during glacial periods
Mass wasting	Inundation	Earthquakes
Compaction	Dessication	
Erosion		
Recrystallisation, crystal tension (?)		
Vandalism		

Table 1: Differentiation of speleothems damage according to spatial reach of processes.

permafrost periods because then seepage paths are completely sealed. Thus cave ice formation is limited to the transition times from warmer to colder climate. Cold winter air can then enter the cave and once the floor is cooled to below freezing water dripping from the ceiling begins to build up an ice body on the cave floor. This process can be observed today in alpine ice caves that are much below the elevation of permafrost. The size of the cave ice body is depending on seepage water supply and on ventilation. Oscillating temperatures like during Dansgaard/Oeschger Cycles can cause thawing and freezing. Depending on altitude and proximity to growing glaciers, permafrost will seal the cave roof for a shorter or longer period during stadials and glacial maxima. It is well conceivable that most caves in Central Europe were filled with cave ice more or less completely.

Another effect of permafrost sealing is the interruption of speleothem growth. In the Sontheimer Cave, Swabian Alb, speleothems dating from warm periods occur, while cold period speleothems are missing (Abel & Rosendahl, 2000) because of wide-spread and long-lasting permafrost in the Swabian Alb during cold periods.

3. Cave Ice Induced Speleothem Damage

Cave ice can inflict speleothem damage in several ways. Once the cave ice formed, encasing speleothems, further temperature reduction will exert a mechanical force: The length of a solid body (in this case ice) is approximately a linear function of temperature. The cubic coefficient of expansion of ice is $\gamma = 3\alpha = 21.3 \times 10^{-5}$ /K, leading to the linear coefficient of expansion of $\alpha = 7.1 \times 10^{-5}$/K. For an ice body with a length of 10 m a change of temperature of 5° C results in a length variation of 3.5 mm. Larger ice bodies and higher temperature fluctuations result in considerable variability of length. A column encased in ice could be exposed to enough pressure to be sheared off its base. Furthermore, build up and melting of cave ice will be asymmetrical, i.e. quicker below drip places and slower at drier places. The resulting slope can cause slow, glacier-like movement by re-crystallization under pressure. Again, speleothems encased in the ice could be broken and moved with the ice. Furthermore the entire ice mass can start slipping if the temperature of the floor rises above the 0°C isotherm.

Figure 1 schematizes the possible effects of cave ice damage within one temperature cycle. Depending on geographical position such cycles could have repeated many times, even within the last Interglacial/Glacial Cycle. Even outside the region of the Glacial permafrost cave ice could have formed

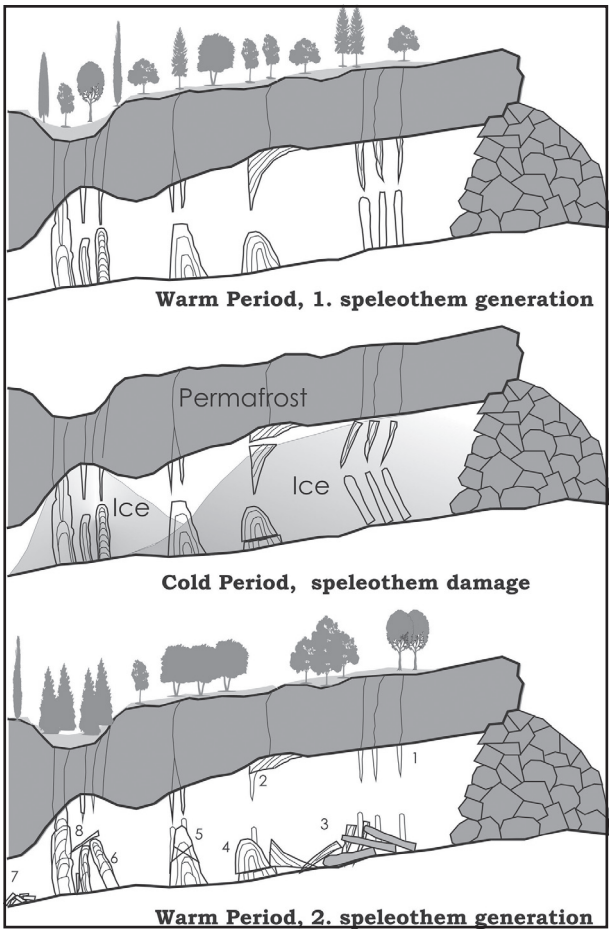

Figure 1: Scheme of possible speleothem damage by cave ice (Kempe, 2004).

during the LGM. The damage inflicted by cave ice could include (Kempe, 2004, Kempe & Rosendahl, 2003):

1. Missing ceiling formations of older generations.
2. Sheared-off stalactites and draperies, deposited on top of floor speleothems.
3. Broken and deposited stalagmites.
4. Sheared-off stalagmites which have been shifted from their base but still stand upright.
5. Cracked conical stalagmites.
6. Tilted and leaning stalagmites.
7. Moraine-like piles of floor flowstone.
8. Precariously placed ceiling formations.

In addition to speleothem damage freezing or the formation of cave ice can leave other traces like scratch marks on cave walls, cryoturbation in cave sediments, solifluction deposits, transport of gravel without evidence of flowing water, loss of uranium due to leaching processes and high collagen content of fossil bones.

4. Case Studies

4.1 Baumann's Cave (Harz, Germany)

The Baumann's Cave (400m above sea level) is the oldest continuously operated show cave, already famous for its speleothems in Baroque times (Kempe et al., 2004). The cave (total length 1950 m) developed in Devonian limestone, following WNW-ESE striking joints. Its large halls (the Goethesaal is 50 m in diameter and up to 9 m high) appear to be of phreatic origin. Speleothem growth commenced once the downcutting of the adjoining Bode valley lowered the ground water table.

In the historic section of the cave many speleothems were damaged by visitors. However, in the sections discovered in 1888, a wide range of naturally broken speleothems occur (Table 2). We recorded a total of 36 natural speleothem damages in detail (Dirks, 2005). None of them appears explainable by earthquakes, former sediment fills or any of the other possible causes or a combination of these causes. For example, there are stalactites, sheared off the ceiling and placed precariously on top of floor speleothems overgrown by the Holocene speleothem generation (Fig. 2). The neighbouring Herrmann's Cave shows a similar spectrum of natural speleothem damage.

Kind of damage	Loc. 1	Loc. 2	Loc. 3
stalactites fixed on vertical walls	3	1	-
speleothems fixed to slopes	4	6	2
stalactites on stalagmites	-	2	4
broken and displaced stalagmites	-	7	3
total	7	16	9

Table 2: Statistics of speleothem damage in the Baumann's Cave. Location 1 between "Schildkrötschlucht" and "Leuchterschlucht"; Location 2 between "Untere Säulenhalle" and "Säulenhalle"; Location 3 "Säulenhalle".

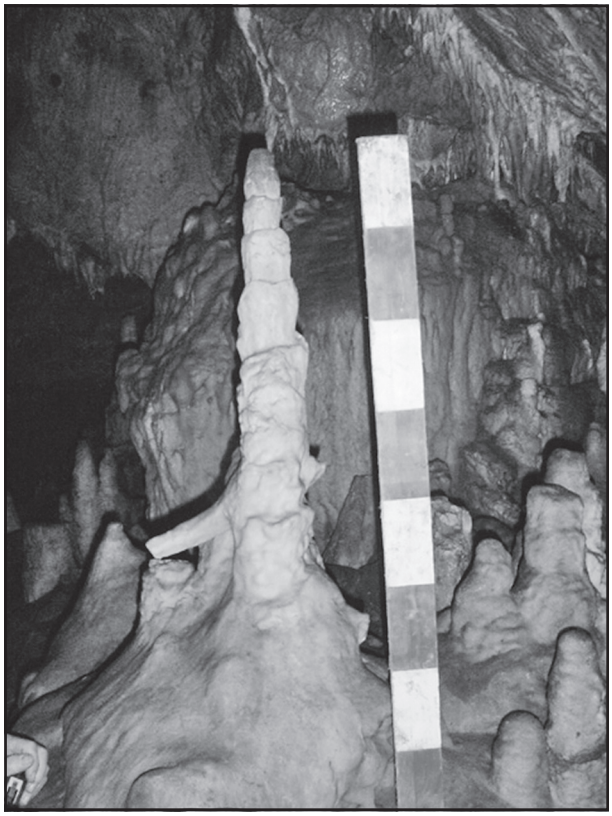

Figure 2: Sheared off stalactite, deposited on a stalagmite and overgrown by new a generation of flowstone (Baumann's Cave).

4.2 Herbstlabyrinth/Rästelhalle (Breitscheid/Rhenish Massif)

The Herbstlabyrinth is a recently discovered cave system also in Devonian limestone. Its speleothems, untouched by visitors, show a wide variety of damages. In the Rästelhalle, previously visited only twice, precariously placed broken stalactites were discovered high up the wall (Fig. 3). There is no way how a former sediment fill or an earthquake could have left these fragments in such a place.

4.3 Geisloch (Germany/Oberfranken)

The Geisloch (455m above sea level) is situated 1 km NNE of Oberfellendorf in Oberfranken, Germany. It was first explored to a length of 26 m by cave inspector J.G. Wunder. In 1968 M. Geyer dug into the currently known parts of the cave, 750 m long. The entrance is secured by a gate and the cave has been kept in its natural state. No vandalism

Figure 3: Precariously placed broken stalactites (Herbstlabyrinth/Rätselhalle).

has yet occurred. The cave consists of a central, phreatically formed, "big room" from where seven short side passages branch off, one of them leading into an underlying labyrinth 15 m below. There is no evidence of speleogenesis by vadose processes or by turbulent water flow.

The big room is profusely decorated with speleothems, among them hundreds of broken specimens. Approximately 70% of the speleothems are broken or show sign of damage (Moser & Geyer, 1981) (Fig. 4). Typical are sheared-off stalagmites, shifted sideward on their bases and "mended" by younger flowstone. Some of the stalagmites were shifted by more than 2 cm (Fig. 5). Common are also sheared-off stalactites, fixed to the wall. Two especially striking examples are shown in Figures 6 and 7. Below the broken fragments the wall formations continue, proving that the deposition of the fragments is younger than the wall formation. If the fragments would have been part of a sediment fill that was later eroded, then the sediment must have been removed from the cave without leaving any trace. Since the cave is situated underneath a hill, there is no way how to move sediment and/or water in and out of the cave in its recent geologic history with a high enough velocity. In the entire cave there is no sign of a former sediment fill to the height of the broken speleothems. Ice can possibly explain all of the observation associated with these specimens: The stalactites were broken off the ceiling, slid down the ice surface when it started to melt, until meeting the wall. There it was fixed by the postglacial onset of flowstone formation, keeping it in place after the ice melted.

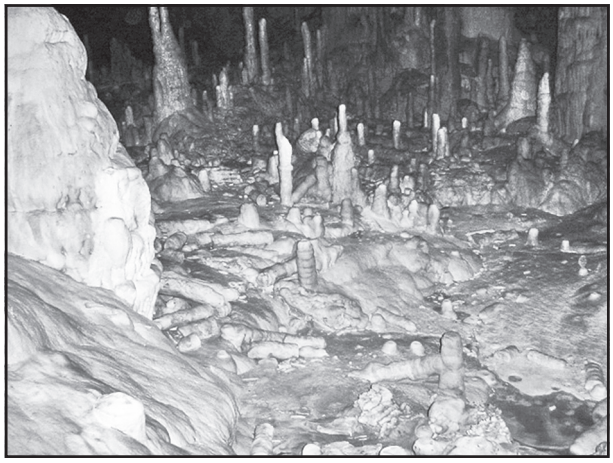

Figure 4: Field of broken stalagmites in the big room of Geisloch.

Figure 5: Broken stalactite, fixed to vertical speleothems (Geisloch).

Figure 6: Piece of stalactite, fixed to vertical speleothems (Geisloch).

Figure 7: Broken and shifted stalagmite (Geisloch).

Large parts of the big room are covered with 10 to 30 cm thick flowstone, overlaying unconsolidated sediments. One could argue that this sediment may be slowly settling into deeper, inaccessible parts of the cave. If this process would be going on, then the large columns reaching to the ceiling should be detached. This, however, is not the case. Instead there are pieces of stalactites adhering to these columns, again making a former ice fill the most probable cause of the breakages.

4.4 Postojnska Jama (Slovenia)

Investigation of speleothem damage in Postojnska jama by the authors (Kempe, 2004; Kempe & Henschel, 2004; Bauer, 2005; Dirks, 2005) has yielded numerous examples of damages that are best explained by cave ice. Specifically in Pisani rov and Brezimenski rov sections of the cave suffered complete loss of the former stalactite and stalagmite generation now on the floor (Fig. 8). The doubly broken and leaning stalagmite in the main passage (Fig. 9), already depicted by Schaffenrath, is only one of the more enigmatic examples of broken speleothems. An earthquake with enough energy to lever the stalagmite off its base would certainly have toppled it. There is no evidence that alternative explanations like sediment fills, sediment subsidence, rockfall or flood waves would produce such a damage pattern.

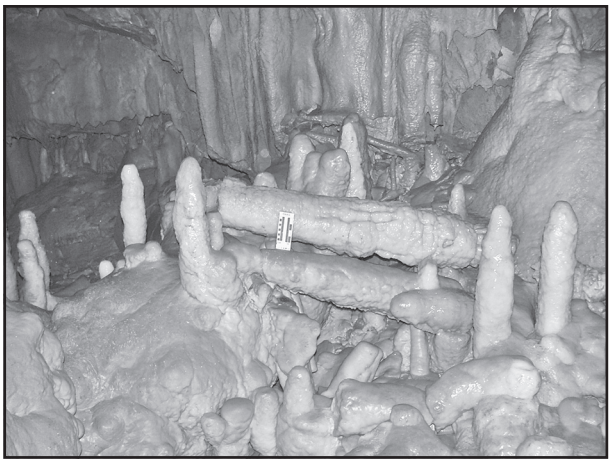

Figure 8: Typical view of the speleothem damage caused probably by cave ice (Pisani rov/ Postojnska jama).

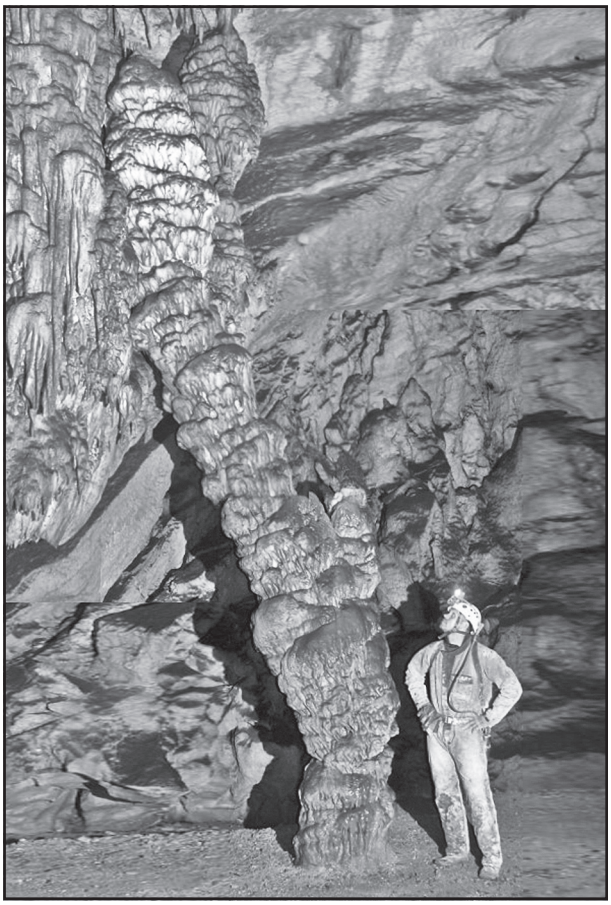

Figure 9: Leaning column in the main passage of Postojnska jama.

5. Conclusions

Investigation of broken speleothems by the authors showed that this phenomenon is wide-spread throughout Central Europe. The results underscore the hypothesis that this damage was caused by cave ice prior to the presently growing Holocene generation. All evidence quoted in favour of earthquakes as a cause (Schillat, 1965; Moser &

Geyer, 1981; Knolle, 1982; Šebela, 2008) is inconclusive at best (Kempe, 1989, 2004). Many caves contain very long Holocene soda straws and up to nearly 10 m high candle stalagmites. These would be most easily toppled by earthquakes. The pattern of speleothem damage is very similar in the various caves, independent if they are situated near major tectonic fault systems like Postojnska jama (near the Idija transform fault) or not, as in the other cases. Broken speleothems seem to constitute an own facies, that could be used to map out Glacial expanse of ice in caves.

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DATING OF SPELEOTHEMS FROM DEEP PARTS OF THE WORLD'S DEEPEST CAVE – KRUBERA (ARABIKA MASSIF, WESTERN CAUCASUS)

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Abstract

Results of ^{230}Th (ICP-MS) dating of speleothems from the Krubera (the deepest cave in the world; -2191 m) and Kujbushevskaja caves in the Arabika Massif, Western Caucasus, are reported in the paper. Most of the dates are from samples taken from the deep part of Krubera Cave, between depths of 1630 and 2010 m below the surface (elevations of 629 and 246 m asl.), which is important for elucidating evolution of karst systems in the area and its relation to changes of the base level (the Black Sea level). The nine dates available scatter through each of the seven marine isotope stages and overlap known periods of active speleothem deposition in the Eastern Alps (e.g., Holocene, 50–60 ka, 67–80 ka, 190–240 ka, 250–280 ka), as well as the period when speleothem growth halted (160–165 Ka; marine isotope stage 6).

The presence of two dates older than 200 ka (max 276 ka) from deep parts of Krubera Cave (depth in the cave -1,640 m and -1,820 m; respective elevations 640 m and 436 m asl) indicates that these parts of the cave were in the vadose zone, not the phreatic zone, before the Middle Pleistocene.???

Two samples from fossil passages located at elevations of 2016-1906 m a.s.l. are dated beyond the limits of ^{230}Th dating (>500 ka).

The results are consistent with the hypothesis that the early development of the karst system, which Krubera Cave is part of, is linked with the Late Miocene (Messinian) period of an extremely low position of the sea level. The significant vertical development of Krubera Cave was influenced by the rapid uplift of the Arabika Massif during the Pliocene-Pleistocene time.

URANIUM MAPPING IN SPELEOTHEMS: OCCURRENCE OF DIAGENESIS, DETRITAL CONTAMINATION, AND GEOCHEMICAL CONSEQUENCES

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The microscopic distribution of uranium and other chemical elements was studied with high spatial resolution geochemical imaging techniques in speleothems unusually rich in uranium. We combined three complementary methods: digital autoradiography of radioactive elements, X-ray fluorescence microspectroscopy (micro-XRF), and nuclear microprobe analysis using a particle accelerator. The application of these techniques to karstology opens perspectives for improving our understanding of diagenesis and crystallochemistry of speleothems. The first studied example is a calcite-aragonite corallite of Pierre Saint-Martin (France). Quantitative imaging of Sr (4909 to 18571 $\mu g.g^{-1}$) and U (88.7 to 350.0 $\mu g.g^{-1}$) reveals that both elements concentrate into the aragonite. In calcite Sr content is 439 to 1097 $\mu g.g^{-1}$ and U 10.9 to 19.3 $\mu g.g^{-1}$. The second example is a calcite-aragonite-opal corallite of Baïkal (Russia). Digital autoradiography and micro-XRF analyses indicated exceptionally high U contents in solution voids filled by neoformation opal (up to 1300 $\mu g.g^{-1}$). The third example is a calcite stalagmite polluted by detrital minerals (Gironde, France). The digital autoradiography shows radioactive rich zones corresponding to detrital contamination. The XRF analysis shows that the origin of radioactivity is due to zircon minerals rich in Zr, Hf and Th. In conclusion the chemical imaging methods are powerful tools to reveal: (1) the evidence and distribution of U or other elements ; (2) particular diagenesis phenomena which can be observed by micropetrography on thin sections ; (3) the opening of geochemical systems which must be considered in U/Th datings and more generally for U geochemical stability in $CaCO_3$.

1. Introduction

The geochemistry of uranium in calcium carbonate constitutes a large topic. The uranium content in $CaCO_3$ is usually low: often <200 ppb for speleothems (EGGINS et al., 2005) and a few µg/g for corals (PONS-BRANCHU et al., 2005). In continental environments, the soluble uranium in the water results from the leaching of soils and weathered material and the dissolution of bedrock (LALOU, 1985). It precipitates almost always in the hexavalent state, in the form of carbonated and hydrated complexes. However, U can combine with Ca in tetravalent form under reducing conditions (STURCHIO et al., 1998). Uranium chemistry in calcium carbonate of continental and marine environment is of considerable interest for validation of $^{238}U/^{230}Th$ dating methods. Sometimes, U-series dating in $CaCO_3$ is altered due to opening of the geochemical system by detrital and organic contamination, or by physical alteration, especially in the corals (THOMPSON et al., 2003; SCHOLZ and MANGINI, 2007). The analysis of uranium and/or other inorganic trace elements trapped into speleothems at a microscopic level requires the use of analytical methods that can provide information on the spatial distribution of trace elements with micrometer resolution. A variety of mapping techniques have been applied in geochemistry to provide chemical information in the form of a spatially resolved image (ORTEGA, 2002). These techniques are based either on mass spectrometry such as secondary ion mass spectrometry (SIMS), and laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), or on X-ray emission such as X-ray fluorescence spectrometry (XRF), electron microprobe, nuclear microprobe, and synchrotron radiation X-ray microanalysis. In this research on several examples of uraniferous speleothems, we use the three following methods to map uranium: digital autoradiography, micro-XRF and nuclear microprobe.

2. Methodology

2.1 Digital autoradiography

Digital autoradiography is a method for analysing radioactive elements. As well as being extensively used in medicine and the biological sciences, it has proved its value

in the environmental sciences (COLE et al., 2003). The method involves placing a sample on a radiosensitive screen that can detect the radioactive particles the sample emits. For the present study we used a Biorad Personal Molecular Imager with a BaFBr:Eu radiosensitive screen. The BaFBr crystals and the Europium ions absorb the energy of the radiation emitted by the sample. This radiation changes the state of the Europium ions from Eu^{2+} to Eu^{3+}. The freed electrons are fixed by the bromine atoms and form an image on the screen. In order to obtain clear images and to avoid saturation or under-exposure problems, a pre-test is carried out to determine the optimum exposure time with respect to the concentrations of radioactive elements in the sample. The analysis was carried out in three stages: (1) The radiosensitive screen was first exposed to a light source of a precise wavelength, in order to eliminate any traces of previous exposures. (2) The polished face of the sample section was then placed on the radiosensitive screen and left for the exposure period. A lead cover was placed over the concretion and radiosensitive screen to protect the system from cosmogenic radiation and to limit background noise. (3) After several days, the samples were removed from the radiosensitive screen, which were scanned to recover the radiographic image. Quantitative analysis was assessed by using a calibration curve established from calcium carbonate pellets with known amount of uranium: 0, 10, 50, 100, 250, 500 and 1000 $\mu g.g^{-1}$, exposed simultaneously with the sample.

2.2 Micro-XRF

This microscopic chemical imaging method has only recently been used in the environmental sciences. It is based either on x-rays produced by synchrotron radiation sources (FRISIA et al., 2005), or by more compact x-ray sources fitted to commercially available instruments (BÖNING et al., 2007). The Horiba XGT7000 X-ray analytical microscope used in the present study present a rhodium source (voltage: 50 kV, current: 1 mA) to produce a beam of x-rays that is focused by a 100µm or a 10m diameter guide tube and directed onto the sample. The spectrum of x-rays emitted by the irradiated sample can be used to determine the sample's chemical composition, as every chemical element has its own x-ray signature. Once again, the analysis time is an important factor, as the signal to noise ratio is proportional to $\sqrt{t}$ (t = counting time). Micro-XRF was applied to several small parts of a speleothem of Siberia, as we wanted to focus on a uranium-rich areas revealed by the autoradiography analysis. Data acquisition for the areas analysed was carried out in a vacuum using a 100-µm diameter beam (1 mA, 50 kv), a 70-µm step and a total analysis time of 11 000 seconds. Element maps were obtained by selecting the energy range for each element to be mapped and combining all the hits in this range. In addition, in order to more precisely define the XRF spectra representative of different areas of the sample, random analyses were carried out using a 100-µm beam and an acquisition time of 1500 seconds.

2.3 Nuclear microprobe

Particle Induced X-ray Emission (PIXE) and Rutherford Backscattering Spectrometry (RBS) were performed first on a Pyrenean speleothem using the nuclear microprobe beamline at the AIFIRA facility (Applications Interdisciplinaires des Faisceaux d'Ions en Region Aquitaine). The nuclear microprobe enables microscopic chemical mapping of trace elements on numerous types of environmental and geological samples. The methodological aspects for nuclear microprobe analysis of speleothems, and quantitative analysis validation, have been described in a technical note (ORTEGA et al., 2003). In brief, the energy of the incident proton beam produced by the Van de Graaff accelerator was 3.0 MeV. The beam diameter was 5 µm, resulting in a proton beam current of 250 pA as measured with a Faraday cup below the sample. X-ray fluorescence measurements were made with a Si(Li) energy dispersive detector using a 650 µm thick carbon filter to cut the strong background contribution due to Ca X-ray fluorescence. The RBS measurements were performed using a Si surface barrier detector placed at 135° from incident beam direction. X-ray fluorescence data were analysed with the Gupix software, and RBS data with RUMP code. The chemical element reference was USGS (United States Geological Survey) basalt Columbia ridge standard certified sample BCR2. A very good agreement between measured and certified values was achieved. Chemical maps of the elements were obtained using the Kα X-ray emission lines for Ca (3.69 keV), Zn (8.64 keV), and Sr (14.16 keV), and Lβ1 for U (17.22 keV). Using 3.0 MeV protons, the maximum scan size achievable with the AIFIRA nuclear microprobe is 683 µm x 683 µm. In the color distribution maps, the element concentration increases from black to yellow. In the black and white distribution maps, each chemical map is coded with 256 levels of grey, the element concentration increasing from black (minimum) to white (maximum). The X-ray fluorescence maps were normalized by local sample mass using RBS data on $CaCO_3$ content to obtain quantitative results expressed in terms of µg of element per g of sample. The local sample mass was calculated from aerial mass RBS data using calcite and aragonite densities, respectively 2.71 g/cm^3 and 2.94 g/cm^3.

3. Results for Three Examples

3.1 Pierre Saint-Martin Cave (Pyrenees, France)

Aragonite and calcite speleothems have been sampled in Aranzadi gallery of Pierre Saint-Martin Cave (QUINIF and MAIRE, 1998). Scintillometer measurements near the aragonitic speleothems show the radioactivity reaches 100-400 counts per second. One corallite concretion (AR2000) can serve as reference sample because of its massive structure showing alternation of aragonite-calcite and convoluted haloes of white aragonite and grey calcite due to recrystallization of aragonite into mosaic calcite with residual aragonite needles (ORTEGA et al., 2005). The auto-radiography made after 13 days of exposure show that radioactivity (grey) is located in aragonite. Micro-chemical images by nuclear microprobe were made from Ca, Sr, U, and sometimes Zn, distributions according to the obtained X-ray fluorescence signal. In all samples, images of Ca are almost uniform, because of the abundance of this element in both aragonite and calcite. U is concentrated preferentially in the aragonite as shown either in large bands of calcite and aragonite, or in alternated aragonitic phases. U is also concentrated in the base of an aragonite bud (Fig. 1).

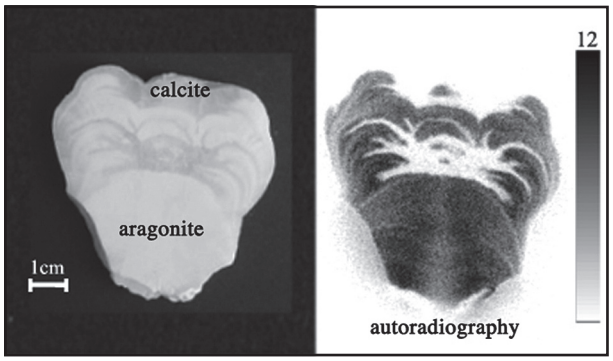

Figure 1: Corallite speleothem from Aranzadi Gallery (Pierre Saint-Martin, Pyrenees). Left : polished section with aragonite (white) and neoformation calcite (grey). Right : autoradiography after 13 days showing radioactive aragonite.

Mapping of Sr gives similar results with the ones for uranium. The quantitative results of PIXE chemical analyses of calcite and aragonite show remarkable values of U from 88.7 ± 10.6 to 350 ± 26 µg/g in the aragonite and 10.9 ± 5.3 to 19.3 ± 3.5 µg/g in the calcite. For Sr content, we have also remarkable values; in calcite Sr ranges between 439 ± 7 and 1097 ± 12 µg/g and in aragonite from 4909 ± 19 to 18.571 ± 98 µg/g, with the maximum in the aragonite bud. The high U concentration has been confirmed by several U/Th datings (TIMS): 12.6 to 15.6 µg/g in the calcite and 206 µg/g in the aragonite. The ^{232}Th content is very low (0.6 to 1.5 ppb) and the ratio ^{230}Th/^{232}Th is exceptionally high: 13,378 and 36,422 in neoformation calcite, and much more in aragonite with a ratio of 195,693 (lab. GEOTOP, Montreal). The uranium oxidation state in calcite and aragonite was determined using XANES spectroscopy at the ESRF (European Synchrotron radiation Facility) in Grenoble, France. The U L2 absorption edge depicts a 2.1 eV shift between U(IV) (20,952.2 eV) and U(VI) (20,954.3 eV) oxidation states. XANES experiments revealed that U is present in its hexavalent both in aragonite and in calcite (ORTEGA et al., 2005) (Fig. 2).

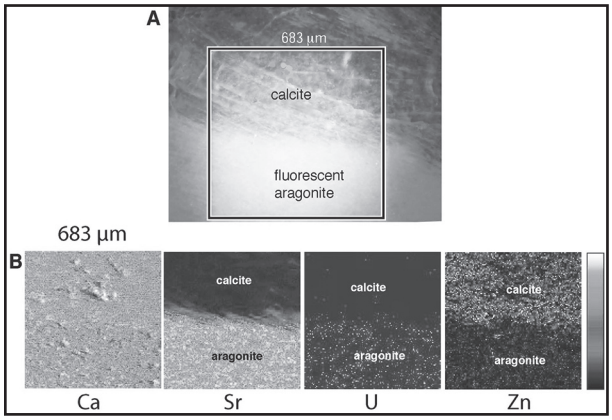

Figure 2: Nuclear microprobe mapping at the contact aragonite-calcite for the corallite sample AR2002 (Pierre Saint Martin, Pyrenees). Sr and U are concentrated in aragonite and Zn in calcite.

3.2 Mechta Cave (Baikal, Russia)

Mechta Cave, 823 m long and 52 m deep, is located in the Precambrian marbles of the west bank of Lake Baikal (Tageran steppe). The sample studied is a corallite concretion that formed slowly by the precipitation from moisture that had condensed underground. Polished sections revealed alternating laminas of grey calcite and white aragonite. The speleothem is older than 400,000 yr BP (U/Th-TIMS), and showed no signs of detrital contamination (^{230}Th/^{232}Th > 10,000). Uranium concentrations for all the samples are indicated in shades of grey, from white (0 µg.g^{-1} U) to black (highest measured concentration). The quantitative analyses corresponding to each shade of grey were determined by comparison with a set of $CaCO_3$ standards of known U concentrations ranging from 10 to 1000 µg.g^{-1}. The mean U content for the whole sample was 80 µg.g^{-1}, a value that is unusually high for a speleothem. Moreover, the uranium distribution is very heterogeneous within the sample. Certain areas of sample Sib25a contained exceptionally high levels of U, ranging from 360 up to 950 µg.g^{-1}. These areas were small, from 2 to 10 mm height, and mostly coincided with the aragonite (white) zones of the speleothem (Fig. 3).

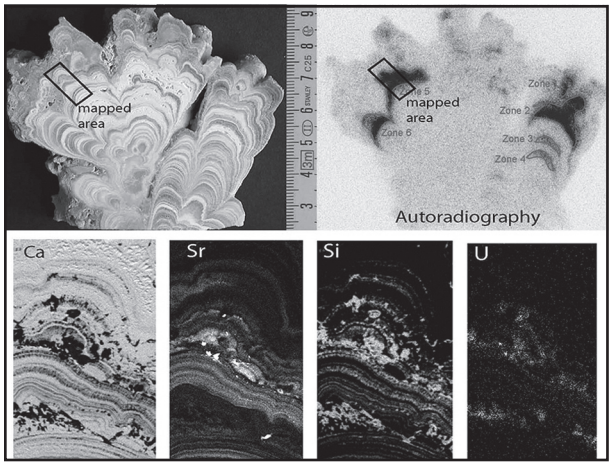

Figure 3: Corallite speleothem in Mechta Cave, Tageran (Baikal, Russia). Top: polished section (left) and autoradigraphy (right) showing the radioactive areas (in black). The rectangle indicates the area analyzed by μ-XRF. Bottom: μ-XRF mapping of Ca, Sr, Si and U. There is a reverse correlation between Ca and Si (opal), and a positive correlation between Si (opal) and U.

Superimposing the autoradiography image (exposure 66 hours) and the speleothem cross-section image shows that the three areas with the highest U contents (zones 2, 5 and 6) coincide with a group of laminas with the same age, although the central parts of these laminas are not affected. The other three uranium-rich areas have lower U contents and are grouped in the right-hand part of the sample; that is to say, near the apex of the speleothem. It is interesting to note that the heart of the concretion, which is the oldest part of the sample, gave much lower (< 10 $\mu g.g^{-1}$) and very homogenous levels of radioactivity. Micro-XRF element mapping was carried out on two small parts of the sample. The first area chosen (5.12 mm x 10.24 mm) covered zone 2, with one of the highest U contents as shown by the autoradiography analysis. The elements detected in this zone were Ca, Sr, Si and U. Another studied area (4 x 1 mm) confirms the highest concentrations of U in opal, locally up to 1300 $\mu g.g^{-1}$. On the maps, we observe an inverse correlation between Ca and U and between Sr and U, but a strong correlation between Si and U (Fig. 4).

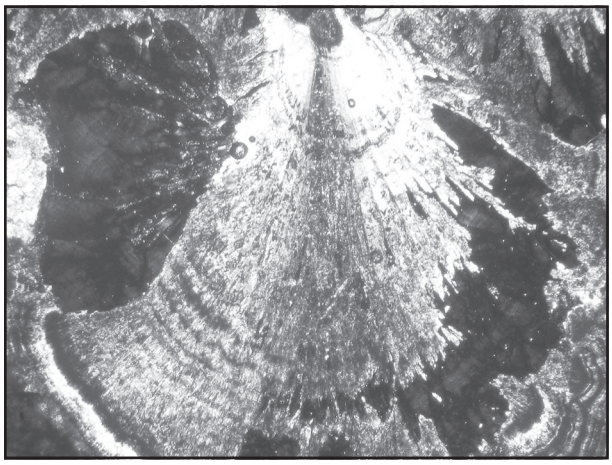

Figure 4: Photo of thin section in polarized light showing an aragonite bud (grey), 1 mm wide, replaced partially by opal (black). Residual aragonite needles are visible in opal because of dissolution. Mechta Cave (Baikal, Russia).

3.3 Trou Noir Cave (Gironde, France)

The Trou-Noir is an active cave system (sinkhole-resurgence) situated in the Oligocene porous limestone of Entre Deux Mers plateau near Bordeaux (Gironde) (LANS et al., 2006). An active stalagmite (TN 05) has been sampled near a narrow passage located in the middle of the cave and responsible of high waters in upstream. This stalagmite, 12 cm high, shows a smooth corroded surface with fissures due to mechanical shocks (floods, floating wood). The polished section shows dark laminated calcite divided in twelve growth cycles. The distribution of radioactivity by digital autoradiography (exposure time 66 hours) is not homogeneous; it is concentrated particularly in the lower part (0-37 mm). On thin section, we observe that radioactive zones are related with levels rich in detrital material. The mineralogical determination, after dissolution by HCl, indicates quartz (80 %), zircon (> 10 %) along with smaller amounts of glass and heavy minerals, such as staurolite and rutile. A three-hour μ-XRF analysis with a carbon filter to stop the Si signal shows the Zr, Fe and Ti rays. A focus between Fe and Zr rays indicate the presence of Hf, Zn and Th. Thorium is responsible for the radioactvity in the detrital particles (Fig. 5).

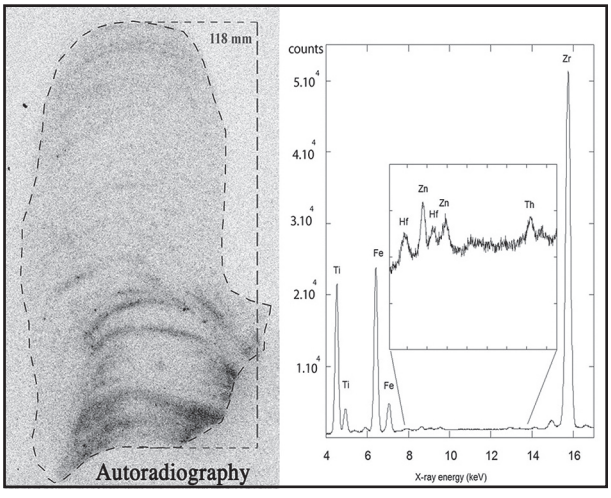

Figure 5: Autoradiography of Trou Noir stalagmite (left) and μ-XRF spectrum of a zircon (right). The radioactivity is due to thorium.

4. Discussion

4.1 Recrystallization of aragonite into calcite (Pierre Saint-Martin : consequences for the geochemical system

U and Sr concentrations measured in the aragonitic speleothems of Aranzadi Gallery are one of the highest of those analysed in cave concretions of meteoric origin. The uranium amount in natural calcites is typically in the range 0.01-3 µg/g. The chemical fixation of uranium in the aragonite and calcite is a complex phenomenon very difficult to identify at the atomic level. When the U content is of the order of a few ng/g to 1 µg/g, it localizes in the structural defects of the crystals. But the abnormal abundance of uranium in calcite, in several speleothems from the Aranzadi Gallery (10.9 to 19.3 µg/g), poses an interesting geochemical problem. The pseudomorphosis of the uraniferous aragonite by calcite, by recrystallization is proved in the top by a series of remarkable occurrences: altered aragonite, residual needles of aragonite partially "consumed" by calcite, microfractures, neoformation mosaic calcite. The abnormal abundance of uranium, as well as Sr, in the calcite is a strong argument in favour of recrystallization. At the time of the recrystallization of aragonite to calcite, the large ionic dimension of the tricarbonated-uranyl anion $UO_2(CO_3)_3^{4-}$ trapped in the orthorhombic structure of the aragonite (with a noncoordinated site) results in both a loss of uranium in the neoformation calcite, and an abnormally strong residual uranium content (Ortega et al, 2005). We conclude as hypothesis the loss of uranium in neoformation calcite is due to U migration towards aragonite through the crystalline system, but we do not know if the the geochemical system is open because U/Th datings do not indicate radiochronologic anomalies in the middle of the sample on the same stratigraphic level: 43426±324 yr in aragonite and 42644±622 yr in neoformation calcite (lab. GEOTOP, Montreal). It is a very important perspective of research; indeed the phenomenon of recrystallization of aragonite into calcite and dolomite is well known in the marine environment for corals. During the recrystallization of a coral reef, U is expulsed resulting in a decreased concentration, from 3 µg/g into initial aragonite to 0.5 µg/g into secondary calcite (methods deLALOU, 1985). Similar to what is reported for marine calcium carbonates, recrystallization of speleothem aragonite into calcite, and subsequent uranium loss, may probably lead sometimes to erroneous dating.

4.2 Diagenesis of aragonite-calcite into opal (Baikal) and origin of U

The map showing the distribution of Ca includes areas with very low Ca concentrations that appear as "voids" in the calcium carbonate matrix. These voids are filled with Si and U. Some of them appear black in crossed-polarized light, indicating that the Si is present in the form of opal (SiO_2, nH_2O) which is amorphous. This neoformed opal is particularly rich in U, with small areas showing concentrations of more than 1300 $\mu g.g^{-1}$. There is a good agreement between the U concentrations obtained using the two analytical methods, as the U concentrations measured by autoradiography (up to 950 $\mu g.g^{-1}$) are of the same order of magnitude as the point values measured using micro-XRF (up to 1300 $\mu g.g^{-1}$). The differences between the two methods can be attributed to the sizes of the measurement areas: autoradiography gives mean concentrations for relatively large areas of the sample, whereas micro-XRF measures concentrations in very small areas (100-µm to 10-µm beam). Both methods demonstrate the presence of small areas that are enriched in U by several hundred $\mu g.g^{-1}$.

The process by which opal replaces calcite and aragonite in speleothems and wall crusts that formed in carbonate environments has been described only in a few cases. For example, a similar process - involving speleothems in basalt lava tubes on Jeju Island in Korea - has been observed. In this case, the source of the Ca and Si was the leaching of the basalt by percolation waters (CHOI et al., 2005). In Mammoth Cave (Kentucky), the opal crust is only in the cave walls, but also in gypsum and aragonite crusts, as well as in the bedrock, and some of it has replaced calcite (PALMER and PALMER, 1995). In hydrothermal caves of New Mexico (USA), opal is quite common because sulfuric acid attacks clay and releases dissolved SiO_2 (as H_4SiO_4), so opal precipitates more rapidly. The acid also dissolves carbonate minerals, and there is a replacement of some of the carbonates by SiO_2 (PALMER, 2007). In Siberia, for Mechta Cave, the most probable hypothesis is silicilic acid-rich and uraniferous solutions coming from the leaching of volcanic ash. Indeed, the presence of uranium in volcanic glass is well known and the Baikal region presents many volcanic areas (ALIOUKA, 1999).

4.3 Role of detrital zircon in Trou Noir cave (Gironde)

In mineralogy and geochemistry, we know the zircons with actinides are the main radioactive minerals in granitoids and syenites, with substitutions and concentrations of U_3O_8 and ThO_2 (BARIAND et al., 2003). In this example, the radioactivity of zircon is due to Th as we can see on the XRF spectrum.

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GEOCHEMICAL STUDY OF A HOLOCENE STALAGMITE FROM THE JEITA CAVE (LEBANON): IMPLICATIONS FOR PALEOCLIMATE RECONSTRUCTION IN THE LEVANT REGION

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Absolute-dated oxygen and carbon isotopic profiles from a Holocene stalagmite (11.9–1.1 ka) from the Jeita Cave (Lebanon), are compared to variations in crystallographic habit, stalagmite diameter and growth rate. The profiles show generally high $\delta^{18}O$ and $\delta^{13}C$ values during the late–glacial, low values during the early Holocene, and again high values after 5.8 ka. Based on the good correlation between the morphological and crystallographic aspect of the stalagmite and its isotopic records, as well as on the isotopic response of speleothems from central and northern Israel, we relate high $\delta^{18}O$ and $\delta^{13}C$ values to drier conditions. Between 6.5 and 5.8 ka an increase in isotopic values, a decrease in growth rate and stalagmite diameter suggests a transition from wet conditions in the early Holocene towards drier conditions in the mid-Holocene. The transition occurred in two steps, first a progressive change to drier conditions started at 6.5 ka but was interrupted by a short (~100 years) return to wetter conditions, followed by an equally rapid (in less than 200 years) change to drier conditions.

1. Introduction

The Levantine region (Lebanon, Israel/Palestine, Syria, and Jordan; Fig. 1A) lies very close to the arid/semi-arid boundary and has a long history of human settlement and habitation (for at least the last 5000 years). This region witnessed important Glacial - Interglacial (G-IG) climate changes as well as a shift of varying climate belts (ROBINSON et al., 2006). The present paper discusses some insights into the Holocene paleoclimatic and environmental evolution of Lebanon, which is an important step for discussing the regional climate changes and vegetation dynamics in that region in order to evaluate climatic predictive approaches for the future.

The Jeita Cave is the longest and most well-known cave in Lebanon (NADER, 2004). It is located within the western flank of central Mount Lebanon. The natural entrance of the cave is situated at about 100 m above sea-level, approximately 5 km east of the Mediterranean coastline and ~15 km north of Beirut City (Capital of Lebanon; Fig. 1A). The average annual precipitation rate at the Jeita Cave site today is around 1000 mm (UNDP, 1970). The climate is seasonal, with rainy winters (between November and February) and dry, relatively hot summers (usually the period from May to October). The cave system is entirely developed in Middle Jurassic grayish fossiliferous limestone rocks (the Nahr Ibrahim Member), a part of the Kesrouane Formation, which has an average stratigraphic thickness of 1000 m (DUBERTRET, 1975; WALLEY, 2001).

The cave hosts numerous speleothems in large chambers, especially in an upper gallery (the touristic part of the cave; Fig. 1B). There, the ceiling is higher than 15 m (Fig. 1C) and most speleothems are characterized by a "dish-stacks" type structure. The stalagmite JeG-stm-1 was retrieved from the upper gallery of the Jeita touristic cave in October 2005, at ~200 meters from the entrance of the upper gallery (Fig. 1B, C). The ceiling of the cave at this location is situated at 16.45 m high, and the thickness of the overburden rock (mainly micritic limestone) is estimated to be 100 m. Water dripping from the high ceiling occurs in the stalagmite site during winter and spring seasons, while possible short-term dryness prevails during the summer. Cave temperature at the stalagmite location is 22.0±0.5°C and remains constant throughout the year.

2. Results

The sampled part of the JeG-stm-1 stalagmite is 121.5 cm long. The inner profile of the stalagmite (Fig. 2) displays a regular deposition of dense calcite, varying in color from dark grey to light yellow-beige. A regular lamination with very thin layers (<0.2 mm) is present but generally only

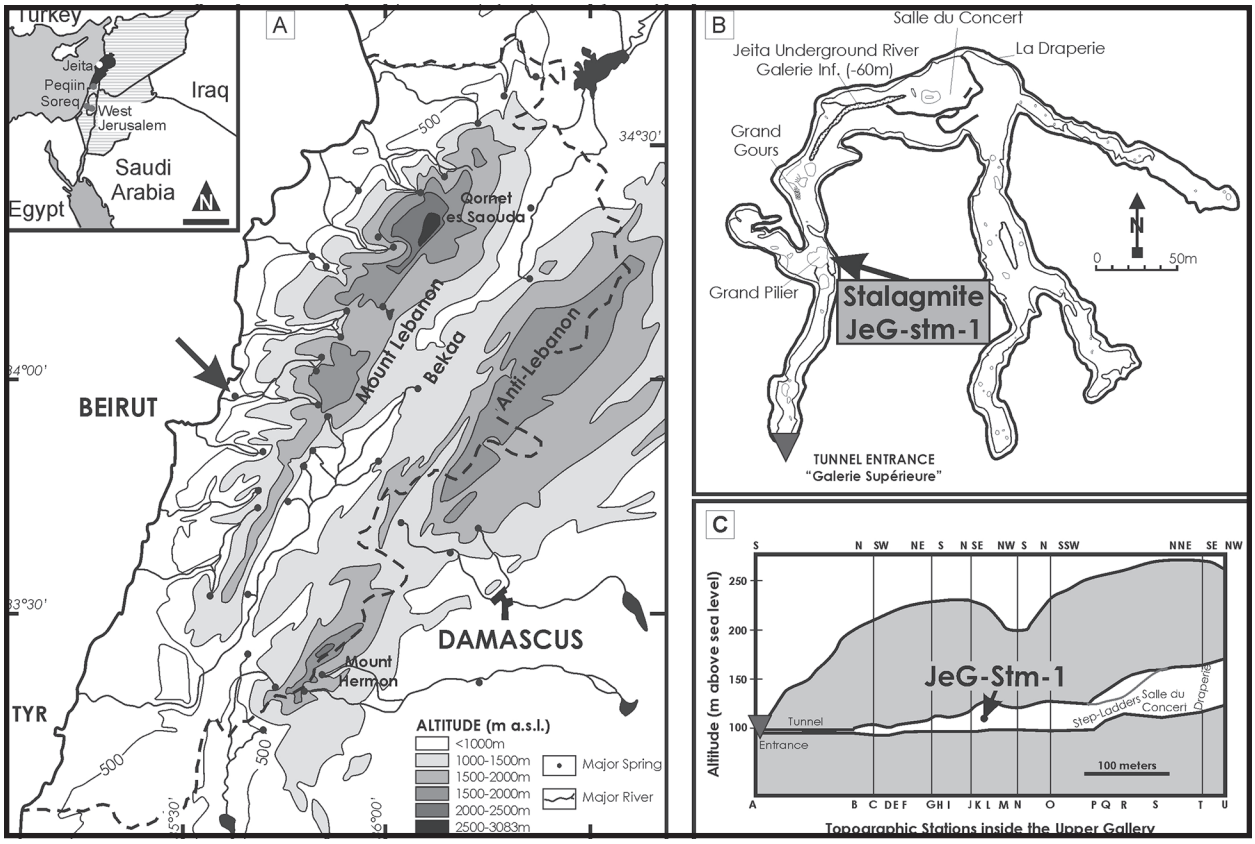

Figure 1: (A) Simplified topographic map of Lebanon showing the main physiographic units (Mounts Lebanon and Anti-Lebanon, and the Bekaa Plain) – the inset map shows the location of Lebanon and the Levant (striped area) in the Middle East – The position of the Jeita cave is indicated with an arrow. (B) Topographic survey of the Upper showcave (Galerie Supérieure) modified from KARKABI (1990), showing the location of the sampled stalagmite JeG-Stm-1. (C) Composite cross-section showing the location of JeG-Stm-1.

visible at the sides of the speleothem. In the central part of the section, the calcite is denser and mainly displays uniform, grey translucent texture. The stalagmite diameter is variable, thickened in its middle part, with a maximal diameter of 18 cm. It becomes thinner towards the top with a diameter of 7 cm at its topmost part and more whitish calcite without dish-stacks structure and a more classical candle-shaped structure.

Dating results presented in this paper are originally published in a previous paper (VERHEYDEN et al., 2008). Uranium-series dating indicates that the stalagmite (JeG-stm-1) was deposited between 11.9 ±0.1 (2σ) ka and 1.1 (extrapolated) ka, when the stalagmite stopped growing. Growth rate varied between 0.50 and 2.62 cm/100 yrs, and no important growth hiatuses were detected. The highest growth rates are observed in the parts of the stalagmite, where the diameter is the thickest and where the dish-stacks structure prevails. The lowest growth rates are observed in parts of the stalagmite with smaller diameter and where the dish-stacks structure disappears, e.g., around 85 cm and about 35 cm from the top of the stalagmite.

The $\delta^{18}O$ and the $\delta^{13}C$ records roughly follow the same trend with relatively high values between 11.9 ka, 11.2 ka, and 10.3 ka. Generally lower values (~ 10.5‰) occur from 11.2 ka onwards with the lowest values (-6.1‰ for $\delta^{18}O$ and -11.2‰ for $\delta^{13}C$) occurring between 8.6 and 6.5 ka (Figure 2). At 6.5 ka, 18O as well as ^{13}C start increasing progressively, and, after a short return to lower values (at 5.9 ka), increases again in less than a century and remain relatively high until the top of the stalagmite at 1.1 ka except for the period between 3.5 and 3.0 ka. According to the $\delta^{18}O$ and $\delta^{13}C$ curves, the stalagmite shows a tripartite partition with a base featuring relatively high carbon signature, a middle part showing decreasing values, and an upper part characterized with relatively higher $\delta^{18}O$ and $\delta^{13}C$ values (Fig. 2).

3. Discussion

Based on a good understanding of the present-day isotopic response at the Soreq Cave (Israel), the $\delta^{18}O$ variations

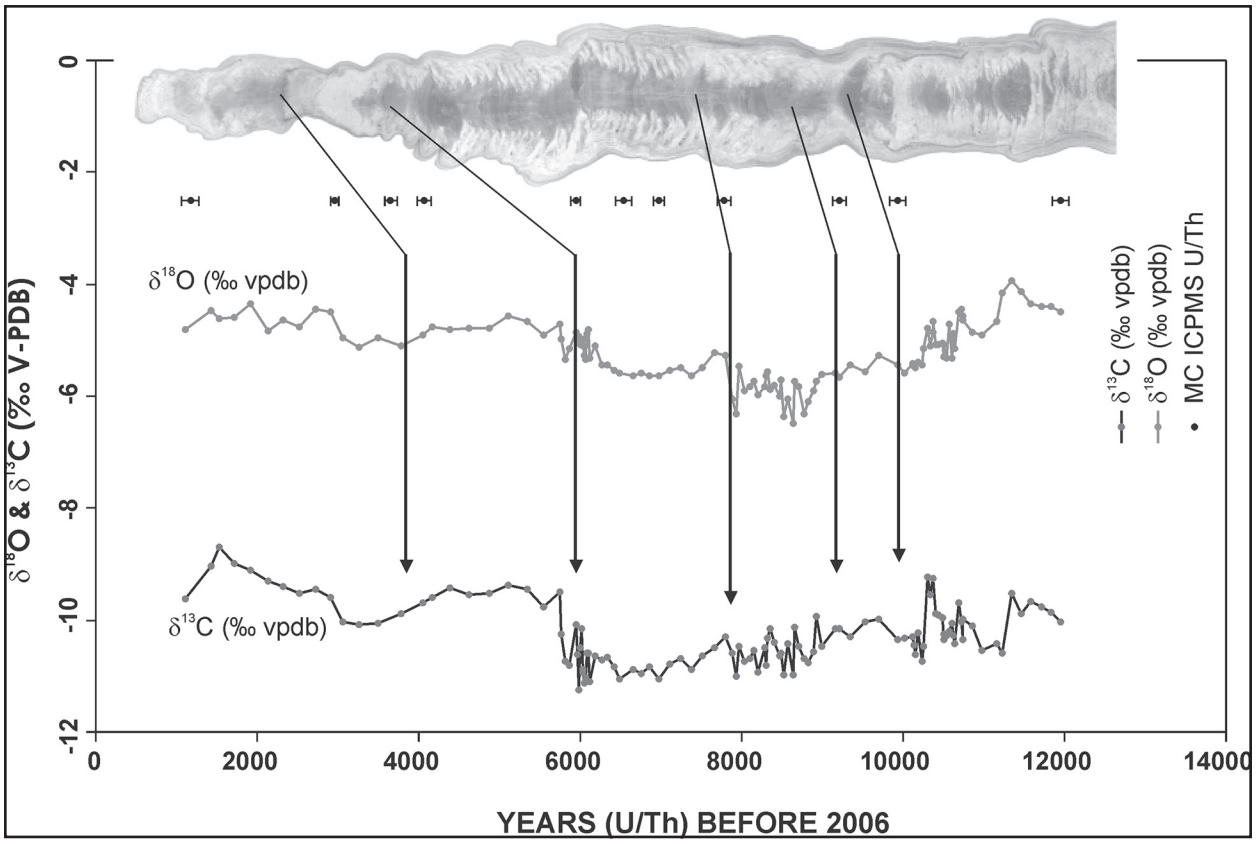

Figure 2: δ 18O and δ 13C profiles (values are in ‰ VPDB) of the JeG-stm-1 stalagmite (Jeita Cave, Lebanon). Slightly modified from NADER et al. (2007).

in the speleothems from this cave were interpreted as mainly linked to variations in amount of rainfall (BAR-MATTHEWS et al., 1997; 1999). Accordingly, the lower $\delta^{18}O$ values were associated with rainy years and the higher $\delta^{18}O$ values with dry years. Changes in carbon isotopic composition ($\delta^{13}C$) of speleothems in central and northern Israel are interpreted as mainly reflecting changes in contribution of the soil CO_2 (BAR-MATTHEWS et al., 1997, 1999; FRUMKIN et al., 1999, 2000) and thus linked to changes in precipitation with periods of low rainfall inducing sparse vegetation and a lower contribution of "light" organic carbon in the speleothem resulting in higher $\delta^{13}C$ value (FRUMKIN et al., 2000). Comparison of the isotopic profiles of the Jeita, Soreq and West Jerusalem cave records reveal similarities during the Holocene period.

The Jeita cave and the West Jerusalem, Soreq and Pequin caves are in the present-day semiarid Mediterranean-type climatic regions, both less than 50 km from the East Mediterranean coast in the western Mediterranean. The Jeita cave is 115 km from the Peqiin cave, 240 km from the West Jerusalem cave, and 260 km from the Soreq cave. The present day similar climate and close geographical location of the four caves invoke a common isotopic response to climate and subsequent vegetation changes (BAR-MATTHEWS et al., 1997, 1999, 2003; FRUMKIN et al., 2000). Furthermore, the similarity of the Jeita $\delta^{18}O$ record to that of the Soreq cave, and that of the Jeita $\delta^{13}C$ record to that of the West Jerusalem cave, confirms that the studied speleothems reflect similar responses to regional climatic variations. Such climatic changes as invoked from the Jeita stalagmite isotopic record and compared to the records from the nearby caves are grouped into three major time periods.

3.1 Period from 11.9 to 10.1 ka

According to the review of multiple datasets of ROBINSON et al. (2006) the Younger Dryas (YD), between 12.7 and 11.5 ka, was a regional event with exceptionally arid and cold conditions. The Jeita cave record starts at 11.9 ±100 ka with high $\delta^{18}O$ values consistent with higher aridity during the YD. The Jeita $\delta^{18}O$ record begins to decrease at 11.2 ka, at the same time compared to the $\delta^{18}O$ decrease in Soreq cave speleothems corresponding to the end of the YD and the transition to more humid conditions of the pre-Boreal (PB). Similar to the $\delta^{18}O$ record, the carbon record starts (at the base of the studied stalagmite) with relatively high values (-9.8‰) in agreement with a less favorable period for soil activity, associated with

the drier conditions of the YD, however not dry enough to significantly decrease speleothem deposition as suggested by a still relatively high growth rate (1.65 cm/0.1 ka) and thick speleothem diameter (between ten and eighteen centimetres).

3.2 Period from 10.0 to 5.8 ka:

During the period 10.0-5.8 ka (Early Holocene), the Jeita stalagmite displays particular low $\delta^{18}O$ and $\delta^{13}C$ values compared to the rest of the stalagmite. The isotopic data from the JeG-stm-1 stalagmite indicate that during the Holocene, most humid conditions in western Lebanon occurred between 9.2 and 6.5 ka. This period corresponds to parts of the stalagmite with particularly high growth rates (between 1.17 and 2.62 cm/100 yrs) and in general the thickest stalagmite diameter giving further evidence for a high water availability and/or a high $CaCO_3$ saturation of the depositing water linked with an active vegetation above the cave. Simultaneously occurs the onset of clear dish-stacks stalagmite morphology; which needs a high ceiling (GAMS, 1981; HILL and FORTI, 1997), but also a high water supply with an important "splash effect" (cf. Fig. 2). Only a short part of the stalagmite around 6.7 ka, displays a slightly lower growth rate (0.92 cm/100 yrs). Since δ18O and δ13C records are remarkably stable during this period, the observed change in growth rate is believed to have no regional climatic or environmental cause. It is more probably related to local changes in the water supply system, as also suggested by the horizontal shift in growth axis occurring at 6.7 ka (see Fig. 2).

A warm and wet Early Holocene is evidenced in several other proxy data (e.g. pollen, lake sediments) in the Levantine region. The Early Holocene (9.5-7.0 ka) could have been the wettest phase of the last 25,000 years across much of the Eastern Mediterranean (ROBINSON et al., 2006). The same period witnessed higher lake levels of the Lisan and Dead Sea lakes. The lake level record was further refined by MIGOWSKI et al. (2006), who dated this period between 10 and 8.6 ka. A wet Early Holocene was also recorded in speleothems from Oman (NEFF et al., 2001; FLEITMANN et al., 2003; 2007), and the probable link with other climate systems such as the Asian monsoon system and the North Atlantic Oscillation (NAO) is explained by STAUBWASSER and WEISS (2006).

A sudden increase in $\delta^{18}O$ and $\delta^{13}C$ values in the JeG-stm-1 stalagmite suggests a decline from wet to drier conditions at around 6.0 ka. The transition occurred in two steps with a progressive decline from 6.5 to 5.9 ka interrupted at 5.9 ka by a short (~100 years) return to wetter conditions and followed by an equal but rapid decline in less than a century. The change to dry conditions indicated by the $\delta^{18}O$ and $\delta^{13}C$ profiles is supported by the decrease in diameter, the drop in growth rate and a progressive change towards a matt white porous calcite (Fig. 2).

3.3 Period from 5.8 to 1.1 ka

The JeG-stm-1 stalagmite displays indications for dry conditions until the end of stalagmite deposition (1.1 ka) through high $\delta^{18}O$ and $\delta^{13}C$ values and smaller stalagmite diameter, as well as changes to a more whitish porous stalagmite without dish-stacks morphology (Fig. 2). The Soreq cave record (BAR-MATTHEWS et al., 1997; 1999) and other terrestrial data such as lake levels, paleosoils and snail records (ROBINSON et al., 2006), suggest wet conditions for the period from 4.5 to 5 ka, while according to the JeG-stm1 stalagmite record, a wetter period occurred only between 3.0 and 4.0 ka (as suggested by a small decrease in $\delta^{18}O$ and $\delta^{13}C$ values). At about 4.0 ka, a brown layering suggests the occurrence of a flood event often responsible for the rapid transfer to the cave of impurities like oxides or clay particles with incorporation in the stalagmite. The absence of a drastic change in petrography as well as in $\delta^{18}O$ and $\delta^{13}C$ values confirms that the brown layering is not due to a regional climate event. Instead, a slight regular decrease in $\delta^{18}O$ and $\delta^{13}C$ values indicates a gradual change towards less dry conditions to 3.0 ka. The relatively wetter period between 4.0 and 3.0 ka seems contradictory with the evidence from other proxies for severe drought during the so-called 4.2 ka climate event brought in relation with the decline of the Accadian empire (DEMENOCAL, 2001) and several other civilizations of the Indus Valley (STAUBWASSER and WEISS, 2006). After the 4.2 ka event, entire regions of northern Mesopotamia, Syria and Palestine were intensively resettled (STAUBWASSER and WEISS, 2006), suggesting a return to relatively wetter conditions in agreement with the indications of JeG-stm-1 in the present study. Between 3.0 and 1.1 ka, soil activity progressively decreased as indicated by increasing $\delta^{13}C$ values; while $\delta^{18}O$ values show more variability and could be ascribed to a decrease in soil activity linked with increasing agriculture and/or grazing.

4. Conclusions

Petrographic and geochemical studies carried out on the JeG-stm-1 stalagmite (11.1 to 1.1 ka) from the Jeita Cave, central Mount Lebanon, as well as regional correlation with speleothem records from several nearby caves in Israel/ Palestine, resulted in the following conclusions:

The wettest period in western central Lebanon occurred

from 9.2 to 6.5 ka.

A two-step transition from wet Early Holocene to drier Mid-Holocene conditions is observed between 6.5 and 5.8 ka.

The JeG-stm-1 stalagmite registered a dry Mid- to Late Holocene until the end of stalagmite deposition at 1.1 ka, with exception of a relatively wetter period between 4.0 and 3.0 ka.

Acknowledgments

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SEA LEVEL HIGH STAND AT 81 KA: EVIDENCES FROM COASTAL CAVES OF MALLORCA

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Abstract

The littoral caves of Mallorca have formed by the mixing of freshwater and seawater in the coastal phreatic zone, and are highly decorated with speleothems (e.g., stalactites and stalagmites) that formed during Quaternary time when the caves were air-filled chambers. Throughout the middle and upper Pleistocene, the caves were repeatedly flooded by glacio-eustatic sea level oscillations. The water level of each flooding event was recorded by a distinct encrustation of calcite or aragonite over existing speleothems and along cave walls. Similar encrustations, called in the literature *Phreatic Overgrowths on Speleothems* (POS) in order to differentiate from biogenic Marine Overgrowths on Speleothems, form at present in a low tide-controlled microenvironment, at or several centimeters below and above the water table. All the sampled caves are within a horizontal distance of 500 m of the coast; thus, the water table of the caves is, and was in the past, fairly coincident with sea elevation. We have identified several well-defined encrustation belts below and above the present-day sea level corresponding to older sea level events.

Sea level chronologies based on this kind of speleothem encrustations that formed at the water table avoid at least four of the major problems encountered when reconstructing past sea level using corals: (1) assumptions about the water depth above the reef (each coral species grows within a range of water depths of several meters to tens of meters), (2) questions concerning the provenance of corals (i.e., in-situ or reworked), (3) less accurate age estimations due to coral diagenesis, and (4) uncertainties regarding the relationship between sea level position and the timing of coral reef or terrace formation. Our findings seem especially robust because of the sub-meter sea level precision of the encrustation mechanism versus the several-meter precision of the coral record. The POS-encrustations approach improves upon the more common utilization of sub-aerial or submerged speleothems, which documents only when the cave became air-filled, not precisely, when, and where the water level was located. Furthermore, the encrusted speleothems allow one to measure precisely, not only the mean sea level positions, but also the tidal range

Using high-precision U/Th ages on the Mallorcan speleothem encrustations, we pinpoint western Mediterranean sea level at ~1.35±0.3 m above modern at ~81 ka during marine isotope stage (MIS) 5a. Dates of 116 and 121 ka (MIS 5e) on encrustations from the same cave at an elevation of 2.6±0.3 m implies that the +1.35 m elevation of our MIS 5a high stand primarily represents eustatic ice equivalent sea level, and has been negligibly affected by isostatic effects. Our findings corroborate the minority view that MIS 5a was as at least as ice-free as present. If, indeed, sea level was higher than present at 81 ka as our data suggests, the apparent 100 ka ice-age cycle seen to dominate the last 700 ka may partly be an artifact of the traditional sea level interpretation of the deep sea $\delta^{18}O$ record supported by coral-terrace dating.

HEINRICH EVENT 4 IN A PUERTO RICO STALAGMITE

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Abstract

Large decadal to millennial-scale climate fluctuations first observed in the oxygen isotope record of Greenland ice cores were later documented from various other marine and continental deposits world wide. Massive surges of icebergs from Northern Hemisphere ice sheets into the North Atlantic during glacial times left behind distinct ice-rafted-detritus layers during climatic episodes known as Heinrich events. Eight such very cold episodes (labeled H1 to H8) occurred regularly over the last ~70 kyr, and potentially disrupted North Atlantic Deep Water (NADW) formation, which in turn may have had a widespread impact on inter-hemispheric climate connections.

In order to better understand and reconstruct the climate of the Caribbean, stalagmites from two caves of the northern karst region of Puerto Rico have been collected. Rainfall on the island is dominantly controlled by the phases of El Niño Southern Oscillation (ENSO) and Northern Annular Mode (NAM). These two coupled climate systems also affect or are related to the seasonal migration of the ITCZ, which imposes wet or dry conditions in the region. The island of Puerto Rico is located within the northern reaches of the Intertropical Convergence Zone (ITCZ) placing it in a transition zone making it sensitive to climate change.

This study presents the stable isotope and ICP-MS U/Th data of a selected section (~16 cm) from stalagmite ENS_1 recovered from Cuevas Ensueño (north-central Puerto Rico), which is developed in the Lower Miocene Aymamón Limestone. The entrance of the cave is located in a collapse doline at an elevation of ~310 meters asl. The total length of its linear passages is ~250 m. The sample was collected at the far end of the cave from a well-decorated chamber.

Six U/Th dates constrain the lower part of the ENS_1 stalagmite growth interval to be between 40.5 and 38.2 (±0.3) ka, and therefore coincident with Heinrich event 4 (H4). Stable isotope measurements (434 subsamples) were performed at a 500 μm-interval, which corresponds to a sub-decadal time resolution. Both $\delta^{18}O$ and $\delta^{13}C$ time-series show an overall small shift towards lighter values during 2000 years of growth. In addition, the stable isotope record exhibits abrupt shifts within this interval not observed in other terrestrial proxies. The most important of these are large (up to 2‰ and 5‰ heavier $\delta^{18}O$ and $\delta^{13}C$ values, respectively) oscillations of not more than 50 years that interrupt the apparently cool H4 interval. The timing of ENS_1 stalagmite growth seems to indicate a significant change in the North Atlantic that affected Puerto Rico, and the isotopic variations during the inter-Heinrich 4 might have been caused by perturbations in the thermohaline circulation, ENSO events or changes in the relative position of the ITCZ.

RECONSTRUCTING PALEO-RAINFALL IN THE WESTERN TROPICAL PACIFIC: DEVELOPING SPELEOTHEM PROXIES

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Extended Abstract

Speleothems are rapidly becoming important paleoclimate archives. They can record changes in climate from weeks to millennia at locations around the world and can be absolutely-dated. In remote tropical locations, stalagmites provide important information about past hydrologic changes where extensive modern studies are logistically difficult. Tropical speleothems record hydrologic changes under various past boundary conditions, such as the mid-Holocene (~6 ka) and Last Glacial Maximum (19-23 ka). These records not only characterize past climate changes in the region, but are also used to help assess how global climate models reproduce past precipitation patterns.

1. Project Overview

The West Pacific Warm Pool impacts global climate, as it is a major source of heat and water vapor to the atmosphere (WEBSTER and LUKAS, 1992). Most notable are changes in the Warm Pool on interannual timescales associated with the El Niño-Southern Oscillation (Fig. 1) (ROPELEWSKI and HALPERT, 1987).

These events have large socio-economic consequences. Unfortunately, past climate changes in the West Pacific Warm Pool are poorly characterized. We propose that speleothem records from Borneo, Guam, The Philippines, The Solomon Islands, and Vanuatu can be used to constrain climate changes in the West Pacific Warm Pool, both spatially and temporally (Figure 1). The speleothem archives will help to understand this important and remote region over the past centuries to millennia, which has been initially characterized but not fully explored.(KIENAST et al., 2001; KOUTAVAS et al., 2002; PARTIN et al.,

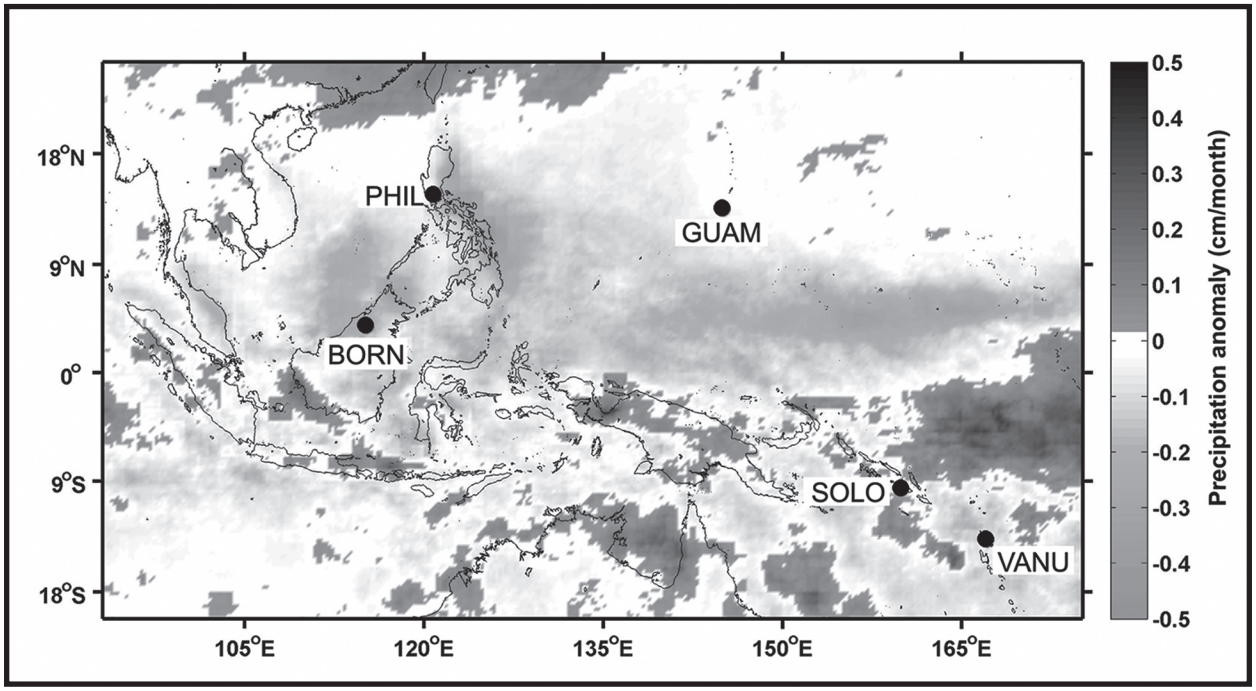

Figure 1. Composite map of December-January-February (DJF) precipitation anomalies during major El Niño events in 1997-98, 2002-03 from the Tropical Rainfall Measuring Mission (TRMM) - 3B43 dataset (Kummerow et al., 2000). Approximate locations are marked for research sites in N. Borneo (BORN), The Philippines (PHIL), Guam (GUAM), Solomon Islands (SOLO), and Vanuatu (VANU).

2007; STOTT et al., 2002)

To aid in the interpretation of cave records, modern dripwater, calcite, bedrock, and soil samples are analyzed, and hydrologic and meteorologic conditions in the caves are monitored. This collection and monitoring program is conducted on regular and intermittent periods. The regular monitoring program is at a site on Guam, where visits occur every 4-5 weeks to collect samples and record conditions. The site in Guam serves as a representative tropical site as the island receives ~2.5 m of rain per year, where 70% falls during wet season (May-October). At other sites, visits depend upon intermittent field trips, which consist of spot measurements during the time of year of the visit.

2. Cave Setting

The modern study cave is located on the NW coast of Guam in Pleistocene carbonate and is categorized as a flank-margin cave. Flank-margin caves form at the contact zone between the island's freshwater lens and saltwater and are generally spherical in shape (MYLROIE and CAREW, 1990). The vertical structure of the cave is thought to be due to sea-level changes. The cave is small (9 m long x 7 m wide) with one opening. The cave descends at ~45° for a height change of ~5 m. The overburden ranges from 1 m near the entrance to 9 m at the rear of the cave.

3. Analytical Approach

A fine line exists between cave conservation and sampling of precious natural resources for scientific purposes. Therefore, we employ non-destructive techniques such as collecting cave dripwaters, controlled deposition on artificial substrates and speleothem coring. These techniques help address which samples will yield useful climate information, such that we maximize the scientific output and minimize cave impact.

Modern system monitoring include dripwater, soil and bedrock chemistry ($\delta^{18}O$, Mg/Ca, Sr/Ca, and $^{87}Sr/^{86}Sr$), drip-rates (both on-site analog and digital loggers), rainfall $\delta^{18}O$, calcite growth rates, modern calcite $\delta^{18}O$, cave air temperature, and cave air pCO_2.

To constrain records of past climate, secondary calcite formations are dated using ^{238}U decay series chronology (EDWARDS et al., 1987). Records of calcite $\delta^{18}O$, $\delta^{13}C$, Mg/Ca, and Sr/Ca ratios record information about hydrologic variability above the cave in the Western Pacific Warm Pool. The modern study will provide a transfer function to translate the chemical changes in the calcite to above-ground climate changes.

4. Preliminary Results

Preliminary results from Guam of trace metal ratios (Mg/Ca and Sr/Ca) and $\delta^{18}O$ indicate a change in dripwater chemistry that is driven by the hydrologic change from wet-season to dry-season. These changes are also recorded in a fast-growing stalagmite from Guam that overlaps with instrumental data of rainfall from 1947 to present. However, dripwater chemistry heterogeneity between sites (Guam, Borneo, and The Philippines) suggests multiple processes, such as water-rock interaction, mixing, and prior calcite precipitation can influence dripwater chemistry. Additional measurements of chemical variables in dripwaters, soils, bedrock and modern calcite will help to constrain how climate changes are recorded in cave stalagmites and how additional processes may mask the climate signal. Specifically the Sr isotopic composition of dripwaters, soils, and bedrocks can help partition how much interaction between the rainwater, soil, and limestone is occurring (BANNER et al., 1996). Speleothems from all 5 locations have been collected and initially, and in some cases completely, dated. The samples cover part or all of the last 30 ka.

5. Future Work

The goal of the study is to generate climate records at all five locations in order to reconstruct the spatial pattern of Western Pacific Warm Pool climate changes that occurred from the Last Glacial Maximum (19-22 ka) to present. Understanding changes in modern dripwaters, soils, bedrock, and calcite chemistry will help to translate the chemical changes in cave formations to past climate changes.

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CAPABILITY OF ISOTOPIC PROFILES FROM CAVE SPELEOTHEMS: NUMERIC CORRELATION

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In our analytical work we usually obtain several stable isotopic profiles from different speleothems. Correlating isotopic dating with analytical records allows a general reconstruction of paleoclimate. On the basis of isotopic dating series and Monte Carlo (MC) simulations we are able to obtain a time scale for every profile. After time-scale construction for all studied profiles, it is necessary to correlate them. Usually every profile is based on a different number of analyses. As a result, each isotopic curve relies on a different numbers of points. The basic question is how to test whether the variations in the records reflect changes in climate, or simply differences in sampling density and location. Another question is how accurate are the record correlations. We can use the non-parametric method based on MC simulation to answer both questions.

Let's imagine that we have two records - one based on very dense sampling (curve A, based on N points) and the second one based on much smaller number of samples (curve B, based on n points). Let's assume also that curve A is a reliable estimator of paleoclimate record. Is curve B a possible n-point estimator of curve A? Using MC simulation we can estimate confidence bands for n-point rea1ization of record A. Comparing both curves (A and B) with these results, we can test if both can reflect the same record.

The next step is to obtain a valid correlation of two such curves. Correlation means finding a position for these curves in which the similarity of records reaches its maximum. We can do this by displacement, in which curves B are compared to basic curves A for every possible position, at which we estimate the coefficient of similarity. The best correlation is achieved when the relation similarity coefficient reaches a maximum. MC methods give us the opportunity to account for the uncertainties of time scale and correlated parameter between records.

These methods can be used for any problem of correlation between records. We show that MC methods are useful tools for estimating confidence intervals and correlations for carbon and oxygen isotope records in paleoclimate studies of speleothems.

1. Introduction

For the last forty years, speleothems have been used as paleoclimate indicators. At first, measurements of stable isotopes from speleothems were used for paleotemperature reconstructions. This use of speleothem data did not work properly and produced incorrect values of reconstructed temperature (HENDY, 1971; THOMPSON et al., 1976; HARMON et al., 1978, 1979; VOGEL, 1983). The concept of a "speleothem paleothermometer" has largely been rejected. However, in the past ten years interest in the investigation of speleothems using stable isotopes and other proxies has returned. There are many reasons for renewed interest in speleothem research: (i) speleothem profiles are good records of local environmental conditions; (ii) preserved profiles are usually continuous and can produce long records; (iii) speleothems can now be more precisely dated; and (iv) the chemical composition of calcite reflects the chemical components in the water, which in turn reflects climatic conditions such as general rainfall and temperature fluctuations near the cave.

In only a few years, much paleoclimatic information has been accumulated from high-resolution geochemical studies, based on high-density sampling profiles. Samples are typically analyzed in two ways: (i) stable isotopic composition of O, C; and (ii) accessory elements, such as Mg, Sr, Ba, which help to indicate paths of water circulation. Some studies are producing records with a resolution of one calendar year (BAKER et al., 1993, BALDINI et al., 2002, FRISIA et al., 2003, ROBERTS et al., 1998, HU et al., 2008, YUAN et al., 2004, WANG et al., 2001, 2005). Aside from "classical reconstruction" (paleoclimatic conditions, temperature, humidity), high-resolution data

from speleothem records is being used to establish precise positions of climatic episode boundaries (e.g., Dansgaard-Oeschger and Heinrich episodes) or internal structure and duration of the "8.2 ka" climatic episode and reconstruction of climatic oscillations such as the North Atlantic Oscillation or Northern Annular Mode.

The accuracy of such a high-resolution reconstruction depends on the precision of the isotopic measurements, as well as on the precision of the chronological data. The uncertainty of both (stable isotope and chronology) is a basic problem of finding the correlation between two independent records.

The other problem in reconstructing paleoclimatic records is how to correlate these records with each other. Paleoclimate records have different values of analyzed time-scale accuracy. Reconstructing the precision should take into account all of the information described above. These problems can be solved by using Monte Carlo simulations as a tool for determining the statistical confidence of matching paleoclimate records.

2. Materials

All presented algorithms will use stalagmite JMR 14 as a data source. JMR 14 is a columnar-type stalagmite ca. 30 cm high and 5-6 cm in diameter. It was collected in Mieru Cave (Low Tatra Mts., Slovakia). A ca. 1 cm thick slice was cut from the axial part of the stalagmite. Two series of samples were then collected by drilling. The first one consisted of 92 samples (N-points curve) drilled with a 0.5 mm diameter bit. The second was collected on the other side of the slice using a bigger drill bit (ca. 1.2 mm in diameter). This series consists of only 37 samples (n-points curve).

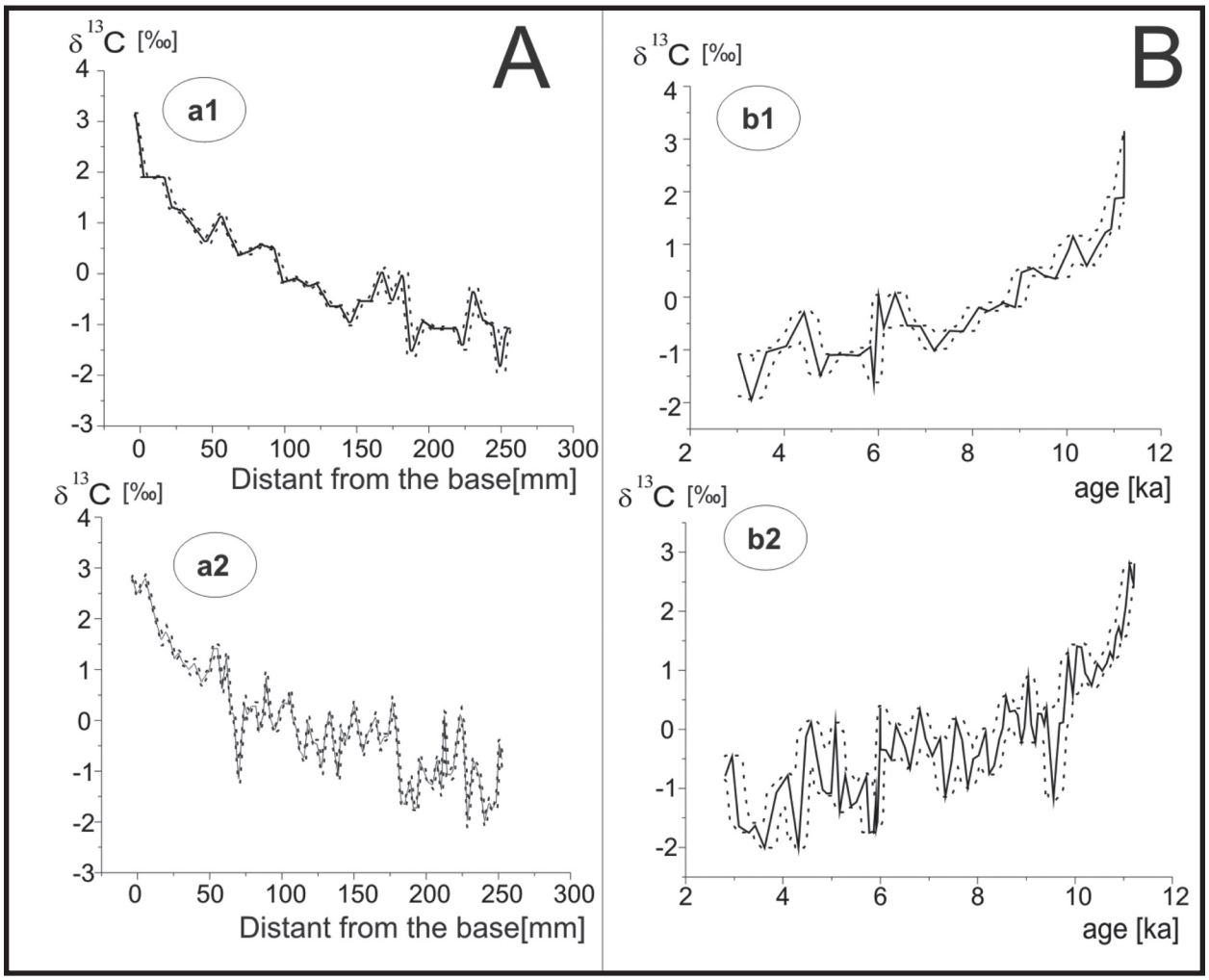

Figure 1: Estimation of 2σ confidence bands for carbon isotopic records of stalagmite JMr 14 . A. Confidence band for carbon isotopic records as a function of depth, where a1 is a low density (37- points) record, and a2 is a high density (92-points) record; B. Confidence band for carbon isotopic records as a function of time (age), b1 is the low density carbon record, and b2 is the high density carbon record.

3. Methods and Results

3.1. Step one – Uncertainty problems related to time, distance, and stable isotope values:

Paleoclimate records are reconstructed on the basis of many individual analytical points. Every point represents two values – depth (i.e., vertical position in sample, representing chronology) and stable isotopic composition (oxygen or carbon). Both values are fitted to a normal distribution, and include standard error determinations. Monte Carlo simulation can be used to estimate the real precision of any of the analytical points.

For the initial data, the mean and standard deviation of the measured isotopic and depth (or age) values are used to construct our simulations. We make the assumption that these two values are described by a normal distribution. From these distributions, depth and isotopic composition are randomly selected (randomized) many times. From many randomization results we can estimate the ellipsoid of uncertainty for every analytical point. For every randomized data set an isotopic record is constructed. Large populations of data enable us to estimate confidence bands for the isotopic record. This estimation takes into account the measured uncertainties of isotopic ratios and depth. On Figure 1 the $\delta^{13}C$ results from stalagmite JMR 14 are presented. This figure shows that records of low density (a1 and b1) and high density (a2, b2) of sampling, using two standard deviation errors, produce very different results. It reflects the lack of precision of sampling with a larger drill-bit diameter. If we compare records of depth vs. time, we see much wider confidence bands for the time records. The final confidence bands take into account the uncertainties not only in depth and isotopic measurements, but also the age accuracy, model ages, and depth errors.

3.2. Step two – Comparison of two records and related sampling density problems

Every isotopic record has to be presented as a function of time for that record to be useful to paleoclimatologists. By using the described algorithm we can also estimate confidence bands of records that are presented as time series (see Fig. 1B). The larger two-sigma band reflects uncertainty of the time-scale estimate. Paleoclimate reconstructions ideally use more than one record. Testing the similarity between two or more paleoclimate records is essential for paleoclimate reconstruction. The problem of variations in sampling density is very important at this stage. Let's imagine that we have a real paleoclimatic record – (curve **a** on Figure 2) that we would like to reconstruct from analyses of two stalagmites that have the same age (Fig. 2: b1 and b2). Because of differing sampling density, and the fact that they are from different stalagmites, the two analytical records look different (Fig. 2: c1 and c2). Additionally these two records might differ from the actual one. This problem is even more difficult if we have two records with different density of sampling points. How can we test whether the differences in records are due to a real climatic effect or

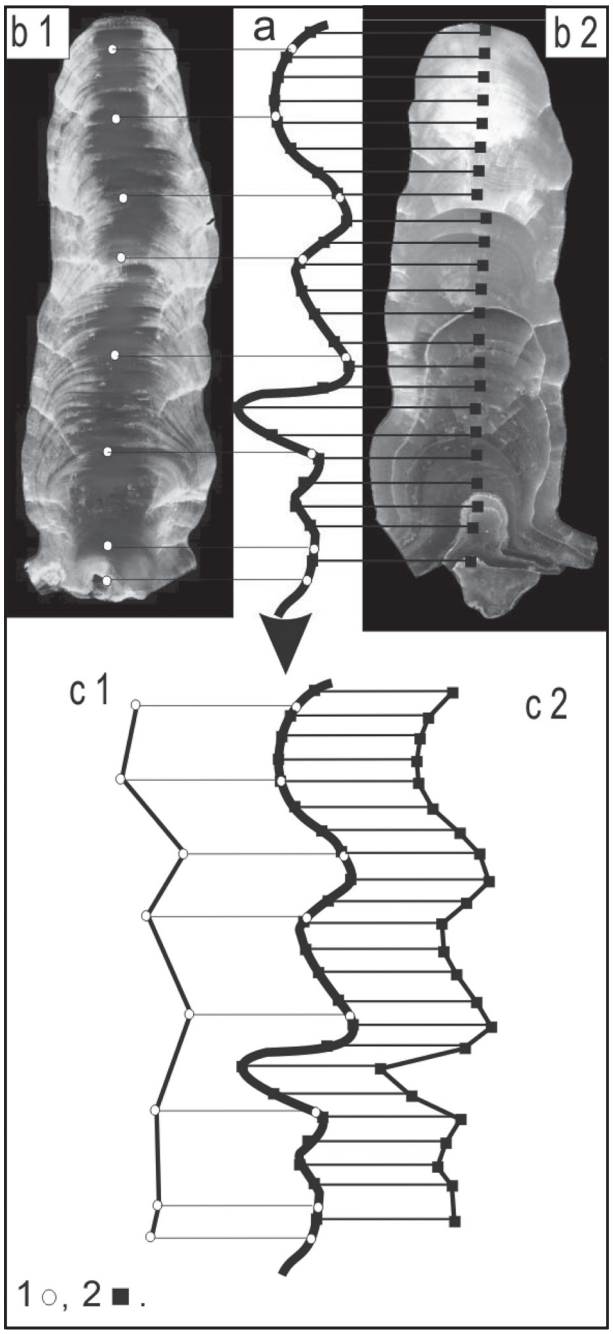

Figure 2: Illustration showing sampling density problem. a is the real (= reconstructed) paleoclimatic record; b1and b2 are the analyzed stalagmites, c1 and c2 are the analytical records from b1 and b2 stalagmites; 1 - low density record sampling points of b1 stalagmite, 2 - height density record sampling points of b2 stalagmite.

only to the sampling? We suggest that it is possible to solve this problem using Monte Carlo methods. Let's assume the high-density record is the principal record and define our question as: ***Is a low-density curve a possible representation of the principal (high-density) record?***

For initial data we use two stable isotopic records presented as a function of time. As a first step in the algorithm, we randomly select data points from the high-density curve (N) such that no point is selected more than once. The total number of selected points is equal to the number of points in the low density curve (n – points). A new (randomized) record based on these selected points is built. This procedure is repeated many times. Based on the generation of several randomized curves we can estimate confidence bands for n-points of the low-density curve that can be applied to the high-density, N-points curve. If the original low-density record fits into the confidence band that we have generated, then we can assume that it is a valid representation of the high-density, principal record. Results of the analyses of the two records from the JMR 14 stalagmite are presented in Figure 3. The $\delta^{13}C$ low density (n points) curve fits into the two-sigma band in more than 95 % of the data. This means that the low-density curve is a general n-points representation of the high-density record.

3.3 Step Three – Correlation of Different Records

Monte Carlo methods can be used to obtain a correlation (i.e., searching of best position) between two independent records. Given that we have two records (1 and 2) presented at the same time scale, let's make an assumption that record 1 is the principal record and record 2 will be adjusted (correlated) to record 1 by shifting its time axis by an appropriate amount (for example 0.02 ka). The optimal position between these two records is therefore selected (the best correlation). As in Step 2, confidence bands will be estimated using the Monte Carlo method between records 1 and 2 such that every position between two randomized records is calculated. Many cycles of randomization and calculation produce a representative value for the best matches between the two records. On this basis we are able to estimate the final confidence bands for these two records.

What parameters of similarity should be used? The first parameter is the mean time/distance differences between appropriate data points of the two records. The second parameter has to do with data dispersion reflected by standard deviations of the principal record. This is the weighted mean of differences in time/distances between the two records. In addition, we could test the fitting into the 1σ and $2\,\sigma$ range of the principal record. Results of correlation using mean distances as similarity parameters between the two $\delta^{13}C$ records from stalagmite JMR 14 are presented in Figure 4. This figure shows a histogram of the results from 1,000 curve randomizations and correlations to random initial positions within the record. The expected result of the time shift is ≈ 0 ka and the range of searching was 1.6 ka (±0.8 ka from 0 position). The median of the distribution of results, i.e., the best result from the estimation, is equal to 0.04 ka, with a 2σ range of -0.1 ka to 0.185 ka. The time-scale uncertainty for stalagmite JMR -14 is ca. ± 0.2 ka. The final result is comparable to the expected result.

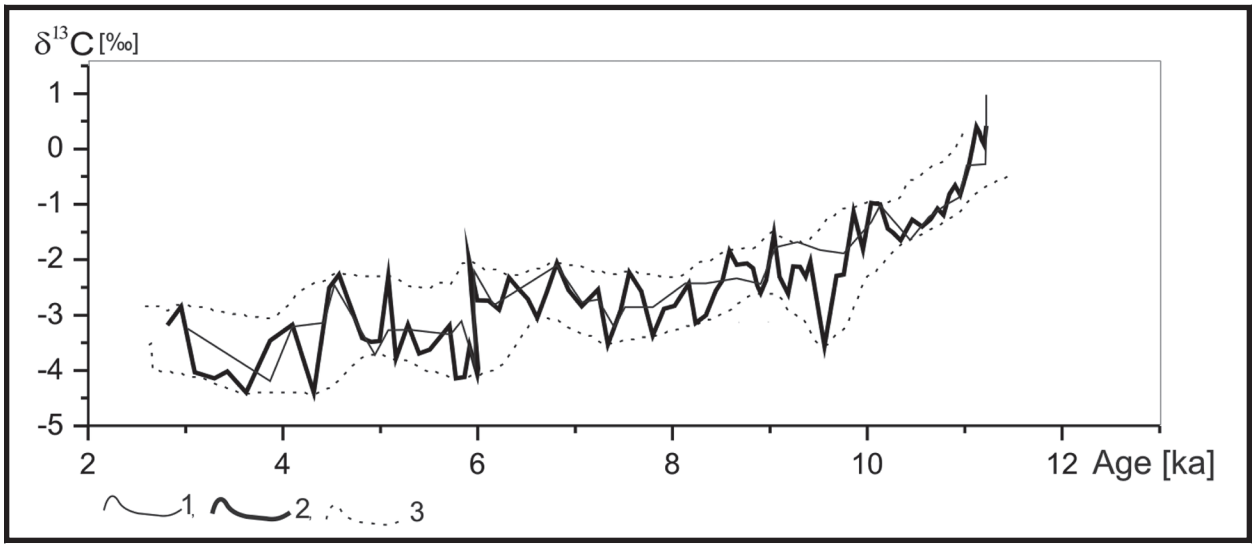

Figure 3: Results of similarity test between high and low density carbon isotopic records from stalagmite JMr 14. 1: Low density (37-points) curve, 2: high density (92 points) curve, 3: 2σ confidence bands for a 37-point reconstruction of the 92-point record.

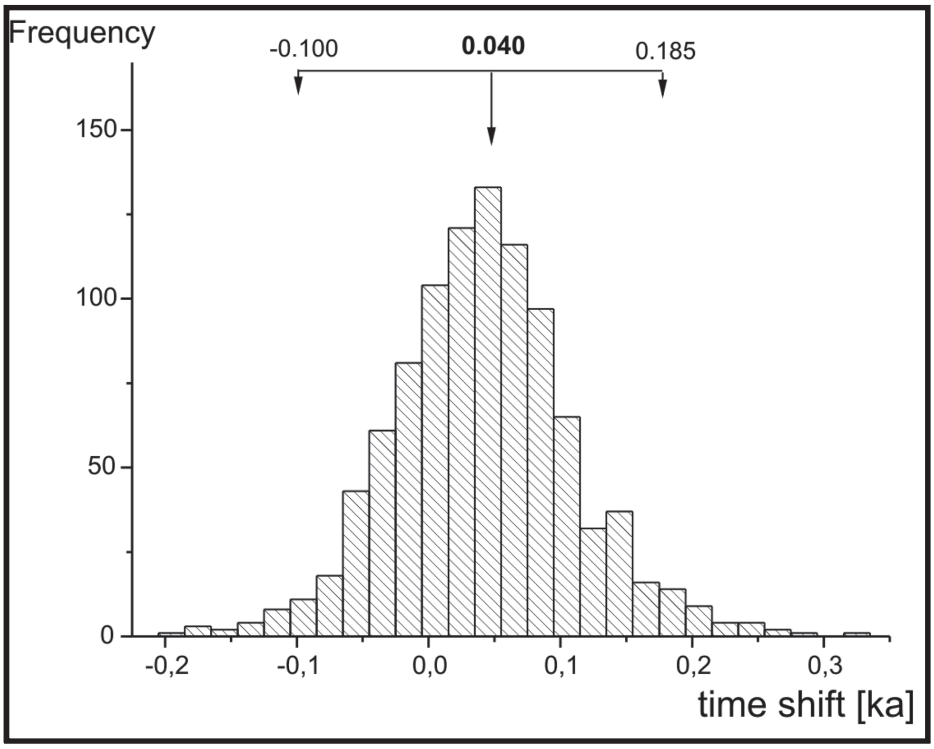

Figure 4: Correlation quality estimation basing on mean record distance as a similarity parameter. Histogram of parameters represented by correlation analyses repeated 1,000 times.

4. Conclusions

The final conclusions from testing Monte Carlo simulations for paleoclimatic reconstruction can be divided into two groups. The first follows from using Monte Carlo simulations in general. The second group is about real resolution of paleoclimatic records and time-scale construction. In the last few years a lot of paleoclimate information has been gained from high-resolution geochemical studies of speleothems, based on high-density sampling profiles. Accuracy of high-resolution reconstruction depends on the precision of stable isotope measurements, as well as on time scale precision. Reliability of any record depends on the reliability of the data (e.g., geochemical parameter vs. time scale). Only by taking into account all possible sources of uncertainties is it possible to protect against overestimation of record accuracy/resolution. One of possible tools for such kind of analyses is Monte Carlo simulation. Using the Monte Carlo simulation methods gives us several advantages:

(1) Monte Carlo methods are non-parametric.
(2) There are no specific assumptions like normal distribution of data, etc.
(3) Monte Carlo algorithms can be easily transformed to solve new problems.

Only the data presented as a function of time can be compared with any other data and used as a paleoclimatic record. Time-scale reliability is a crucial point for any paleoclimatic reconstruction. Construction of time scale as a result of linear approximation of ages versus distances, a standard method, will lead to overestimation of record accuracy.

Acknowledgements

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COMPARATIVE ISOTOPIC STUDY OF DIFFERENT TYPES OF ICE IN SCĂRIŞOARA ICE CAVE, ROMANIA

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Abstract

Here we present a comparative study of oxygen and hydrogen stable isotope measurements in different types of cave ice from Scărişoara Ice Cave, Apuseni Mts., Romania, and assess the value of this proxy in studying past climatic changes.

Stable isotope measurements were performed on ice samples collected in four different settings inside the cave, as follows: (i) newly formed ice from a frozen stream of water on the surface of the main ice body - "floor ice" (collected in January 2005),(ii) layered ice formed during the freezing of stagnant water - "lake ice" (collected in January 2005 and 2008 and in November 2008), and(iii) ice samples from a 22.5-m long ice core drilled in February 2003.

Ice in caves forms in two distinct periods: one in late autumn, and one lasting from winter through late spring. In autumn, the lake standing on the top of the ice block freezes downward from the top to form a layer of stratified ice up to 15 cm thick ("lake ice"). Winter and spring ice forms as seepage waters progressively freeze in thin layers ("floor ice") superimposed on the autumn ice. This "floor ice" melts away in summer, so the ice block is formed mainly of "lake ice".

The $\delta^{18}O$ values in precipitation are positively correlated with the air temperature ($r^2 = 0.7$), and the Local Meteoric Water Line (LMWL; $\delta^2H = 8.14*\delta^{18}O+10.227$) is almost identical to the Global Meteoric Water Line (GMWL). Stable isotopes in ice show a smaller range of variability than those in precipitation, and differences occur among samples collected from different settings, indicating that the values are influenced by time and the way the ice develops. The stable isotope data of the "lake ice" shows that the freezing proceeds from top to bottom, and a continuous enrichment in heavy isotopes of the ice and depletion of remaining water occurs. This model is valid for both modern and old ice. On a $\delta^2H/\delta^{18}O$ plot, the samples of "lake ice" align on a slope lower than the LMWL (between 4 and 6), called "freezing slope". By intersecting this freezing slope with the LMWL it is possible to obtain the initial isotopic composition of water. Present day observations have shown that this water's isotopic composition is close to that of precipitation between late summer and early autumn.

Based on stable isotope data and ice-dynamics monitoring, we consider that the ice block is built up mainly from lake ice, and that the isotopic composition of the ice reflects that of the water standing on the surface of ice at the beginning of the freezing process in autumn, a mixture of late summer through autumn precipitation and ice-melt water.

A HIGH-RESOLUTION RECORD OF ATMOSPHERIC-OCEANIC TELECONNECTIONS DURING THE LATE HOLOCENE FROM A FLORIDA SPELEOTHEM

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Understanding atmospheric teleconnections between tropical, subtropical, and higher-latitude regions of the North Atlantic Ocean is necessary to better evaluate the anthropogenic contribution to climate change. Here, we present a precisely dated, high- resolution speleothem record of stable oxygen and carbon isotopes and trace elements from Florida spanning the last ~1,500 years. The record shows the Medieval Warm Period and Little Ice Age periods and the environmental response in the isotopic record. By using a multi-proxy approach, the different climatic influences were deconvolved, including the NAO, ENSO, PDO, and ITCZ, which all can affect Florida in different phases.

Further comparison using time-series analysis between our data and other high-resolution records covering this same period reveal differing influences of these teleconnections on geographic regions. Our record shows both the influence of changing rainfall above the cave and the influence of sea surface temperatures on atmospheric convection caused by atmospheric-oceanic variability over time.

1. Introduction

Understanding natural climate variability is essential to determine the full extent of anthropogenic contribution to global warming. The last few decades have seen much progress in this research area, but there are still geographic regions where little is known about local or regional climate processes. The terrestrial subtropics of North America are one such area, and although studies have begun to emerge from the Gulf of Mexico (POORE et al. 2003; MECKLER 2006; RICHEY et al. 2007), only a few long term, low resolution studies from lakes (ALVAREZ ZARIKIAN et al. 2001; GRIMM et al. 2006) provide a window into Florida's paleoclimate. Several speleothem based papers have appeared on the Florida climate covering the last few millennia (VAN BEYNEN et al. 2007a-b; VAN BEYNEN et al. 2008). Here, we introduce a new speleothem record to investigate the regional climate over the last 1500 years, including possible teleconnections between the tropical Atlantic, Gulf of Mexico (GOM), and peninsular Florida. This period encompasses two anomalous climatic periods, the Little Ice Age (LIA) and the Medieval Warm Period (MWP). Speleothems provide reliable records of climate change for a variety of regions (DORALE et al. 1992; BURNS et al. 2002; FLEITMANN et al. 2003; POLYAK et al. 2004).

2. Methodology

^{234}U-^{230}Th (uranium-series) isotope measurements were performed at the Radiogenic Isotope Laboratory, University of New Mexico (Table 1). About 50 to 200 mg of clean carbonate powders for dates were dissolved in nitric acid and spiked with a mixed ^{229}Th-^{233}U-^{236}U spike. U and Th were separated using conventional anion exchange chromatography. Some of the U and Th isotopic measurements were done on a Neptune multi-collector inductively coupled plasma mass spectrometer (MC ICP-MS) and the remainder were done on a Micromass Sector 54 multi-collector thermal ionization mass spectrometer (TIMS). In the MC ICP-MS all U and Th isotopes were measured in a static mode utilizing a mix of 10^{11} 10^{12} ohm resistors and an ion-counting SEM, following the method described by (Asmerom et al 2006). SEM-Faraday gain was established using CRM-145 U standard for U and an in-house Th standard for Th analyses. Mass fractionation correction was done using the $^{233}U/^{236}U$ ratio of 1.0046 for U isotope analyses. For Th analyses standard-sample bracketing was used to correct for mass fractionation and instrument drift. The TIMS analyses utilized a single ion-counting Daly multiplier in peak jumping mode. $^{233}U/^{236}U$ ratio (1.0046) was used for fractionation correction for U analyses. Th fractionation in TIMS is negligible. CRM145 U isotope standard was measured with every batch obtaining the conventionally accepted $\delta^{234}U$ value of -37.09 ± 0.23 ‰ (n=82). $\delta^{234}U = ([^{234}U/^{238}U_{sample}/ {}^{234}U/^{238}U_{secular\ equilibrium}]-1) \times 10^3$, where, $^{234}U/^{238}U_{secular\ equilibrium}$ is equal to the ratio of the decay constants of ^{238}U and ^{234}U ($\lambda_{238}/\lambda_{234}$). U and Th procedural blanks were in the range of 5-10 picograms and therefore have no effect on ages. The ages were corrected for initial ^{230}Th.

Oxygen stable isotope ratios (^{16}O and ^{18}O) were measured for 300 calcite samples drilled at 1 mm intervals. Approximately 60 μm of calcite was weighed for each sample and reacted with anhydrous phosphoric acid at 70°C in individual reaction vessels of a Keil III carbonate-extraction system coupled to a ThermoFinnigan DeltaPlus XL mass spectrometer. Precision ($\pm 2\sigma$) was monitored by daily analyses of the NBS-19 standard and was within <0.1‰ for both oxygen and carbon. Values are reported in standard ‰ notation relative to Vienna Peedee belemnite (V-PDB).

3. Results and Discussion

We have previously demonstrated that the NAO is influential on Florida's climate, more so than the El Nino-Southern Oscillation and the Pacific Decadal Oscillation (VAN BEYNEN et al. 2007a). However, RAJAGOPALAN et al. (1998) found the NAO was strongly influenced by the tropical Atlantic. Consequently, it is prudent to investigate whether we can find close connections between our speleothem-derived Florida climate record and the low latitude climate proxies of the Americas region. If there is indeed agreement, then we can determine the spatial extent of these teleconnections for the low latitudes of the Americas. The speleothem isotopes indicate changes during both the Little Ice Age (LIA) and Medieval Warm Period (MWP) as seen in Figure 1. The isotopic record is annually resolved and illustrates variability in both the carbon and oxygen isotopes throughout the Late Holocene.

Several records exist for climate change in the Gulf of Mexico (GOM), which is a main source of precipitation for Florida. Work by RICHEY et al. (2007) and MECKLER (2006) suggest that GOM and Caribbean SSTs correspond, indicating a strong link between the GOM and tropical Atlantic. Our speleothem record shows close agreement with GOM SSTs. Additionally, time series analysis of the speleothem record indicates periodicities of 11, 60-80, and 200 years, possibly corresponding to an influence of the 11-year solar cycle, the Atlantic Multidecadal Oscillation, and the 200-year solar cycle. These influences could affect SSTs and evaporation, thereby influencing the speleothem isotopes. Generally, as annual SST increase, evaporation would be enhanced, augmenting atmospheric convectional processes leading to precipitation forming at higher altitudes. Such a shift would increase the isotopic composition of the precipitation falling above the caves in Florida.

4. Conclusions

Close comparison between the Florida speleothem record and other GOM and tropical Atlantic marine records suggests strong teleconnections between these regions. Strong similarities between the records suggest possible teleconnections between the tropical Atlantic and GOM regions over the last 1500 years. Increased sea surface temperatures and aligned enhancement of atmospheric convection in the subtropics appear to be connected to shifts in the tropics through movement in the mean position of the ITCZ. Only through the development of more proxy records at higher annual resolution can we delve into more detailed investigations of causal factors of the regional climate change that can be modeled by climate dynamists.

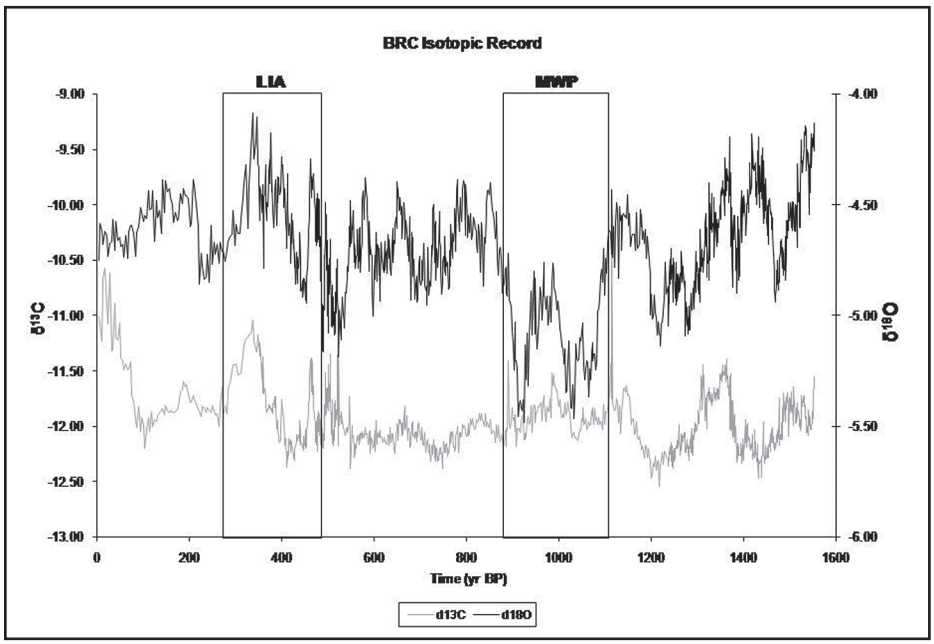

Figure 1: Oxygen and carbon isotopes from BRC03-02 for the last 1,500 years.

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OVERCOMING INITIAL ^{230}TH PROBLEMS IN URANIUM-SERIES DATING WITHOUT USING ^{234}U/^{232}TH - ^{230}TH/^{232}TH ISOCHRONS

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The study of speleothems has opened up new frontiers in paleoclimatology, as a result of our ability to obtain high-precision chronology coupled with other high-resolution climate proxies such as carbon and oxygen stable isotope variations. Getting high-precision chronologies is not always possible, especially in low uranium young samples due to the difficulty of constraining the initial amount of the daughter isotope, 230-thorium (^{230}Th). Ideally ^{234}U/^{232}Th versus ^{230}Th/^{232}Th isochrons could yield accurate initial ^{230}Th/^{232}Th ratios of the speleothem calcite, and therefore more precise ages. However, isochrons are time-consuming, expensive, and less practical to obtain for all speleothem layers needed to produce high-resolution chronologies. Moreover, many times it is not possible to get meaningful isochrons. For example, multiple sources of detrital thorium may each have different ^{230}Th/^{232}Th values. To overcome some of these problems, we used a method that corrects U-series ages by assimilating the multiple sources of detrital thorium by (1) sampling near-zero-aged calcite subsamples (each having different ^{232}Th concentrations), and (2) by comparing uranium-series ages with band-counting ages (adjusting the initial ^{230}Th/^{232}Th ratio to match the band age). Given that there are multiple sources for initial ^{230}Th and that ^{230}Th correlates with ^{232}Th concentration, this curve must be non-linear. In our example, the correlation is negative, and our initial ^{230}Th/^{232}Th ratio tied to ^{232}Th concentration, ^{230}Th/^{232}Th$_{in,}$ is equal to 0.0033 x $TH^{0.6664}$ ppm, where TH = Th concentration in ng/g. Accurate U-series-dating of young speleothem samples having significantly high initial ^{230}Th/^{232}Th values is made possible on a regional scale, for example samples from the Guadalupe Mountains, New Mexico, using our method.

1. Introduction

Interest in the use of speleothems for advancing the study of past climates has accelerated over the last 30 years. Uranium-series (U-series) analyses are essential for establishing and tying a chronology to the proxies (i.e., δ^{18}O) used in these studies. U-series dating utilizes ^{238}U-^{234}U-^{230}Th, where ^{230}Th is the radioisotope daughter of the decay of ^{234}U. In most karst systems, U, which is soluble, is naturally separated from thorium (Th), by groundwater seeping through carbonate rocks because Th is considerably less soluble. As a consequence, U is deposited in speleothems along with only minute amounts of Th, making U-series dating useful and convenient, especially Pleistocene-aged or high-uranium speleothems. See RICHARDS and DORALE (2003), DORALE et al. (2004) for a comprehensive description and review of U-series chronology in speleothems. The ppt-levels of Th transported by groundwater to speleothems is referred to herein as 'detrital' Th (i.e., ^{230}Th at time = 0, not accumulated by decay of ^{234}U after speleothem calcite deposition). Minute amounts of detrital ^{230}Th deposited with ^{234}U and ^{238}U in speleothem calcite has to be taken into account in the U-series age calculations. This correction assumes an initial ^{230}Th/^{232}Th ratio for the detrital Th and the correction is typically minuscule and not applicable. However, this correction in young (Holocene-aged) low-U speleothems can be sensitive to the value of the initial ^{230}Th/^{232}Th ratio. Determination of ages reflecting true ages is becoming increasingly essential as high-resolution chronologies and other proxies become more comparable regionally and globally. For samples from Carlsbad Cavern and caves in the Guadalupe Mountains, southeastern, New Mexico, USA, we have established a correction for excess or detrital ^{230}Th based on isochrons, modern calcite, and annual bands. Our results suggest a vadose groundwater setting where at least two sources of detrital Th make up the initial ^{230}Th/^{232}Th ratio of detrital Th in these speleothems: (1) the soil and (2) the bedrock.

2. Methods

We approached the determination of detrital ^{230}Th in three ways; (1) construction of ^{234}U/^{232}Th versus ^{230}Th/^{232}Th two-dimensional or ^{230}Th-^{234}U-^{238}U three-dimensional isochrons, (2) collection and analysis of modern calcite deposits, and (3) correction of ^{230}Th/^{234}U-dates (U-series dates) to true ages from counting annual bands. Isochrons from total-dissolved rather than leachate subsamples is the recommended method (RICHARDS and DORALE, 2003). Because of the cost and time restraints, isochron-ages are infrequently reported for speleothem paleoclimate work. Our isochron-age measurements were determined

from three to five subsamples along a single same-aged layer. The isochrons and errors on the intercepts were determined using ISOPLOT (LUDWIG, 1991, 2001). Modern calcite samples were also collected as a way to determine initial ^{230}Th concentration. For example, a small drapery sample was collected from a man-made tunnel in Carlsbad Cavern. The drapery had to have grown since 1928, when the tunnel was blasted (personal communication, Stan Allison, 2002). In addition, another sample of over-growth on a broken stalagmite stub was collected. These two samples were analyzed and their ages were adjusted to obtain 10-60 years by changing the initial ^{230}Th/^{232}Th ratio. The ratio that corresponded to the modern age was used for determination of our correction curve. The error on these values reflected the possible maximum and minimum ages of the calcite. We also adjusted our U-series dates using the initial ^{230}Th/^{232}Th ratio to match ages determined by counting annual bands in two samples. In addition to the three methods above, the application of multi-collector ICPMS now makes it possible to more easily measure the amount of ^{230}Th in cave drip waters as an additional and quick way of testing the initial ratio as advocated by RICHARDS and DORALE (2003).

3. Results

The data from isochrons, modern calcite, and annual banding (Table 1) were used to establish a correction curve that could be applied to samples from caves in the Guadalupe Mountains. These data are exhibited in Figure 1. Our results produced a non-linear curve representing a significant negative correlation (r=0.8) between detrital ^{230}Th and ^{232}Th concentration. Our correction curve shows that cleaner calcite (small ^{232}Th concentration) yields higher initial ^{230}Th/^{232}Th ratios. This non-linear relationship supports an interpretation that the detrital Th in the samples is from more than one source with each source having very different isotope ratio signatures. Our depositional environment is within the caves, so emphasis is placed on vadose-zone water. For simplicity, we suggest two sources contributing to the detrital components, soil-zone source, and bedrock source (Fig. 2). We also suggest that the bedrock-derived component of the detrital thorium is significantly higher in value, although the carrier for the thorium (colloids and clays, organic complexes, Fe-hydroxides, etc. (RICHARDS and DORALE, 2003)) might originate from the soil zone. The Permian bedrock limestone and dolostone will ideally have ^{230}Th in isotopic equilibrium with ^{238}U, and in combination with moderately low concentrations of ^{232}Th, any ^{230}Th/^{232}Th contribution from the bedrock should have very high ^{230}Th/^{232}Th values. The soil zone, containing abundant clay and organic matter, will likely be young in comparison to the bedrock and contain high concentrations of ^{232}Th. The ^{230}Th/^{232}Th ratios in the soil should more closely reflect assumed bulk Earth values (^{230}Th/^{232}Th$_{atomic}$ = 4.4 x 10-6). The high-value 'bedrock' component is minor and becomes increasingly more important with decreasing ^{232}Th concentrations in the calcite, thus producing a non-linear trend.

4. Discussion and Conclusion

Constructing a correction curve from data generated by isochrons may not be the most efficient and useful way. The difficulty with the isochron method relates to the need for usually more than four subsamples to construct a meaningful isochron. Another problem arises if multiple sources of detrital ^{230}Th exist in the groundwater-speleothem system. Even with subsample numbers greater than four, a spread in data point values is needed to obtain robust initial ^{230}Th/^{232}Th ratios from isochrons. Too much spread will likely result in an initial ^{230}Th/^{232}Th ratio that is incorrect if the initial ^{230}Th/^{232}Th ratio in the dirty subsamples has a different value than the initial ^{230}Th/^{232}Th ratio in the clean subsamples. Not only will intercepts be incorrect, this could also produce isochrons with negative intercepts (initial ^{230}Th/^{232}Th ratio).

Adjustment of U-series ages to ages determined by counting annual bands provided much of the data that made up the correction curve. Annual banding in our stalagmites is well documented (ASMEROM and POLYAK 2004). Some of the data were taken from RASMUSSEN (2006) and RASMUSSEN et al. 2006). Figure 1B shows the results from the band record of a single stalagmite.

A similar result can be achieved by finding historical materials of known age that are coated with calcite or aragonite, or calcite that is growing on recently broken speleothems. Part of the curve in Figure 1 was generated from data measured from calcite growing in a man-made tunnel and new growth on a broken stalagmite stub in Carlsbad Cavern. An optional way to obtain the same information is to plant seeds under drips and wait one to two years for deposition of modern calcite. For studies that last multiple years, this is feasible. About 10 to 20 seed samples might be a suitable number of samples needed to construct a useable correction curve. This is the equivalent number of analyses needed for two or three isochrons, which give only two or three data points for such a curve, if a correction curve is needed. This seed method does not require isochrons or annually banded stalagmites.

Table 1. ^{232}Th concentration versus initial $^{230}Th/^{232}Th$ for each subsample.

subsample	remarks	^{232}Th conc pg/g	error (pg/g)	$^{230}Th/^{232}Th$ initial	error (ng/g)
bc7 new growth	~30 yrs old	1097	17	3.51E-05	1.76E-05
Tunnel Outer	~10-20 yrs old	6747	544	1.14E-05	5.69E-06
BC11-a	U-series ages adjusted to band ages	460	21	3.70E-05	9.25E-06
BC11-c		620	18	3.87E-05	9.68E-06
BC11-d		2233	32	1.59E-05	3.98E-06
BC11-e		1338	25	2.51E-05	6.28E-06
BC11-f		926	15	2.23E-05	5.58E-06
BC11-g		2609	19	1.70E-05	4.25E-06
BC11-i		512	13	3.92E-05	9.8E-06
BC2-tt4a	Band age from (tree ring record)	1998	19	1.72E-05	8.60E-06
BC2-HT	initial $^{230}Th/^{232}Th$ adjusted by isochrons	1543.705	1906	1.55E-05	3.10E-06
BC2-900		3971.728	1564	2.10E-05	4.80E-06
BC2-TH		872	759	7.44E-05	3.20E-05
C10-1-top		921	504	6.97E-05	3.50E-05
PD-3		2500	411	2.33E-05	9.70E-06
C102-top		37316	26000	2.28E-06	9.00E-06
BC2-hunder		10384	156	5.88E-06	1.10E-06

Stalagmite BC7 new growth was precipitating on broken stalagmite stub when collected. Tunnel outer is the outer layer of a small drape that precipitated in a man-made tunnel in Carlsbad Cavern. See RASMUSSEN (2006) or RASMUSSEN et al. (2006) for ages of each of the BC11subsamples; all are from a 3000-year old stalagmite. The BC11 values were used to construct Figure 1B. Subsample BC2-tt4a has a band age tied to the Guadalupe Mountains tree ring record. See ASMEROM and POLYAK (2004). All subsamples are from Carlsbad Cavern except for C10-1-top and PD-3, which are from cave #10 in Carlsbad Caverns National Park and Pink Dragon Cave, Lincoln National Forest. All errors are absolute 2σ.

We have constructed a working correction curve based on initial "detrital" ^{230}Th and detrital ^{232}Th concentrations where initial $^{230}Th/^{232}Th$ atomic ratio is equal to 0.0033 x $TH^{0.6664}$ ppm, where TH = Th concentration in ng/g. Our results suggest that the detrital ^{230}Th component has at least two general sources interpreted to be a Th component from soil and a Th component from bedrock. The negative correlation between initial $^{230}Th/^{232}Th$ and ^{232}Th concentration suggests that lower ^{232}Th concentration in calcite has a greater percentage of ^{230}Th from bedrock. This type of non-linear correction can be especially useful for U-series studies of speleothems that are young and consist of calcite with low-uranium and/or relatively high-thorium concentrations.

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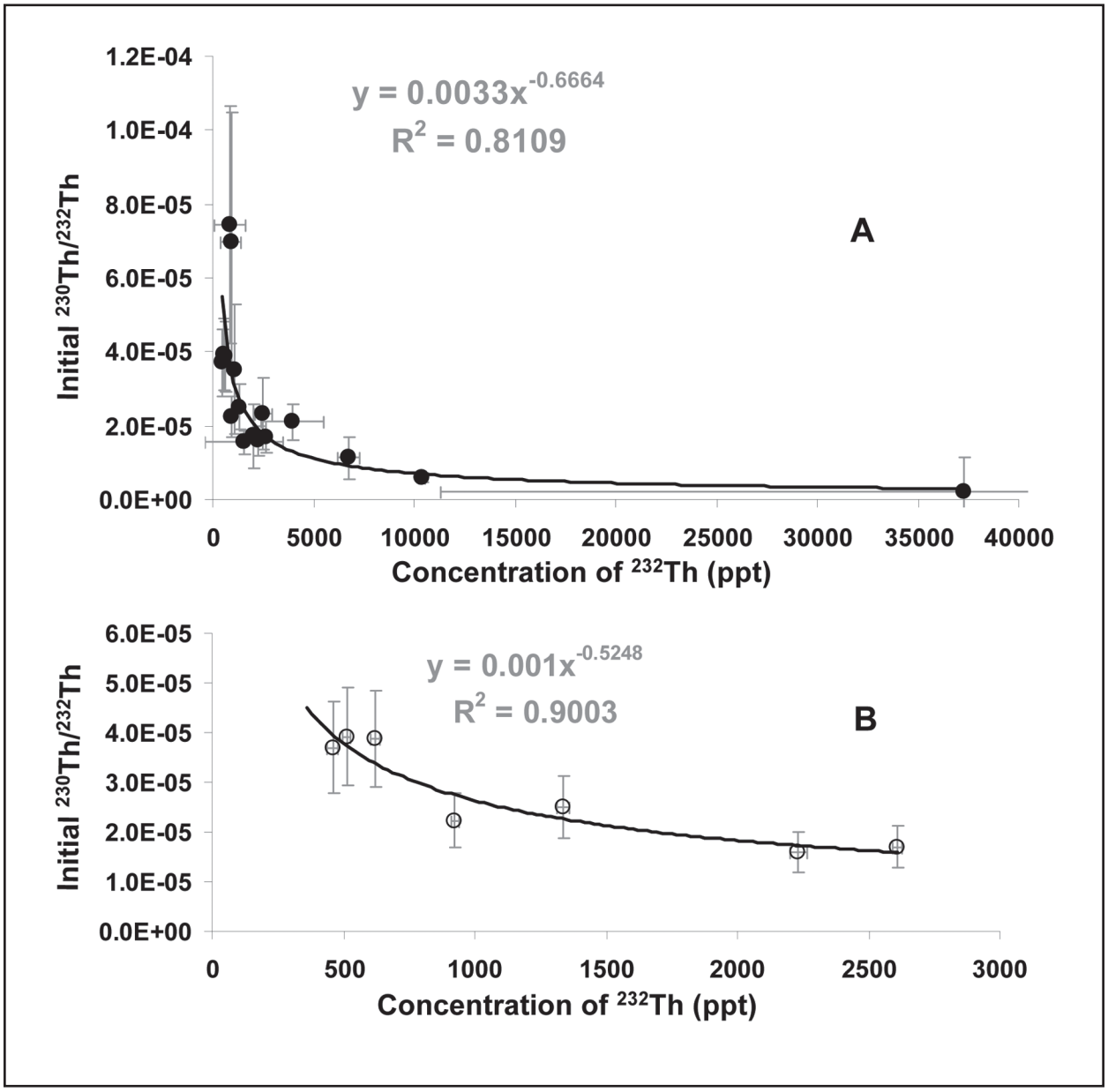

Figure 1: U-series data showing varying initial 230Th/232Th values from 234U/232Th versus 230Th/232Th two-dimensional or 230Th-234U-238U three-dimensional isochrons, modern calcite, and stalagmite band ages. (A) Curve constructed from data from isochrons, modern calcite, and banding. (B) Curve constructed from band ages from a single stalagmite (BC11).

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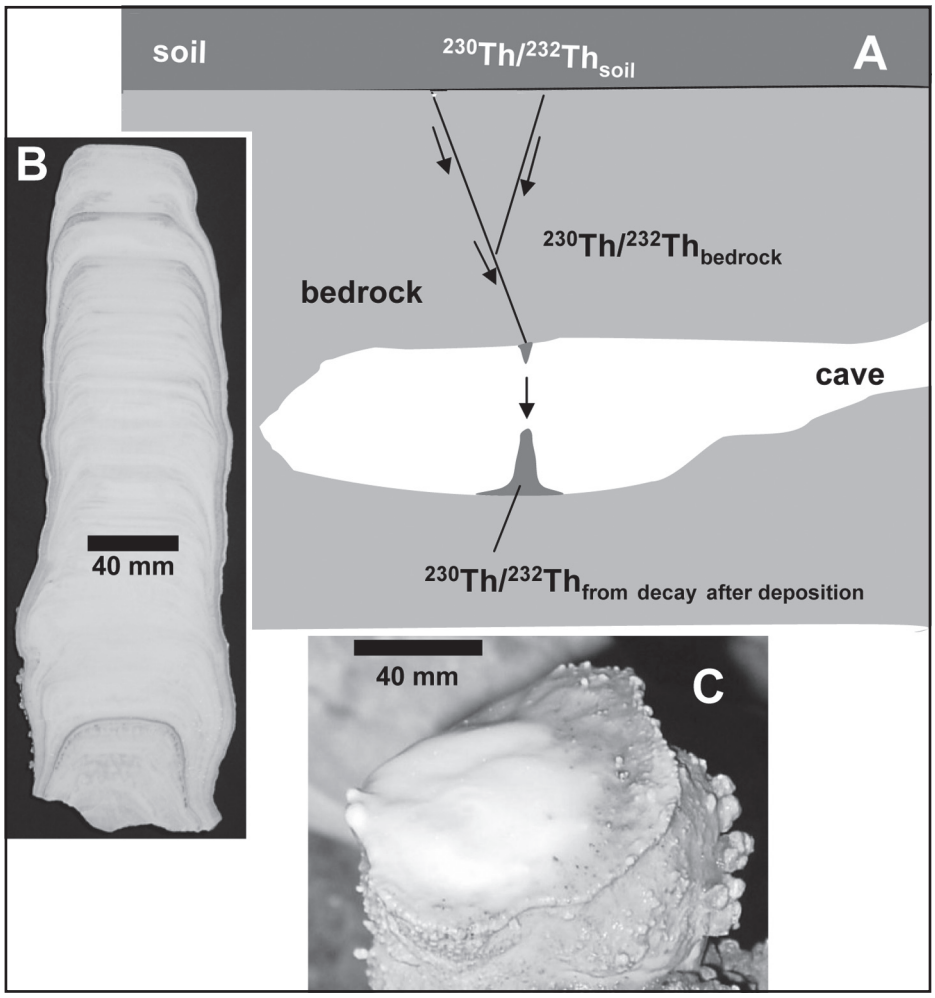

Figure 2: (A) Depositional setting showing two different sources for initial 230Th232Th, a low-value source (soil), and a high-value source (bedrock). (B) Stalagmite BC2. (C) New calcite growth on Stalagmite BC7.

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COMBINED NEW PALEOCLIMATOLOGIC AND CHRONOLOGIC EVIDENCE FROM PETRALONA CAVE, GREECE

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Petralona Cave in northern Greece was discovered 50 years ago, in May of 1959. The paleoclimatologic and chronologic study of the cave sediments and findings have been advanced over the past half century through many scientific publications, often quite controversial. Initial age estimates of ~50 ka offered in 1968 were corrected toward much older dates. Currently, the debate is internationally oriented around two main axes. One indicates ages of about 0.3–0.5 Ma while the other 0.6–0.8 Ma. Considering the previous data and the importance of paleoclimatic evidence for understanding present-day climatic and environmental conditions, this paper presents preliminary new results of relevance to the issue. The results are based on new U/Th dating and oxygen isotopic analyses of three surface stalagmite samples (from the 1st layer of the Petralona stratigraphic series). The sample ages range from 500 to 235 ka and indicate significant differences in growth rates likely corresponding to different hydrologic and climatic conditions. Highest growth rates (approximately 3 cm/ka) are observed in two samples that grew between 246 to 235 ka and 420 to 416 ka, most likely corresponding to warm interglacial stages 7 and 11. An oxygen isotopic shift of 3 per mil in the latter sample is consistent with the climatic transition over termination IV (stage 11–12 transition). The results support earlier evidence for major climatic changes in the region that emerged through the stratigraphic studies and excavations of the Anthropological Association of Greece. Further details of the paleoenvironmental evolution and the oscillations of warm and cold periods from Petralona speleothems are in progress for the future.

1. Stratigraphy and relative chronology

In September 15th, 1960, a skull of a male human was found covered by sinter at Petralona cave. Initially its age, along with the associated faunal remains, were attributed to the Upper Pleistocene (50–70 ka). During the 1968 excavations of A. POULIANOS (1968, 1971), the age of the Petralona findings was re-proposed at about 500-800 ka based mainly on paleolithic stratigraphic data. Since then the Anthropological Association of Greece has maintained oversight of the investigation.

The cave's stratigraphic evidence suggests the following: in the northern compartment, 34 geologic layers have been revealed, while in the southern compartment, only those beneath the 11th are preserved. A little above the ground surface (~25 cm) of the southern cave compartment, in a chamber named "Mausoleum," the Petralona human skull was found attached by a sinter bar (3–4 cm long) to the limestone cave's wall. Therefore, Petralona man lived some time between the formation of the 11th layer and deposition of the 14th layer. There are two main stalagmitic layers developed in the cave's stratigraphy, the 1st (upper) and the 10th, providing the possibility of absolute chronological control.

The associated faunal evidence reaffirmed the above mentioned chronology given by A. Poulianos. Because of space limitation in the present paper, paleolithic, statigraphic, and faunal data are not further discussed. For more details, see A. POULIANOS (1982) and N. POULIANOS (1995). The Petralona cave map is elsewhere in this volume (VENI et al., 2009).

2. Absolute Chronology

Several different methods have been utilized in order to determine the chronology of various materials obtained from Petralona cave sediments. The above mentioned studies are summarized in the following Table 1, based on references listed in the bibliography.

LAYER	LEVEL (FUSED)	SECTION	AGE (yrs x 1000)	METHOD
1	SUP.	Alpha	0 - 70	U/TH, ESR
1	MED.	Alpha	250	U/TH, TL, ESR
1	INF.	Alpha	>350	U/TH, E.S.R.
4		Alpha	max. 670	TL
10	(+1?)	Alpha	? 200	U/TH, E.S.R.
10		Beta	>350	U/TH, E.S.R.
10		Beta	670	E.S.R.
10		Beta	350 - 670	U/TH (EXTRAP.), E.S.R.
10	(+1)	MEDITER.	≥350	U/TH, E.S.R.
10	(+1)	MAUSOL.	300 - 600	U/TH, E.S.R.
11		Beta	530 - 650	AMINO ACID
11		MAUSOL.	600 - 675	AMINO ACID, ESR, PALEOMAG
14 -16		Beta	600 - 700	AMINO ACID
24 - 25		Beta, Gamma	730	PALEOMAG., E.S.R
26		Beta	>730 -?	PALEOMAG.
28 - 34		Beta	?	-

Table 1: Summarized dating results of Petralona Cave sediments and fossils.

The results presented here are based on new U/Th dating and oxygen isotopic analyses of three surface stalagmite samples (from the 1st layer of the Petralona stratigraphic series) (Fig. 1). The sample ages range from 235–500 ka and indicate significant differences in growth rates likely corresponding to different hydrologic and climatic conditions. Highest growth rates (approximately 3 cm/ka) are observed in two samples that grew from 235–246 ka and 416–420 ka, most likely corresponding to warm interglacial stages 7 and 11. An oxygen isotopic shift of 3 per mil in the latter sample is consistent with the climatic transition over termination IV (stage 11–12 transition). The results support earlier evidence for major climatic changes in the region that emerged through the stratigraphic studies and excavations of the Anthropological Association of Greece. Further details of the paleoenvironmental evolution and the oscillations of warm and cold periods from Petralona speleothems are in progress.

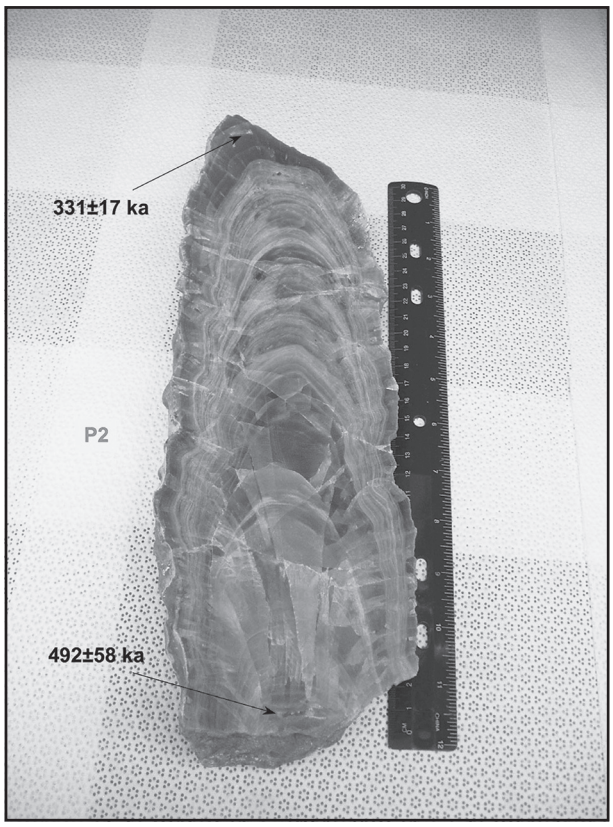

Figure 1: Stalagmitic sample 2 dated at the ages indicated.

Based on these dates and the previous data presented above, it is possible to conclude that the dates obtained for materials from Petralona cave range from 350 ka to 1 Ma, with the most like interval being 500–800 ka. Thus, the Petralona human skull appears to have an age of about 700 ka, a date that is concordant with recent paleoanthropological (mainly paleolithic), paleoecological and paleontological studies.

We look forward to continued analysis of the materials from this site thanks to cooperation from the Greek Ministry of Culture and the international scientific community.

As always, the Anthropological Association of Greece welcomes collaboration with institutions and scholars all over the world.

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APPLICATION OF U-SERIES DATING METHOD TO FOSSIL BONES: NEW PERSPECTIVES

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Abstract

During the last 40 years, fossil bones have been investigated repeatedly in order to determine the possibility of dating using the U-Th method. Bone accumulates uranium from infiltrating water during burial in sediments. This means that bone is an open system for uranium ions migration; it does not fulfill assumptions of the uranium-thorium geologic clock. Through the years, the main approach to this problem has been to construct the mathematical models to estimate the amount of accumulated uranium using statistical and mathematical simulations of accumulation process.

Bone is a biological material and as such is not a homogenous substance. It combines several organic and inorganic phases that react individually during fossilization and diagenesis. These processes also affect uranium accumulation process.

A similar problem was discovered for ^{14}C dating of fossil bones. Analysis revealed that the method of sample pretreatment affects the results of dating. Using simple chemical reactants and a controlled reaction environment, it is possible to decompose bone to its main components: carbonates, phosphates, lipids, proteins etc. Some of these bone-phases are less stable during diagenesis and degradation, so dissequilibration of the radiocarbon geologic clock occurs. For this reason, extracting the most resistant phase, which is a closed system for Carbon isotopes, is necessary. Now, standard procedure for the radiocarbon dating of fossil bones utilizes only the collagen acquired from bone samples through extraction and purification.

This study was (1) to estimate the potential of uranium (and thorium, if it occurs) accumulation in each of the bone-phases and (2) to verify suitability of fossil collagen for U-Th dating of fossil bones. Recent (whole) bones and bone-phases were analyzed to define the starting point of the system. Next, a similar analysis of fossil bones of various ages and sites was performed. Comparing these two sets of data allows the mechanisms of the accumulation process to be determined. The study found three main conclusions: (a) There is no thorium accumulation in fossil bones; (b) Uranium accumulation potential is strictly connected with the chemistry of a phase and differs widely among main bone-phases. The chemistry of a phase determines the processes that take place during fossilization, diagenesis, and degradation; (c) The collagen phase has the least, if any, potential of uranium accumulation and may be a closed system for uranium and thorium isotopes migration.

Several preliminary U-Th and ^{14}C datings of the same sample of fossil collagen have been made. Unfortunately, the age of the sample is at the edge of the ^{14}C method's range, so the certainty of the comparison of these data is not fully satisfactory. However, acquired dates were not contradictory. More samples are being processed to provide a better test of the method.

STABLE ISOTOPE VARIATIONS DURING MARINE ISOTOPE STAGE 3 RECORDED IN A STALAGMITE FROM V11 CAVE, NW ROMANIA

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Abstract

Stable isotope analyses on a 40 mm stalagmite growth sequence yield a paleoclimate record for the interval 59–46 kyr BP (Marine Isotope Stage 3). The chronology is based on four U-Th ages obtained by thermal ionization mass spectrometry.

V11 Cave is located in the Bihor Mountains (W Romania), at 1254 m a.s.l. The cave is formed in Anisian limestones and dolomites, has 1,166 m of surveyed passages and a vertical extension of 67 m (–37 m; +30 m). The cave area is a typical karst plateau, with vegetation mainly consisting of spruce stands and alpine herbs. The present-day climate of the area is predominantly influenced by west-northwest oceanic air masses. The mean annual temperature is 5°C and the mean annual precipitation exceeds 1200 mm. The mean annual temperature and the relative humidity in the cave are 6.5° C and 97–98%, respectively.

S22 is a 34-cm stalagmite formed on a limestone block fallen from the ceiling of the cave passage. Growth episodes were determined at 124 kyr, 116 kyr, 99 – 81 kyr, 59 – 46 kyr, and 14.5 – 5.6 kyr. The stable isotope record of the previously studied Lateglacial – Early Holocene growth sequence has shown a strong dependence to climate variations.

On the interval studied, growth intervals were determined at 59 – 56 and 52 – 46 kyr BP (Marine Isotope Stage 3), with one more hiatus occurring before 46 kyr, probably of short duration. The stable isotope record shows two cold intervals, separated by a hiatus at 56 – 52 kyr BP, and then a warm period between 50 and 46 kyr BP. Variations in O isotopes can be correlated to Dansgaard-Oeschger events recorded in the Greenland ice cores.

The maximum variations in the $\delta^{18}O$ record are ca. 1.5‰. Oxygen values recorded during the cold intervals, averaging -8.2‰, are close to the ones documented during the Younger Dryas (GS-1) on the same sample, while values recorded between 49–46 kyr average present day calcite values, around -7‰.

The data demonstrates that seepage water was available for stalagmite growth even during colder periods within the MIS 3 stadials, whereas hiatuses may be associated to warmer/wetter periods and are due to corrosion by unsaturated dripping water.

NEW ZEALAND CAVE RECORDS SHOW THE SOUTHERN HEMISPHERE TO BE PALEOCLIMATICALLY DIFFERENT: LGM AT STAGE 4, NO YOUNGER DRYAS, AND A POLYNESIAN WARM PERIOD

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Abstract

Results from a huge amount of paleoclimatic research in the Northern Hemisphere dominate the world view of paleoclimatic history. But research from the Southern Hemisphere is increasingly showing a different story, as illustrated by the results of speleothem-based research from New Zealand, a country located in a mid-latitude oceanic environment between Antarctic and tropical influences.

The stable isotope record from New Zealand speleothems is presented from the last interglacial to the present. Broad similarities are found between New Zealand and comparable records from the Northern Hemisphere, but there are also some marked differences. Three in particular are of interest because they show that the climatic systems of the Northern and Southern Hemispheres do not work entirely in unison: (1) the Last Glacial Maximum in New Zealand was not at isotope stage 2 but at stage 4; (2) a Late Glacial cold reversal occurred that in timing and form resembles the Antarctic Cold Reversal rather than the Younger Dryas; (3) a late Holocene warm interval occurred, termed the Polynesian Warm Period, because its start and end dates are different to the Medieval Warm Period experienced in Europe; and (4) the recent phase of global warming only became evident from the beginning of the 20th Century. However, the Little Ice Age occurred at about the same time in both hemispheres and many D/O events have the same timing.

It is concluded that at a time scale of 10^5 years or more the hemispheres are broadly in step, but at the millennial and centennial scales there are often, but not always, significant differences. In comparing last glacial cycle events in New Zealand with those in the Northern Hemisphere, one must also remember that one is comparing climatic responses in an alpine glacial environment to those in a continental glacial system. The alpine system is much more responsive to short-term change. The intensity of climate change recorded in New Zealand, and perhaps also in much of the rest of the oceanic Southern Hemisphere, may also be less than in the Northern Hemisphere because the moderating effect of the sea dampens extreme changes.

INVESTIGATING THE CONTROLS ON NON-LINEAR REALTIONSHIPS BETWEEN DRIP RATE AND DRIP-WATER COMPOSITION IN CENTRAL TEXAS KARST, USA

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This study investigates the controls on the geochemical evolution of vadose drip water in karst associated with the Edwards aquifer of central Texas. A multi-year monitoring study in a cave in the aquifer's Contributing Zone identifies processes responsible for non-linear relationships between water flux (i.e., rainfall and drip rate) and drip-water composition. We delineate three groups of drip-water based on (1) drip water compositions, (2) drip rate characteristics, and (3) correlations between water flux and drip-water compositions. We use observed soil and limestone compositions to constrain and quantitatively model the geochemical evolution of vadose drip water. Drip-water $^{87}Sr/^{86}Sr$ values are key in demonstrating the capability of model water-rock interaction (i.e., calcite and/or dolomite recrystallization) curves to account for drip water compositions that exhibit linear relationships with water flux. Invariant $^{87}Sr/^{86}Sr$ values suggest that another process subsequent to water-rock interaction is needed to account for drip water compositions that exhibit little to no correlation with water flux. Drip water compositions that are decoupled from water flux exhibit high values and large ranges of trace element ratios (Mg/Ca and Sr/Ca) relative to drip water compositions that exhibit linear relationships with water flux. These characteristics of drip water trace element ratios provide strong evidence that calcite precipitation is 1) decoupled from water flux, 2) occurs subsequent to water-rock interaction, and 3) increases trace element ratios beyond values for which water-rock interaction can account. Our results suggest that drip-sites with both linear and non-linear relationships between water flux and drip water composition may be useful for reconstructing records of paleoclimate.

1. Introduction

Speleothems are commonly used to reconstruct terrestrial paleoclimate records for the Pleistocene and Holocene. Numerous studies have investigated modern mechanisms of speleothem deposition from drip water and the links between climate and drip water composition to better understand the geochemical proxies (oxygen, carbon, and strontium isotopes and trace element ratios) used in the reconstruction of paleoclimate records (see review by FAIRCHILD et al., 2006a). Drip water Mg/Ca and Sr/Ca are influenced by variations in water residence time linked to variations in water flux, but this relationship is often non-linear due to complexities in flow routing (TOOTH AND FAIRCHILD, 2003; BALDINI et al., 2006; FAIRCHILD et al., 2006b). Drip water $^{87}Sr/^{86}Sr$ values have been used as a proxy for water residence time and variations in water flux (BANNER et al., 1996; MUSGROVE AND BANNER, 2004). This study uses results from a multi-year monitoring project to quantitatively model mineral-solution reactions and delineate the process responsible for both linear and non-linear relationships between water flux and drip water compositions. The goal of this study is to better understand the processes that control drip water compositions, and ultimately dictate drip water composition, in order to improve paleoclimate records that are interpreted from speleothems.

2. Hydrogeologic setting

Drip waters were sampled from within Natural Bridge Caverns in central Texas, USA, at depths ranging from 30 to 60 m. The cave is developed within the Balcones Fault Zone, the en echelon down-faulted margin of the Edwards Plateau, a regionally extensive karstified Cretaceous marine carbonate platform. The project area is also within the recharge zone of the Edwards-Trinity aquifer and the contributing zone of the Edwards aquifer. The hydrogeology and geomorphology of the area is discussed by ELLIOTT AND VENI (1994) and MUSGROVE AND BANNER (2004). Natural Bridge Caverns is one cave, separated into two parts by collapse. It is formed in the Krainer and Glen Rose formations, which consist of interbedded limestone, marly limestone, and dolomite (SMALL AND HANSON, 1994). The climate is semi-arid with an average rainfall of 740 mm and a range of 250 – 1320 mm. There was little to no discernible seasonality of rainfall during the period of study. Mean temperatures for summer and winter are 29°C and 11°C, respectively. The surface above the cave is covered with thin (<30 cm) clay rich mollisols and juniper, oak, and

savanna grasses (COOKE et al., 2007).

3. Methods

Nine drip sites were visited every four to six weeks, from May 2004 to April 2008, to collect drip-water and physical data (drip rate, cave-air temperature and CO_2). Drip rate was measured at a higher resolution at three drip sites using tipping buckets and data loggers. Rainfall was measured by an on-site rain gauge, and supplemented by a nearby U.S. Geological Survey site (site no. 08167347) from 08/23/07 to 11/25/07 when the rain gage was not functioning. Surface air temperature data was retrieved from a nearby NOAA station (Canyon Dam, COOP-ID 411429), and supplemented by another nearby station (New Braunfels, COOP-ID 416276), from 1/1/06 to 6/1/06, when the prior station was not reporting.

Soil samples were collected from above drip sites and leached in ammonium acetate to obtain the exchangeable fractions of cations. Limestone samples were collected from the surface and in the cave near drip sites. All geochemical analyses were conducted in the Department of Geological Sciences at The University of Texas at Austin. Cation concentrations were measured on an Agilent 7500ce quadrupole ICP-MS. Analytical uncertainty for Ca, Mg, and Sr is 10%, 8%, and 6%, respectively, and for Mg/Ca and Sr/Ca is 6% and 9%, respectively. The average percent difference for sixteen replicate unknown water samples for Mg/Ca and Sr/Ca is 6% and 8%, respectively. Strontium was measured for $^{87}Sr/^{86}Sr$ ratios dynamically using a seven collector Finnigan-MAT 261 thermal ionization mass spectrometer, following methods in BANNER AND KAUFMAN (1994). The mean NIST SRM 987 standard values measured during the duration of the study was 0.710261 (2σ = 0.000014, n=56). Measurements were normalized for fractionation to $^{86}Sr/^{88}Sr$ = 0.1194 using an exponential fractionation law. Replicate analyses on eight unknowns are within 0.000010.

4. Results

4.1 Drip water compositions

Three groups of drip-water compositions can be delineated based on drip-water composition, drip rate characteristics, and correlations between measures of water flux and drip water composition. Group 1 drips (n=3) have high Mg, Sr, Mg/Ca, and Sr/Ca and low Ca and $^{87}Sr/^{86}Sr$ values (Table 1). Group 2 drips (n=4) have lower Mg, Sr, Mg/Ca, and Sr/Ca and higher Ca and $^{87}Sr/^{86}Sr$ values relative to Group

Table 1. Geochemical characteristics of drip-water, soil, and limestone compositions

	Mg (ppm)	Sr (ppm)	Ca (ppm)	Mg/Ca (mol/mol)	Sr/Ca (mmol/mol)	$^{87}Sr/^{86}Sr$
Group 1						
NBVC	24-34	0.08-0.17	16-64	0.58-2.45	0.89-1.88	0.70837-0.70841
NBBC	21-32	0.07-0.10	30-74	0.68-1.05	0.51-0.86	0.70833-0.70835
NBGN	14-33	0.07-0.10	29-87	0.38-1.93	0.57-1.68	0.70838-0.70874*
Group 2						
NBEL	4-10	0.04-0.06	46-98	0.09-0.26	0.27-0.43	0.70879-0.70883
NBFE	6-9	0.04-0.07	85-150	0.09-0.12	0.17-0.27	0.70897-0.70904
NBFT	2-3	0.03-0.06	80-155	0.02-0.04	0.12-0.32	07.0880-0.70883
NBWS	3-4	0.04-0.05	95-319	0.01-.06	0.07-0.21	0.70904-0.70907
Group 3						
NBCD	9-17	0.05-0.10	29-109	0.22-0.69	0.30-0.84	0.70884-0.70896
NBCA	7-9	0.05-0.07	38-108	0.11-0.27	0.26-0.60	0.70881-0.70886
Soil leachate				0.04-0.06	0.19-0.28	0.70906-0.70917
Limestone	2,050 - 6,060	10-70		0.08-0.15	0.03-0.31	0.70755-0.70787

* This is an anomalous value for this drip site, and without this point, the range would be 0.70838-0.70840 (n=8).

Drip sites NBCA, NBEL, and NBWS were a part of Musgrove and Banner, 2004, and NBCA and NBWS of Banner et al., 2007.

n.a. = not applicable for soils as concentrations are dependent on the leaching procedure and carbonates as a concentration of 400,000 ppm was assumed.

1 (Table 1). Group 3 (n=2) have Mg, Sr, Ca, Mg/Ca, Sr/Ca, and $^{87}Sr/^{86}Sr$ values that are in between Groups 1 and 2.

4.2 Drip rate characteristics

Drip rate characteristics (drip rate maximum and drip rate variability) are commonly used to deduce the type of flow routes that supply water to drip sites (SMART AND FRIEDERICH, 1987). Group 1 drip sites have low drip rate maximums and high drip rate variability, indicating that they are supplied by diffuse-dominated flow routes. Group 2 and 3 drip sites have high drip rate maximums (with the exception of one site from Group 3) and low drip rate variability, indicating that they are supplied by conduit-dominated flow routes.

4.3 Correlations between water flux and drip-water composition

Group 1 exhibits fewer and weaker correlations between water flux (rainfall and drip rate) and drip water composition (Mg/Ca, Sr/Ca, $^{87}Sr/^{86}Sr$) than Group 2 (Table 2). Group 2 exhibits positive linear correlations between a) rainfall and drip rate, b) water flux and drip-water $^{87}Sr/^{86}Sr$, and negative linear correlations between a) water flux and Mg/Ca and b) water flux and Sr/Ca. Group 3 exhibits variable correlations between water flux and drip water compositions (Table 2).

4.4 Soil and limestone compositions

Drip-water compositions are in between those of soil and limestone compositions. Soil leachates have Mg/Ca and Sr/Ca ratios that are consistent with Group 2 values, but are lower than Groups 1 and 3. Soil $^{87}Sr/^{86}Sr$ values are higher and/or equivalent to those of Group 2 drip-water and higher than those of Group 1 and 3 drip-water (Table 1). There is no compositional spatial variability between soil sampled from above drip sites relative to the variability seen in drip-water compositions. Measured limestone $^{87}Sr/^{86}Sr$ values are lower than all drip-water values (Table 1). As with soils, there is no compositional spatial variability in limestone samples above or within the cave relative to the variability seen in drip-water compositions.

5. Discussion

We observed drip-water compositions that have both linear and non-linear relationships with water flux. Sr isotope values of drip water and system components are used to demonstrate the ability of water-rock interaction modeling to account for linear relationships between water flux and drip-water composition (BANNER et al., 1996; MUSGROVE AND BANNER, 2004). We then use Sr isotopes to show that non-linear relationships between water flux and drip water composition are caused by additional calcite precipitation that occurs subsequent to water-rock interaction.

To understand how non-linear relationships may be useful, we first review the controls on drip-water compositions. Vadose water acquires its initial composition from interaction with the soil through which it infiltrates. Beyond

Table 2: Correlations between water flux and drip water composition, expressed as r^2 values.

	Flow path[1]	Rainfall - DR*	Rainfall - Mg/Ca**	DR - Mg/Ca**	Rainfall - $^{87}Sr/^{86}Sr$*	DR - $^{87}Sr/^{86}Sr$*	Mg/Ca - $^{87}Sr/^{86}Sr$**	CO_2 - Mg/Ca***	Temp - Mg/Ca**	Density[2] - Mg/Ca*
Group 1										
NBVC	diffuse	0.03	-0.10	< 0.01	< 0.01	0.05	< 0.01	0.80	0.53	0.55
NBBC	diffuse	< 0.01	< 0.01	< 0.01	0.04	0.07	< 0.01	0.50	0.23	0.18
NBGN	diffuse	< 0.01	-0.11	0.01	0.47	0.04	0.05	0.90	0.23	0.34
Group 2										
NBEL	conduit	0.40	0.24	0.43	n.a.	n.a.	0.83	0.23	0.03	
NBFE	conduit	0.43	0.28	0.53	0.52	0.07	0.86	< 0.01	0.07	
NBFT	conduit	0.41	0.40	0.16	0.25	0.23	0.44	0.14	0.03	
NBWS	conduit	0.76	0.13	0.43	n.a.	n.a.	0.08	0.06	< 0.01	
Group 3										
NBCD	conduit	0.29	0.00	< 0.01	0.74	0.36	0.04	0.57	0.04	
NBCA	conduit	0.01	0.34	0.08	n.a.	n.a.	< 0.01	0.13	< 0.01	

[1]Flow paths are classified as either diffuse or conduit, see text; [2]Density refers to the density difference between surface and cave air; DR = drip rate; Temp = surface air temperature; n.a. = not applicable due to insufficient measurements; *Positive linear correlation; ** negative linear correlation, ***inverse correlation

the soil horizon, water then interacts with host bedrock material, and may or may not undergo additional calcite precipitation upon entering the cave environment. The extent of water-rock interaction and/or calcite precipitation that occurs is influenced by the type of flow route, flow route complexities (i.e., lag time, piston flow, re-routing of flow routes under varying hydrologic rainfall conditions), variability of soil and host carbonate compositions, and variations in water flux (FAIRCHILD et al., 2006a).

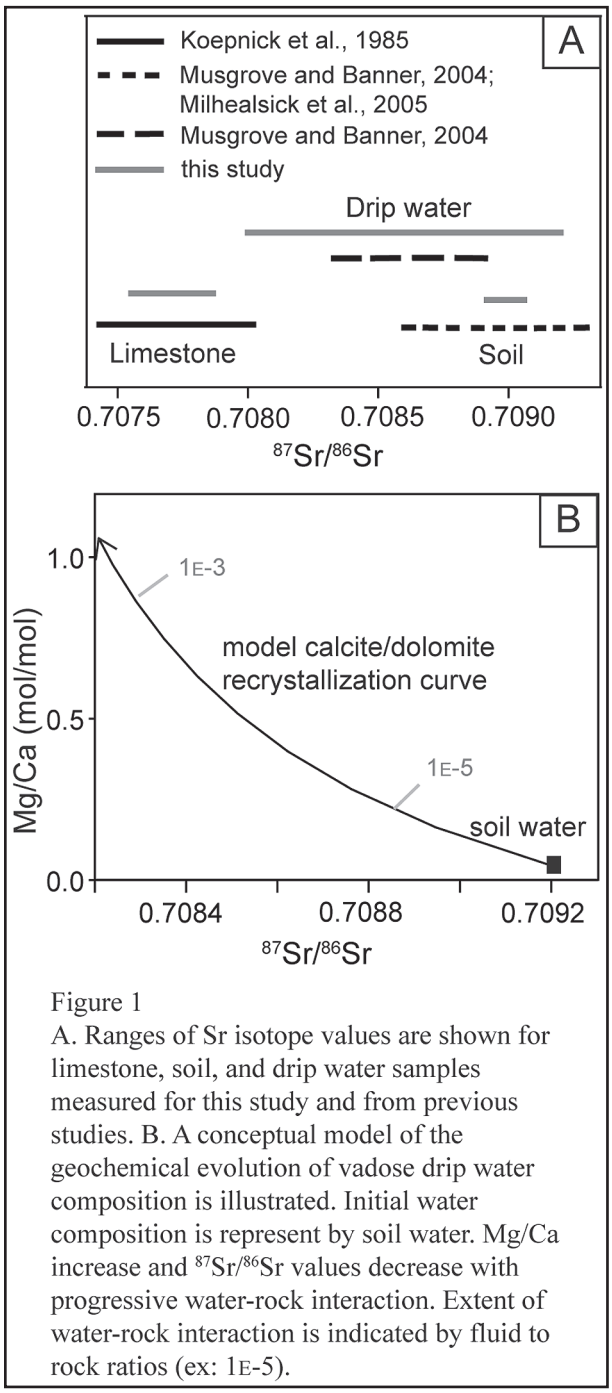

Figure 1
A. Ranges of Sr isotope values are shown for limestone, soil, and drip water samples measured for this study and from previous studies. B. A conceptual model of the geochemical evolution of vadose drip water composition is illustrated. Initial water composition is represent by soil water. Mg/Ca increase and $^{87}Sr/^{86}Sr$ values decrease with progressive water-rock interaction. Extent of water-rock interaction is indicated by fluid to rock ratios (ex: 1E-5).

Figure 1: A. Ranges of Sr isotope values are shown for limestone, soil, and drip water samples measured for this study and from previous studies. B. A conceptual model of the geochemical evolution of vadose drip water composition is illustrated. Initial water composition is represent by soil water. Mg/Ca increase and 87Sr/86Sr values decrease with progressive water-rock interaction. Extent of water-rock interaction is indicated by fluid to rock ratios (ex: 1E-5).

The silicate soils have a distinctly higher $^{87}Sr/^{86}Sr$ value than the Cretaceous carbonate bedrock that they overlie on the Edwards Plateau in central Texas (Fig. 1A). This difference makes $^{87}Sr/^{86}Sr$ values a useful indicator of relative extents of water-rock interaction and water residence time. Vadose water progresses from a high $^{87}Sr/^{86}Sr$ value, acquired from the soil, to a lower $^{87}Sr/^{86}Sr$ value, more similar to limestone, as it dissolves carbonate minerals (BANNER et al., 1996). The progression from high to low $^{87}Sr/^{86}Sr$ values is coincident with low to high trace element ratios as the re-precipitation of calcite increases Mg and Sr relative to Ca in water (Fig. 2A). The calcite-water distribution coefficients (K_D) of Mg and Sr are less than one, which indicates that Mg and Sr are preferentially partitioned to the fluid phase and Ca to the crystalline phase. Following water-rock interaction, continued calcite deposition will increase trace element ratios while not altering $^{87}Sr/^{86}Sr$ values (BANNER AND HANSON, 1990). This makes Sr isotopes useful tracers of water-rock interaction, and enables the distinction between increases in trace element ratios linked to water-rock interaction, and increases caused by calcite precipitation subsequent to water-rock interaction (Fig. 2).

We use mass balance equations to model mineral-solution reactions after methods of BANNER AND HANSON (1990). Initial vadose water compositions are constrained by measurements of the exchangeable fraction of ions of soils collected from surface sites directly above drip sites throughout the cave. While regional variability in soil compositions has been demonstrated to account for regional differences in vadose drip water between central Texas caves (MUSGROVE AND BANNER, 2004), the variability of soil compositions at Natural Bridge is insignificant and unable to account for the spatial variability of drip water compositions observed in the cave.

Our model is further constrained by measured compositions of limestone from above and within the cave at Natural Bridge. The observed $^{87}Sr/^{86}Sr$ values of Walnut and upper Glen Rose limestone is within the range of corresponding limestone measured by KOEPNICK et al. (1985) and distinctly lower than both soil and drip water samples. While spatial variability in host carbonate material has been

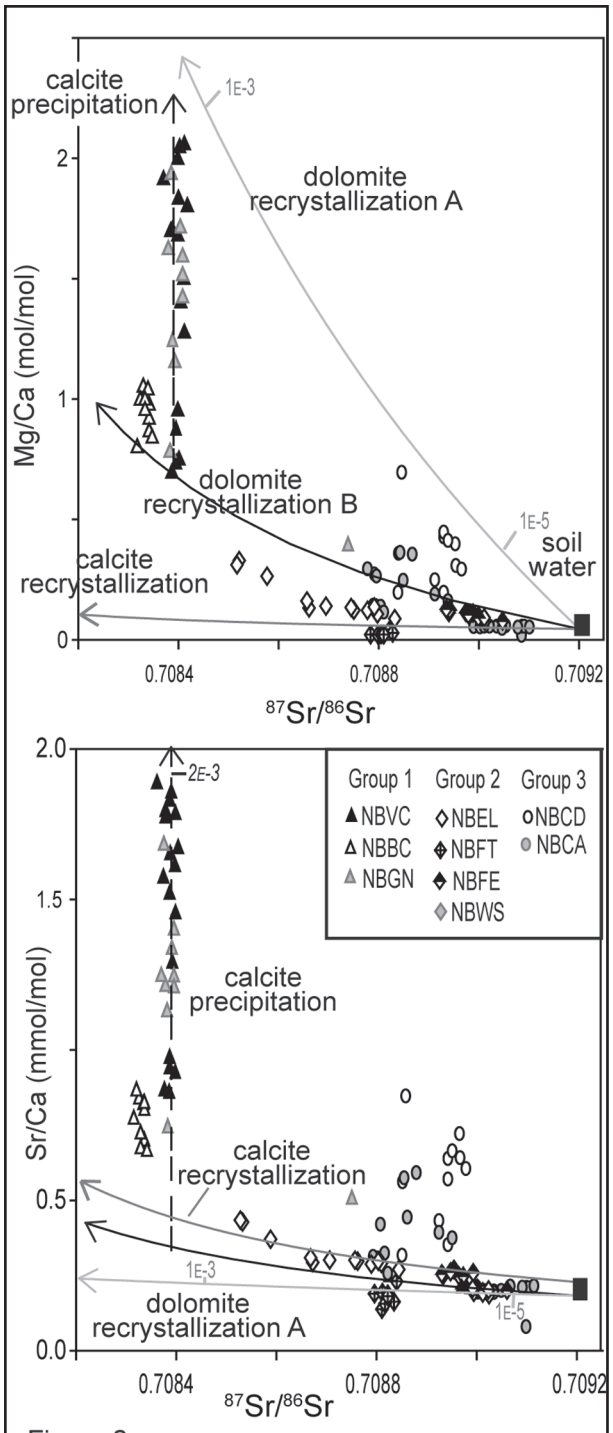

Figure 2
Possible rock-water interactions that could account for drip water compositions from each drip sites are shown. Initial vadose water composition is represented by soil water, Mg = 1.35 ppm, Sr = 0.02 to 0.025 ppm, Ca = 50 ppm, Mg/Ca = 0.045, Sr/Ca = 0.00018, and $^{87}Sr/^{86}Sr$ = 0.7092. Calcite recrystallization uses a model rock composition of Mg = 3,500 ppm, Sr = 50 ppm, and $^{87}Sr/^{86}Sr$ = 0.7076. Dolomite recrystallization uses a model rock composition of stoichiometric Mg, Sr = 150 ppm for "A" and 30 ppm for "B", and $^{87}Sr/^{86}Sr$ = 0.7076. The direction of increasing rock water interaction is indicated by the arrows and the fluid to rock ratios (ex: 1E -5). Calcite precipitation is modeled subsequent to rock-water interaction, with mols of calcite precipitated marked along the curve (ex: 2E -3). K_D values for Mg and Sr are 0.04 and 0.12, respectively. Modeling indicates that the processes of calcite recyrstallization and incongruent dissolution of dolomite cannot account for high trace element ratios at the observed Sr isotope compositions, and demonstrates that calcite precipitation following rock-water interaction can account for these drip water compositions.

Figure 2: Possible rock-water interactions that could account for drip water compositions from each drip sites are shown. Initial vadose water composition is represented by soil water, Mg = 1.35 ppm, Sr = 0.02 to 0.025 ppm, Ca = 50 ppm, Mg/Ca = 0.045, Sr/Ca = 0.00018, and 87Sr/86Sr = 0.7092. Calcite recrystallization uses a model rock composition of Mg = 3,500 ppm, Sr = 50 ppm, and 87Sr/86Sr = 0.7076. Dolomite recrystallization uses a model rock composition of stoichiometric Mg, Sr = 150 ppm for "A" and 30 ppm for "B", and 87Sr/86Sr = 0.7076. The direction of increasing rock water interaction is indicated by the arrows and the fluid to rock ratios (ex: 1E -5). Calcite precipitation is modeled subsequent to rock-water interaction, with mols of calcite precipitated marked along the curve (ex: 2E -3). KD values for Mg and Sr are 0.04 and 0.12, respectively. Modeling indicates that the processes of calcite recyrstallization and incongruent dissolution of dolomite cannot account for high trace element ratios at theobserved Sr isotope compositions, and demonstrates that calcite precipitation following rock-water interaction can account for these drip water compositions.

a critical factor in accounting for spatial variability of drip water compositions at other sites (MCDONALD et al., 2007), the variability of limestone compositions at Natural Bridge is insignificant and unable to explain the variability in drip water compositions.

Modeling demonstrates that water-rock interaction can account for Group 2 drip-water compositions (Fig. 2). Group 2 drip-water exhibits temporally varying $^{87}Sr/^{86}Sr$ values, relatively low and limited variability in Mg/Ca and Sr/Ca, and correlations between water flux and drip-water composition. Drip-water compositions lie along model water-rock interaction curves suggesting that drip-

water composition is dictated by the extent of water-rock interaction that is determined by variations in water flux.

Water-rock interaction modeling alone cannot account for Group 1 or 3 drip water compositions. Model dolomite recrystallization curves can account for the covariation of Mg/Ca and $^{87}Sr/^{86}Sr$ values if dolomites of ranging Sr isotope compositions are modeled (Fig. 2A). Model curves, however, cannot account for the covariation of Sr/Ca and $^{87}Sr/^{86}Sr$ values as observed Sr/Ca cannot be attained by water-rock interaction at the given $^{87}Sr/^{86}Sr$ values (Fig. 2B). The near vertical trend of Group 1 Mg/Ca and Sr/Ca at nearly invariant $^{87}Sr/^{86}Sr$ values is indicative of another process, calcite precipitation – a process that would increase trace element ratios without altering $^{87}Sr/^{86}Sr$ values, as modeling shows.

Group 1 drip-water exhibits diffuse flow characteristics, low and invariant $^{87}Sr/^{86}Sr$ values, and little correlation to water flux. These characteristics indicate that Group 1 drip water compositions have not only experienced extensive water-rock interaction, but remarkably homogenous amounts of water-rock interaction. These drip water compositions appear to be buffered from short-term (0-4 years) variations in water flux by long residence times and well-mixed vadose storage. High trace element ratio values and variability suggest that calcite precipitation plays a dominant role in dictating drip water Mg/Ca and Sr/Ca ratios. While drip water compositions are not linked to water flux, trace element ratios are correlated to cave-air CO_2 and differences in surface and cave-air density. We suggest Group 1 trace element ratios vary seasonally with cool season density driven ventilation of cave-air CO_2 increasing calcite growth rates and drip water Mg/Ca and Sr/Ca (WONG et al., in prep.).

Modeling also demonstrates that water-rock interaction cannot account for Group 3 drip water compositions. Group 3 drip-water has higher Mg/Ca and Sr/Ca than model water-rock interaction curves can account for at varying $^{87}Sr/^{86}Sr$ values. Group 3 exhibits variable $^{87}Sr/^{86}Sr$ values that are between Groups 1 and 2 and some correlation between water flux and $^{87}Sr/^{86}Sr$ values. This suggests that Group 3 drip water is subject to variable extents of water-rock interaction. Drip water Mg/Ca and Sr/Ca are in between Groups 1 and 2 and exhibit more variability than Group 2. We suggest that calcite precipitation increases trace element ratios after variable amounts of water-rock interaction occur. The interplay between variable extents of water-rock interaction and calcite precipitation would explain the linearity observed between water flux and $^{87}Sr/^{86}Sr$ values, but not between water flux and trace element ratios.

6. Conclusions and Implications

Results from a four-year monitoring study of the modern karst system were used in combination with mass balance modeling of mineral solution reactions to delineate and quantify multiple processes that control drip water compositions. The use of Sr isotopes is critical to decipher the processes responsible for increasing Mg/Ca and Sr/Ca ratios, and explains the presence of both linear and non-linear relationships between water flux and drip water composition. Modeling demonstrates that drip water compositions linked to water flux can be accounted for by water-rock interaction. Drip water compositions with little correlation to water flux exhibit evidence of calcite precipitation increasing trace element ratios following water-rock interaction.

Our results suggest that drip-sites with both linear and non-linear relationships may be useful for reconstructing records of paleoclimate. Sites with linear relationships between water flux and drip water compositions may provide records of short-term (sub-annual) variability in water flux. Sites with non-linear relationships between water flux and drip water compositions may still be useful as long-term (decadal to centennial) records of water flux. Additionally, sites at which drip water trace element ratios are dictated by seasonal ventilation and variations in calcite precipitation hold the potential to preserve chemical indications of seasonal lamina in speleothems.

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Symposium 13

2009 INTERNATIONAL CAVE AND KARST MANAGEMENT SYMPOSIUM: WORLDWIDE HORIZONS IN CAVE AND KARST MANAGEMENT

Arranged by:
Mike Warner
Jean-Pierre Bartholyens

DEVELOPMENT AND SPATIAL DISTRIBUTION OF KARST SYSTEMS ON THE TONGASS NATIONAL FOREST, SOUTHEAST ALASKA

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Abstract

The Tongass National Forest is the largest forest in the National Forest System in the United States, encompassing over 6.9 million hectares. The Tongass contains 85% of the total karst in southeast Alaska, approximately 240,100 hectares. Much of the carbonate rock on the Tongass exists as part of the Alexander terrain, a large crustal fragment with a depositional history ranging from the late Precambrian to the Early Jurassic. The Alexander terrain is partially composed of fossiliferous and largely undeformed and unmetamorphosed interbedded massive carbonate breccias of the Heceta Limestone. The Heceta Limestone represents collapsed island shelves as well as reef and shallow water limestones originating in the Northern Hemisphere during the Late Silurian period (417–423 Ma). This terrain collided obliquely with the landmass of North America and accreted onto the continental margin during the middle Jurassic to Late Cretaceous time. The process of accretion resulted in fragmentation and smearing of sections of the terrane northward, while other portions remained in place. As a result, areas of carbonate exist on the Tongass from the Chilkat Peninsula in the north to Prince of Wales Island in the south. The intense development of karst on the Tongass National Forest is controlled by several factors including the high percentage of calcium carbonate ($CaCO_3$) in the limestone of southeast Alaska – averaged at 97.65%. In addition, faults and fractures resulting from the northward movements of the Alexander Terrane are dominated by northwesterly trending strike-slip faults and second order intersecting north-trending strike-slip faults, which influence karst conduit formation. The highest concentration of solution caves found in Alaska is on the north end of Prince of Wales and surrounding smaller islands, where over 500 caves have been mapped.

KARST AND CAVES OF THE HOHOLITNA RIVER REGION, SOUTHWESTERN ALASKA

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Abstract

In 2004, the U.S. Geological Survey conducted geologic mapping and mineral resource assessment of portions of the Taylor Mountains 1:250,000-scale quadrangle in southwestern Alaska. Prior to this mapping effort the presence of karst features had been noted in the Silurian limestone in the northeastern portion of the quadrangle. During 2004 geologic mapping, karst development was noted in three units mapped as part of the Neoproterozoic to Jurassic Farewell Terrane. Karst features were mapped in Ordovician, massive gray limestone, Late Silurian massive limestone, and Late Triassic medium bedded to massive limestone in the Hoholitna drainage in the northeastern portion of the Taylor Mountains quadrangle. The karst area explored extends approximately 45 km east to west by 12 km north to south with elevation of the karst features ranging from 165 m to 516 m above sea level (asl.). A total of 32 possible caves and vertical pits, and 32 sinkholes were noted within carbonates in the study area. The Holitna Lowland has been characterized as an ice-free refugium throughout the Pleistocene and early Holocene. The caves of the Hoholitna karst area have the potential to contain important paleontological and paleoenvironmental deposits. Several caves were discovered that may contain important archaeological information. This area provides an opportunity study the development of karst and caves in a high latitude setting.

GEOHYDROLOGY OF A SONORAN DESERT MOUNTAIN-FRONT KARST AQUIFER

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Abstract

Kartchner Caverns State Park in southeast Arizona, hosts a number of caves (accessible and inaccessible) that lie within a series of exposed low-lying, limestone hills. These hills represent fault blocks and slivers that were impinged and perched along the western margin of the San Pedro River Valley. The valley was shaped by several Cenozoic-age episodes of transtension and extension that affected the region. Later incision and exposure of rim deposits along with differential faulting and tilting reveal a complex aquifer along the front of the Whetstone Mountains. More recent analysis of geophysical and drilling log data, reveal that the exposed "Kartchner block," which contains the show caves, extends for several kilometers north and south of the park boundaries.

The highly transmissive Kartchner aquifer lies beneath a blanket of faulted, younger alluvial fan deposits that were shed from the nearby Whetstone range. Since thickness of the fan units varies along the flank of the range, the underlying karst aquifer was not penetrated by many shallow water wells. Detailed geologic mapping across the region, in combination with geomorphic analyses, shows that the alluvial units mask a hydrologic linkage that exists not only between bedrock of the rim and upland areas, but also between bedrock buried at depth and the overlying fan deposits. Mapping of surface units and within the caverns, and laboratory modeling have provides researchers and cave managers a unique 3-D glimpse into the structure and geohydrologic attributes of a rim aquifer that intercepts, sequesters and redistributes groundwater on its way to recharging deeper basin units. Although park area receives an average only 33 centimeter (13 inches) of precipitation annually, the caves remain wet, and exhibit active cave and karst processes. The moisture budget is sustained by a number of elements that are not fully appreciated or understood by some resource managers and users in the region. These elements include a nearby perennial natural spring, stream runoff and infiltration where upland streams intersect surface faults in the rim area, and rainfall that infiltrates bedrock strata above the caves. Less understood are linkages between faulted upland rocks and deformed basin rim strata as demonstrated by our detailed geologic mapping project. The presence of faulted upland strata means that infiltration, mountain recharge, and the interception of down-gradient subsurface flow across the rim may be sustaining our cave and surface ecosystems during the current drought cycle that is gripping the region.

High-resolution mapping appears to be mandatory in order to correctly decipher the architecture and behavior of karst aquifers in the region as demonstrated by water well data. The economic and ecologic sustainability of mountain-front settings in the Sonoran Desert will best be achieved as land planners and resource conservation and extraction managers partner and invest in new data and interpretation, instead of relying on outdated, low-resolution information that often favors short-term business returns above sustainability.

RUSTICLES OF KARTCHNER CAVERNS STATE PARK—LESSONS IN SPELEOGENESIS, ENGINEERING, AND SHOW CAVE MANAGEMENT

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Abstract

To enter the large chambers and cavern complex at Kartchner Caverns State Park in southeast Arizona, visitors must first pass through a labyrinth of man-made underground tunnels to begin their exploration of this stunning and fragile subterranean world. The tunnels incorporate a variety of effective cave conservation features, one of these being environmental isolation chambers. Located just inside the surface entrances, and again before the entrances of the magnificent show rooms of the Kartchner cavern complex, these conservation chambers (herein referred to simply as chambers) isolate, buffer, and conserve the high humidity and the cool environment of the caves. They also protect the fragile geohydrology and ecosystems of the cavern complex from the extreme aridity and temperatures of the overlying Sonoran Desert climate. Each chamber is sealed at both ends by large heavy stainless steel doors, similar to those used to maintain large commercial freezer rooms. The chambers also serve to minimize the introduction of particulates and exotic species that might be transported in by visitors and staff. Another reason for the placement of these reinforced chambers was to maintain the structural integrity of tunnel sections that intersected major fault zones within the thick interval of limestone that hosts the caves. The surfaces of the walls and ceilings of the chambers are coated with a painted shotcrete material that helps bind and masks an internal assemblage of steel mesh, concrete, and iron girders that maintain the safety and structural integrity of the complexly faulted tunnel sections. Whereas the shape of the ceiling and walls in the non-chambered sections of the tunnel is relatively concave in shape, the general architecture of some of the chambers is box-like. It is within these chambers that iron-rich soda straws are forming, which we affectionately refer to as "rusticles." Although rusticles occur repeatedly only in specific locations across the tops of the flatter chamber ceilings, they exhibit significant variation in growth rate, color, and composition.

Although similar features have been studied beneath road bridges and within other man-made underground structures, few studies have incorporated detailed data on environmental, hydrologic, and geologic linkages like those that are associated with Kartchner's rusticle development. This may be the first study of its kind to address the significance of rusticles in relation to show cave management and interpretive education. Labeled as "man-made" by some staff, rusticles are actually natural formations. We employ rusticles as time-lapse examples of some of the natural processes and the controlled chamber settings in which rusticles form. They provide ideal venues to explore variations in genesis and development of soda straw formations and stalactites within the cave. Our study of rusticles has improved our understanding of the local geology and hydrology hidden behind the chambers. They have also showcased the role that microorganisms and metabolic processes play in speleothem growth and distribution throughout Kartchner Caverns. Our presentation reveals how the geochemistry, chamber environment, geology, and other attributes of the Kartchner's rusticles offers insights for future cave development, engineering and scientific research, and interpretative education at the park.

THE ISCA MANAGEMENT GUIDELINES FOR SHOW CAVES

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The most recent draft of guidelines addressing good show cave management resulted from wide co-operation among the International Show Cave Association (ISCA), the Union Internationale de Spéléologie (UIS) and the International Union for Conservation of Nature and Natural Resources (IUCN). The guidelines are intended to set minimum standards, while recognizing that many existing show caves may not initially be able to comply with the specified guidelines. The intention is to create commonly accepted guidelines that all ISCA member show caves can work towards, by taking into account both the protection of the environment and the socio-economical constraints.

Introduction

The concept of establishing guidelines that the members could use for good show cave management originated during informal discussions between members of the Association at the time of the inaugural meeting of the organization in Genga, Italy, on 4 November 1990. These discussions developed and were first written for consideration at an ISCA meeting held on 17 September 2004 during the 30th Anniversary of the opening of Frasassi Cave, Italy, to the public. The idea of creating guidelines such as the ISCA Management Guidelines received strong recommendation from the UIS Department of Protection and Management at the 14th International Congress of Speleology held in Kalamos, Greece, in August 2005.

Such guidelines are intended to set minimum standards, accepting that many existing show caves may not initially be able to comply with the specified guidelines. The intention is to create commonly accepted guidelines that all member show caves can work towards, by taking into account both the protection of the environment and socio-economical constraints. At present a draft is circulated among ISCA members, the UIS Protection and Management Department and IUCN (Int. Union for Conservation of Nature and Natural Resources).

These guidelines are intended to be a living on-going work. Many recommendations and suggestions are currently being received and it is very predictable that the October 2008 Draft set out below will be changed and be augmented a number of times before the finalized version is placed before the 6th Congress of ISCA in Slovakia in 2010.

The October 2008 Draft of the ISCA Management Guidelines is here reported:

1. Development of a wild cave into a show cave

Since a show cave may become a relevant source of income resulting in an important change of the economy of an area, rather frequently proposals of development are advanced.

Before such proposals become a real project, it is necessary to carry out a careful and detailed study to evaluate the benefits and the risks by taking into account any factor as: access, synergism/conflict with other tourist attractions availability of funds, etc. Only if the balance is positive a plan may be developed. Otherwise a wild cave developed into a show cave and successively abandoned will be surely vandalized in a short time. On the contrary a well managed show cave assures a safe protection of the cave itself, is a source of income for the local economy and may contribute to a number of scientific studies.

1-1 A careful study of the suitability of the cave development by taking into account any factor influencing it must be attentively evaluated.

2. Access and pathways within the cave

Often the access to a show cave is obtained by means of a tunnel for an easy entrance of tourists. Such an artificial entrance could change the air circulation in the cave with a disruption of the energy balance. To avoid this effect an air lock should be installed. On the other hand it must be recorded that in some special case a change of the air circulation could revitalize the growth of formations. In any case a decision not to install an air lock must be taken only after a special study.

2-1 Any new access into a cave must be fitted with an efficient system, such as double set of doors, to avoid creating changes in the air circulation.

Caves are natural archives where an incredible amount of information on the characteristics of the environment and the climate are kept. Therefore any intervention on the cave must be carried on with great care to avoid the total destruction of these natural archives.

2-2 Any development work inside the cave should avoid disturbing the structure, the deposits and the formations of the cave as much as possible.

When a wild cave is developed into a show cave pathways and other installations must be built. Therefore, in general, the materials used are taken from the outside. There materials should have the least possible impact both from a point of view of aesthetics and the disturbance to the underground environment. Concrete is in general the closest to the rock where the cave is excavated, but once concrete is cast it is extremely expensive to modify or to decommission it. Stainless steel has the advantage, as the concrete, to last for a long time with little or no repair, but it is rather expensive and requires special techniques to assemble each part of a handrail or any other facility, some plastic materials developed in the last years have the advantages of a very long life, light weight, easy installation and possibility to modify easily the structure in order to face future developments.

2-3 Only materials that are compatible with the cave and have the least impact on the cave should be used in the cave. Cement, concrete, stainless steel and plastics are examples of such materials.

The cave environment is often isolated from the outside ad therefore any introduction of energy from outside would modify the equilibrium balance. Such changes could be due to the heat release by the lighting and the visitors and, also, by the decay of organic material, as an introduction of food in the food chain of the cave ecosystem. In ice caves the environmental characteristics are compatible with wood, normally used for pathways because it is not slippery.

2-4 Organic material, such as wood, should never be used in a cave unless it is an ice cave where, if necessary, it can be used for pathways.

3. LIGHTING

As reported above the energy balance of a cave should not be modified outside its natural variations. The electric lighting releases both light and heat inside the cave. Therefore high efficiency lamps must be preferred. Discharge lamps are rather efficient (i.e. most of the energy is transformed into light) but only cold cathode lamps can be switched on and out frequently without any inconvenient. LED are also very promising. As long as possible the electric network of a cave should be divided into zones and only the part where tourists are present should be lighted. When possible a non-interruptible power supply would avoid troubles to the visitors in case of failure

1-1 Electric lighting should be provided in safe, well-balanced networks. The power supply should preferably not be interruptible.

As just reported above, it is necessary to assure a safe visit to tourists also in case of a power supply failure. Also in case of a main electric network with a non-interruptible power supply, an emergency lighting with an independent power supply should always be assured. According to the local requirements it may consist in battery lamps or in a network of LEDs or similar devices.

1-2 Adequate emergency lighting should be available in the event of a power outage.

Lampenflora is a rather common consequence of artificial light supply into a cave. Many kinds of algae and other superior plants may develop. An important tool to avoid the growth of green plants is the use of lamps, which do not release a light spectrum to be absorbed by chlorophyll.

1-3 Lighting should have an emission spectrum with the lowest contribution to the absorption spectrum of chlorophyll (around 440 nm and around 650 nm).

Another way to avoid the growth of lampenflora is the reduction of the energy reaching any surface where the plants may live. Obviously the safe distance between the lamp and the cave surface depends of the intensity of the lamp. As a rough indication a distance of about 1 m would be safe. A special care should also be paid to avoid the heating of formations and rock paintings.

1-4 Lighting sources should be installed at a distance from any component of the cave to avoid the growth of lampenflora and damage to formations and rock painting.

As already reported above the lighting switched in only where necessary would decrease the cost of energy supply as well as the heating of the cave environment.

3-5 Lighting should only be switched on when

visitors are viewing the relevant portion of the cave.

4. Frequency of visit and number of visitors

As reported before the energy balance of a cave environment may be modified also by the heat release by visitors. Any human being moving in a cave releases about 150 W (as a good incandescent lamp!). Therefore there is also a limit to the number of visitors, which can be accepted into a cave without implying not reversible effect on its climate

4-1 A cave visitor capacity per defined time period should be determined and this capacity should not be exceeded. Visitor capacity is defined as the number of visitors to a given cave over a given time interval which does not permanently change the main environmental parameters beyond their natural fluctuation range. A continuous tour utilizing an entrance and another exit can reduce the time visitors spend in a cave compared to the use of a single entrance/exit.

Many show caves, in addition to the normal circuit for visitors, have arranged special visits, called sometimes "adventure tourism", where the visitors are provided with speleological equipment to be driven to wild sections of the cave. If such a practice is not properly planned it may imply serious damages to the caves

4-2 When visits to wild parts of a cave are arranged by providing visitors with speleological equipment and the visitors are guided by an experienced caver, the pathway where the visitors are allowed to proceed must be clearly defined, e.g. by red and white tape, and the visitors are not allowed to walk outside. Special care must be taken to avoid any damage to the cave environment and the parts outside the pathway must be cleaned in necessary.

5. Preservation of surface ecosystem for development or building, parking, scraping of surface vegetation, waste recovery

In the vicinity of the cave entrance buildings, parking areas, etc. are obviously located. Sometimes it happens that the surface occupied by these structures is just above the cave itself or, at least, relevant parts of it. In this case the hydrogeology above the cave must not be modified by any intervention as, e.g. the watertight of a parking area. In fact a modification of the rain water seepage into the cave could have a bad influence on the growth of its formations.

5-1 Any structure (building, parking area, etc.) above the cave, as any other intervention, must be avoided in order to keep the natural seepage of the rainwater from the surface to the cave in its original conditions.

6. Monitoring

After the environmental impact evaluation of the development or any other study of the cave environment, it is necessary to monitor the relevant parameters in order to identify any deviation outside acceptable limits.

Therefore show caves should have a monitoring network to keep the cave environment under control.

6-1 Monitoring of the cave climate should be undertaken. The air temperature, carbon dioxide, radon (if its concentration is close or above the level prescribed by the law) and if applicable water temperature should be monitored. Airflow in and out of the cave should possibly be monitored.

According to the experience gained after many years of show caves management a group of cave scientists (the so called "Scientific Commission) is extremely useful to advice the cave management in order to avoid serious troubles endangering the cave environment. It is very important that such scientists would have a good experience of the cave environment; otherwise also competent scientists not fully aware of the cave environment could result in wrong advices.

6-2 Specialized cave scientists should be consulted to carry out further research when situations warrant.

7. Managers formation

The cave management must never forget that the cave itself is "the golden goose" to be preserved with great care. Therefore it is necessary that the persons involved in this activity receive a suitable education not only on the management from the point of view of economy, but also on the environmental issues concerning the protection of the environment at large.

7-1 Cave managers should be competent both in the economy of management and in the environment protection.

8. Guides formation

The cave guides have a very important role because are the "connection" between the cave and the visitors. Unfortunately in many instances the guides have not been trained and notwithstanding they are doing their best, the results is not very good. Therefore it is very important that the guides receive some simple instructions both about the cave and the behaviour with the public. Concerning the last point, the relationship with the visitors must be based upon kindness to avoid discussions. On the other hand the guides are the first guardians of the cave; therefore they must be ready to stop any misbehaviour, which could endanger the cave environment.

8-1 Cave guides should be trained to correctly inform the public about the environment of a cave.

Acknowledgements

These Guidelines are the result of contributions from many people, particularly during the discussions after their presentation to congresses and meetings. Recently some suggestions from André David, Guilhem de Grully, Elery Hamilton-Smith, Stein-Erik Lauritzen and David Summers were instrumental to finalize the text. Special thanks are due to anyone of those who provided comments.

THE INTERNATIONAL COMMISSION ON SUSTAINABLE DEVELOPMENT IN SHOW CAVES

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Sustainable development means that the environment meets the needs of the present without compromising the ability of future generations to meet their own needs. This concept must obviously be applied to any activity and, therefore, also to the show caves whose number of admissions sometimes increases beyond a level compatible with the principle of sustainable development. The International Show Caves Association, ISCA, has established an International Commission on Sustainable Development in Show Caves aiming to consider ways and means by which show caves can achieve sustainable development, to propose long term plans by which the world's show cave community can deal more effectively with the achievement of sustainable development, and to recommend ways that the concern for the achievement of sustainable development in show caves can be translated into recognition and greater co-operation among the different countries of the world.

1. Introduction

The world first really heard the message of sustainable development from the United Nations World Commission on Environment and Development, created in 1983, a full twenty-five years ago. Not last year – but a quarter of a century ago. The Commission presented their report to the United Nations General Assembly in 1987. Somehow, it has taken the world a long time to react to this farsighted report. Maybe it was a shock of harsh reality to northern countries. Maybe it came as a surprise to southern countries. Whatever it was, the world has now started to mobilize to the call of sustainable development.

Sustainable development means that the environment meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development means meeting the basic needs of all. The "environment" is where we all live and "development" is what we all do in attempting to improve our lives within that abode. After 25 years of virtual standstill and deterioration, our brave new world starts to move forward. It is time for change. It is time for global cooperation to move forward.

The world of show caves has its own "United Nations Organization of Show Caves" – it is called the International Show Caves Association (ISCA). ISCA can provide the necessary link between scientists and the public. Public interest in the scientific world is growing. The media is accelerating this. The challenge for us in the world of show caves is to ensure that our caves are sustainably managed. Our number one enemy is environmental degradation. We must fulfill our responsibilities towards global sustainable development.

ISCA has already taken into consideration the aspects of environmental protection by developing the ISCA Management Guidelines. They are intended to set standards, while accepting that many existing show caves may not initially be able to comply with all of them. The intention is to create commonly accepted guidelines that all member show caves can work toward, by taking into account both the protection of the environment and socio-economical constraints. Presently, a draft is being circulated among ISCA members, the UIS Protection and Management Department, and the International Union for Conservation of Nature and Natural Resources (IUCN). The principles included in the guidelines are the basis for correct development but sustainability requires a further step. With this scope, by resolution of the Board of Directors of the International Show Caves Association on 13 October 2008, it was resolved to establish an International Commission to deal with all aspects of sustainable development in show caves.

2. Structure of the Commission

The Commission is a structure within the organization of ISCA and therefore the ISCA Board shall appoint its members. Nevertheless, it is deemed important to keep participation in the Commission open, by accepting

members who might not be members of ISCA.

By taking into account the general definition of Sustainable Development, as reported above, the following terms of reference were adopted:

(i) To consider ways and means by which show caves can achieve sustainable development.
(ii) To propose long term plans by which the world's show cave community can deal more effectively with the achievement of sustainable development.
(iii) To recommend ways that the concern for the achievement of sustainable development in show caves can be translated into recognition and greater co-operation among the different countries of the world.

3. Program and Management of the Commission

We need to grow closer to each other. We need to collaborate and share our experiences. We need to share our successes and, even more importantly, we need to share our failures. Do we want to have another Lascaux tragedy on our hands? The answer is a resounding – no. We need to collaborate more

There is a global need for sustainable development of show caves. There is a need for international collaboration to achieve sustainable development of show caves. We need worldwide solidarity to achieve this critical goal. Let's start with the very term "sustainable development." In many ways our subterranean worlds are sensory monitors of what is occurring above ground. Even our entry into these natural systems can harm them. In any show cave, environmental matters must rank as the highest consideration. The often-touted need for economical profit pales against environmental considerations. If the environment of the cave is not good, then its economical future will not be good. Conversely, of course, if the economics of the show cave are not good, then the environmental quality will suffer.

Where do we start? Clearly the item that must always be at the top of the list for a show cave is the protection of the cave.

Vandals, with senseless malicious intent, can cause immeasurable damage to any cave - damage that can take thousands of years to overcome. In considering time spans in the life of a cave, it must always be kept in mind that the time since caves were first developed for showing to the public can be equated to the blink of the eye compared to the time taken to create the cave.

Protection of a show cave must fundamentally prevent entry into the cave by unauthorized people. It is pointless to rely on methods of discovering the identity of the intruder in order to punish them. We must protect caves against vandalism through unauthorized entry. Cameras simply will not protect the cave. Proper gating of a show cave can perhaps be considered the first step in pursuing sustainable development.

Another critical component of developing and operating a show cave is the protection of the formations from the prying fingers of visitors. All too frequently we hear of renowned formations that are irretrievably lost through this type of vandalism. Consequently, protection of the cave from authorized visitors is fundamental to sustainable development.

After the cave is protected, the next question that must be answered is – what is the purpose of the show cave? The primary purpose of a show cave has to be education, be it academic education or enlightenment of the public. Show caves are where the public needs to be directed in order to enable them to see the incredible underground spectacles that exist in our underworld. The general public does not belong in wild and unimproved caves. Caves are inherently dangerous places if the lay visitor is not properly trained and equipped. In accepting the general visitor into their caves, the show cave operator must be aware that the average visitor is becoming more educated and will also have a greater awareness and appreciation of the environment.

A show cave is an incredibly valuable natural resource. Providing we protect it and preserve it, we can achieve sustainability. Nowhere are the words, "the environment is both physical and social," more applicable than in a show cave. The show cave owner/operator has a clear responsibility to ensure that their guides are well trained and have ongoing education. The responsibility of the guides is to ensure that they are providing a good educational tour. They are not the star of the visit – the cave is.

A show cave is the absolute best medium to let the public see and understand the wonders of the underground. Without this opportunity to physically witness the interior of a cave, it is predictable that the public will not be as concerned about the need to preserve and conserve caves. We must all work to ensure that the old notion that a cave is simply a hole in the ground, with its best use being a dumping ground, is no longer prevalent.

The ongoing need to promote and educate the public is a global need. This very same credo is the same in every continent of the world. International collaboration is fundamental to the achievement of these objectives. We cannot expect to achieve this in isolation as individuals.

In assessing these objectives, it is important to bear in mind that not every cave needs to be a show cave. Show caves are an incredibly small percentage of the total number of caves in the world. We, as owners and operators of show caves, have a responsibility to ensure that show caves are operated with the absolute highest environmental standards. The matter of need becomes fundamental. In assessing "need," the economic impact that a show cave can have on a locale must always be remembered. Not only are there obvious economic advantages arising from direct benefits to be considered, but also the obvious indirect benefits.

The notion that a show cave must be economically successful in order to support environmentally sound practices is alive and well. Find a cave that is not performing well economically and it will follow that there are insufficient funds available to support the environmental needs. While the owners and operators of show caves are generally working hand in hand with the environment, there clearly is a need to be cognizant that this can always be improved. We must be vigilant and remain on the cutting edge of environmental matters. To do this, the clear benefits of international collaboration must be enhanced and utilized more.

We have the ability to ensure that our show caves are sustainable. The future need not be threatened as long as we are vigilant and ensure that we are not promoting interlocking crises that can happen with indiscriminate economies and ecology.

Sustainable means that we must avoid using up natural resources. We must be in harmony with the productive potential of the ecosystem. In the end, sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are made consistent with the future as well as present needs.

4. Conclusion

There is an overwhelming need to make informed choices. The need to adopt sound sustainable development practices is upon us. The transition to sustainable development can be achieved. Part of our environmental management practices must focus on after-the-fact repairs of damage and the restoration of natural habitats. We must accept that change will happen. We must produce more with less.

There is a clear challenge facing the world of show caves. We must protect, conserve, and preserve our incredible displays of the earth's natural systems. Show caves are not simply curiosities, but very important vehicles to aid and promote public awareness. The last component that we must meet is the need to remain viable. We are charged with a very fragile and delicate world, a world that requires a co-joining of economy and science. This is what the International Show Caves Association is all about.

We do not have a resource that we can rebuild within periods of time that are less than thousands of years into the future, if at all. We are all aware that once something in a show cave is lost, it is effectively lost forever.

The future need not be threatened if we collaborate, collaborate and collaborate.

PRELIMINARY DEVELOPMENTS FOR KARST PROTECTION IN QUINTANA ROO, MEXICO

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The State of Quintana Roo, Mexico contains many of the longest underwater caves in the world. These caves serve as shallow fresh water drainage conduits, directing a large volume of inland precipitation toward the Caribbean Sea. The majority of caves are located within the nascent Municipality of Tulum, where over 650 km of underwater cave passage is documented within a 1096 km^2 region. Current research confirms the area's affinity for coastal and near-coastal speleogenesis. Horizontal cave development is limited to an 11 km zone that progresses inland from the Caribbean Sea. Displaying little topographic relief, it is punctuated by an extensive and widespread array of interconnected passage collapse entrances (cenotes). Their associated underwater caves are highly developed at an interface where the fresh water aquifer is buoyed by a lower, static salt water intrusion.

Karst features and the associated fresh water aquifer in Quintana Roo face numerous threats. Large tourist resorts continue to be developed on the Caribbean coast of Mexico; many are positioned above underwater caves. Resorts also require a substantial labor pool to support their activities. The city of Tulum is planning to triple the size of its residential zone in the near future to provide for an expanded work force. These residential areas may impinge on, or be constructed above significant cave systems. Plans for municipal water and waste services remain under question. Escalation of cave ecotourism is becoming an increasing threat to the region's caves and cenotes. Private and commercial landowners are modifying cenote entrances to accommodate the growth of ecotourism. Alterations to cave entrances may range from simple landscaping, to destructive methods calculated to enlarge both cenotes and caves.

With the recent inception of the Municipality of Tulum, local citizens and business owners are establishing informal associations to investigate a reasonable approach to conservation of regional karst attributes. Cave explorers are providing concerned residents with maps, photographic documentation, and their insight on current cave and karst conditions.

1. Introduction

The administrative state of Quintana Roo, Mexico, occupies the eastern portion of the Yucatan Peninsula proximal to the Caribbean Sea. As a small region of the Yucatan Platform, it consists of a low relief pitted karst plain containing few surface drainage systems or lakes. A steady rise in elevation is observed from the coastal perimeter, three meters above sea level, to its inland borders with the states of Yucatán and Campeche at nearly 30 meters above sea level (Lutz et al., 2000). The sequence of limestone stratigraphy of Quintana Roo is not well documented, however it has parented a stable platform that is receptive to the mechanisms of speleogenesis. Crowned by dense tropical scrub forest, the area receives an average of over 150 cm of precipitation per year (Ward and Weidie, 1978; Ward, 1985; Tulaczyk et al., 1993). Approximately 10 percent of the precipitation filters through the topmost calichified limestone layer and into lower fractured strata. The remainder is lost to evapotranspiration. Acidified by atmospheric carbon dioxide and tannic acids from the calichified zone, precipitation meets a shallow freshwater aquifer where it is directed through bedding fractures and joints toward the Caribbean Sea. The process of aquifer recharge encourages conduit dissolution in the parent limestone strata, while conveying pollutants to ocean discharge vents (caletas and lagunas).

Underwater cave systems in Quintana Roo are considered to be anchialine caves. These caves contain pools of salt or brackish water that fluctuate with ocean tides, without a surface connection to the ocean (Holthuis, 1973). Anchialine caves in Quintana Roo contain an upper lens of freshwater that flows over a near-static saltwater intrusion. A mixing zone occurs at a well-defined density interface. Both interface depth and thickness of the freshwater aquifer increases with distance from the coast. Periods of sustained precipitation, ancient sea level fluctuations,

and modern oscillations in ocean tides encourage random depth variations at the mixing zone. Investigators conclude that inherent fracture zone speleogenesis coupled with preferential dissolution of limestone at the mixing zone produces an accelerated growth in size and complexity for these anchialine caves (Back et al., 1986).

Modern underwater cave explorations in Quintana Roo commenced in 1979. Although two small caves were mapped, reports from two independent expeditions dispelled any likelihood for significant cave development in the area. Explorations were resumed in 1985 by a small group of expatriates residing in Quintana Roo. By 1989 six cave systems were under exploration, having a combined length of over 50 kilometers. Given endless possibilities for exploration, over 38 cave systems (370 km) were under investigation by 2001. In 2009, over 88 caves systems in Quintana Roo are recognized. With an additional 89 single entrance caves, over 755 km of underwater cave passage is documented in this region. Two caves (Sistema Ox Bel Ha and Sistema Sac Actun) are among the 10 longest caves in the world. Four of the five longest caves in Mexico are in Quintana Roo, including the two longest caves in Mexico (Quintana Roo Speleological Survey, 2009).

The majority of explored underwater caves in Quintana Roo (over 85%) are situated in the Municipality of Tulum. The municipality includes an expanding assemblage of coastal tourist resorts and services, all dependent on a substantial workforce situated in designated towns inland from the resorts. Obligations to provide an increase in population with residential zones, storm water drainage systems, roads, municipal water supplies, and sanitation systems are overwhelming local administrations. State and local agencies have offered preliminary strategies to address future infrastructure needs. However specific measures to provide environmentally sound designs for sewage and rubbish disposal are not outlined in the proposals. These plans also identify large tracts of jungle to be cleared for future urban and residential intensification. Georeferenced cave surveys demonstrate that proposed areas for urban expansion will intrude on territories that incorporate important caves and aquifer drainage complexes.

A further concern implicates mismanagement of cenote entrances and excavation of caves, with subsequent distress placed on the cave environment and aquifer. All cave entrances in the Municipality are located on private property, or collective lands owned by a local community (Ejidos). Both private landowners and Ejido landowners are eager to capitalize on an expanding ecotourism economy. Alterations to cenote entrance areas can include clear cutting of trees and undergrowth, to more damaging practices where small cenotes are excavated by heavy machinery to increase their size and speculative value as tourist attractions. Freshwater currents in the aquifer transport disturbed silts and biological materials from excavation sites to distant areas of the cave. Laws that prevent cave modifications, or those safeguarding aquifer quality are ineffective and often circumvented.

Education for local residents concerning the karst environment is clearly essential. Unfortunately cave explorers in the municipality were generally disinclined to provide more than a casual summary of their activities until recent years. Today they are assuming a more effective role in collaborative efforts with emerging citizen groups by sharing georeferenced cave maps, visual media depicting existing conditions within the cave environment, and hydrological data concerning the municipality and the city of Tulum. This knowledge allows citizens in the municipality to scrutinize applications for building permits and governmental development plans as informed individuals.

2. Discussion

Accelerated growth in the tourist industry places key demands on the coastal karst of Quintana Roo. Physical damage to caves may occur during the initial construction of resort complexes. Governmental regulations calculated to limit construction above shallow subterranean voids are ambiguous and problematical to enforce. Resorts are designed as elaborate compounds of oversized buildings; these are normally sited along a narrow strip of coastal property that can include caletas, cenotes, and ocean bays. Coastal limestone deposits consist of thin or unconsolidated strata of Pleistocene or Holocene origins. The water table is encountered within a few meters of the surface. Construction techniques for large building complexes on the coast call for an extensive array of deep foundation columns to maintain their structural integrity. Cave explorers have documented the consequences of this construction technique. Foundation piers are found to pierce the surface strata, and into underwater cave conduits of varying size. They may penetrate strata below the cavities, or rest on the conduit floor (Bogaerts, 2005, Phillips, 2001; Schmittner, 2005). Many piers are shattered or contain fractures where they meet the conduit's floor. This can transfer the weight of the structure to weaker surface strata above the voids, precipitating a collapse of the cave passage and building. Resort developers are largely unaware of karst characteristics below their properties. However their investment in developing a site for a potentially high

return in wealth often counteracts concerns for coincidental damages to a cave or aquifer. Nearly all resorts prohibit trained divers to enter cave entrances on their property; this circumvents unwanted publicity on the stability of their buildings and the condition of the caves below their lands.

Expansive tourist complexes rely on expeditious methods to manage wastewater and rubbish. Hotels and resorts vented raw sewage to the Caribbean Sea until this became an indefensible and illegal procedure. Deep injection wells (pozos profundos), artificial wetlands systems, aerobic digesting systems, and traditional anaerobic systems with leaching fields are unsatisfactory methods when disposing high volumes of solids and wastewater. The region embraces a shallow and vulnerable karst aquifer that lacks protective soil horizons for traditional near-surface disposal systems. Deep injection wells utilize freshwater waste slurries that are pumped into the deep saltwater intrusion zone. These slurries are inclined to rise from the containment area to the upper freshwater aquifer, allowing fresh water currents to disperse raw sewage over a wide area. Sewage disposal systems also require scheduled removal of residual solids from closed sewage systems to environmentally secure holding ponds, those lined by impermeable materials. Yet the current volume of residual solids that are produced by residential and tourist centers already surpass the capacity of existing ponds to contain the wastes safely.

Current rubbish disposal methods are also strained. Recycling programs within resorts and Tulum municipality are in their infancy, existing more as a symbolic gesture than as an effective campaign. Business and public participation in recycling is minimal, given a low level of public awareness and a negligible infrastructure for area-wide recycling. Rubbish disposal in the area utilizes unlined landfills that are situated in deserted limestone quarries. These quarries were excavated to within centimeters of the water table, providing materials for past highway construction. As open pits, they are attractive sites for depositing large quantities of rubbish. This includes automotive lubricants and batteries, medical refuse, construction materials, and oil-based paints. Without an impermeable barrier between the refuse and water table, rainfall extracts pollutants from the trash and delivers them to a highly vulnerable aquifer. Wells for monitoring groundwater quality near landfill areas are not employed. This practice may prove to be disastrous for the city of Tulum. Their water supply is dependent on a series of interconnected wells that draw from the same aquifer that is found beneath the present landfill. Less than two kilometers of porous limestone separates the landfill from the municipal water supply.

State and Federal economic policies are focused on sustaining a growing tourism industry, specifically along the narrow coastal strip adjacent to the Caribbean. To succeed in this strategy, a large and sustainable labor force is key to meeting the needs for future tourist services. Massive projects are being planned to enlarge inland urban and residential areas in Tulum municipality. The cities of Akumal and Tulum are projected to absorb nearly one million workers in coming years. These plans raise many fears when contemplating a balanced scheme for regional planning, while insuring a responsible stewardship of a unique and irreplaceable karst environment. Urban and residential areas in Tulum city are expected to expand threefold, yet provisions for municipal sewage, surface drainage, and secure water supply systems go unaddressed. Cave divers provide compelling evidence for pollution invading the aquifer beneath the city of Tulum at this date. By entering a cenote southeast of Tulum city, divers negotiated 900 meters of underwater cave passage to video the cave environment and collect water and biological samples 11 meters below the urban area of Tulum (Schmittner and Aviles, 2007). As present sewage disposal systems for the city appear substandard, plans to accommodate further enlargement of residential areas in Tulum city are met with skepticism. Preliminary maps provided by government agencies indicate that new zones for municipal expansion will encroach on, or occupy lands above several of the most significant underwater caves in Quintana Roo.

Proposed economic strategies for a steady growth in ecotourism are encouraging for landowners who maintain cave entrances on their lands. A landowner fortunate to own a popular cenote or dry cave entrance may sustain a lucrative business by charging entrance fees to their property. To compete for a larger profit in ecotourism, landowners with smaller cave sites are transforming their karst windows into more impressive attractions. Cave and aquifer protection laws are rarely enforced on private property, allowing landowners greater latitude to initiate any excavation measures they chose to increase their business. This can range from enlarging their cenote pool to removing limestone strata above cave conduits on their property to support a variety of water sport activities. In all cases, organic and limestone debris from the construction is carried downstream by the aquifer to distant areas of the cave. There is little doubt that these activities place enormous stress on cave life, the freshwater aquifer, and the cave environment.

Citizens of the municipality are cognizant of a seemingly uninterrupted acceleration in the urbanization and tourist

development of their community. It is difficult to overlook a procession of new construction projects that occupy lands deemed worthless just years ago. Large areas of old jungle are surrounded by kilometers of new fencing with occasional entrance gates manned by security guards. Speculation on future property values and percentages of tourist hotel occupancy often saturate local periodicals. There are companies and local residents that aim to profit from this growth. However a small group of residents find this unbridled growth unsettling. They perceive the quality of their community and environment as attractive pawns, those surrendered to developers and urban planners in stimulating a larger tourism economy. Aquifer pollution issues become paramount, as the aquifer is proven to be an extensive and important attribute for the area's environment. Collaboration with cave divers has allowed a transfer of maps and knowledge of the area's caves. This has improved the resident's knowledge of the aquifer, while strengthening their position when questioning disingenuous development schemes.

3. Conclusion

The karst area is clearly in peril. Documentation of cave explorations is becoming more accessible to emerging environmental groups in the municipality. Cave surveyors are sharing georeferenced cave maps and visual media of the cave environment with these groups. By communicating this knowledge and providing counsel, cavers are initiating the essential process of public education. This enhances deeper public awareness regarding issues that may threaten the vitality of local karst conditions. However this primer must continue beyond that of a general overview of explored conduits that are highlighted by cave maps and photography. Fundamental knowledge of a karst environment must be enhanced to include tutelage on the hydrological and biological components of the environment in simple layman's terms. Yet any collaboration between cavers and municipal residents on the area's intricacies results in a basic conundrum. Will public desires for short-term economic prosperity outweigh long-term conservation efforts for the karst environment and its economic consequences? Cavers and karst researchers are hopeful that a reasonable balance between both will be attained before this unique karst region suffers further damage.

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CAVERN OF SANTA CATALINA'S MANAGEMENT PLAN

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Abstract

This work represents the first Management Plan approved for a cave in Cuba. Administration for the cave has been granted to the Speleological Society of Cuba.

Santa Catalina, in a karstic coastal plain of marine terraces near the city of Matanzas, has been documented by several international publications. It contains an unusual type of speleothem: mushroom shape stalagmites. The cave is formed by 11 km of galleries explored to date.

This area was declared a National Monument in 1996 by the National Commission of Monuments. Later, the Ministry of Science, Technology and Environment (CITMA) in Matanzas proposed it as an Area of National Significance, categorized as a Natural Outstanding Element.

Given the designation of "cavern" in the Protected Area, the classification was determined by two strata: the Covering Surface and the Cave Surface, which carry out specific management actions for each. The Cave Surface has two areas: Conservation and Public Use. The Covering Surface have Conservation, Public Use, and Buffering areas. Four programs were developed: Protection and Handling of Resources, Public Use, Scientific Investigation and Supervising, and Administrative. In addition, seven other subprograms were formed. This classification constitutes a contribution to the Methodology of the National Center of Protected Areas (CNAP).

The second contribution is programmatic and consist of "Goal Programs", which express future actions to achieve objectives in matter of conservation of the natural resources. Also incorporated inside the Program of Scientific Investigation and Supervising are two new routines: Epidemic Supervising and Climatic Sampling.

MITIGATING OIL AND GAS DRILLING AND PRODUCTION OPERATIONS IN KARST LANDS: TEN YEARS OF PROBLEM SOLVING AND PROGRESS

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Karst lands pose a unique set of problems for the oil and gas industry and for the cave and karst environments. The United States Department of the Interior, Bureau of Land Management (BLM) is considered to be on the leading edge in developing the best management practices in this field. The Bureau of Land Management has been working with the oil and gas industry to develop the best and most effective methods to protect karst resources and reduce impacts to the industry. This has resulted in a two-fold advancement. One is educating the oil and gas industry about karst land environments and the second is developing the best management practices for oil and gas drilling and operating in karst lands.

Over the past 10 years significant advances have been made in identifying problems and developing methods to minimize or avoid undesirable events associated with oil and gas drilling and production in karst lands. The primary impacts are associated with karst groundwater aquifers and how to protect them over the life span of the well and hundreds of years beyond. A three phased approach of detection, avoidance, and mitigation is used to limit the impacts to karst resources and minimize the impacts to the oil and gas industry. The detection phase involves identifying known and/or suspected caves and karst features that could cause problems to both the oil and gas industry and to karst resources. This approach uses existing karst data bases, geophysical methods, and field exploration to locate potential problem areas. The avoidance phase involves moving or rerouting actions to minimize disturbance of karst features and resources. The mitigation phase requires the oil and gas industry to change their standard drilling operations and apply more stringent methods of operation. These changes affect their pad construction, drilling, casing, cementing, abandonment procedures, and long term well monitoring.

1. Introduction

The Bureau of Land Management is a part of the United States Department of the Interior. Management is based on the principle of sustained yield and multiple-use of our nation's resources within a framework of environmental responsibility. BLM recognizes that it must manage for future generations as well as for present needs. Its mission is to find a balance between developing and protecting public land resource. In southeast New Mexico the BLM must balance developing oil and gas resources with the protection of cave and karst lands and the critical water supplies associated with them.

The risks to industry of operating in karst lands include excessive loss of drilling fluids, loss of tools and equipment down-hole, down-time while fishing for tools, and expense for extensive cementing programs. In extreme instances the loss of drilling rigs and equipment due to the collapse of shallow cave passages add risks to public health and safety.

The potential hazards to cave/karst resources result from contaminants entering the cave/karst systems. These contaminants include lost drilling fluids (which sometimes contain chemicals) and cements, and hydrocarbons from spills or leaks from well casings, storage tanks, mud pits, pipelines, and production facilities. This contamination could result in pollution of groundwater and aquatic and atmospheric habitats of caves, causing a die-off of cave life. Additionally, cementing operations may affect portions of underground drainage systems by restricting groundwater flow and introducing pollutants into karst systems. This could alter the quality and quantity of water reaching springs and resurgences.

Other possible impacts are vented or escaped gases, such as natural gas or hydrogen sulfide, collecting in sinkholes and caves. These gases can cause a die-off of plant and animal life that use the special habitat created by the microclimate of the cave entrances or sinkhole. In the extreme, buildup of these gases has the potential to cause underground explosions and/or asphyxiation of plant, animal, and in some cases human life.

Over the past ten years the BLM has been working closely with the oil and gas industry to develop the best practices for addressing the concerns of both; protection of karst resources and minimizing costs and problems encountered during the drilling and production of oil and gas. This has resulted in a three phased approach:

(1) Detection of Cave or Karst Features,
(2) Avoidance of those Features,
(3) Mitigation of Impacts to Cave or Karst Resources that cannot be avoided.

2. Detection

Detection indicates where possible avoidance measures might be needed and would make avoidance measures more effective. Detection and avoidance measures combine to reduce the chances of needing mitigation measures. However, noting is certain until the well is actually drilled. Detection methods ranged from very simple methods such as field examinations to very sophisticated geophysical methods. Methods were evaluated to determine reasonableness and cost effectiveness. Some of the methods identified were:

(1) Field examinationscave—exploration and survey,
(2) Satellite imagery and topographic map review,
(3) Lineament surveys,
(4) Natural potential surveys,
(5) Electro-resistivity surveys.

3. Avoidance

Avoidance of cave and karst features can be accomplished in two basic ways. The first is a long range approach involving BLM's planning system. Areas identified as having significant cave or karst resources can be established as "no surface occupancy" which would not allow any equipment or disturbance of the surface. Drilling restrictions could also include "no oil and gas leasing", this is the best protection.

A second method of avoidance in areas that are already leased is relocating a proposed drilling location or right-of-way to reduce the possibility of conflict with caves or karst features. The decision to move a location, with certain constraints, can be a condition of approval of an Application for a Permit to Drill (APD). This method of avoidance would be used in conjunction with site-specific detection methods, such as field examinations or lineament surveys.

Another method of avoidance may be directional drilling. Lateral moves of the original surface location greater than 200 meters may require the operator to drill a directional well in order to hit the desired down-hole target. The directional portion of the well is typically below any cave or karst zones.

4. Mitigation

There may be instances when drilling operations may still impact cave or karst resources even after detection and avoidance measures have been conducted and applied. The third step in the process is mitigating the impacts that cannot be avoided. Mitigation measures may be required that call for:

(1) modifications in surface operations, and
(2) changes in drilling operations.

Changes in surface operations may require the use of steel tanks to hold all drilling fluids and cuttings. These materials would be hauled off after drilling operations are completed and disposed in an approved facility. This eliminates the use of conventional reserve pits and any leakage, spills, or other means of drilling fluids migrating into the aquifers. To reduce groundwater contamination coming from the well pad, berms may be required to reduce possible contaminated runoff from entering recharge areas. Tank batteries are required to be bermed and lined with permanent 20 mill plastic liners sufficient to contain 1.5 times the capacity of the largest tank. Tank batteries and pipelines may also be required to have leak detection systems that will alert operators of any tank rupture or leakage. Pipelines may be required to have corrosion-inhibiting coatings and cathodic protection.

Changes in drilling operations may include special drilling, casing, and cementing programs. Immediate down-hole impacts to caves and karst systems would first occur during the drilling process. To eliminate or reduce these impacts initial drilling is required to be started with **fresh water** through the karst zones. If lost circulation zones are encountered resulting in fluid loss of 75% or a bit drop of one meter or greater additional casing strings are required to ensure that there are at least two strings of casing and three strings of cement through each of the lost circulation zones. Casing will be cemented using a first stage to cement the bottom of the string and an external packer would be used to isolate the cement in the second stage of the casing above the lost circulation zone. An additional string of casing and cement would be required to ensure adequate protection through the lost circulation zone. All strings of casing would be cemented to the surface. (See figure 1 sequence) All casing should meet the highest standards. The cave protection string should be set at least one hundred feet below the last known cave bearing stratum as limited by the uppermost hydrocarbon bearing zone.

When the well is abandon the plugging procedure should require that a casing integrity test be run and if the casing shows to be perforated then cement should be squeezed to seal the perforation. The production casing should then be cemented from 15 meters below the lowest karst zone to the surface.

There are potentially long term impacts related to the escape of hydrocarbons from the drill hole into surrounding rock formations. In porous rock the hydrocarbons could migrate, contaminating groundwater and/or the water quality in the caves. This could impact the growth of speleothems, cave microclimates, and cave biota. In a worst-case situation, human life could be endangered by gaseous hydrocarbons escaping from a well into the cave environment. Because of these impacts the requirement for additional casing and cementing is warranted.

5. Conclusions

The potential impacts of oil and gas drilling and production to cave and karst resources require a deliberate approach of detection, avoidance and rigid mitigation measures to ensure long term resource protection. The implementation of stringent oil and gas drilling, casing, cementing, and production operations is essential to safeguarding cave environments and karst aquifers from the impacts of oil and gas drilling. This long term protection is afforded through the elimination and avoidance of surface contaminants from entering the karst recharge zones. A minimum of three strings of casing and two strings of cement are currently considered by petroleum engineers to be sufficient to give the needed protection to critical ground water supplies while a well is in production. Additionally, it is thought that plugging the well from the base of the karst zone to the surface provides the best long term protection.

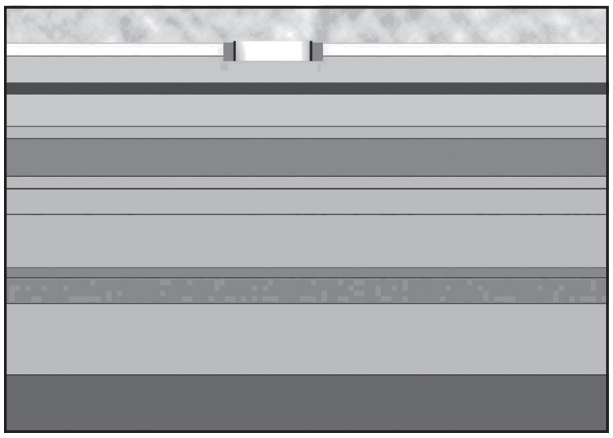

Figure 1-1: Conductor casing and cement.

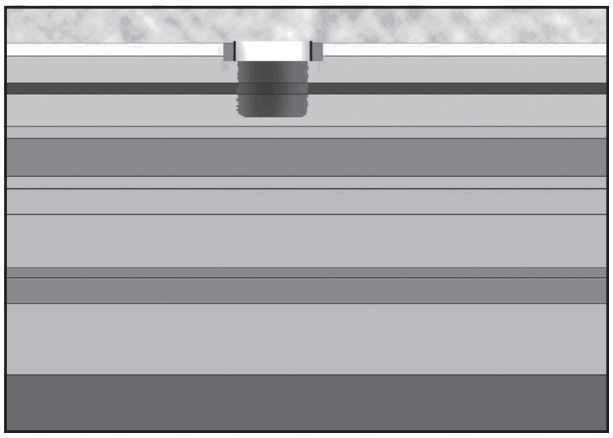

Figure 1-2: Surface hole.

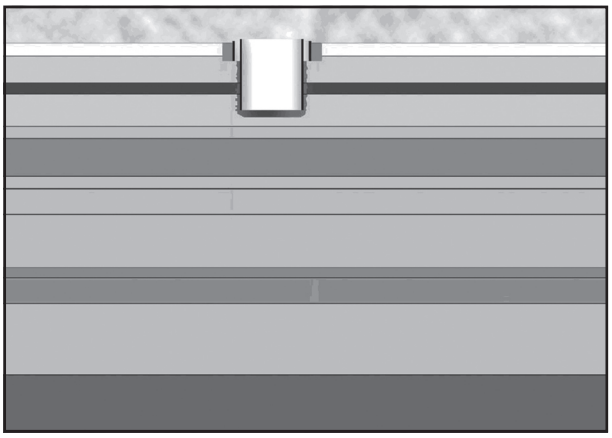

Figure 1-3: Surface casing set in competent formation.

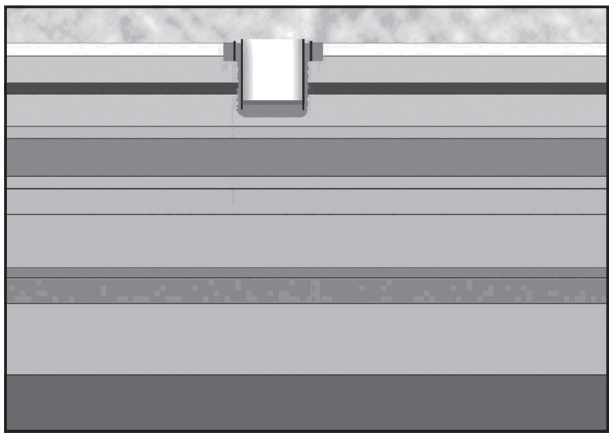

Figure 1-4: Cement casing to surface.

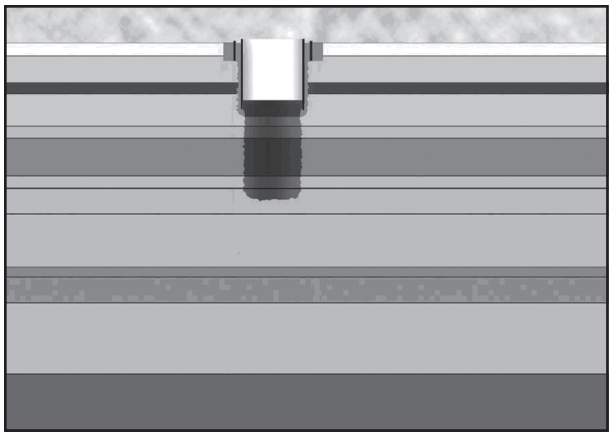

Figure 1-5: Intermediate hole.

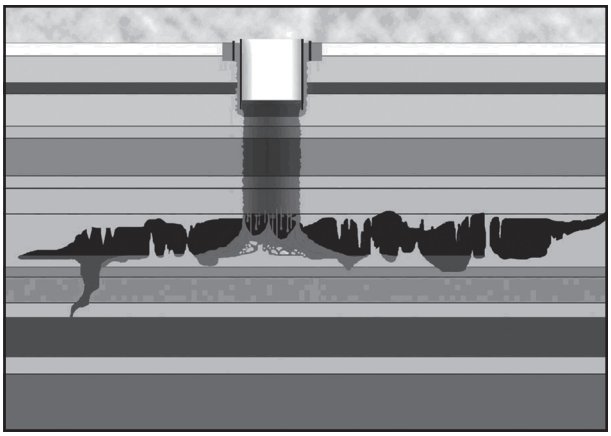

Figure 1-6: Drilling intersects cae, fluids enter cave system.

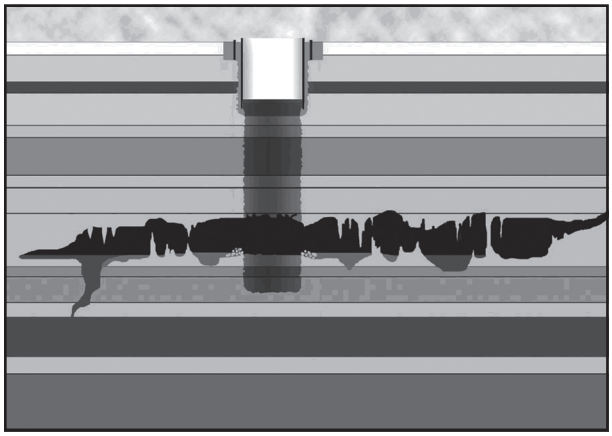

Figure 1-7: Drill into competent formation below cave.

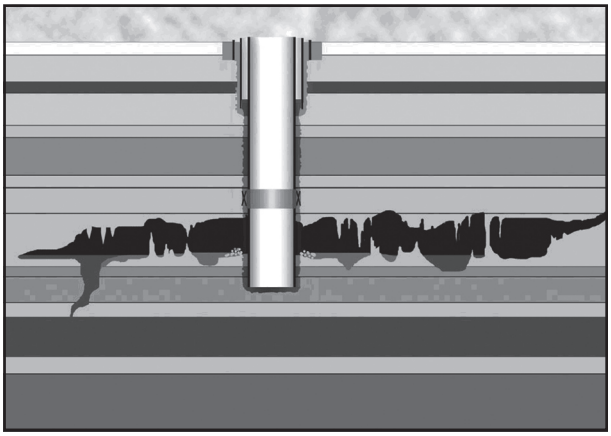

Figure 1-8: Set intermediate casing with external packer.

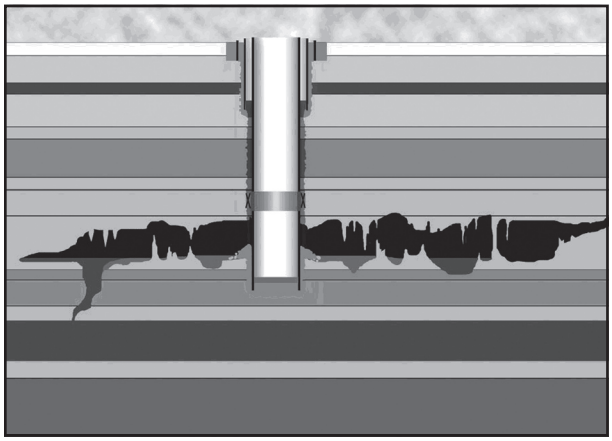

Figure 1-9: Cement first stage at base of cave.

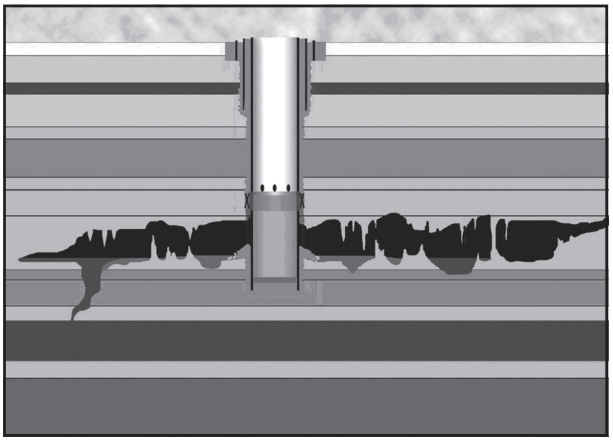

Figure 1-10: Cement second stage to surface above cave.

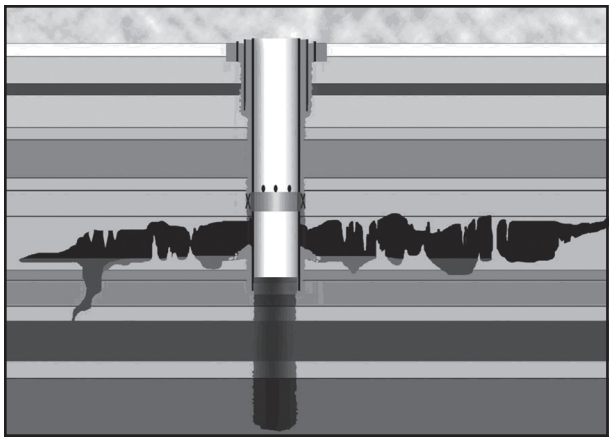

Figure 1-11: Continue drilling.

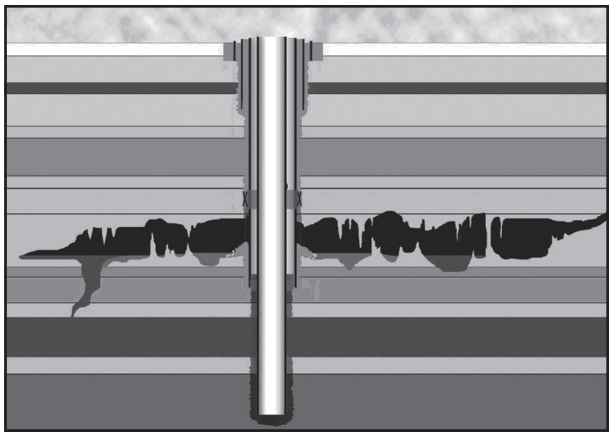

Figure 1-12: Set second intermediate or production casing.

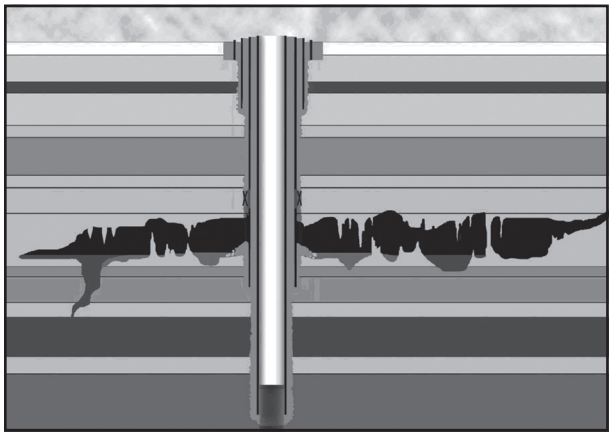

Figure 1-13: Cement Intermediate casing and continue drilling.

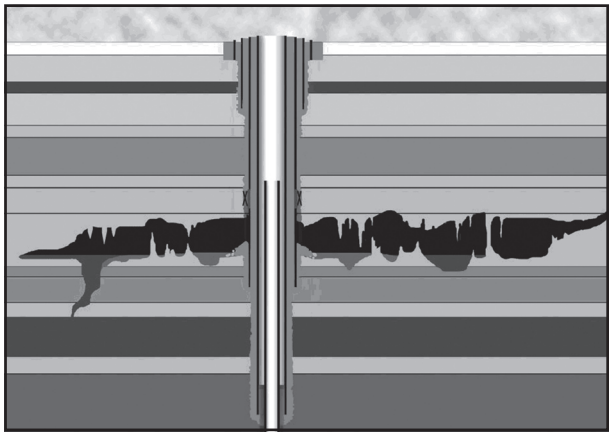

Figure 1-14: Set production liner.

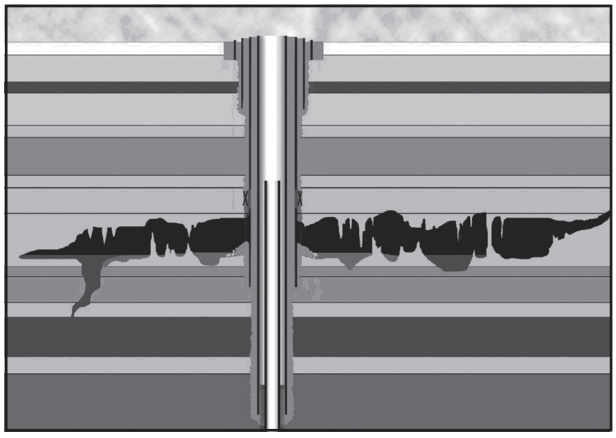

Figure 1-15: Cement liner.

THE EUROPEAN CAVE PROTECTION COMMISSION (ECPC) - A NEW MOVEMENT FOR CAVE PROTECTION IN EUROPE

C. GREBE, V. LASCU, I. MELEG, and A. S. REBOLEIRA
European Cave Protection Commission, European Speleological Federation

Abstract

The European Cave Protection Commission of the FSE was founded during the Baltic Speleological Congress in Gotland, Sweden 2007 as an initiative of several European speleologists. Nowadays it consists of speleologists from over 20 countries, who engage themselves on different aspects of cave and karst protection like legislation, techniques, science, public campaigns and politics, education, publications etc organized in work teams. The activities of the ECPC are concentrated on different levels of action. First, of course, the commission is involved as part of the European Speleological Federation (FSE) on European wide actions such as setting up a political lobby for speleology and cave protection, render expert opinion for public authorities and co-operation with the EU-institutions etc. in Europe, as example the authors will present the "Save the hole world" campaign for the written declaration 66 for cave protection in the European Parliament and other projects related to that. Second, the commission aims also to support the national, local and regional actions on cave protection, for example with the "EuroSpeleo Protection Label," an award for qualitative cave protection projects in Europe. Especially the exchange of strategies, know-how and ideas for cave protection from different regions and countries shall be encouraged, the "1st EuroSpeleo Protection Symposium" held during "*Vercors 2008" (4th European Speleological Congress*) is an example for that. The commission's aim is to become the partner for cave protection in Europe, also for the other non-governmental organizations, public authorities and above all to represent the interests of the European speleologists.

As one of the results of the work we have done so far, we show through the organization of the commission's work that sustainable and long-term cave and karst protection is only possible in big networks and through a equally continuous work on the European level such as on the national and regional level, as also on the political and educational level. Cave protection without the speleological community in Europe is as impossible as without an engagement on a public level.

EUROPEAN SPELEOLOGY IN EUROPEAN POLITICS

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Abstract

For the first time, European speleologists have formed working groups to address legislation at the European Parliament and working on related research at the European Union (EU) level. Following the recent "Save the Hole World" campaign, the European Cave Protection Commission (ECPC) is working in close co-operation with other institutions of the EU. In November 2008, we had a meeting with one of the directors of Director General on Environment of the EU commission and discussed future projects for European speleologists assisting the EU Commission. The director was interested in a co-operative effort and asked how we can implement cave protection inside the EU. One of results is the new "EuroSpeleoGIS project." In this project, we will prepare a GIS karst map for Europe that will be used to identify the correlation between existing protected areas (e.g., through Natura 2000) and all karst areas in Europe. We agreed to prepare this map for the EU commission, which facilitate cave and karst protection in Europe and the implementation of new regulations, directives, and/or revisions of the existing tools of environment protection inside the EU.

European Speleology in European need to show and demonstrate to public officials that the fundamental work of exploring, surveying caves and any other work carried out in the different fields of research in cave and karst related science are the partner for qualitative, sustainable, and long-term cave and karst protection in Europe. Without the knowledge of speleologists, cave protection is not possible and without the active co-operation of speleologists with associated with public institutions like the EU commissions, we will remain in an outsider position in the future. We would find it very difficult to represent our interests in the future. For this reason, the ECPC has started a long-term engagement because cave protection needs a long-term base in Europe in order to preserve our speleological heritage for the next generations. And we, as speleologists, must be involved in this process. If not we, who knows better about it? Exploring caves demands that we take responsibility for the protection of the underground world.

LEYE-FENGSHAN, A NEW APPLICANT OF GLOBAL GEOPARK IN GUANGXI, CHINA

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Leye-Fengshan Geopark in Leye County and Fengshan County in the northwestern Guangxi, China, is in the transitional slope zone from southeastern Yunnan-Guizhou Plateau to Guangxi Basin. It has an area of nearly 900 km^2 in the subtropic monsoon climatic region and in neo-tectonic uplifting area. The geopark exposes Devonian to Neogene carbonate and clastic rocks, including a continuous sequence of Devonian to Permian carbonate rocks more than 3,000 m thick. Clastic rocks surround the exposed karst and lots of allogenic water from clastic areas flow into karst areas with S-type geologic structure and rhombus geologic structure, and they developed two big underground river systems in karst inlier areas, i.e. the 81.5-km-long Bailang and the 162-km-long Poxin underground river systems, they controlled the development of karst tiankeng (great dolines) group and very large cave chambers, respectively.

There are 132 geosites in Leye-Fengshan Geopark, including 6 kinds of geologic formations, tiankeng, large cave chambers, fengcong (high cone karst), and poljes, rivers relics, fossils, and rocks. Tiankeng is the great doline with vertical cliffs around and with more than 100m in entrance diameter and in depth; it is mostly related with an underground river at the bottom of doline. There are 27 tiankengs developed in the Bailang ground river drainage area. Of them, Dashiwei is the biggest with its 600 m x 420 m diameter and 613 m maximum depth, 70,000,000 m^3 volume, and 100,000 m^2 floor of sub-primeval forest. It is the biggest tiankeng in the world. There are more than 100 caves in the geopark. Jiangzhou Cave is the biggest, with 42.5km in length, 11,400,000 m^2 in cave floor area, and 28.9 Mm^3 in volume. It contains 24 cave chambers with more than 10,000 m^2 in floor area. Hongmeigui Cave Chamber is the largest, with 50,000 m^2 in area. Sunlight Cave Chamber is the highest, with a maximum height of 365m high and 260m average height. It is the most concentrated cave chambers area in the world with 7 of the world's 23 largest (more than 25,000 m^2) cave chambers. There are also lots of light through caves and natural bridges. Buliu Natural Bridge and Jiangzhou Natural Bridge are the biggest and the second biggest spans in the world, with 177m and 144m respectively. The geopark features typical fengcongs, at about 1000 m asl and with 150-500 m differences between peaks and depressions. Lots of poljes developed between karst area and non-karst area as allogenic water from clastic area is more aggressive than carbonate-derived waters. The river relics are famous for Yuanyang springs, one blue and the other green, only 20 m away. The famous fossils of *Ailuropoda microta* were discovered in Panda cave; it is the most complete skull fossil known in the world. The rocks are massive and thick Permian limestone around Dashiwei Tiankeng.

The Leye-Fengshan Geopark reflects the main features of the south China karst, including massive and hard, carbonate rocks without glacial scour in the last glaciations, hot and humid climate, new tectonic uplifting, and the region's significant potential karstological research.

1. Introduction

Leye-Fengshan Geopark in Leye County and Fengshan County in the northwestern Guangxi, in the neo-tectonic uplifting area of southwestern China (Fig.1) has an area of nearly 900 km^2 in the subtropic monsoon climatic region. It has abundant rainfall and distinct wet and dry seasons; average annual rainfall is 1550.7-1356.4 mm. The rainy season extends from May to October. The average annual temperature is 16.4–19.2° C and July is the hottest month while January is the coldest.

The geopark is in the transitional slope zone from southeastern Yunnan-Guizhou Plateau to Guangxi Basin, where it developed landforms such as large poljes, karst valleys, depressions, and peaks, as well as tiankengs (great doline) and large cave chambers for different dynamic role of hydrogeology. With gradually decreasing abundance of negative landforms (valley and depression), the relative height difference of stone peak increases. Correspondingly, cave depth also increases gradually. For example, Dashiwei Tiankeng, in the middle of the geopark, has a maximum depth of 613m.

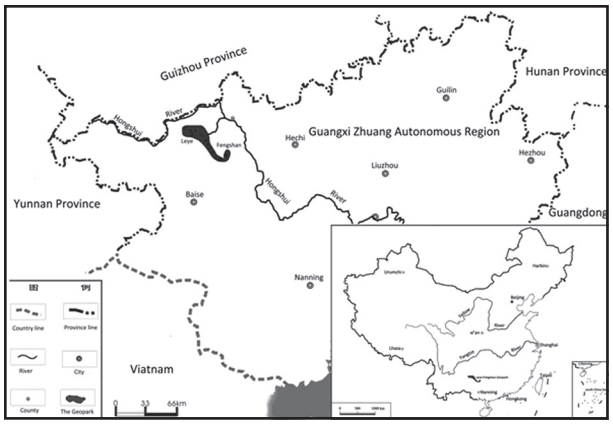

Figure 1: Location of Leye-Fengshan Geopark.

The geopark exposes Devonian to Neogene carbonate and clastic rocks, as well as few igneous rocks, including a continuous sequence of Devonian to Permian carbonate rocks more than 3,000 m thick and Triassic sandstone and shale more than 2000 m thick. Clastic rocks surround the exposed karst and lots of allogenic water from clastic areas flow into karst areas with S-type and rhombus geologic structures. They developed two big, subterranean river systems in karst inlier areas, i.e. Bailang and Poxin subterranean river systems which are 81.5 km and 162 km long. They controlled the development of karst tiankeng group and very large cave chambers, respectively (Fig.2).

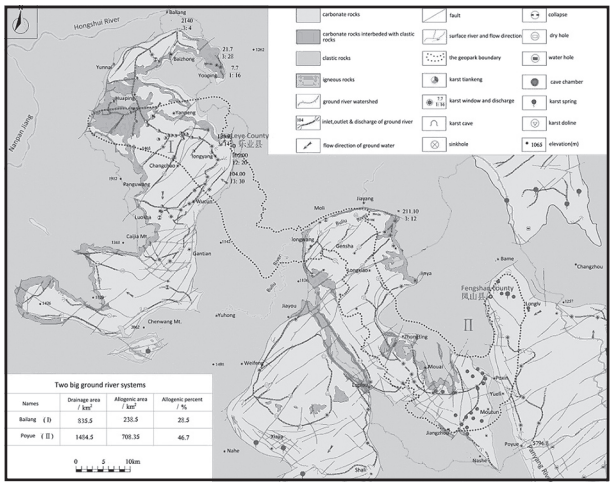

Figure 2: Hydrogeological map of Leye-Fengshan Geopark.

2. Karst Inlier and High Fengcong

Regionally, carbonate rocks around Leye-Fengshan Geopark were surrounded by clastic rocks, and karst inlier formed (Fig.2). Geologically, faults form the boundaries between karst area and non-karst area and result in short axis structure inside the karst area. Hydrogeologically, carbonate rocks were destroyed by tectonic stress along these geologic structures, resulting in well-developed secondary permeability in carbonate rocks. Lots of allogenic water gathers on clastic rocks area then flows into karst area at the contact zone, but precipitation on the surface and vertical permeation in the center of karst area dominates at high elevation. Tectonically, the geopark is in an uplifting area. Geomorphologically, it is in the transitional slope zone from southeastern Yunnan-Guizhou Plateau to Guangxi Basin, and the watershed area between the Hongshui River and You River. The vadose zone is very thick and the hydraulic gradient is large. Because of these factors, poljes formed at the contact zone between karst and non-karst, karst valley and typical high fengcong (cone karst) from marginal karst to karst watershed (Fig. 3). Poljes have become sites for farming, housing, living, and engineering construction. Leye County and Fengshan County are located in poljes. Karst valleys are transitional landforms. High fengcong is a kind of landform composed of high peaks and deep depressions; peaks are tall and straight, elevations of the majority are above 800m; most of depressions are in rounded and elongated shape; height difference between peak and depression is about 150-500 m. Scenes of fengcong in Dashiwei karst tiankengs, Huaping, Longping, and Dacao of Leye County, and Poxin, Liangli, Renan, Polong and Nongzhe of Fengshan County are the most beautiful ones.

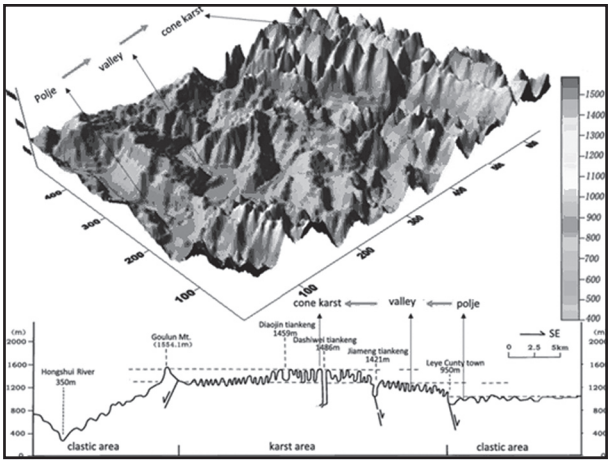

Figure 3: Landform profile in northwestern Leye-Fengshan Geopark.

3. Bailang Subterranean River and Tiankeng Group

Bailang subterranean river is one of two big river systems in Guangxi. It flows from south to north, finally discharging into Hongshui River. It is composed of one main stream and 11 branch streams with a total length about 162 km, including the 64.2 km long main stream. Its drainage area is 835.5 km^2, minimum flow is 2.04m^3/s, and maximum flow 121m^3/s (Yi, 1983).

The development of the Bailang subterranean river was controlled by S-type structures. The S-type structures extend from south to north and developed the Jinzhudong Anticline, Wucun Anticline, Langquan Fault, Leye Fault and other arc structures in the middle and north (Fig. 4). The main stream developed along Wucun Anticline and Jinzhudong Anticline following their extension and fold axis directions. In particular, northeast faults and fissures developed very well crossing the Wucun anticlinal axis in the middle of a S-type structure, and carbonate rocks were destroyed, which was ultimately advantageous for the tiankeng group development (Fig.2).

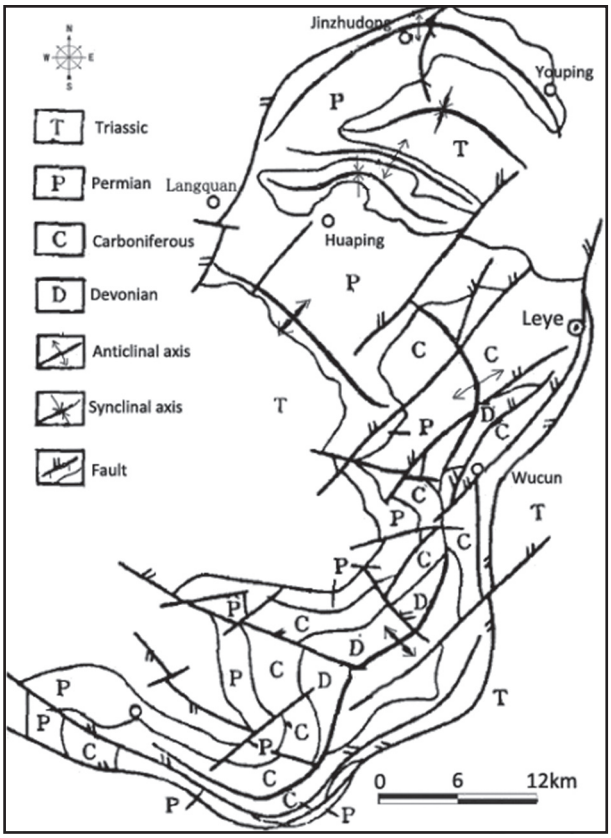

Figure 4: S type geological structure.

Tiankeng is the great doline with vertical cliffs around and more than 100 m in entrance diameter and depth. It is mostly resulting from a subterranean river at the bottom of doline. Its development includes three stages of subterranean river development, cave chamber collapse, and exposure to the surface (Zhu, 2003). There are 27 tiankengs in the middle of Bailang subterranean river system, which transported very large volume of collapsed rocks. Dashiwei is the biggest of 27 tiankengs. It is 600 m x 420 m in diameter with a maximum depth of 613m, 70,000,000 m^3 in volume, and 100,000 m^2 of sub-primeval forest in area (Fig.5).

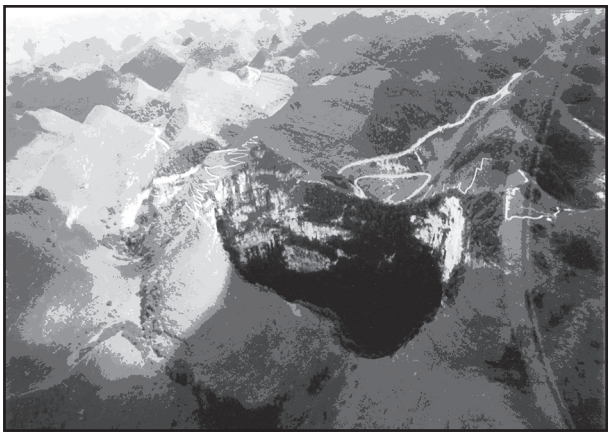

Figure 5: Dashiwei tiankeng (Zhu, 2003).

4. Poyue Subterranean River and Large Caves

In dendritic shape, Poyue subterranean river has two branches in east and west directions, respectively. The branch in east runs from north to south, while the one in west runs from west to southeast and finally discharges into Hongshui River. Total length of the river system is about 81.5 km; its drainage area is 1484.5 km^2, its average flow is 0.58 m^3/s (Zhu, 2003).

The development of Poyue subterranean river was controlled by rhombus geologic structures (Fig.2 and 6), which mainly extends northwest, northeast, and north-south. It formed two main branches to the east and west; the easterly one runs from north to south, and the westerly

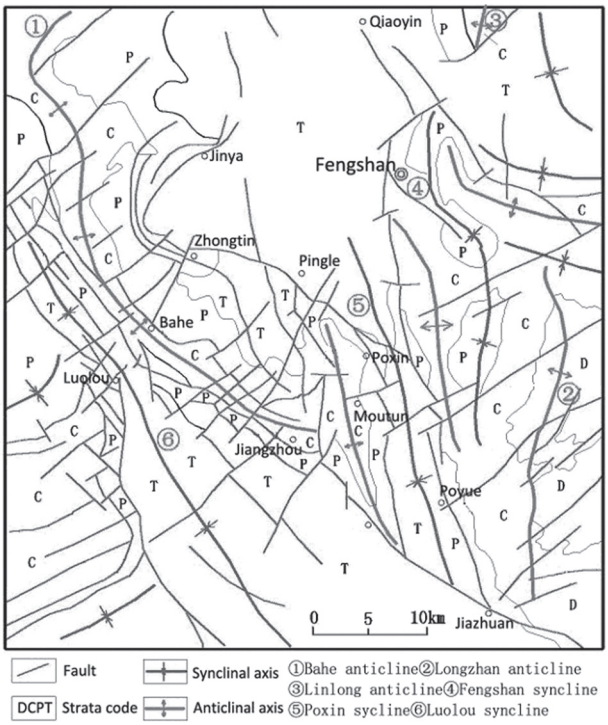

Figure 6: The rhombus geological structure (Huang, 2002).

Figure 7. Buliuhe River Natural Bridge (Huang, 2002).

one runs from west to southeast, due to partition of fault structure and sandy shale. Similar to Bailang subterranean river, allogenic water originating from clastic rock areas and precipitate water in karst area are the two main sources for the Poyue subterranean river. This river has formed more than 100 caves, including the third longest cave in China, Jinagzhou Cave with 42.5 km in length (Benseley, 2005), 11,400,000 m^2 in cave floor area, and 28.9M m^3 in volume. It formed 24 large cave chambers that contain more than 10,000 m^2 in floor area. Hongmeigui Cave Chamber is the largest, with 50,000 m^2 in area, Sunlight Cave Chamber is the highest with 365m high at most and 260m high on average. It is the most concentrated cave chamber area in the world as 7 of the 23 cave chambers with more than 25,000 m^2 is here.

5. Buliu River and Karst Gorge

Buliu River is in the middle of the geopark and between Bailang and Poyue subterranean river systems (Fig.2). It formed a deeply incised gorge cutting through the karst fengcongs in the middle stream, and left a very large Buliuhe River Natural Bridge resulting from its big component of allogenic water from widespread clastic in its upstream drainage area. The natural bridge has the widest span in the world, up to 177m (Fig.7).

6. Conclusions

The geopark is sited on the slope of transition zone from the Yunnan-Guizhou Plateau to Guangxi Basin. Its karst inlier high fengcong developed two large-scale subterranean rivers as well as the beautiful Buliuhe River. In each river basin, many of the world's largest karst tiankengs, cave chambers, and karst natural bridges formed. Leye-Fengshan Geopark reflects the main features of the south China karst, including massive and hard, carbonate rocks without glacial scour during the last glaciations, hot and humid climate, new tectonic uplifting, and the region's significant potential for karstological research.

The geopark features poljes, karst valleys, karst depressions, and karst tiankengs along the karst watershed contact zone. As the average elevations of fengcong getting higher, the vadose zone deeper, the height difference between peaks and negative landform bigger, as well as the area of negative landform such as valley and depression become smaller, caves passages or chambers are bigger, showing obvious different degrees of karstification and karst water intensity from horizontal surface water flow to vertical precipitation, and then to horizontal surface water flow again.

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WHAT CAN YOU DO WITH A WORN-OUT SHOW CAVE? DUNBAR CAVE, TENNESSEE AS A SUCCESS STORY

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Dunbar Cave is damaged and justifiably considered worn out. No longer is it a traditional show cave, illuminated by electricity. It has been the victim of perhaps 10,000 years of graffiti and some 200 years of enthusiastic breakage of speleothems. In a few remote, far-flung areas of the nearly 13-km cave, splendid speleothems serve as a reminder of past glories of the accessible remainder. In these accessible chambers, the concentration of graffiti staggers the imagination. In earlier decades, it was widely admired as a healing mineral spring, complete with typical wooden resort hotel. Then came a cement-floored nightclub in its cool, shaded entrance: Roy Acuff's Dunbar Cave. Its dance floor, orchestra stand, and fort-like bar concealed much of its Native American heritage.

Yet today, Dunbar Cave and its wooded 45 hectare tract constitute an especially popular state park. This was not because of traditional restoration projects; these quickly were abandoned as damaging to historical resources. Instead, the cave tour was restored to a much-admired semblance of wild caving. Remnants of the electrical system were stripped away, and decades' trash and garbage carted off after careful inspection. The cave trail was cleaned and returned to its original dirt flooring. Remaining graffiti and cave art were treated as historical resources. Ultimately, near-daily cave tours were conducted by the light of participants' flashlights. Tour reservations are by telephone, limited to twenty persons per tour - primarily to protect the cave art. Research by the University of Tennessee and other institutions still occasionally yields additional cave art and further knowledge of the cave's aquatic biology. The cave is not promoted beyond the local community, and its announcements are historically and scientifically accurate. All this is accomplished by two full-time administrators plus a few seasonal guides and a small maintenance staff, a modest budget, and an enthusiastic unpaid corps of cavers and other volunteers. And there is no interest in replacing the historic but long-obsolete resort hotel that burned in the 1950s.

Thus, Dunbar Cave again is a popular show cave, but on a scale and in a mode appropriate to its features and for the needs of the local community. It serves as a creative and positive model of adaptive natural resource management for other popular but "worn out" caves, such as Oregon Cave, whose management has been the subject of vigorous discussion in the NSS News and at two recent National Cave and Karst Management Symposia.

1. The Problem of Abandoned Show Caves

The life expectancy of American show caves is dismayingly short. Less than half the caves opened in the 20th Century as commercial or non-profit enterprises remain viable today. And publicity inherent in the development of the show cave continues to attract visitors after each cave is closed. Once abandoned, protection of the cave from onslaught of determined vandals commonly ranges from extremely difficult to impossible. More and more it appears that no cave should be commercialized without a fail-safe strategy for its protection if the venture fails.

2. The Concept of "Worn-Out Show Caves"

Numerous factors are involved in failures of American show caves: remote location, inadequate or counterproductive publicity, unimpressive features, dull guides, and others. Recently the concept of overuse leading to what some term "worn-out show caves" has entered the vocabulary of American cave management. The term may have originated in a Los Angeles Times writer's 2004 telephone conversation discussing Oregon Cave, about which he wrote as "damaged goods" (Reynolds, 2004). Much of this cave is too low, too narrow, and too tortuous for the usual National Park Service management principles to be effective. Speleothems, walls and floor of the tour route and the parallel route for electrical cables have been devastated, and the bulk of the cave can best be described as a shattered husk. Restoration experts have been able to return only small patches to

their original milk-white color, and gleaming stainless steel handrails and stairs have further destroyed remaining semblances of naturalness. These and other management problems have been the subject of vigorous discussion in the NSS News and at two recent National Cave Management Symposia., without positive conclusions (e..g., Halliday and Swofford, 2003).

3. Dunbar Cave as a Worn-Out Cave and What Has Been Done About It

Dunbar Cave is even more worn out than Oregon Cave. It has been the victim of perhaps 10,000 years of graffiti and some 200 years of enthusiastic breakage of speleothems. As in the case of Oregon Cave, in a few remote, far-flung areas, splendid speleothems serve as a reminder of past glories of the remainder. In the accessible passages and chambers, the concentration of graffiti staggers the imagination. A century ago, it was widely admired as a healing mineral spring, complete with typical wooden resort hotel. A mid-century dance floor, orchestra stand, and fort-like bar concealed Native American heritage and still dominate its entrance (Matthews, 2008).

Yet today, Dunbar Cave and its wooded 45 hectare tract constitute an especially popular state park. This was not because of traditional restoration projects. These quickly were abandoned as damaging to historical resources. Instead, the cave tour was restored to a semblance of wild caving. Remnants of a short-lived electrical system were stripped away, and decades' trash and garbage carted off after careful inspection. The cave trail was cleaned and returned to its compacted dirt flooring. Graffiti and cave art, both aboriginal and modern, were treated as historical resources. Handrails and bridges are notably unobtrusive. Ultimately, near-daily cave tours were conducted by the light of participants' flashlights. Tour reservations are by telephone, limited to 20 persons per tour, primarily to protect the cave art. Research by the University of Tennessee and other institutions still occasionally yields additional cave art and further knowledge of the cave's aquatic biology. The cave is not promoted beyond the local community, and special care is taken to ensure that its announcements are historically and scientifically accurate. It is securely locked when a tour is not in progress. All this is accomplished by two full-time administrators plus a few seasonal guides and a small maintenance staff, a modest

Figure 1: Modern cave art in Dunbar Cave. Several other portraits also are present. This and other photographs by W.R. Halliday.

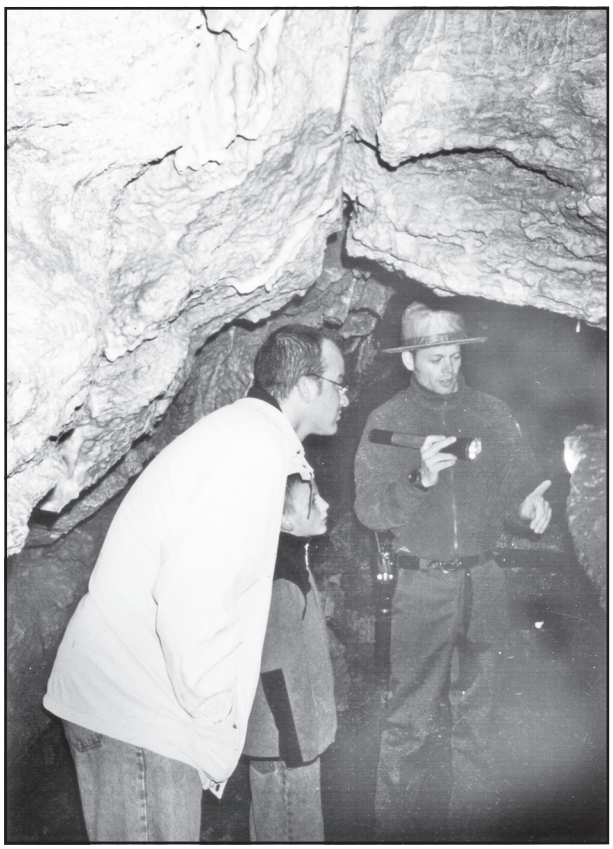

Figure 2: Typical view in Oregon Cave. Much of the cave is too low, too narrow and too twisty to permit application of usual National Park Service standards.

Figure 3: Possible American Indian art in Dunbar Cave.

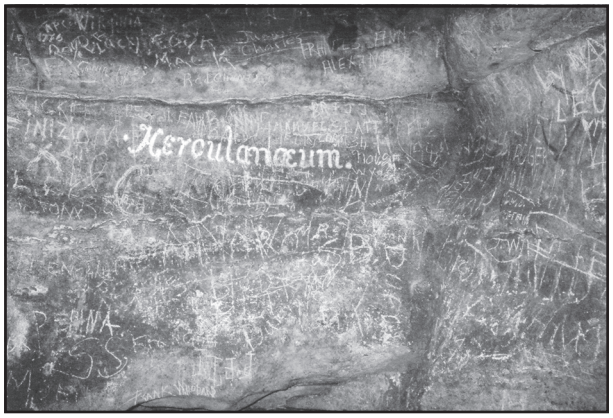

Figure 4: Typical old and new graffiti in Dunbar Cave.

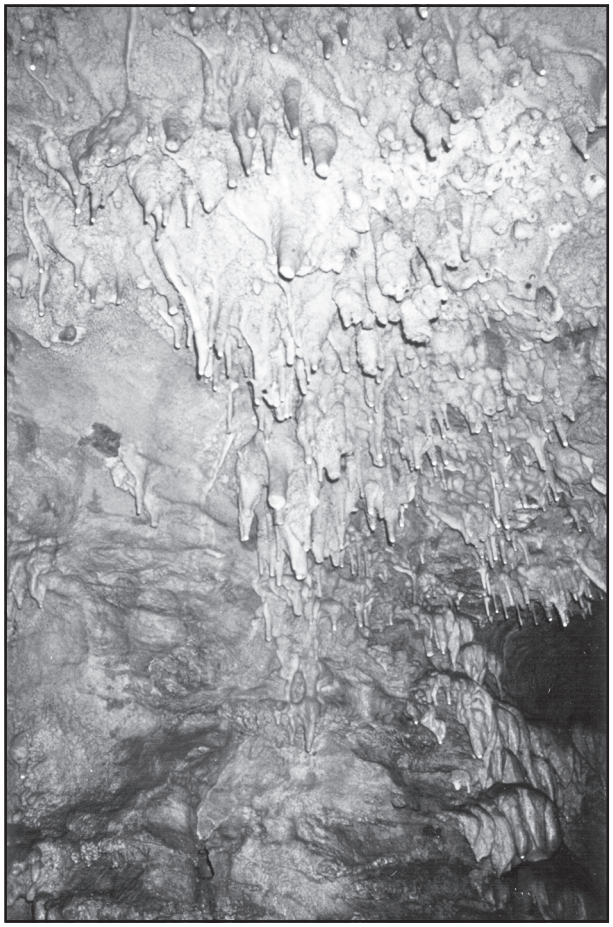

Figure 5: Along the tourist route and the parallel route of the electrical system in Oregon Cave, nearly everything that can be broken, has been.

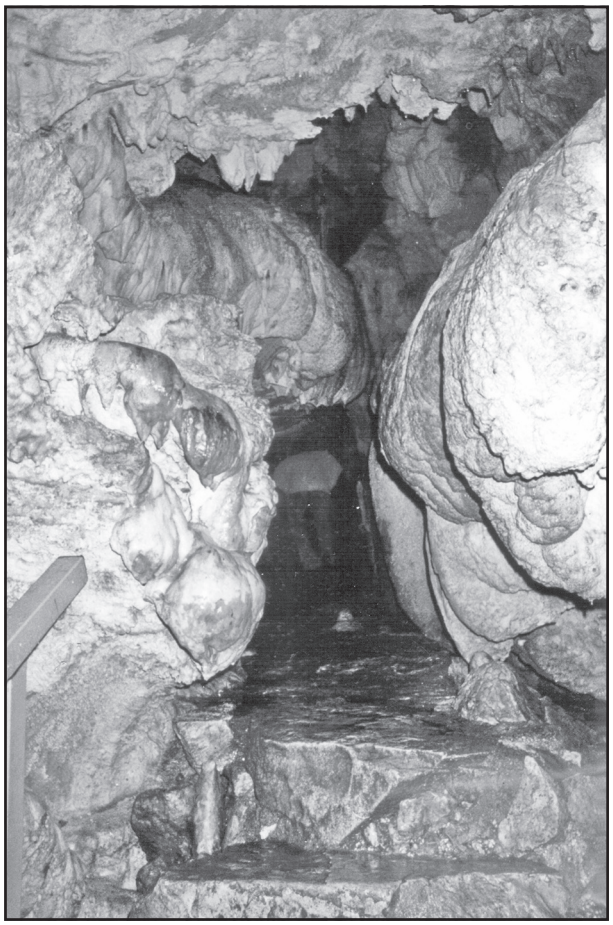

Figure 6: At especially narrow points on the tourist trail, a requirement of gloves might prevent further deposition of skin oils.

budget, and an enthusiastic unpaid corps of cavers and other volunteers. And there has been no interest in restoring the historic but long-obsolete hotel that burned in the 1950s.

4. The Outcome

Dunbar Cave again is a popular show cave, but on a scale and in a mode appropriate to its features and for the needs of the local community. It serves as a creative and positive model of adaptive natural resource management for other popular but worn-out show caves such as Oregon Cave. Such caves must not be abandoned to unrestrained vandalism.

Figure 7: American Indian art in Dunbar Cave.

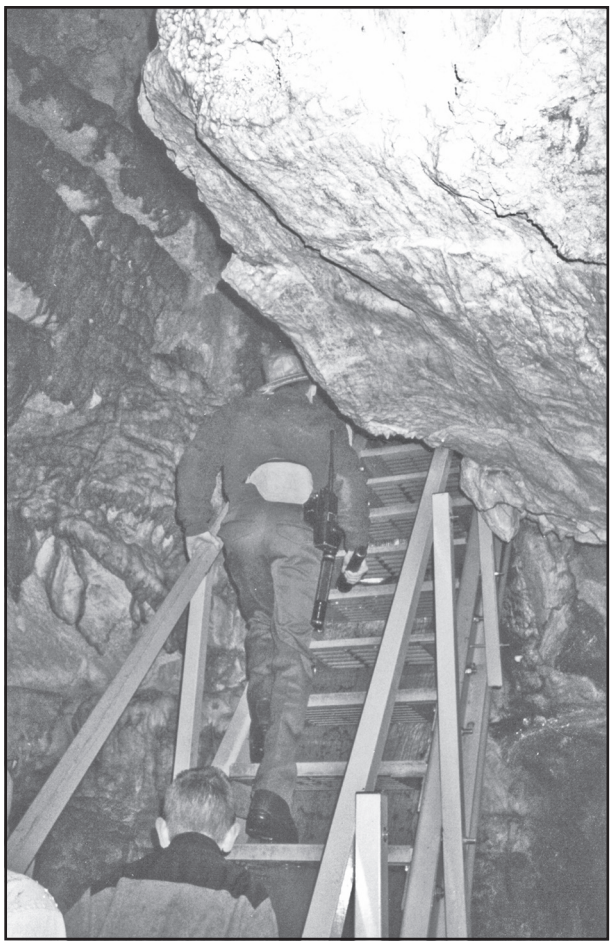

Figure 8: Paradise Lost is the most scenic section of Oregon Cave. Unfortunately the recently installed gleaming stainless steel handrails detract greatly from naturalness of the cave.

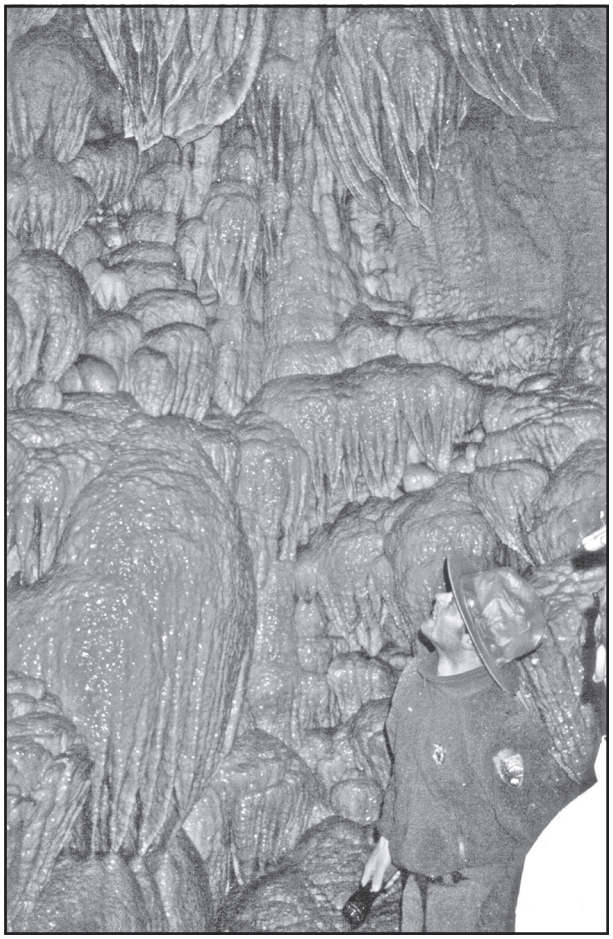

Figure 9: The flowstone in Paradise Lost was milk-white in 1948. Now it is moderately brown.
All photographs by William R. Halliday.

Acknowledgments

My heartfelt thanks to Larry Matthews for providing me with much unpublished information about Dunbar Cave and to its staff for special opportunities to familiarize myself with the cave and photograph its features unencumbered by tour groups. And to Steve Knutson, author of a notable recent NSS book on Oregon Cave, for similarly providing me with detailed maps and much unpublished information about that cave.

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ENVIRONMENTAL PROBLEMS OF *TELAGA* (DOLINE POND) IN GUNUNSEWU KARST, JAVA INDONESIA

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T*elaga* is a pond formed in the dolines as a result of ponor plugging. A total number of 443 *telaga* are randomly distributed within Gunung Sewu Karst (3,200 km^2). *Telaga* used to provide approximately 90% of the local people's water supply (before 1990s). However, most *telaga* are currently drying up, only 30 *telaga* remain perennial. The environmental problems of the *telaga* can be grouped into three categories, namely (a) diminishing storage,(b) rapid water loss, and (c) water quality deterioration. Diminishing storage has been resulted from rapid sedimentation (caused by extensive agriculture to the karst hills) and the increase of infiltration (caused by the lost of karst soil cover). Rapid water loss is due to basal leakage (caused by removal of bottom soil during *telaga* deepening practices or embankment construction) and higher evaporation (caused by higher wind velocity and warmer local temperature). Water quality deterioration has been resulted from multiple usages (human bathing, washing, animal bathing, animal drinking, fishery) inside the *telaga*, as a result waste is retained in the *telaga* water body. Major contaminants of *telaga* water are phosphate, COD, nitrate, detergent, collie bacteria, and suspended solid. Proposed rehabilitation options which may be easily applied among others are, (a) leaving the upper slope of karst hills for perennial crops, (b) imposing *Guyang Warak* tradition, (c) sealing *telaga* bottom with asphalt soaked sacks buried in clay, (d) replacing concrete levy with a sandwich of stone pile and clay, (e) planting readily consumed perennial crops along *telaga* sides, and (f) establishing simple bathrooms outside *telaga* so that waste will not remain in the *telaga* water body.

1. Introduction

Water resource is a pivotal issue of Gunung Sewu karst. During dry season, this area undergoes severe water shortage. More than 41 per cent of the population of Gunung Sewu karst has no access to safe drinking water. In some localities, the population is forced to carry water from distant springs or *telaga*. Resurgences emerge in the southern coastline which is far from settlement. Underground river course, on the other hand, are found in great depth (> 100 m) and not readily assessed by local people. High investment and operational cost make under ground water taping infrastructure is not affordable to local government and private sectors.

The most assessable water, though in small quantity, are springs and *telaga*. Karst springs however emerge only in few places and provide water demand for only few nearest villages. Instead, the most assessable water resource is *telaga*. Telaga are more abundant and dispersedly distributed. For that reason, telaga were used to be the main water resources, especially before 1990s, when water supply infrastructure had not been established yet. Unfortunately, the existing water supply infrastructures only provides 0.25% of entire water demand. Local people thereafter still use telaga for they daily live, especially for bathing, washing, and animal drinking. For drinking water, local people relay on rain water collected during rainy season and water tanker brought from distant areas. Telaga currently are facing several problems, most of telaga are drying up, and less than 10% remains perennial. This paper accordingly tries to discuss the environmental problem of telaga, the affecting factors, and possible rehabilitation measures. Analyzes and discussion are based on data form previous works, field observation, and measurement from topographical map and aerial photograph.

2. The Settings of Gunung Sewu Karst

Gunung Sewu karst is well known for its typical morphology which is generally considered a type example of cone or kegelkarst (Lehmann, 1936). Gunungsewu karst stretches 85 km west-east covering three provinces of Yogyakarta, Central Java, and East Java. Its north-south width varies between 10 and 29 km with approximate area of 1300 km^2. The Gunung Sewu karst is adjacent to the Indian Ocean on the south central coast of Java. Elevation range is between zero and 512 m above mean sea level, and the highest portions centrally located about 25 km from the cost line. The annual rainfall varies between 1500 mm and 2986 mm annually. Mean annual temperature is about 27° C (Haryono and Day, 2005).

The Gunung Sewu karst is made up of Neogen (Middle

Miocene and Upper Pliocene) limestone of Wonosari-Punung Formation. The limestone is composed of massive coral limestone in the south and bedded chalky limestone in the north (Balazs 1968; van Bemmelen 1970; Waltham *et al*. 1983; Surono et al. 1992; Rahadjo et al., 1995). Total thickness of the limestone exceeds 650 m. The underlying rocks of the area are volcanic clastic rocks, including tuff, andesitic breccias, and tufaceous sandstone. The areas have been subjected to uplift since the Late Pliocene forming plateau morphology. Gunung Sewu karst has also been tectonically active resulted in severe jointing and faulting.

3. *Telaga* Characteristics

In addition to conical morphology, *telaga* is the second characteristic of Gunung Sewu karst. This phenomenon is rarely found in other karst areas of Indonesia. *Telaga* are formed in the base of cockpits as a result of ponor plugging. The sediment is consisted of silty clay material with depth up to more than 2 meters. No further researches are available explaining the occurrences and genetic of *telaga*. The only information easily observed from topographical map is that *telaga* are randomly distributed within entire area of Gunung Sewu Karst reaching a total number of 443 (Fig. 1). Such random distribution is confirmed by nearest neighborhood index. Nearest neighbor index of telaga distribution in Gunung Sewu karst is 9.11. The area of telaga ranges approximately from 0.25 to 3.5 ha forming several plan forms. Telaga plan forms are controlled by bottom cockpit morphology.

Telaga are recharged by direct rain fall and surface runoff from surrounding areas within the cockpit. Works by Setyahadi (2002) and Macdonald and partners (1984) showed that coefficient runoff in the area generally varies between 3 up to 28%. Runoff is drained to the telaga through galleys or man-made ditches. The recharge area is mostly characterized by limestone outcrop with limited soil cover. Soils are patchy distributed with very small coverage within terraces. As a result of limited soil cover, thereafter subcutaneous flow in the area is likely not a significant control in telaga hydrology, especially in recharging telaga. *Telaga* water is drained through ponor as a shaft flow and dry up through evaporation.

Measurement from geometrically corrected aerial photograph founds that cockpits area varies between 0.018 and 2,105 km^2 or 0.146 km^2 in average (N:3,86). Land covers of the area are combination between dry land cultivation and mix timber plantation. Settlements are located scatterly in the entirely karst area with average population density of 348 people/km^2. Bare lands are also found in some localities forming karren field in various forms. In some places, karren outcrops up to 1.5 m high indicating severe soil losses.

4. Environmental Problems

Environmental problems of *telaga* are summarized in Table 1. The environmental problems of the *telaga* can be grouped into three categories, namely a) decreasing storage, b) rapid water loss, and c) water quality deterioration. Decreasing storage has been resulted from rapid sedimentation caused by erosion. Accelerated erosion has taken place since the

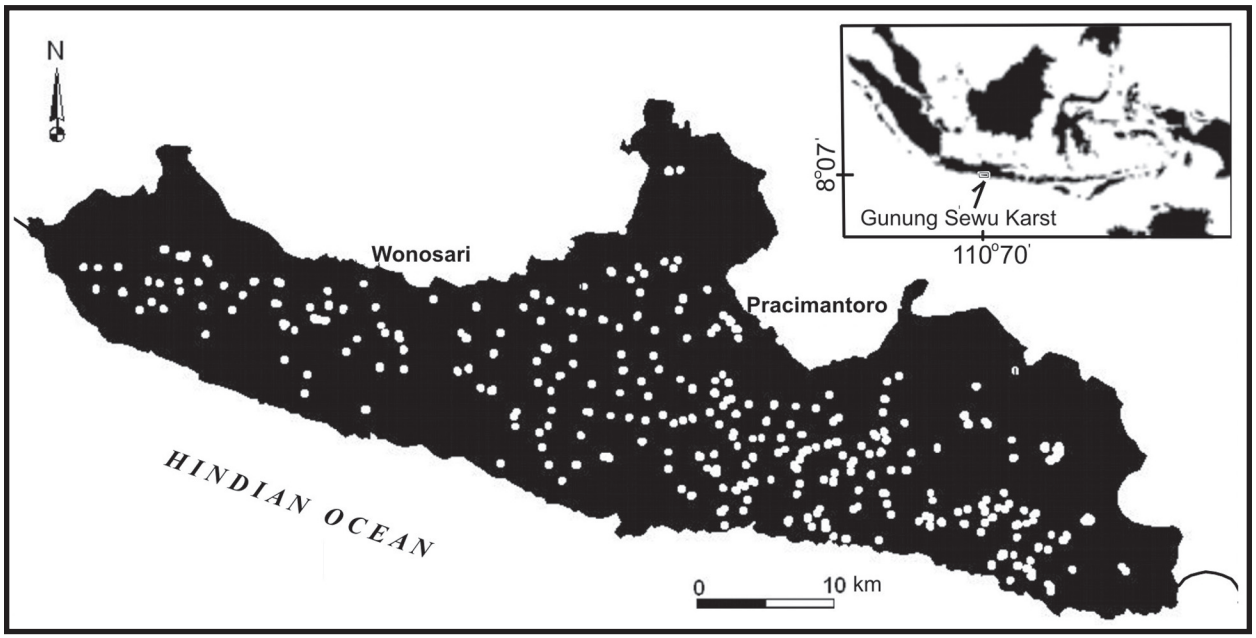

Figure 1: Distribution of telaga in Gunungsewu Karst (compiled from topographical maps).

early 19th century due to deforestation and agricultural extensification. Higher population growth and limited land have forced people to cultivate upper slope of karst hills. Soil plowing during land preparation does loosens soil aggregate and increase soil erodibility. As a result, in the beginning of rainy season when plantation has not grown yet, severe soil erosion takes place. High erosion rate of Gunung Sewu rate can be also indicated by the occurrences of karren protruding up to one meter high (Haryono, et.al., 2002). Further consequence of soil erosion related to *telaga* storage is the decrease of surface runoff recharging *telaga*. Less soil cover has brought about opening of secondary porosity. This in turn will inevitably account for the higher infiltration rate and less surface runoff.

Rapid water losses are caused by basal leakage and evaporation. Basal leakage is resulted from removal of bottom sediment during *telaga* rehabilitation practices. Since the 1990s, public work office has deepened and constructed embankment encircling *telaga*. Sediment has been removed in bid of increasing telaga storage. This practice unseals ponors and inevitably increases water losses. It has been echoed by Setyahadi (2002) and Putra (2003) that natural *telaga* have longer inundation period than rehabilitated telaga. From five telaga measurement conducted by Setyahadi (2002) and 14 telaga by MacDonald and Partners (1984), water losses of telaga through infiltration ranges between 0-26.3 mm/day. Ponor opening is likely also caused by accelerated dissolution in the underlying rock of *telaga*. Higher dissolutions rate is resulted from accumulated soil CO_2 brought by erosion from upper slope areas.

Accelerated water losses in karst Gunungsewu is also resulted from higher evaporation. Changing of micro climate due to less vegetation cover around *telaga* is the factor accounted for higher evaporation. Less vegetated area in this case increases local temperature and wind velocity. Land in the surrounding *telaga* is cultivated for dry land field. Average temperature is 27° C and the highest temperature during mid day is up to 34°C. Average evaporation of the area measured from pan evaporation is 5.4.mm/dy (Putra, 2003). This finding is higher than Setyahadi (2002) measurement in area with denser vegetated cover which resulted 4.4 mm/day.

Water quality deterioration has been resulted from multiple usages inside telaga including human bathing, washing, animal bathing, animal drinking, and fishery, thus waste is left and retained in *telaga.* The only measure imposed by local people is separating telaga into two compartment for human and animal by constructing dike. This practice only able to separate waste from animal and human, not to keep telaga from waste produced by bathing and washing activities. Contaminants are also brought by surface runoff either from surrounding areas, especially from agricultural land and settlement. Major contaminants of *telaga* water are phosphate, COD, nitrate, detergent, collie bacteria, and suspended solid. Phosphate and nitrogen are resulted from fertilizer. Bacteria collie is either from animal feces inside

I. Decreasing volume/storage capacity	1.1. Sedimentation	1.1.1. deforestation and agricultural extensification in the doline recharge areas 1.1.2. Loosening soil aggregate due to soil preparation practice in the end of dry season
	1.2. Decreasing recharge due to less surface runoff	1.2.1. Thinning soil cover
II. Increasing water losses	2.1. Basal leakage	2.1.1. Sediment excavation in doline bottom
	2.2. Increasing evaporation	2.2.1. Increasing temperature due to less forest cover 2.2.2. Increasing wind velocity due to less forest cover around doline pond
III. Decreasing water quality	3.1. Waste from inside utilization (bathing and washing) 3.2. Waste from recharge area	3.1.1. Bathing and washing in doline pond 3.2.2. Organic and inorganic waste brought by surface runoff

Table 1: Environmental problems of Telaga (doline pond) in Gunungsewu Karst.

telaga or brought from the cathment area by surface runoff. Cattle are the second income generation of the Gunung Sewu people. Each family in the area has in average two cows or lamb, 20 chickens.

5. Proposed Measures for *Telaga* Rehabilitation

Telaga rehabilitation must be treated comprehensively for the sake of environmental management of Gunung Sewu karst entirely. Any measures can not be attributed solely for the *telaga* rehabilitation. In the case of Gunung Sewu karst, greater attention must be devoted to rehab vegetation coverage through replanting perennial crops (reforestation). Since Gunung Sewu people are much relays on land resources, attempts should be made to ascertain that the perennial crops not only for the shake of conservation but also for income generation. Otherwise the program will fail. Agriculture is still the main activities to make living in Guung Sewu. In that regards, reforestation must not cover entirely plot of land but there must be mix or combination between seasonal crops and perennial crops. Seasonal crops is cultivated to fulfill staple food daily need, on the other hand perennial crops are both for conservation and consumption. In that regards perennial crops are planted in the upper slope of karst hills and seasonal crops are placed in the lower slope (Fig. 2.). In attempt to keep the upper slope vegetated, perennial crops in the upper slope must be mixture between timber crop and non timber crops. If timber crops are cut down there still vegetation left. Re-vegetation measure in upper slope is intended to reduce erosion so that suspended material in *telaga* water and sedimentation can be reduced. Reforestation is also intended to improve micro climate especially in reducing temperature, wind velocity, and furthermore reducing evaporation. Planting perennial crops such fruit crops in telaga riparian area is also advisable, especially when the area is not cultivated for seasonal crops.

The second measure is sealing the *telaga* bottom. Several practical techniques can be applied for this purpose. In some places of Gunung Sewu Karst, there is local wisdom dealing with telaga. The tradition is well known as *Guyang Warak* (bull bathing). *Guyang Warak* is a traditional ceremony conducted thorugh bringing as many as cows to the *telaga* in an attempt to stir up sediment in the base of telaga. Such old tradition was believed to have sealing mechanism. Empirically, this practice does improve sealing capability of sediment. It has been understood that high content of Ca in soil makes clay to be aggregated forming a porous structure that lets water seeps through easily. But stirring up the sediment, clay will be dispersed. This tradition has already been forgotten and never been applied anymore. Revitalizing such local wisdom surely will help not only for *telaga* rehabilitation, but also important for cultural preservation. If this practice is organized well, the event can be developed as a tourist attraction.

Rehabilitation of telaga concerning with leakage problem can be solve also through engineering treatment. However the better one is those affordable and applicable. Depending much upon imported material will no be effective. The easiest way to seal leakage is putting asphalt soaked sacks in the base of *telaga*. Asphalt and sacks are local material that is sold in local market. This treatment is carried out by excavating sediment telaga one up to two meter deep, putting asphalt-soaked sack to telaga bottom, and overlying sacks with clayed soil or with previously removed sediment at 0.5 m thick. Another engineering rehabilitation of *telaga* is replacing concrete embankment with a sandwich

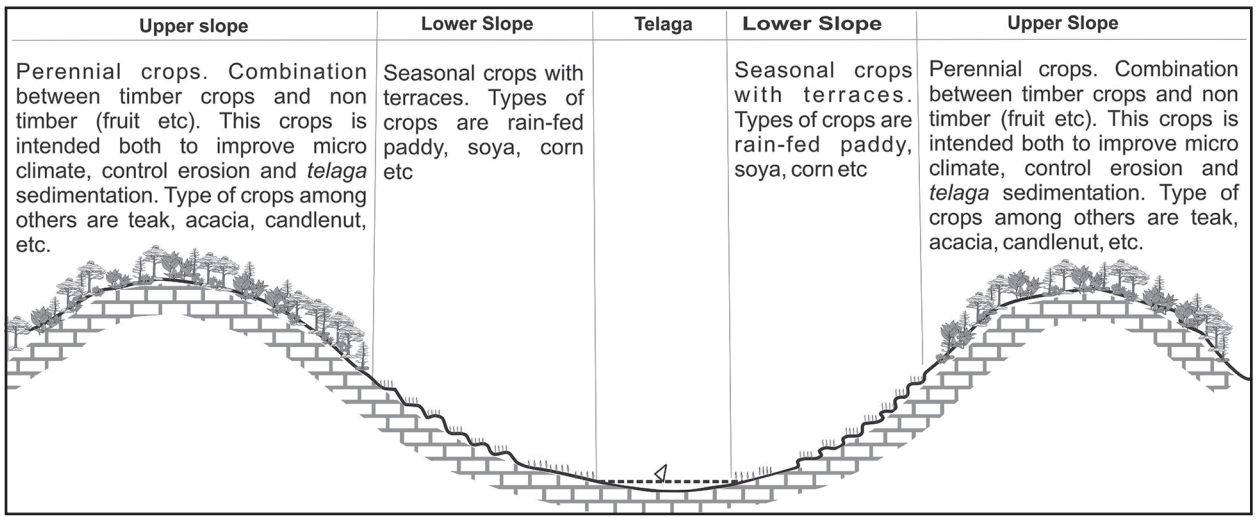

Figure 2: Recommended cropping pattern for telaga rehabilitation.

of stone pile and clay. Many masonry *telaga* embankments are cracked and even broken leading to water leakage. Cracking of concrete embankment is resulted from shrinking and swelling properties of clayed soils in the area. In such condition, stone piling and with clay inside is more favorable and will not be affected by swelling and shrinking of soils. Asides of those technical advantages, embankment with stone pile and clay are simpler, easier, and cheaper construction.

The last rehabilitation measure of *telaga* is controlling waste entering *telaga* water. As mention early, water quality deterioration is resulted from washing and bathing inside telaga. To coup with this problem, washing and bathing must be placed outside *telaga*. Bathroom must be provided outside telaga but still near telaga area. The bathroom must be provided with well. The well actually is not real well, but it is just small part of *telaga* which is separated by embankment functioned as water filter. On the contrary waste from bathroom is also provided with sanitary system in such a way that waste water from bathroom can be filtered before re-entering *telaga*.

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UTILITY OF CAVE CRICKET MONITORING METHOD DEVELOPED BY CUMBERLAND PIEDMONT NETWORK ECOLOGISTS FOR MAMMOTH CAVE NATIONAL PARK

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Cave crickets (*Hadenoecus* spp.) meet all three requirements to be considered a vital sign as defined by the National Park Service National Inventory & Monitoring (I&M) program. Since the ubiquitous *H. subterraneus* subsidizes two cave invertebrate communities at Mammoth Cave National Park (MACA) monitoring their populations provides valuable insight into the overall condition of the cave's terrestrial ecosystem. Data collected at both managed and unmanaged caves will provide valuable insight to MACA resource managers on the effects of hypothesized stressors (e.g., changes in cave infrastructure) on cave cricket populations. Finally, highly visible cave crickets represent an excellent opportunity to educate the touring public regarding cave ecosystems and I&M's mission. For the first time in MACA's history, the physical and biological data we collected in 2006, during the implementation of the cave cricket monitoring protocol that we developed, revealed significant differences between managed and unmanaged caves. For example, our data show that winter temperatures at cave cricket roosting sites were significantly lower in closed, managed caves relative to open, unmanaged caves. These differences were likely due to thermal convection associated with managed caves being attached to the main cave system. Our photomonitoring data revealed that overall, cave crickets clusters were significantly larger near the entrances of managed caves relative to unmanaged caves, however, there was no effect farther inside caves regardless of management status. These results were supported by the significantly greater density of cave crickets roosting in transects near managed cave entrances relative to unmanaged caves. Finally, in another first, we tracked the locations of roosting cave crickets over time. Our data showed that cave crickets responded to the altered lighting regime in one cave by shifting their habitat use to an area they formerly avoided. Data gained during our first year of monitoring have demonstrated the utility of the methods used in this protocol.

1. Introduction

Obligate subsurface communities require energy subsidies from the surface because most caves do not support primary productivity. In the southeast, cave crickets, such as the wide-spread *Hadenoecus subterraneus,* are important to subsurface food webs because they are generally the primary conduits for regular input of organic matter into the subsurface habitat. Cave crickets feed in the productive surface habitat and the guano and eggs they deposit on formations and cave floors subsidizes two invertebrate communities. Given the importance of *H. subterraneus* to southeastern cave communities, the two primary objectives for monitoring cave crickets at Mammoth Cave National Park (MACA) are:

1. Determine temporal changes in population structure (e.g., age class) and relative abundance of cave crickets in developed and undeveloped caves across MACA.
2. Detect and assess potential effects of active management decisions, e.g., alteration of cave entrances, lighting regimes, visitor load, etc., on cave cricket ecology within managed caves.

One of MACA's management questions regards whether the alteration of cave infrastructure affects cave cricket abundance and population structure. From 1994-1998, as part of a biomonitoring cooperative agreement between MACA and the Cave Research Foundation, MACA cave cricket populations were visually censused at nine cave entrances (six with varying degrees of anthropogenic modification and three without). Among all cave entrances, the overall cave cricket abundance declined significantly from 1994-1997 (Poulson et al. 2000). However, at Austin cave, the most heavily modified entrance, the data on changes in cave cricket abundance of different size classes indicated that the rate of decrease for smaller cave crickets doubled immediately after it was altered, whereas decrease

rates observed in larger, mature individuals remained relatively stable (Helf unpublished data). The modifications also led to significant declines in other trogloxenes in that there was a large in-cave die-off of eastern Pipistrelle bats (*Pipistrellus sublflavus*) which apparently could not leave due to Austin entrance's new configuration. These data strongly suggest the cave entrance modification was a causative factor in small cave crickets' increased rate of decline (Poulson et al. 2000). Hence, there is a need for a rigorous method to monitor the status and trends of cave cricket populations at both developed and undeveloped caves at MACA.

2. Methods

In this section we summarize data collection methods used during sampling sessions. For detailed information on the methods summarized in this report the reader should consult http://science.nature.nps.gov/im/monitor/protocoldb.cfm where the full monitoring protocol, entitled "Cave Cricket (*Hadenoecus subterraneus*) Monitoring Protocol for Mammoth Cave National Park, Kentucky" (Woodman and Helf 2005) is available as a pdf document.

We gathered data on cave cricket populations from twelve caves at MACA. The six unmanaged "control" caves are closed to the public, visited infrequently by MACA facilities management, and have either open entrances or relatively unobtrusive gates that allow passive resource (e.g., leaf litter) flow from the surface to the subsurface. The other six managed "treatment" caves are open to tours, actively managed by MACA facilities management, and passive resource flow from the surface to the subsurface is largely restricted by one or more locked door(s). Thus, obligate cave invertebrates reliance on cave cricket subsidies in "treatment" caves should be greater relative to "control" caves.

Sampling involves two parallel methodologies with which we collect two sets of biotic and abiotic data in each cave. They are executed in two sampling regions located proximally and distally relative to human accessible entrance of each cave. A fixed landmark (e.g. a prominent formation) serves as an anchor point that orients the two sampling methodologies in each sampling region. "Dynamic plot cluster photo-monitoring" involves taking digital photographs of eight or more objectively located plots keyed on clusters of aggregated crickets. In conjunction with photo-recording cricket clusters, we collect air temperature and relative humidity data adjacent to each cluster with a Testo thermohygrometer. We locate plots by measuring their distance from the region's fixed landmark using a Sonin Combo Pro electronic distance measurer. We use a compass to determine the bearing of the plot relative to the baseline compass bearing of the region's fixed landmark. Thus, the locations of cave cricket clusters can be plotted on a cave map and we can track their habitat use over time. We use photoprocessing software to analyze the eight best photographs and record data on cave cricket population characteristics (e.g., age class). Photoplot data are square root transformed and analyzed, along with their continuous and categorical covariables, with the General Linear Model using Systat.

The other method involves visual censusing of cave crickets within five sets of paired, parallel laser "chalk" lines projected across the cave ceiling, These transects are oriented perpendicular to a baseline which basically bisects each sampling region. Data are recorded on "Rite-in-the rain" data sheets customized to each cave. Cave cricket density is calculated by dividing the mean number of animals in each paired transect by the area of each transect. Cave cricket density in each region of managed and unmanaged caves were also analyzed with the General Linear Model in Systat..

3. Results and Discussion

During the winter of 2006, temperatures at roosting sites in region one (proximal to the cave entrance) were significantly lower at managed caves with airlocked entrances relative to open, unmanaged caves without airlocked entrances ($F_{5,426} = 3.98$, $p<.005$). Though region two is deeper inside the cave, temperatures at roosting sites were still significantly lower in managed caves with airlocked entrances ($F_{1,376} = 6.34$, $p<.05$) among some months sampled ($F_{5,376} = 14.22$, $p<.001$). These data, however, are most likely not related to cave infrastructure. Rather, the managed cave entrances we monitor are lower elevation entrances attached to the main cave system and so thermal convection (or "the chimney effect"), wherein winter cold surface air is drawn into lower elevation entrances, is likely the cause of these observations (Tuttle and Stevenson, 1977). During the summer months, air is drawn in from high elevation entrances and cooled while moving through cave passages, thus the air blowing from managed cave entrances is at significantly lower temperatures than those at unmanaged entrances.

Our 2006 data showed that mean cricket abundance varied significantly in all size classes over time in all caves (Fig. 1). Mean abundance of large cave crickets, i.e. size classes 3 and 4, was significantly greater relative to small size classes, i.e., size classes 1 and 2, throughout 2006 ($F_{15,3328} = 18.32$, $p<.001$). Our data also show significant increases in small cave crickets' mean abundance in December (Fig. 3) and so photographer bias, due to large cave crickets' higher

visibility, may not be important. The significant decline of adult cave crickets from October to December supports observations from previous studies wherein adults migrate to deep cave sites for copulation and oviposition (Hubbell and Norton, 1978). The highly significant increase in size class 3 cave crickets in August was unexpected as significant declines among large cave crickets late in the year have long been observed (Poulson et al., 2000). These data could show a foraging response due to 11.3mm rainfall on the day prior to the monitoring session. Indeed, cave cricket foraging bouts are strongly associated with rainfall; but then we should expect all cave crickets to respond (Helf, 2003). Alternatively, these data may represent a recruitment event from earlier instars into size class 3. Similarly, the significant increase in small cave crickets that occurred in December may also represent recruitment from hatchlings into early instars. Hubbell and Norton (1978) observed that newly hatched cave cricket nymphs were most abundant in summer and three months is likely more than adequate time for hatchlings to pass through at least one instar (Hubble and Norton 1978). These data are particularly noteworthy because they demonstrate that we can obtain photographic data on even the smallest size classes. This permits us to make detailed interpretation of trends in cave cricket population structure.

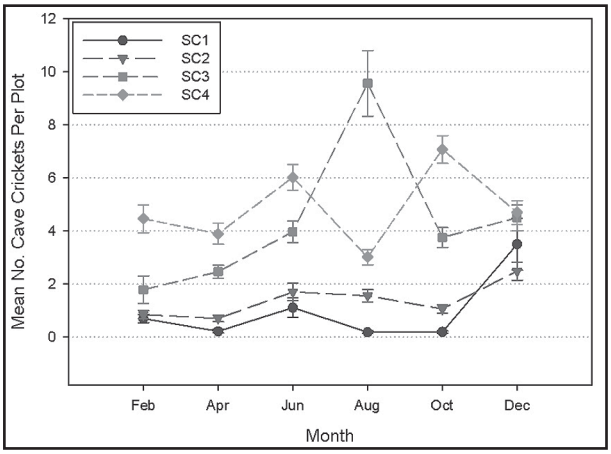

Figure 1: Mean number of cave crickets by size class as a function of sampling month among all caves in 2006. Error bars are ± 1 Standard Error (SE). The highly significant increase in size class 3 suggests recruitment from smaller size classes since large crickets are typically absent during hot, dry months of late summer. A similar significant increase among small crickets in winter also suggests recruitment.

There was a significant statistical effect of temperature and cave "treatment" on cave cricket abundance in 2006 ($F_{1,3328}$ = 24.21, p<.001). Peaks in cave cricket abundance occurred at ca. 12° and 20° C in managed caves and at ca. 6° and 15° C at unmanaged caves. Despite the significant statistical interaction, most of the cave crickets that we photographed were found at temperatures in the 11-20°C range regardless of cave "treatment" and so there may not be a significant ecological effect. It is interesting to note that temperature in unmanaged caves ranged from ca. 2-25°C of which the upper limit is near lethality for cave crickets (Studier and Lavoie, 1990). We photographed significantly greater numbers of cave crickets at roosts near cave entrances relative to roosts deeper inside caves regardless of "treatment" ($F_{1,3328}$ = 23.28, p<.001). Significantly higher cave cricket abundance in cave regions proximal to entrances is supported by our transect data. If these trends are observed in future, then the management implications will be clear: care must be taken in timing implementation of major construction projects in near entrance regions of managed caves because a possibly significant cave cricket population may be found there depending on the time of year.

In 2006, cave cricket density was significantly higher among region 1 transects in managed caves relative to unmanaged caves [($F_{5,348}$ = 2.45, p<.05) (Fig. 2)]. Only in June was cave cricket density significantly higher in region 2 transects of managed caves relative to unmanaged caves ($F_{5,348}$ = 3.77, p<.01). Indeed, the expanding variance in density among transects in both regions of managed caves, in addition to reflecting differences in density among treatment caves, may reflect the movement of cave crickets between regions as opportunities to forage increase. We note that there was precipitation prior to monitoring sessions from June-December. This expanding variance in density is again apparent in that cave cricket density in region two was higher earlier in the year than region one in both managed and unmanaged caves (Fig. 2). In fact, in as much as cave crickets largely use the human-sized passages (from which these data are collected) to access the surface, they truly reflect patterns of cave cricket transit between the entrance and deep cave roosting sites. It is important to note, however, that these data only reflect the density of cave crickets in those fixed transects. To be sure, cave cricket habitat use overall is extremely patchy and these data do not at all reflect their density throughout the cave.

Our use of polar coordinates and distance from permanent landmarks to track cave cricket cluster locations proved particularly effective at detecting the effects of management actions on cave cricket habitat use at Frozen Niagara Cave. Judicious lighting in tour caves is an important part of reducing disturbance on cave ecosystems (Slaney and Weinstein, 1997). Further, cave crickets are particularly sensitive to sustained exposure to light (personal

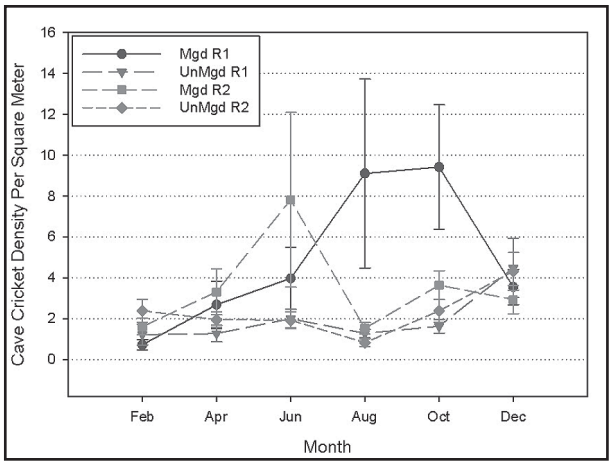

Figure 2: Mean cave cricket density as a function of transect among managed and unmanaged caves in 2006. Error bars are ± 1 SE. Note that cave cricket density in region one is positively correlated with increasing foraging opportunities later in the year.

observation). Between April and June 2006, a fluorescent light illuminating a portion of the ceiling in Frozen Niagara Cave was disconnected by MACA personnel. Our data show that after the light's removal cave crickets rapidly moved into and began to roost in the previously unavailable ceiling habitat (Figure 3). Thus, removal of the light appears to have opened up new roosting habitat for the cave crickets. Subsequent guano deposition beneath the new roosts created new foraging habitat for obligate cave invertebrates dependent on such subsidies. Having worked at MACA for many years, I and my colleagues have personally observed the lack of cave crickets roosting on that portion of Frozen Niagara Cave's ceiling.

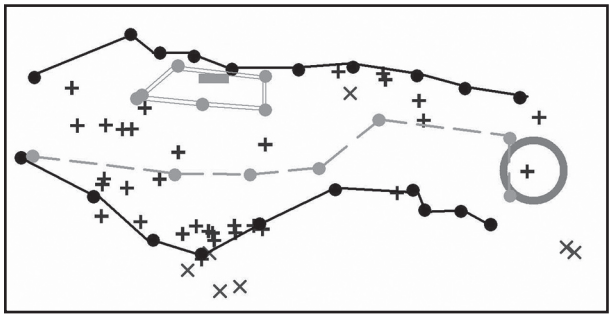

Figure 3: Cave cricket habitat use in Region Two of Frozen Niagara Cave in 2006. The heavy black lines are cave walls, the gray dashed line is the tourist trail, the gray polygon shows the approximate extent of the brightly illuminated cave ceiling, and the gray circle is a prominent cave formation. Xs and plus signs depict cave cricket habitat use before and after the fluorescent light was removed, respectively. Note cave crickets did not roost in or around the brightly lighted area before the light was removed and so its removal opened up new roosting habitat for the cave crickets.

Acknowledgements

This project was funded by and developed in collaboration with the USGS-BRD, Leetown Science Center, Kearneysville, WV as part of the interagency development of the Long-Term Ecological Monitoring Program for MACA. We would like to thank the staff of Mammoth Cave National Park, Kentucky for allowing us access to the magnificent caves and other resources, including field assistance, during our monitoring sessions. We would also like to thank the many interns and SCAs for their assistance throughout the entire monitoring process.

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A COMPARISON OF TWO CAVE CRICKET (*HADENOECUS SUBTERRANEUS*) MONITORING PROTOCOLS

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Abstract

In 2006, Mammoth Cave National Park began full implementation of the Cave Cricket (*Hadenoecus subterraneus*) Monitoring Protocol. One of the monitoring objectives is to determine potential effects of management decisions on cave cricket use of ceiling roosts within actively managed caves. Use of roosting sites by cave crickets in Frozen Niagara Cave has been monitored over time using transects (Transect Protocol) and photography (NPS Protocol). The Transect Protocol has been in use since we (Poulson, Lavoie, and Helf) began biomonitoring in 1994. In April of 2006, our data showed a significant shift in ceiling habitat use by cave crickets near the entrance of Frozen Niagara. The shift in ceiling habitat use was indicated by the sudden appearance of roosting clusters in a previously unused portion of Frozen Niagara's ceiling. Our data suggest the shift was precipitated by the alteration of the lighting regime in Frozen Niagara, a popular tour cave, by Mammoth Cave's Facilities Management staff. Prior to April a bright fluorescent light illuminated the entire ceiling in this area. Bright lights disturb cave crickets. With the change in lighting, this area of the cave was now used as roosting area. The Transect Protocol is quick and inexpensive, but misses small-scale details, while the NPS Protocol is more expensive and time-consuming, but can pick up more subtle changes in cricket roosting behavior. We present both Cave Cricket Monitoring Protocols and show how they are useful in detecting changes in habitat use due to management practices.

ENVIRONMENTAL DETERIORATIONS, POLICIES, AND MANAGEMENT OF INDONESIAN KARST

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Abstract

Since early 19th Century, some Indonesian karst areas have been subjected to environmental degradation. The worst environmental strain was undergone by karst areas of Java Island. Major environmental deterioration first took place in the early 19th Century when deforestation occurred for wood production and agricultural extensification. As a result, some karst areas became bare land with less biodiversity. The other major environmental problems, especially since the last three decades, have been caused by limestone quarrying and water pollution from domestic waste. To cope with those problems, the Indonesian government enacted ministerial decrees in 1999 and 2000 on karst management. The decrees regulate that all karst areas are classified into three categories. The first category (Class I) is assigned for protected area, second category (Class II) is assigned for buffer zone, and third category (Class III) is for non-protected area. This ministerial decree mainly emphasizes mining activities. Currently, to have more comprehensive regulation and to accommodate the new act on spatial planning (No 26 Year 2007), the Indonesian government has prepared new government regulation on karst management. The government regulation does not merely concern mining affair, but also regulate other affairs. An environmental management action plan and detail karst spatial planning were also already drafted for several karst areas of Java Island. Those planning products documented all steps in environmental management issues including land reclamation, water quality management, biodiversity rehabilitation, society empowerment, regulation strengthening.

AN OVERVIEW SURVEY OF CAVE AND KARST RESOURCES MANAGED BY PARKS CANADA

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Canada presently has a National Park system of 42 areas. Parks Canada, the land-managing agency, is drafting national cave and karst management policy and directives. There was no consolidated data as to which parks contain these resources.

To understand the significance these new policies and directives may have across the country, a system wide survey was conducted. Who has what and where? How is each park understanding, managing and interpreting those resources?

Questions were posed if cave and karst resources were known to be present in each park. If present, then more detailed information was requested, if known. For karst, what is the area extent, landforms, and land use activities occurring on these lands. For caves, what types, number, and use activities. For both resources information was collected regarding past and present research, management plans, staff expertise, interpretive displays, talks, printed media and internet presentation. Follow up phone and e-mail interviews clarified questionnaire answers as well as revealed forgotten or misunderstood survey results.

The survey results will be a useful tool to assist with the implementation of national policies and directives.

1. Background of Agency – Roots in Caves

The Parks Canada Agency manages the federal heritage areas of Canada. This includes National Parks, National Marine Conservation Areas and National Historic Sites. The majority of the land surface area is encompassed in 42 established National Parks (and several more in the planning stage) and three National Historic Sites.

The first National Park was established in 1885 in the area around present day Banff, Alberta. The catalysis was a hot spring complex. Associated with the springs are several small caves, the largest of which the first European explorers descended into by climbing down a log into the warm steamy chamber heated by the thermal waters (now known as Cave and Basin National Historic Site) (Marty 1984). It is a good example of thermal (or hypogene) karst cave development, the water coming from a wide catchment area and taken deep by geologic structural controls (Ford 2009).

By 1904 Nakimu Caves near Rogers Pass in Glacier National Park had been discovered and soon determined to have tourist attraction potential. The early explorers and developers knew of some 1.5 km of passages. Infrastructure such as wooden ladders, metal railings, passage modifications and additional man-made entrances were built. At its peak visitation in 1909, over a thousand tourists in a season visited the caves (Rollins 2004). Closure of the show cave came in 1935 due to declining visitation because of changes in the railway facilities for tourism and probably the Great Depression. In 1965 to 67, McMaster University team expanded Nakimu to 6 km of mapped passage.

In 1921 an outfitter looking for his horses, Cecil Smith, chanced upon what would become known as Castleguard Cave, in Banff National Park. An eight metre vertical drop, very near the entrance, blocked any early exploration. Horse outfitters limited their interest in the place to bringing clients there to watch impressive afternoon floods resulting from glacial melt in summer. It was not until 1967 that Derek Ford et al. from McMaster University began the exploration and study of Canada's longest (20 km), most famous and arguably most impressive cave. By chance, Castlerguard is located in a National Park. For many countries of the world a cave of this class would rate national protected area status on its own.

Much further north in western Canada, in the Northwest Territories, is the South Nahanni River. The 1970's saw

interest in a hydroelectric dam being developed on this spectacular wild river. Support to protect the river from such a project grew and led to the creation of the Nahanni National Park Reserve (later to become one of the first UNESCO World Heritage Sites). A couple chance discoveries identified the cave and karst possibilities of the area. Jean Poirel et al. found Grotte Valerie along the Nahanni River a cave famous for its many Dall Sheep skeletons and ice formations (Thompson 1976). Numerous other caves are found nearby in the Lafferty Creek area, Grottes Andre and Mickey being the most significant. In 1971 during an aerial reconnaissance the world class Nahanni North Karst was found by Derek Ford et al. This is an area that was missed by the most recent continental glaciation period and maybe not since 350,000 years or more ago.

Although the North Karst is not within the current boundaries of the park reserve, there is a strong possibility it may be included as part of a large expansion of the park.

2. System of Protected Areas

Parks Canada's system of protected heritage areas spans the extreme cardinal compass points of the country. Up to 1970, 20 national parks had been established, but not according to any real system. They represented, rather, a collection of special places, created in some cases by heroic efforts, accidents of geography or political opportunism that had been set aside for a variety of purposes - to protect scenery for national and international tourist resorts, to provide regional recreation areas, to create sanctuaries for wildlife, to stimulate flagging economies in areas of chronic underemployment. There was no vision or long-term goal for a system of national parks (Parks Canada, 1997). At times, little thought was made to encompass ecosystem boundaries or considerations while drawing up the legal limits to these national parks.

This required vision was provided by a national parks system plan devised in the early 1970s. Its fundamental principle was to protect a representative sample of each of Canada's landscapes. In order to guide the development of a finite system of national parks using this principle of "representativeness", Canada was divided into 39 distinct "National Park Natural Regions" based on (the appearance of the land) and vegetation (Parks Canada, 1997). With these defined regions, park planners were able to see where gaps in national park representation existed. Then efforts were directed towards new park establishment. Some of these regions do not have the "in your face" type of scenic attractions or easily accessible wildlife populations that founded older traditional national parks.

Parks Canada does not in general incorporate into its selection of national parks small unique features such as a cave, karst terrain, waterfall, canyon, fossil bed, a single species location of flora or fauna etc. The exception is Pingo Canadian Landmark. Up to the present no national park in Canada was ever created solely to protect caves and karst resources. These resources may have figured somewhere in the list of positive attributes an area has or more often it was simply by chance that caves and or karst are inside national park boundaries. The National Parks Branch did contract a review of karst regions of the country, feature significance and prospective National park sites (Ford 1973). The report both identified what became very important areas of cave concentration over the next three decades and missed some notable ones.

Nahanni National Park Reserve expansion has the potential to break from this track record and feature in one of its expansion areas the North Karst, the most accentuated periglacial karst yet reported from the Arctic or Subarctic (Ford 2004). The other future national park site that might contain very short caves and karst as prominent features is Manitoba's Interlake Region (McRitchie & Monson 2000). The park contains wide areas of karstically drained shallow plateau and a few fine examples of dolomite pavement landforms; also ecologic alvar assemblages that appear not to have been studied (Ford 2009).

3. Survey Motivation and Purpose

In 2001, United States National Park Service representative, D. A. Ek gave an overview presentation on the Caves and Karst of the National Park Service at the 15th National Cave and Karst Management Symposium in Tucson, Arizona. Canada's National Parks could benefit from such a summary, as there is no consolidated picture of where and what Parks Canada manages in terms of terrestrial caves and karst.

By 2008 Parks Canada was in the process of drafting national policy and directives on cave and karst management, timing would never be better to conduct a country wide survey its heritage areas to determine which parks contain such resources, what activities are occurring and what management strategies are in place.

3.1 Survey design

Even in parks with abundant caves and karst, their priority for management is very low for park staff. Workloads are overwhelming and for participation in a survey to happen, it had to be near painless. This means very little writing

- multiple choice and check list items that apply. Follow up e-mails and or phone interviews to tease out details and clarify answers were completed by the author. Even with this designed low effort format, some parks required multiple encouragements to fill out the survey.

The subject matter of this survey is not a field of park resource management that most Parks Canada staff are familiar with. In fact, some staff might have reservations acknowledging that caves even exist in their park. This is a combination of not being interested in or understanding the resource, knowing that Parks Canada has no formal rescue capability and no capacity to take on "new" visitor activity management. As well, few field staff have formal education or training in geology.

In fact, Parks Canada does not have staff that solely are responsible for geology, geomorphology or glaciology within its agency. In the past, the park naturalist or interpretive service of many parks had staff who took great interest and enthusiasm to collect data and present to the public information about earth science stories of their parks. Staff reductions and agency reorganizations over the last two decades has greatly cut this in-house expertise. Presently, investigation and management of earth science related topics in a park are usually handled by the Geological Survey of Canada, contract consultants and or academic institutions.

The survey respondents were given a set of definitions for karst and caves.

3.2 Survey karst definition

Karst is terrain with distinctive hydrology and landforms that arise from a combination of high rock solubility and well developed secondary (fracture) porosity. Such areas are characterized by sinking streams, lakes with no surface outlets, enclosed depressions, fluted rock outcrops, and large springs (Ford & Williams 2007). Caves may not be present. This especially occurs on bedrock of limestone, marble, salt and gypsum. These bedrock types may not necessarily be exposed on the surface.

3.3 Survey cave definitions

The legal definition of a cave, as used in Parks Canada's General Regulations of the Canada National Parks Act, is *"cave" means any subterranean cavern or area, either natural or man-made.* This is not specific enough for the purpose of the survey. Two cave definitions were created to accommodate the vastly different landscapes of Canada.

Cave Definition A

A natural underground opening in bedrock or talus, large enough for humans to enter, to an extent that artificial light is required for safe travel and or observe small detail. A total zone is not a mandatory criterion, but if it exists then the location is by default a cave. It can be partly or completely water filled (seasonal or year round).

The frequency of frost pockets (A joint or bedding plan surface exposure that has been enlarged by weathering, especially freeze-thaw action. Frost-pockets take on the appearance of cave entrances, but rarely go back far enough to lose daylight (Rollins 2004)) and glacier caves in western or northern parks requires this more restrictive meaning.

Cave Definition B

The same as Definition A but it may include smaller caves, at least 5 metres in length, and longer than the maximum dimension of the entrance. Length, in the case of a vertical shaft or crevice, could be the depth or vertical extent (Buck 1997). A total dark zone is not necessarily present in the smaller caves.

This definition works in a non-mountainous or coastal landscape.

If respondents felt that neither Definition A or B fit their caves, they had the option to select "other natural formed caves"

Glacier Caves

For the purposes of this survey, glacier caves and mill wells will not be included. Every park with glaciers will have these temporal features.

Mines or Man-made "Caves"

The last category is man-made. This survey will focus on abandoned mines not sealed shut. These can be very important habitat as seasonal bat roosts or winter hibernacula. As well, these features may shelter other cave-adapted life or contain cultural artifacts. Confirmed presence of use by bats is not required.

Other man-made subterranean cavern or areas (as per CNPA definition) should not be included unless containing cave-adapted life. Therefore, Jasper's active railway tunnel in which Bighorn Sheep spend time to avoid flies and use as a shortcut travel route would be an example of what not to include.

3.4 Survey questions

Using a pick list format respondents were given a choice of five typical and easily understood karst features to check off if karst was present in their park. Of course, there can be many other possibilities besides the five chosen. This question did not have a mandatory answer requirement. If a respondent checked the park has karst but none of the five choices was indicated, then this scenario was a good candidate for a follow up contact. Respondents were asked to estimate the area of the park covered by karst terrain. This question proved very difficult for most to answer and was probably unfair given lack of time and expertise. Additional pick list questions inquired about land use occurring on karst terrain, research, and interpretation/ information mediums to visitors about karst.

For the purpose understanding the magnitude of the resource, respondents were asked to indicate the exact number inventoried or to estimate numbers of each of the four categories (three types of caves and mines).

Then a series of questions using pick list format were posed to tease out the types of use occurring in caves and mines, the interpretive or information medium being used to educate and inform visitors, the types of data management and or management documents in place and finally whether research is taking place and by whom.

Each manager of Resource Conservation was e-mailed a request by Stephen Woodley, PhD, Chief Scientist, Ecological Integrity Branch, Parks Canada National Office – Ottawa, to complete the survey and given a link to either a French or English site of SurveyMonkey.com. Two hiccups occurred that caused a bit of grief and are easy to correct for future type surveys. The entire survey should have been attached in pdf format so managers can preview the questions for homework reasons and to determine which of their staff can best complete the survey. Secondly, the author chose to only allow one survey response per individual e-mail address, some respondents were completing multiple surveys because they were answering for two or more parks. People got creative by answering the second one in French or using another e-mail address. SurveyMonkey allows multiple responses from the same address if that option is selected.

4. Results

4.1 Results - overview

Caves and karst resources are found across the country on heritage lands managed by Parks Canada. Twenty-five of 42 established National Parks or National Park Reserves (NP or NPR) and one National Marine Park (NMP) with a land component contain caves and or karst. As well, at least one National Park candidate site, Manitoba's Interlake Region, is known to have cave and karst features.

The magnitude and significance of these resources is not evenly distributed across the country. Starting in the east, Bruce Peninsula NP and Fathom Five NMP together in Ontario have a complete range of both caves and karst features. Then jumping west to the cordillera, the boreal forest and Pacific coast many National Parks have national and world class assets. These range from Nahanni NPR, at latitude 61 degrees north, in the Northwest Territories, the huge gypsum karst of Wood Buffalo NP through the National Parks of the Rocky Mountains and neighbouring mountain ranges in British Columbia to Gwaii Haanas NPR of the Queen Charlotte Islands in the Pacific Ocean.

All across the country many other parks are cave and karst resources that are often not appreciated or recognized because of their reduced scale or importance. Still, these elements have local value and are worth managing using the best practices available. The same cave categories as used D. Ek, (2001) were chosen; solution, talus, tectonic, erosion.

Follow up e-mails and phone calls were made to many parks which had the surveyed resources. A quick determination of the type(s) of caves present was constructed by a combination interviews and personal knowledge of some parks.

4.2 Results – detailed

Nine heritage areas have significant cave and karst resources, often together, in notable quality.

Bruce Peninsula and Fathom Five

Two smaller parks along the shores of Lake Huron with impressive concentrations of littoral caves, stream caves, and a variety of surface karst landforms, primarily excellent examples of dolomite pavements and alvars (Ford 2009). Bruce Peninsula has a full range of land use activities occurring on their karst lands. They both have many modes of public information and education about their resources as well as extensive cave management protocols, documents and databases.

Wood Buffalo

It is the largest National Park in Canada, 44,800 square kilometers. Located in the boreal forest of northeast Alberta

and the southern edge of the Northwest Territories, it contains the largest gypsum karst area in North America (Rollins 2004). It has more than 2000 sinkholes >20 m in diameter, some sinking rivers and impressive springs. Caves do not figure prominently in the park (most are breakdown passages between individual collapse sinkholes), but those known have interesting features and include a bat hibernaculum.

Banff

Located in Alberta's Rocky Mountains, this is the oldest national park of Canada. The park system's creation began with protecting a karst hot spring and its associated cave, now known as Cave and Basin National Historic Site within the park. Its spring waters are habitat for a very rare aquatic snail, *Physella johnsoni*. Its most famous cave, Castleguard, is the longest in Canada and a world class resource. This alpine cave is located under the Columbia Icefield and at its remote end several passages terminate with glacial ice forced into the cave. Elsewhere there are smaller karst features and caves.

Kootenay

This park, also located in the Rocky Mountains of British Columbia, has an excellent collection of active alpine caves totaling well over one kilometer of combined passage. Radium Hotsprings are of karstic origin, like those of Banff.

Jasper

Its most notable feature is the Maligne Valley karst. Surface waters collecting in the polje of Medicine Lake make up the largest sinking river in Canada (Ford 2004). No associated cave has yet been discovered despite many searches. Derek Ford refers to it as "Canada's largest undiscovered cave"! The park has a concentration of alpine caves in an area known as the Snaring Karst and a scattering of other cave and karst sites mainly in alpine terrain.

Glacier

This park, of the interior mountain ranges of British Columbia, features Nakimu Caves, an active river cave system. Nakimu, the historic location of one of Canada's first commercial show caves, it is now partially rehabilitated. It is the second longest cave (4.5 km) within the National Park system.

Nahanni

Found in the Mackenzie Mountains of the Northwest Territories, the current park encompasses many caves and karst features near the Nahanni River. Caves have undetermined bat use. A potential park expansion may include the North Karst, an area very worthy of National Park status. It includes textbook examples of karst labyrinth, poljes, cenotes and towers all of which are some of the most northern known occurrences.

Gwaii Haanas

The park includes a major portion of Moresby Island, the second largest of the Queen Charlotte Islands off the west coast of British Columbia, in the Pacific Ocean. The landscape is temperate rain forest having a small component of karst terrain with caves of the same character as those of Vancouver Island. As well, the coastline has many shallow sea caves. Numerous caves through the park contain important, both culturally and for archeology, sites of past aboriginal use.

5. Conclusions

Without doubt, there is more karst terrain and caves outside of lands managed by Parks Canada in the country. The Province of British Columbia has the most protect areas specifically established for cave protection. This is not surprising since the province has the greatest number of caves in the country.

What Parks Canada may lack in terms of quantity is made up by the quality of the resource found in the previously mentioned national parks. For the most part, these superb cave and karst features were included within park boundaries by a fair dash of luck.

The recent development of national cave and karst management policy /directives signifies the agency is acknowledging their importance and the responsibility to become exemplary stewards.

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HIGH CO_2 CONCENTRATIONS AND CAVE VENTILATION TEST IN THE MILANDRE CAVE, JURA MOUNTAINS, SWITZERLAND

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CO_2 concentration in the atmosphere of the Milandre Cave has been measured once a month since 2005. It shows an annual cycle with concentrations ranging between 0.25 and 2.5%. In 2008 extremely high concentrations (up to 3.3%) were measured. Considering the breathing problems encountered by the cavers, we can assume that such a high level was never reached during the last 40 years.

Several hypotheses can be made about the reason for such a high CO_2 concentration. One of the tributaries feeding the underground stream flowing through the cave has been polluted since 2005, but a clear increase in the pollution was observed in 2008. Biofilms and filaments grew on the stream floor feeding a significant number of worms and leeches in the cave. This increased bioactivity is probably the explanation for the high CO_2 level. Meteorological and climatic variations could also possibly explain the phenomenon. A change in agriculture practices could also have occurred although no clear evidence is known to us.

A ventilation of the cave has been attempted in fall 2008. The natural ventilation was first tested by starting the experiment with closed doors at both ends of the cave, then by opening doors and then by sucking air out of the upper entrance of the cave with a fireman ventilator at three different powers (up to about 20,000 m^3/h).

1. Introduction

CO_2 concentration in the atmosphere of the Milandre Cave has been measured once a month since 2005 (Fig. 1). It shows an annual cycle with concentrations ranging between 0.25 and 2.5%. Already in 2007, but especially in 2008, very high concentrations (up to 3.5% at some given locations) were measured. Cavers got sick and needed several days after caving trips to recover. Such a situation was never encountered before and we can assume that such a high CO_2 level was never reached during the last 45 years.

Several hypotheses can be made about the reason for such a high CO_2 concentration. One of the tributaries feeding the underground stream flowing through the cave has been polluted since 2005, but a clear increase in the pollution was observed in 2007 and especially in 2008. Biofilms and filaments grew on the stream floor feeding a significant number of worms and leeches in the cave. This bioactivity is probably the explanation for the high CO_2 level. However, other explanations such as meteorological and climatic variations could also possibly explain the phenomenon. A change in agriculture practices could also have occurred although no evidence of this is known to us.

The origin of the pollution will hopefully be found and cancelled in the next months and we will be able to see if the situation in the cave atmosphere will significantly improve or not.

Another question related to the cave ventilation is to know if a group of caver specialists could enter the cave in case of pollution by hydrocarbons. In other words, we would like to know if gases can be evacuated and how much time it would take.

Thus, a ventilation of the cave has been attempted in September and December 2008. This short paper presents results of the cave ventilation tests and their effect on the cave atmosphere. This note is not meant as a complete scientific interpretation, but rather as the presentation of the results of these experiments.

2. The Cave

The Milandre Cave is a 10.5 km long cave located in Northern Switzerland (central Europe). The main stream passage of the cave is 4.6 km long (3 km as the crow flies) with one entrance at each extremity (135 m of difference in elevation). The cave lies below a limestone plateau at an

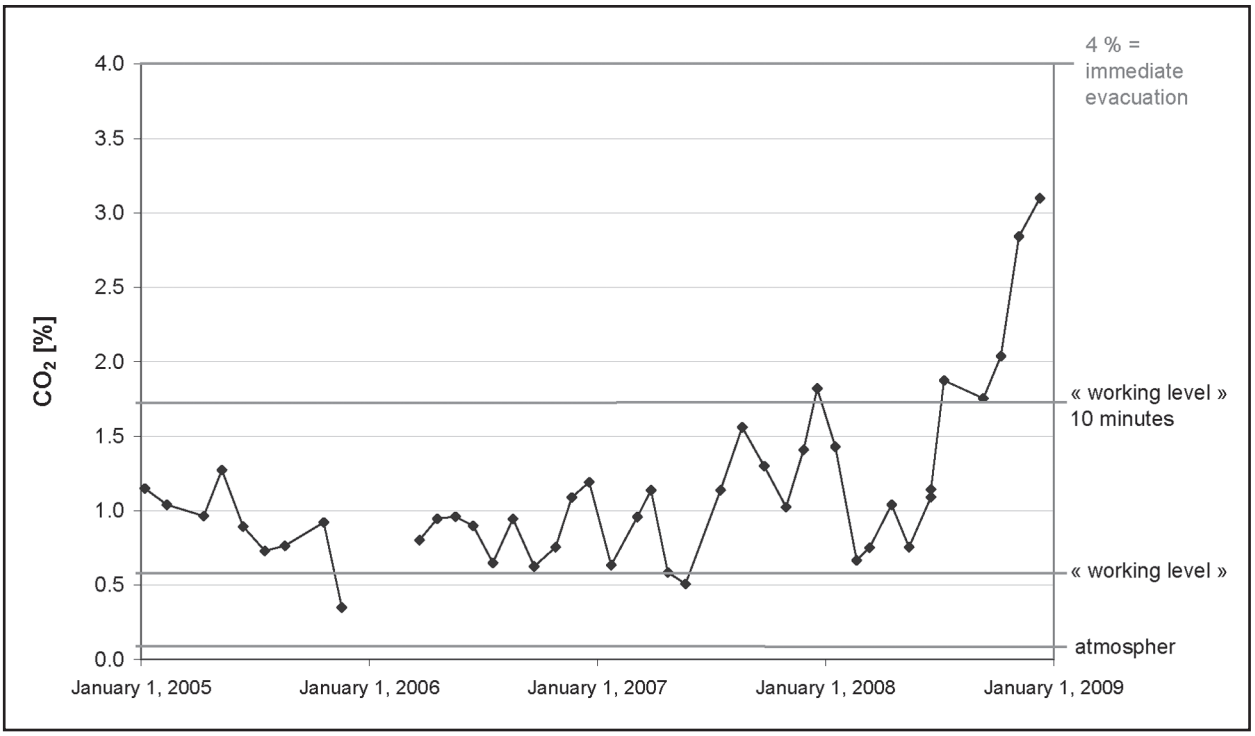

Figure 1: Average CO_2 concentration from 4 different measurement stations in the Milandre Cave between 2005 and 2008. The lowest values are usually observed in between December and March, and the highest values in shortly before. Concentration in 2008 reached very high values.

elevation of about 500 m.a.s.l.

3. The ventilation Tests and Their Monitoring

The first ventilation test was conducted in September 20, 2008. Ten cavers made measurements at various places in the cave (Fig. 2). Air drafts (velocity and discharge rate), PCO_2 and air temperatures were recorded at three main locations in the cave (upstream, middle and downstream parts of the cave). PCO_2 was measured at several other locations. Four firemen operated a strong ventilator at the upper cave entrance in order to suck an increasing air discharge rate out of the cave.

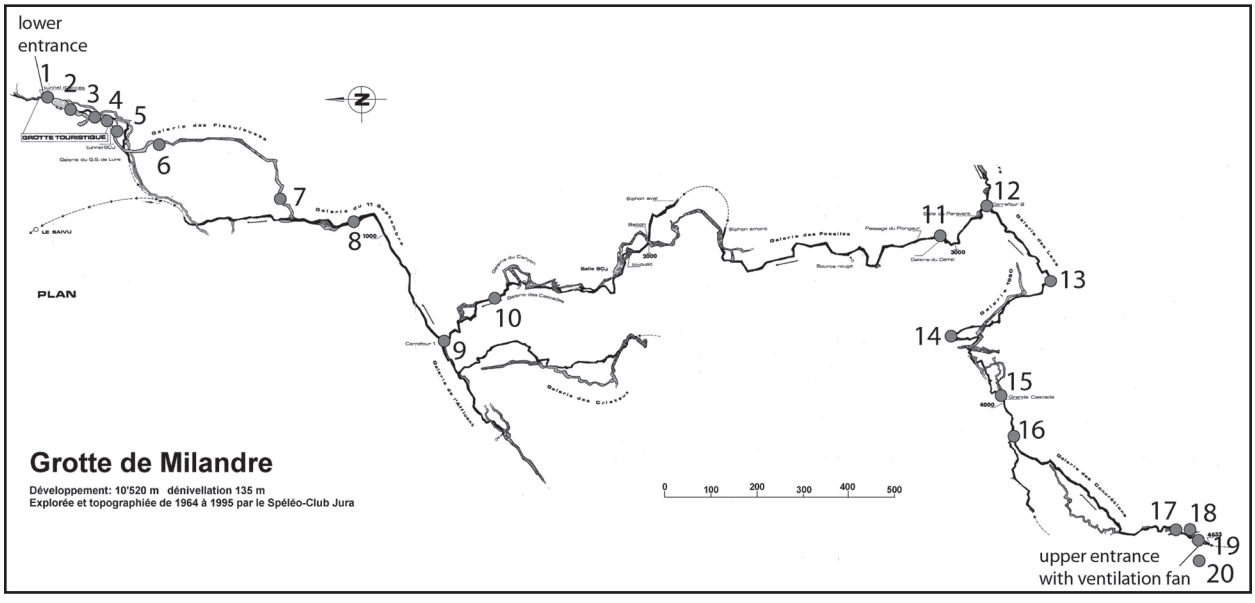

Figure 2: Map of the cave with the observation points within the cave.

The program of the test is described hereafter and the measurements in the cave have been conducted all along the flowing steps:

Step 1: 8:15 to 8:30 Downstream and upstream doors closed
Step 2: 8:30 to 8:45 Upstream door open
Step 3: 8:45 to 9:00 Both doors open
Step 4: 9:00 to 10:30 Downstream door open and the upstream door half open (setting of the ventilator)
Step 5: 10:30 to 10:50 Sucking upstream power 1
Step 6: 10:50 to 11:11 Sucking upstream power 2
Step 7: 11:10 to 11:30 Sucking upstream power 3
Step 8: 11:30 to 12:30 Sucking upstream power 4 (max)
Step 9: 12:30 to 13:30 Upstream door closed, downstream door open.

Measurement frequency was increased at steps changes and all measurements were synchronized within 5 seconds in order to be able to identify the step changes. The outside temperature has been recorded during the experiment.

In December 2008 the CO_2 concentration in the cave was so high (more than 3.4 %) that we decided that visits were not possible anymore. We decided to open both doors for seven days in order to let the CO_2 concentration decrease. This was the second ventilation experiment, which was unfortunately only documented by a few measurements before the opening of the doors and a series of measurements one week later.

Hereafter we present results mainly from the first ventilation test (September 2008).

4. Results

4.1 Air draft and temperature

The outside temperature was about 8° C at the beginning of the experiment. It reached the cave temperature (10° C) around 9:30 and increased up to 16° C at 13:30.

Cave temperature measurements displayed some variations (mainly a decrease during the ventilation), which cannot really be interpreted because they are probably influenced by evaporation processes of the temperature probe.

Results concerning draft measurement are presented in Figure 3.

The draft velocity meter used at the upstream end of the cave was not sensitive enough for this experiment. Measurements have been made by assessing the breathing vapor velocity. As the velocity was obviously variable, the method was more a coarse averaging assessment than a real measurement. However the values should be within a factor 2 of the real draft velocity. Data clearly show that the draft velocity increased together with the ventilation power. In the upper station (point 18) it was quite low during the step with doors open but no ventilation.

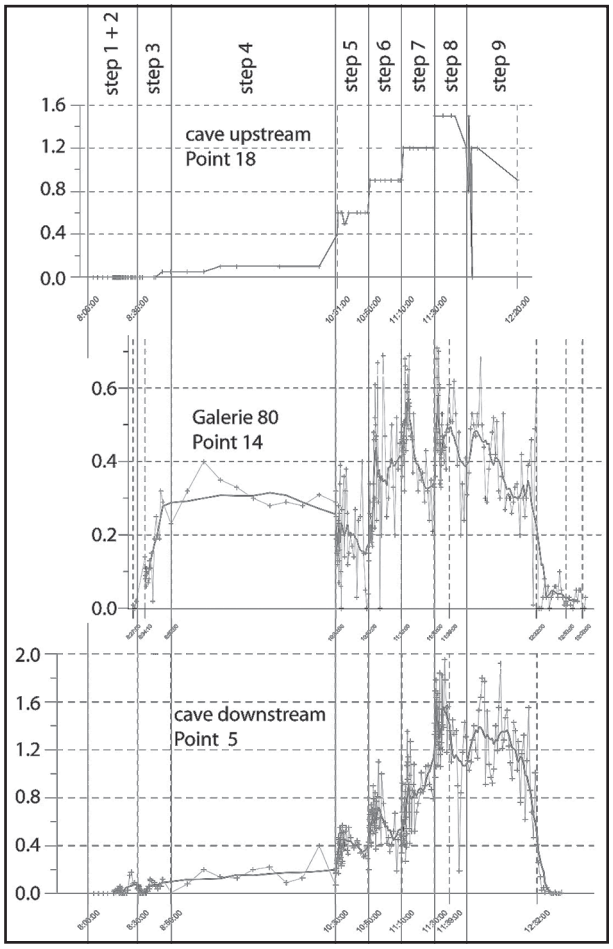

Figure 3: Draft velocity in m/s measured at three locations in the cave.

The curve in point 14 (Galerie 80) is pretty much the same with a clear effect of the artificial ventilation. Data are much more precise and thus look more chaotic.

The result is less clear in point 5 (lower door) where natural ventilation during step 3 seems quite high compared to the other two locations.

At the two "well measured" locations it must be noticed that the draft velocity increases first at the beginning of each step and decreases after a few minutes.

4.2 CO_2 concentrations

Figure 4 shows the approximate distribution of CO_2 concentrations in the cave before the beginning of the experiment. In fact not all measurements are synchronous, but all values have been measured between 7:50 and 10:39 am. It shows that concentrations are the lowest in the downstream part of the cave, and are quite variable along the cave. The highest values are measured shortly upstream from the Affluent de Bure (points 12, 13 and 14).

During the experiment CO_2 concentrations tend to increase in most locations (e.g. Fig. 5). A clear decrease can be only found in the downstream measurement points (Fig. 1). At point 7 the concentration decreased from 2.2% at the beginning of the experiment down to 1.54% at the end (2:17 pm).

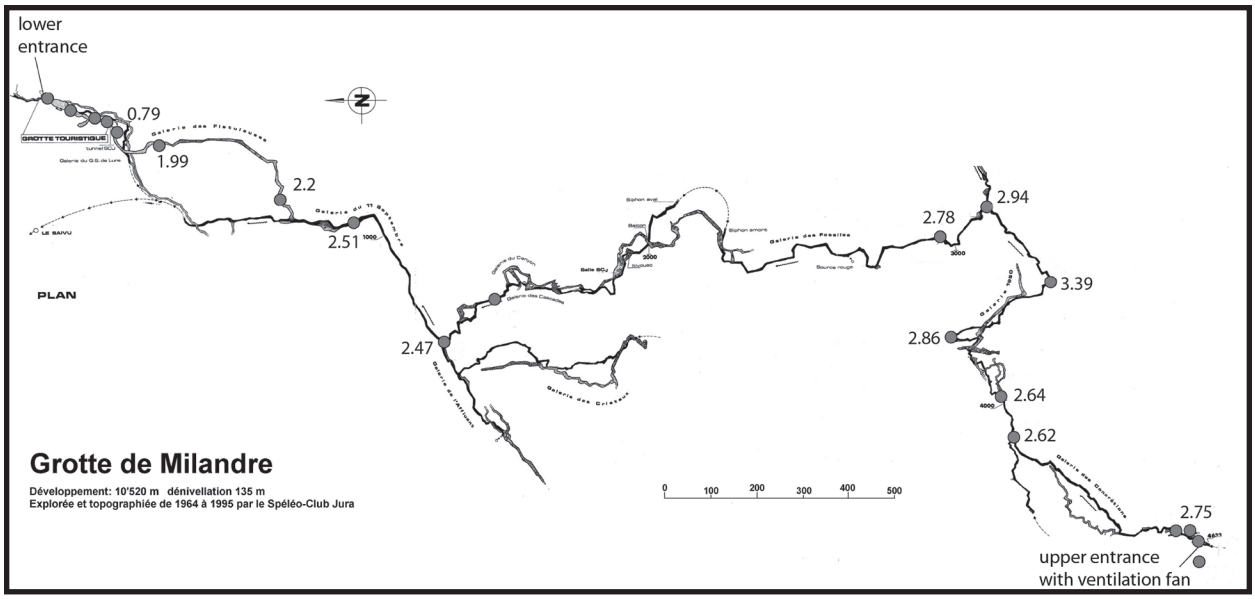

Figure 4: Approximate distribution of CO_2 concentrations in the Milandre Cave before the beginning of the ventilation experiment in September 2008.

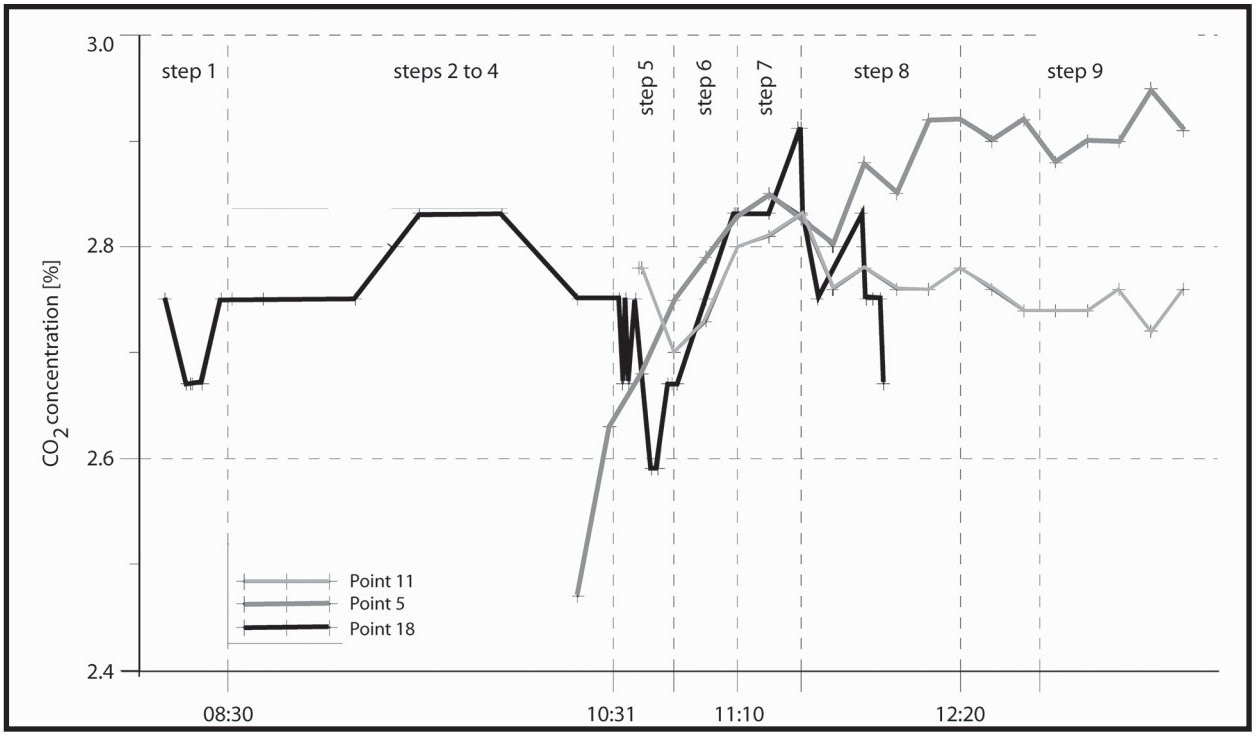

Figure 5. CO_2 concentration at three locations in the cave during the ventilation experiment. Point 18 is located at the upstream end of the cave, point 11 in the middle, and point 5 close to the downstream entrance.

Very high concentrations, up to 3.5% have been measured in December 10th. For this reason the visit in the cave has been cancelled and both doors have been opened. A new visit took place 7 days later and the CO_2 concentrations were all included between 0.4 and 0.75%. The effect of the ventilation was quite spectacular!

5. Interpretation

In September the cave temperature was higher than the outside temperature at the beginning of the experiment and lower at the end of the experiment. Assuming a "wind tube" behavior we should observe a reversal in the air draft direction. This was not observed and we can thus say that the cave does not behave as a simple "wind tube" with two entrances. Its reaction is obviously more complex.

For all steps of the ventilation experiment the propagation of the changes at the cave entrances was very quick through the whole cave (within a few seconds). This was already observed by Lismonde (1993 and 2002).

Obviously the downstream part of the cave was influenced by the input of fresh air (lower CO_2concentrations), over a distance of about 800 meters. This is fully compatible with the observed draft direction. From point 8 upstream concentrations increased up to a maximum a few hundred meters upstream from the Bure tributary. This observation supports the hypothesis that CO_2 could be produced by the biodegradation of the pollution brought by this tributary.

CO_2 decreases and increases observed at some fixed positions during the experiment can be explained by the displacement of the cave air over a distance of about 600 to 1200 meters. The air volume extracted from the upper entrance is about 30,000 m^3. The volume calculated from measurement points 10 and 4 were obviously smaller with about 5,000 m^3 at the lower entrance. This implies that air from side passages and fissures was sucked into the cave during the experiment. If we consider a conduit cross-section of 15 m^2, which is appropriate for many parts of the cave, the estimated air displacement of about one km is consistent with the estimated extracted volume and conduit cross-section.

This means that a total volume of 120,000 to 150,000 m^3 should be extracted from the upper entrance to "refresh" the air of the whole cave. This would correspond to about 5 hours of artificial ventilation and to 24 to 48 hours of natural ventilation.

6. Conclusions

The experiments conducted in 2008 make it possible to say that the cave can be successfully ventilated in order to improve the air quality in case of pollution. It takes about 5 hours with an artificial fan to suck air out of the cave and it takes one or two days by simply opening the doors at both ends of the cave.

Both entrances are artificial and in its natural state the cave was therefore not strongly ventilated. We thus want to solve the CO_2 (pollution) problem in order to close the doors again because the impact of the ventilation on the cave atmosphere is obviously significant.

Further data are being recorded in order to better understand the climate of the Milandre cave.

Acknowledgement

This study is part of an investigation concerning the impact of the freeway (A16) construction on top of the Milandre Cave. We thank the federal and canton road services who support us for minimizing the impact and make those studies.

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CAVE AND KARST CONSERVATION AND MANAGEMENT IN SWITZERLAND

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Cave and karst protection has to be initiated by the cavers, because they are specialists for that topic. Therefore the Swiss Speleological Society (SSS) has approved a program in 1997 for the conservation and protection of the Swiss caves and karst areas. This program focuses on three different parts:

1. Prevention: The commission for cave and karst protection of the SSS promotes sensitivity and has an active relationship with the cavers and the caving clubs. The main goal is to use the media, teach lessons in schools, present public talks to inform the population as a whole, and also to contact directly politicians and the government on all levels.
2. Supervision and classification of caves: Not all caves and karst areas need protection in a similar way. If schemes for classification are based on objective arguments, they are also accepted by the government and other non-governmental organizations (NGOs). If problems were to be noticed during the supervisions or due to a construction project, the Swiss legislation would allow several possibilities for NGOs to interfere.
3. Restoration: the communities and the cantons are obliged by the federation to restore contaminated sites. The government subsidized the last few years several projects for restoring and cleaning caves. Actions for cleaning caves have also been done by cavers for free and benevolently.

The application of this program is a major task of the commission for cave conservation of the Swiss Speleological Society. In order to prioritize real improvements of the situation in the field, 13 regional groups have been created in Switzerland. Each group is composed of active cavers and has to establish contacts with the local authorities, has to advertise on this topic, has to supervise and classify caves and karst in its region, and finally has to organize cleaning or restoration actions for specific caves (or dolines). Regional groups are encouraged and supported by a committee and by the Swiss Institute of Speleology and Karstology. This structure is financially supported by the Swiss Government.

An important lesson learned with this experience is that it took about 1 year to set up a concept accepted by all Swiss cavers. It took another year to define a strategy to decide how this concept could be realized. Then it takes 5 to 10 years to establish the necessary contacts and information to obtain real results in the field.

1. Introduction

About 20% of Switzerland is covered by karst terrains. Karst represents a very significant part of groundwater and is the only water resource in some parts of the country. Karst landscape and biotopes are also recognized as highly valuable. However, most administrations and organizations do not really care about caves and karst, mainly because their knowledge of the specific character of karst regions is too low. Thanks to some karst specialists (cavers and hydrogeologists) working at the national geological survey a method was developed for the delineation of groundwater protection areas (EPIK-method, Tripet et al. 2004, Doerfliger et al. 1999). However, other aspects of cave and karst protection had to be initiated by the Swiss speleological Society (SSS/SGH). In 1997 this Society has approved a program for the conservation and protection of Swiss caves and karst areas (Bitterli & Arbenz 1997). This program focuses on three different parts:

1. Prevention
2. Supervision and classification of caves and karst landscapes
3. Restoration

Based on this document a strategy was designed in order to achieve the goals of this program and the commission for cave and karst conservation of the Swiss Speleological Society was reorganized. The strategy and reorganization are described in a new document (ISSKA 2000), which is now being applied since about 10 years. This paper presents some aspects and results obtained in this context.

2. Prevention: Goals, Actions and Results

Public authorities, environmental experts or agencies and politicians do not know much about caves and karst. One major reason for that is that this topic is not taught in schools, high schools and universities. The main goal of the "prevention" aspect of our actions is to inform the public in a broad way as well as the authorities in a more targeted way.

To reach this goal we developed a teaching section, which is in charge of organizing public courses, conferences and excursions and to provide didactic material for teachers. We also regularly inform the media about caves and karst in order to reach a large public as well as the politicians. A more direct and targeted action was also undertaken. We convinced the national environmental authority to support our action. The aim was to establish contacts all over Switzerland with local authorities in charge of nature, landscape and water. We visited about 20 authorities of the 26 states (cantons) of Switzerland. All of them were interested in learning about karst and caves and some of them were directly open to support our action. We also talked to politicians and invited them to some special actions in order to try to improve or modify some laws (Fig. 1).

After about one decade of activity we can say that many things, which seemed almost unthinkable 10 years ago are now becoming reality. For example, some cantons voted new laws dedicated specifically to cave and karst protection. Politicians took part to some actions and realized that this

Figure 1: A canton minister in charge of the environment taking part to the placement of a "prevention" board on the edge of a doline.

part of the Nature needs protection. Some also decided that polluted caves and dolines should belong to the past and support many cleaning actions. There is still much to do in order to reach the same "level of awareness" in all regions, but we are on the right way.

We are currently writing a concept for the evaluation of the impact of any project on karst and caves. We will then make this concept a reference for any authorities in Switzerland. This will take another 10 years for this concept to be recognized and applied...

3. Supervision and Classification of Caves: Goals, Actions and Results

The aim of this group of activities is to know the state of existing caves and dolines, to prevent caves against degradations related to new constructions or human activity and to asses which caves (or karst landforms) are the most valuable, sensitive and endangered.

The main action is to visit all caves (or dolines) and to report about their status. After each visit a database is filled up with the evolution of the cave. A list of sites to be visited twice or once a year, or every 2 to 5 years is created. This evaluation considers essentially the pollution or degradation degree of the objects. If a new degradation is observed, a short investigation is undertaken to look for its origin. Most of the time authorities are warned, and a procedure is started in order to encourage the guilty person to remediate.

Another action is to prevent site degradation before it happens. In Switzerland any construction project has to be announced and can be contradicted. The Swiss Speleological Society (SSS) has the right to contradict projects, which could degrade caves and karst. Therefore a series of people within SSS are in charge of carefully reading official journals where projects are announced,

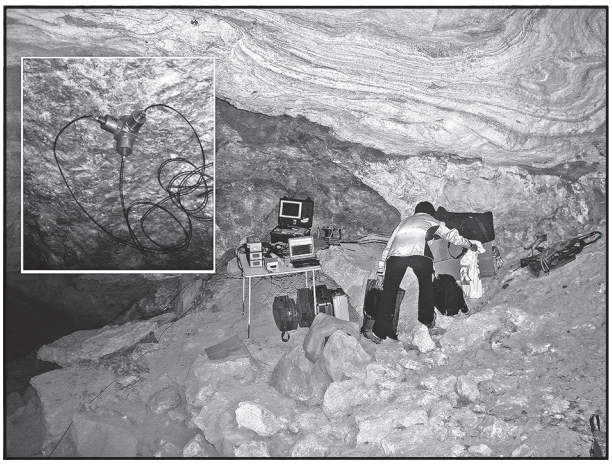

Figure 2: Shaking tests carried out in order to delineate the protection perimeter around a cave endangered by the expansion of a quarry. SSS could convince the owner of the quarry to make appropriate investigations for protecting the cave from destruction.

Figure 3: Typical cleaning action carried out by SSS and SISKA (left: before, and right: after the cleaning up of about 20 m3 of garbage. Between 2004 and 2008 about 100 polluted sites have been cleaned up within the framework of our national program.

and to claim in case a cave or a karst system is potentially concerned. A group of expert of the SSS then assesses the risk and, depending on the assessment, a "veto" is sent to the authorities. This forces the project leader to handle with SSS for decreasing the impact of the project on caves and karst to a reasonable minimum (Fig. 2).

In some cases SSS, with the help of SISKA has to conduct a so-called "impact-study" for a more detailed assessment of the effect of a project onto caves and karst. SISKA also provide advises for the management of one specific cave, or of a larger karst area.

Another type of actions in this group of activity is the evaluation of "speleological geotopes". SSS defined a concept for the evaluation of the patrimonial value of cave and karst objects. The evaluation is mainly based on the existing documentation of caves (or of other karst objects). This requires specialists. A list of sites of national significance has already been completed (about 40 sites of a pre-selection of more than 400).

In regions where this strategy has been steadily applied over more than five years, we can observe that most problems are becoming "under control". This does not mean "solved" but at least managed by the authorities together with cavers, in a way to find an appropriate solution within the next two-three years. An overview about the patrimonial value and the management schemes of all karst objects was established, and specific management rules and measures were established for the most sensitive objects.

4. Restoration: Goals, Actions and Results

This type of actions corresponds to work in the field. The aim is mainly to clean up sites, which are polluted or degraded. In Switzerland we assess the number of polluted karstic sites to about 800 to 1,000. About 75% are small sites with less than 10 m^3 of garbage. The largest ones are in the order of 1,000 m^3. These are all "unofficial" repositories dispersed all around within the landscape. There is probably between one and two hundred further "official" repositories with garbage volumes up to several hundred thousands of m^3.

By law, all sites in Switzerland were listed and documented between 1990 and 2005. The next action is the investigation of selected sites in order to demonstrate their impact on the environment. Concerning karstic sites, on the one hand the link with groundwater is evident for most sites, and on the other hand, investigations to demonstrate their impact on the environment are more expensive than their cleaning up. Thus we can manage to clean up most sites.

About 100 sites have been cleaned up between 2004 and 2008 in Switzerland (Fig. 3) and 20 to 30 sites will be cleaned each year over the next 3 years, and hopefully further. In this context we expect to clean up most polluted karstic sites in Switzerland over the next 20 years.

SISKA, which is directly related to the Swiss Society of Speleology conducts many actions by himself. Often young people having to accomplish a civil service for the Country (instead of military service) can be employed for this task. This makes those cleaning action not too expensive and thus increase the number of sites which can be cleaned up.

5. Structure and Organization

The Swiss Speleological Society (SSS) has about 1000 members. Since several decades it encloses a commission for the conservation of karst and caves. After the International Congress of Speleology held in La Chaux-de-Fonds in 1997,

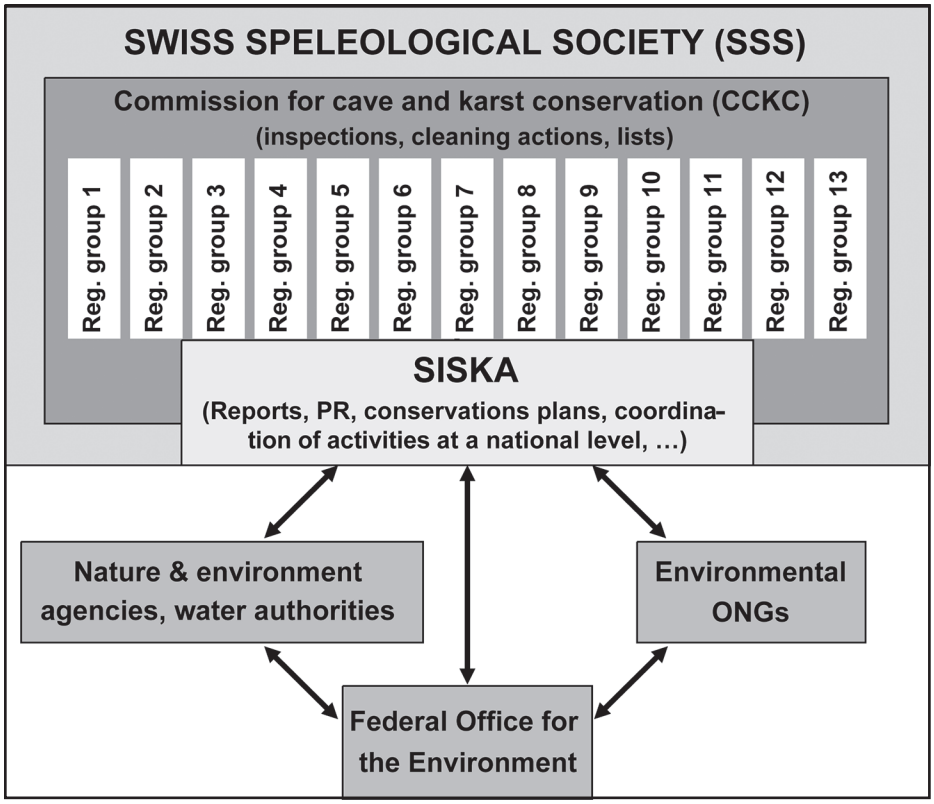

Figure 4: The structure in charge of the conservation of karst and caves in Switzerland. The Swiss Speleological Society with its commission for the conservation of karst and caves and its 13 regional groups work in a direct collaboration with SISKA (Swiss Institute for Speleology and Karstology). Contacts with authorities and NGOs are being established in order to reach real improvements concerning cave and karst conservation in the field and in the Society.

it was decided to create a "Swiss Institute of Speleology and Karstology (SISKA)" in La Chaux-de-Fonds. From the beginning on one task of this institute has been to support the SSS in some activities, especially in cave conservation because this task was clearly beyond the scope of a pure volunteer work.

As a result the commission was restructured is now made up of 3 entities (Fig. 4):

1. Volunteers working in regional groups (13 groups for the whole Switzerland)
2. Group leaders together with the commission president forming the committee of the commission
3. SISKA staff with some people working on more administrative and coordination tasks (general secretary) and others mainly on the organization and success of cleaning actions. SISKA also supports some activities of the regional groups, when special duties or competences are required.

Most decisions are taken within the committee of the commission. On the one hand it supervises the activity of the regional groups as well as actions carried out by SISKA.

This structure is fully developed in some regions, where regional groups are active in all aspects described in the first part of this paper. In many regional groups, however, the activity is still low to moderate. By the way, it tends to expand year after year.

A major task of SISKA and/or regional groups is to establish contacts local authorities in order to be officially recognized as an organisation for the protection of caves and karst. Contacts are also established with non-governmental organizations (NGOs) in order to organize collaborations when it is useful. The whole structure is financially supported by the federal office for the environment and some local groups are supported by local authorities. In theses cases the activity of the local group is strongly enhanced and the recognition of our work too. We hope to be able to expand this type of collaboration with a financial support from the local authorities to most part of Switzerland.

6. Conclusions

The application of this program (prevention, supervision and restoration) is a major task of the commission for cave conservation of the Swiss Speleological Society. After almost 10 years of field actions and information for the public and authorities we are proud to see that much progress has been done. The number of cleaning actions is considerable and we can reasonably think that most polluted caves and dolines will be cleaned up within the next 20 years.

However, there is still much to do in order to protect caves

and karst in a more homogeneous way over the whole Switzerland. Also an effort has to be dedicated to expand our inventory of sites with a patrimonial value and to manage those sites in a proper way. We are now starting to produce a new concept for the defining the limit of acceptance for any project impacting a cave or a karst landform. A wide variety of projects is being considered: road construction, hydropower plant, factory construction or even scientific activities (e.g. speleothem sampling).

An important lesson learned from the experience of the last 10 years is that it took about 1 year to set up a concept on cave & karst conservation accepted by the Swiss Speleological Society. It took another year or two to define a strategy in order to decide how this concept could be applied. Then it takes 5 to 10 years to establish the necessary contacts and information to obtain real results in the field.

More information (in French and German) is available at: http://www.speleo.ch/commissions/protection/index_fr.php.

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KARST FEATURES DISCOVERED DURING MOTORWAY CONSTRUCTION

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One of the major ongoing projects in Slovenia is to link the country with modern expressways. Almost half of Slovenia is karst and more than half of its supply of water comes from karst aquifers. Slovenia is the home of the Classical Karst region, which gave its name to numerous world languages for the type of landscape that develops on carbonate rock and where the science of karstology began to develop. Comprising an important part of our natural and cultural heritage, the sensitive karst landscape demands from us good knowledge and serious effort for its preservation.

Since 1994, Slovene karstologists have cooperated closely in the planning and construction of expressways in karst regions. With the consideration of the integrity of the karst landscape in the foreground, we have recommended avoiding more important areas of karst phenomena (sinkholes, poljes, collapse dolines, karst walls, etc.) and already known caves in the selection of routes for expressways and railway lines. We have devoted special attention to the impact on karst waters of building and using the expressways. Expressway should be impermeable. Water from the road surface is first collected in oil separators and then released clean into the karst. We have also studied the pollutants in the water that flows off the expressways everyday.

Construction work has provided a series of important discoveries about the formation of karst and its development on various bedrock, in different conditions and through various processes. We have studied the karst along expressways between towns Razdrto, Kastelec, and Fernetiči (southwest Slovenia), the central part of the Dolenjska karst region (south Slovenia), and the young karst in the Vipava Valley (southwest Slovenia). This selection of sites includes the most important areas of our karst regions. We have acquired a great deal of information about surface karst phenomena and the epikarst, and where excavation work has cut deeper in the surface and in tunnels about the vadose zone and the paleokarst. Everywhere the development of the karst left important traces, above all in the numerous old caves. More than 350 new caves have been opened.

The regular research of karst features revealed during the construction of expressways has enriched our knowledge of the natural and cultural heritage and deepened karstological knowledge. The research results are also a starting point for spatial planning in karst areas and for protecting the karst landscape.

1.Introduction

One of the major ongoing projects in Slovenia is to link the country via modern expressways. Almost half of Slovenia is karst and more than half of its supply of water comes from karst aquifers. Slovenia is the home of the Classical Karst region, which gave its name to numerous world languages for the type of landscape that develops on carbonate rock and where the science of karstology began to develop. Comprising an important part of our natural and cultural heritage, the sensitive karst landscape demands from us good knowledge and serious effort for its preservation.

Since 1994, Slovene karstologists have cooperated closely in the planning and construction of expressways in karst regions (Knez & Šebela, 1994; Šebela & Mihevc, 1995; Slabe, 1996, 1997a, 1997b, 1998; Mihevc & Zupan Hajna, 1996; Mihevc, 1996; Kogovšek, Slabe, Šebela, 1997; Mihevc, Slabe, Šebela, 1998; Šebela, Mihevc, Slabe, 1999; Knez & Slabe, 1999, 2000, 2001, 2002, 2004a, 2004b, 2005, 2006, 2007). With the consideration of the integrity of the karst landscape in the foreground, we have recommended avoiding more important areas of karst phenomena (sinkholes, poljes, collapse dolines, karst walls, etc.) and already known caves in the selection of routes for expressways. We have devoted special attention to the impact on karst waters of building and using the expressways. Expressway should be impermeable (Fig. 1). Water from the road surface is first collected in oil separators

and then released clean into the karst. We have also studied the pollutants in the water that flows off the expressways everyday.

Figure 1: Construction of motorway. Representation of cave, rock scarps, and tubes for water collection from road.

2.Expressway Construction in Slovenia

Construction work has provided a series of important discoveries about the formation of karst and its development on various bedrock, in different conditions, and through various processes. We have studied the karst along expressways between Razdrto, Kastelec, and Fernetiči (southwest Slovenia), the central part of the Dolenjska karst region (south Slovenia), and the young karst in the Vipava Valley (southwest Slovenia). This selection of sites includes the most important areas of our karst regions. We have acquired a great deal of information about surface karst phenomena and the epikarst, and where excavation work has cut deeper in the surface and in tunnels about the vadose zone and the paleokarst. Everywhere the development of the karst left important traces, above all in the numerous old caves. More than 350 new caves have been opened (Fig. 2).

In the karst region of western Slovenia we have studied surface karst phenomena such as dolines and karren. The numerous newly opened caves (Fig. 3) have revealed the perforation of individual parts of the aquifer. These include old caves that today are dry since they are located high above the water table and caverns through which water flows from the permeable karst surface to the aquifers below. A good part of the caves is filled with alluvial sediments. In combination with other speleological features, patterns of cave networks and their parts, and subsoil rock forms, these sediments helped to determine important periods in the formation and development of caves and their age. Paleomagnetic determination of the age of sediments assists us here. The oldest sediments probably filled the caves after the Messinian crisis and are therefore more than five million

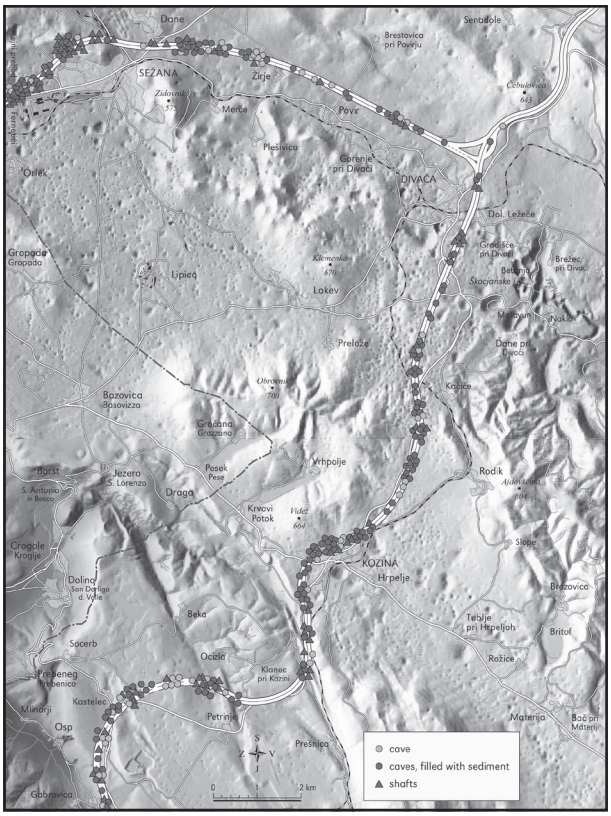

Figure 2: Caves discovered during expressway construction in west Slovenia.

years old (Bosak et al., 2000). We can therefore rank them among our oldest caves, and their age exceeds our previous estimates. The opening of unroofed caves also provided important information, as we discovered that these traces of the development of the aquifer helped form the karst surface much more than we previously suspected. Unroofed caves, which are the consequence of the lowering of the karst surface, comprise a new form that we have added as a unique form to the international list of karst forms**.** On the majority of karst surfaces overgrown with forest, traces of human

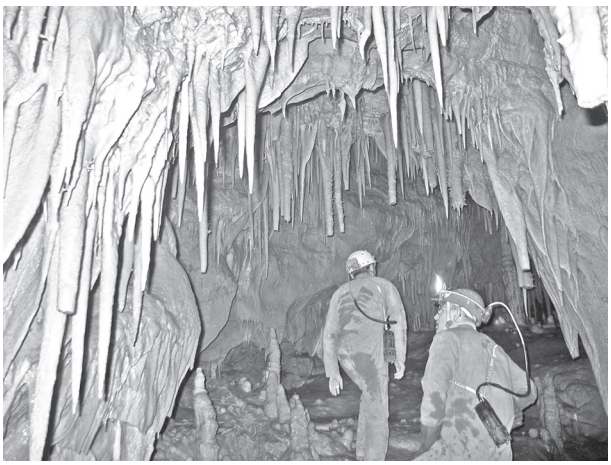

Figure 3: Cave in the tunnel below the motorway.

activity have been discovered, the history of their former intensive exploitation, primarily for agriculture and water supply.

Construction work on the low and largely alluvium-covered Dolenjska karst primarily revealed the subsoil shaping of the karst. Here we can find subsoil stone forests (Fig. 4) and subsoil shafts, forms first comprehensively recorded in Slovenia's karst region in all their glory and eloquence. Large areas of stone forests with their characteristic subsoil rock forms have revealed all the wealth of the subsoil

Figure 4: Subsoil stone forest in south Slovenia.

shaping of karst surfaces. The water that penetrated through the soil and sediment uniquely shaped the different carbonate rock. Consolidated subsoil streams of percolating water carved subsoil shafts, hollows that are similar to empty shafts but more or less completely filled with alluvium.

Excavation work building the expressway through the Vipava Valley provided a unique discovery. Here the karst formed in young breccia that developed from the consolidated slope rubble below Mount Nanos. With the percolation of water from the surface, sinkholes of similar shape began to form. Many types of caves were

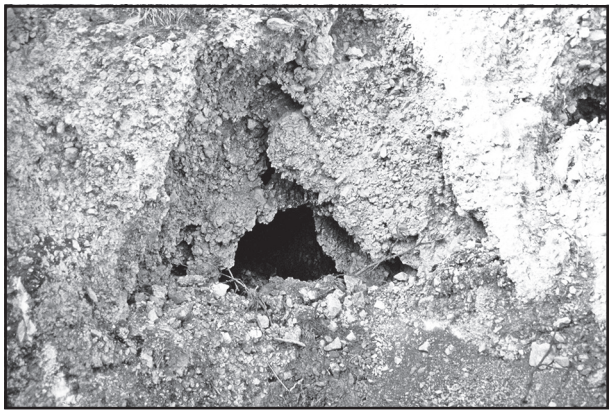

Figure 5: Cave in breccia.

discovered. Smaller caves characteristic of karst developed in the most consolidated parts of the breccia and larger caves formed at the contact with the flysch that lies below the breccia (Fig. 5). The majority of water also flows at such contacts. Fissure caves are the consequence of stresses in the slope breccia that lies on inclined flysch bedrock.

3. The Preservation of Caves and New Knowledge about the Development of Karst Gained During Expressway Construction

We tried to preserve as many caves as possible. Shafts were the easiest to preserve since we simply closed their smaller entrances with concrete slabs (Fig. 6). It was possible in a similar fashion to preserve old caves whose

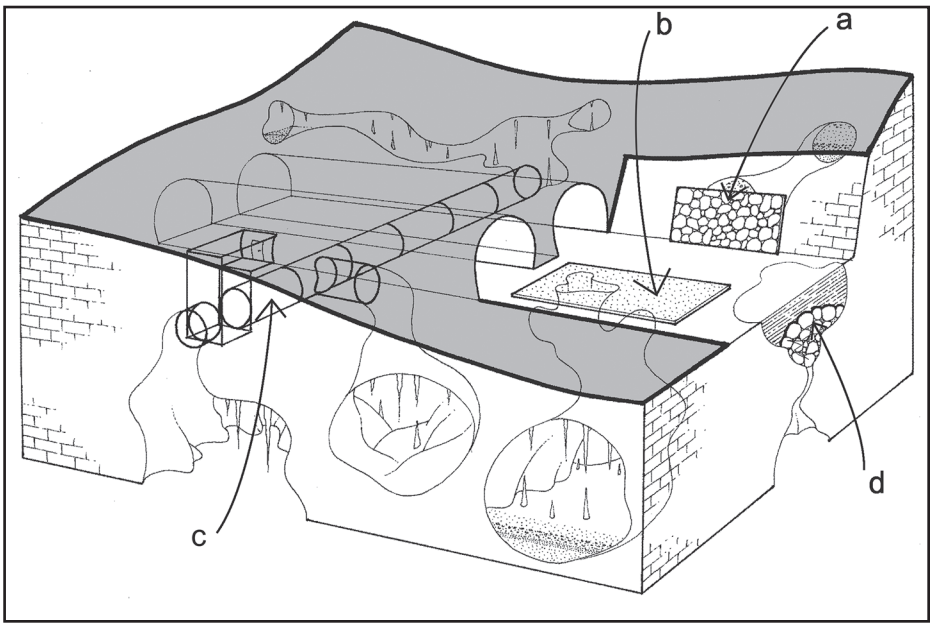

Figure 6: Preservation of caves. a: in road cuts the caves are hidden behind rocky scarps, b: the caves lying below the road with narrow mouth and if their rim is not too much damaged by blasting are covered by concrete lids, c: in the side of the tunnel pipe there is a special door leading to the caves. Below traffic belt caves are connected with large concrete pipes, d: karst openings (bottom of dolines, tops of shafts) are often reinforced by arches of big rocks poured over by concrete.

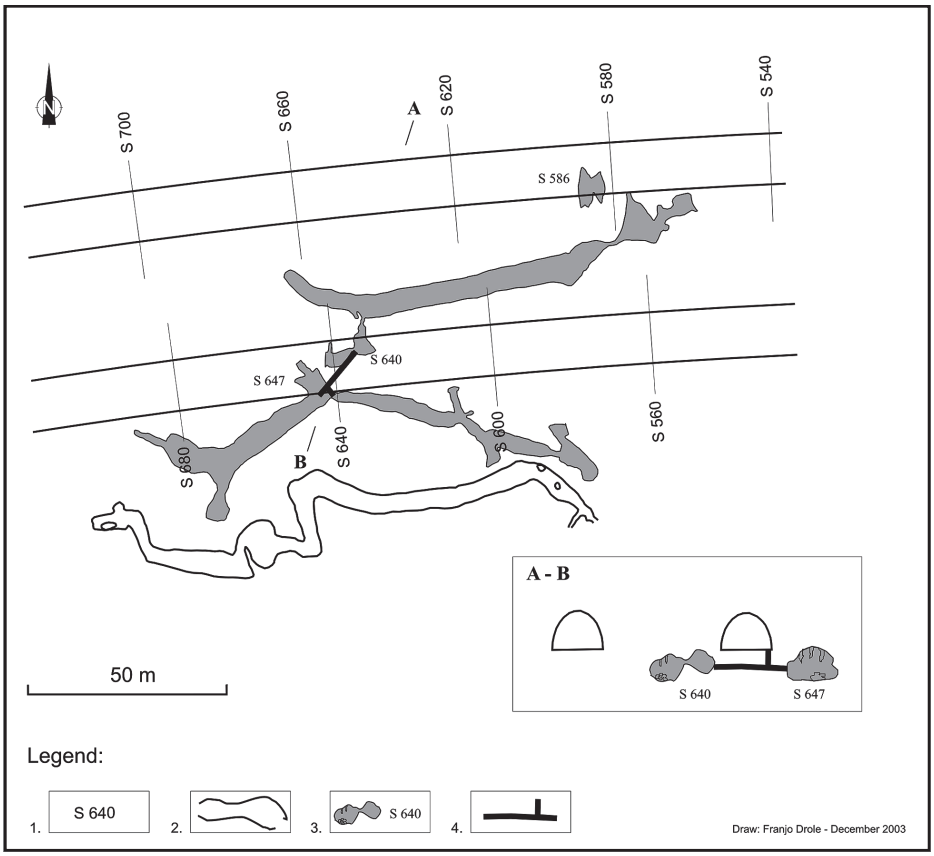

Figure 7: The expressway lay-out with newly discovered caves. 1: profile, 2: cave known before construction accessible from the surface, 3: newly discovered cave accessible from the tunnel, 4: concrete tube connecting newly discovered cave and tunnel.

circumferences were solid. However, caves opened due to blasting and located in perforated rock had to be reblasted and filled in. Caves split by road cuts whose entrances were in the embankments were closed with rock walls. Their circumferences were too fractured and therefore they were unsuitable for further visiting. Furthermore, water could carry clay from caves filled with alluvia and deposit it on the road. One well-preserved cave was left open for viewing by visitors crossing the border with Italy. The most interesting and well-preserved caves were protected completely, even though they are under the expressway (Fig. 7). These are accessible through concrete pipes closed with locked grids beside the road. We also studied the consequences of various types of blasting in caves, which will help in future construction and the preservation of karst phenomena.

The unroofed cave is a special and frequent karst form. Today, this significant karst surface feature is a familiar phenomenon, but it had not been thoroughly studied before the construction of the expressway across Kras. Great attention was devoted to unroofed caves since the occurrence of this phenomena turned out to be considerably higher than previously expected, and a number of articles on unroofed caves and the construction of new expressways are now available (Knez & Šebela, 1994; Slabe, 1998; Mihevc, 1996; Mihevc, Slabe, Šebela, 1998; Šebela, Mihevc, Slabe, 1999; Knez & Slabe, 1999, 2000, 2001, 2002, 2004a, 2007). Unroofed caves are also an important part of the epikarst and an outstanding trace of the development of the karst aquifer.

A great proportion of the caves were filled with alluvia. In most cases, these were inundations of fine-grained flysch alluvium with intervening layers of gravel. We took alluvia samples for paleomagnetic research from caves at Kozina and Divača and discovered they were older than the top of the Olduvai chron. We conclude that the caves were formed before the Messinian phase and to a large extent were filled with alluvia after the refilling of the Mediterranean basin with water approximately 5.2 million years ago (Bosak et al., 2000) when the groundwater level in aquifers around the Mediterranean Sea rose relatively rapidly and high. We are studying the oldest preserved periods of karstification in Kras—not counting paleokarst, of course—and establishing that the oldest caves in Kras are much older than karstologists previously thought. In pockets of paleokarst dated during the Upper and Lower Cretaceous periods, the remains of dinosaurs and numerous other animals from that period have been found.

The karst surface and epikarst that developed over the traces of older periods in the development of the karst are typically formed on different bedrock. On Cretaceous limestone, karren often occurs with distinct subterranean fissures below it; on Paleogene limestone, however, the surface is more smoothly rounded and in some places covered with rubble that originated due to the disintegration of the surface in the Pleistocene epoch, and the rock, although most often fractured more densely, is crisscrossed with fewer distinct

fissures. Some of the caves are filled with rubble as well.

4. Conclusions

The regular research of karst features revealed during the construction of expressways has enriched our knowledge of the natural and cultural heritage and deepened karstological knowledge. In any case, the construction work assisted by karstologists has exposed karst features and presented and preserved them for further study. The research results are also a starting point for spatial planning in karst areas and for protecting the karst landscape.

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SHILIN-LITHOLOGICAL CHARACTERISTICS, FORM AND ROCK RELIEF OF THE LUNAN STONE FORESTS (SOUTH CHINA KARST)

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Stone forests are unique karst surface landforms. The Lunan stone forests developed from underground karren, and where this type of surface is highly developed in China, it is defined as a "shilin" landscape.

Numerous examples of stone forests (shilin) that developed in almost identical conditions show that the diverse shape of the pillars is primarily a consequence of the properties of the rock, the distribution and density of joints and fissures in the rock, and its diverse stratification and composition.

The Lunan stone forests formed in early Permian carbonates of the Qixia and Maokou formations. Characteristic of these are frequent alternations of very pure limestone, dolomitized limestone and dolomite, the alternation of thin and thick layers, and in some places distinctive late diagenetic dolomitization and secondary porosity. The layers are mostly horizontal or inclined by five to ten degrees. Due to vigorous tectonic action, they are fractured by numerous vertical and subvertical joints and fissures.

The diverse fracturing, stratification, and rock composition are reflected in the shapes of the stone forests and their stone pillars. In the same stone forest, which developed on diversely composed rock, pillars may be of various but typical shapes, the consequence of their development on different levels of a diverse rock column.

The shape of stone pillars occurring on thicker and uniformly composed rock strata reflects primarily the development from subsoil karren into a stone forest, and the traces of subsoil factors are gradually reshaped by rainwater. Cross sections of stone pillars occurring on thin rock strata are often jagged, and their tops (even of thinner pillars), which as a rule are pointed, are often flat, the consequence of the rapid disintegration of thin strata. Porous rock strata are most often perforated below the ground and disintegrate faster on the surface; the pillars are therefore narrower and the tops on such rock have no characteristic shapes. More resistant rock strata protrude from the cross section. The tops of the narrower pillars are sharp, sharpened as much by subsoil factors as by rainwater. The broader tops, however, are dissected by points and funnel-like cups.

Because of the exceptional characteristics of this karst phenomenon in China, we propose that the term "shilin" be used for this type of stone forest in the professional literature. Good knowledge of the origin and development of shilin and its presentation was one of deciding factors for UNESCO to add this exceptional landscape on their list World Heritage treasures.

1. Introduction

Stone forests are unique karst surface landforms (Fig. 1). The Lunan stone forests developed from underground karren. Where this type of surface is highly developed in China, it is defined as a "shilin." The extensive stone forests composed of many several-meter high pillars are an international tourist attraction, and to karstologists they offer a unique insight into the formation of karst landscapes. The development of stone forests has been presented many times (Ford et al., 1996;), and the descriptions of their forms even more often (Song Lin Hua, 1986; Huntoon, 1997; Chen Xiaoping et al., 1998; Maire et al., 1991; Yuan Daoxian, 1997; Zhang Faming et al., 1997; Knez and Slabe, 2001a; 2001b; Šebela et al., 2004). Increasing emphasis has also been placed on the study of anthropogenic influences on the karst landscape and on its protection (Kranjc and Liu Hong, 2001). The development of some caves under the stone forests and their influence on the formation of the forests has also been

examined (Šebela et al., 2001). This article compiles our current knowledge about the formation of stone forests and their rock relief, which are the result of the way the rock was formed, and of characteristic processes on various carbonate rock.

Figure 1: Stone forest as a unique landforms on karst surface landscape.

The core of this article is the effect of the close interdependence of stratification, fissuring, and composition of the bedrock with various processes in diverse conditions in the formation of the karst landscape, and is illustrated by the accompanying figures. The prevailing process of karst formation is the dissolution of soluble rock in different conditions and by different factors. With the formation of stone forests, the most important variable factors are dissolution of rock below the ground by soil water and vegetation, and dissolution above the ground from rainwater. Most dissolution occurs below the soil where organic substances increase the rate of carbon dioxide production (Urushibara-Yoshino and Miotke, 1999). Of course, the resulting morphologies offer a general insight into the interweaving of the diversity of stone forest forms and the pillars that comprise them. The rock relief of the stone forests reveals subsoil processes, the hollowing of the rock by rainwater, and the diverse transformation of subsoil rock forms later by rainwater.

2. Geology

The stone forest area consists of early Permian carbonates of the Qixia and Maokou formations. These are two of the most important basal formations from which numerous stone forests emerged in the southern Yunnan province of Lunan. Typical for Qixia formations are micrite limestone with intercalated dolomite and dolomitized limestone with intervening layers of shale. In the lower part of Maokou formations, limestone alternates with dolomite and dolomitized limestone. In the upper part we find a succession of limestone layers that in some places are thin and in others several meters thick, as well as solid limestone that contains several-decimeter large nodules of chert in individual horizons. The main lithologic properties of the Maokou formations are roughly similar to those of Qixia formations, except that in Maokou carbonates we do not find a major influence of late diagenetic dolomitization and in some places a considerable secondary porosity. However, both show a strong diagenetic alteration of the basic rock, which is undoubtedly also a consequence of intensive volcanic (basalt lava) activity during the transition from the Paleozoic to the Mesozoic Era. The rock contains an extremely high percentage of carbonate.

3. The Formation of Stone Forests

Effectively horizontal layers of rock of various thickness and composition are crisscrossed by vertical fissures or cracks. Each of these features can have an important influence on the formation of the network of pillars in a stone forest, on their size and shape, and consequently on the rock relief as well. They interact in various combinations, fostering a vast diversity of stone forests. As a rule, however, one of the following features of the rock or factors of their shaping is dominant:

- the influence of rock fissuring on the shape of the forest and size of stone pillars
- the influence of rock strata on the shape of stone pillars
- the influence of rock composition on the shaping of stone pillars
- the influence of subsoil factors on the shape of the stone forests.

Exposed subsoil karren is reshaped by rainwater. The long-lasting development of stone forests allowed the creation of large karst forms. Due to the development of caves beneath the forests and the erosion of alluvium and soil that previously covered the carbonate rock, exposure takes place faster than the dissolving of rock by rainwater.

3.1. Fissuring of rock and its influence on the shape of the forest and size of stone pillars

The networks of distribution of the pillars, that is, the ground plans of the stone forests, are congruent with the fracturing of the rock, which are mostly vertical. Various distribution patterns can develop. The pillars can be linked in rows between distinct fault areas or close together, or the stone forest or parts of it can consist of individual wide or narrow pillars. Cracks between the pillars may be corroded to various widths ranging from a few centimeters to >10

meters. This diversity in the network of pillars can occur in the same forest, as for example in the Naigu forest (Fig. 2). As a rule, pillars with smaller cross sections occur within a dense network of fissures (provided, of course, they are not diminished primarily by corrosion) and larger pillars occur within a sparser network. The latter, which can often be described as larger rock masses, have broader tops dissected into several points on thickly-stratified rock.

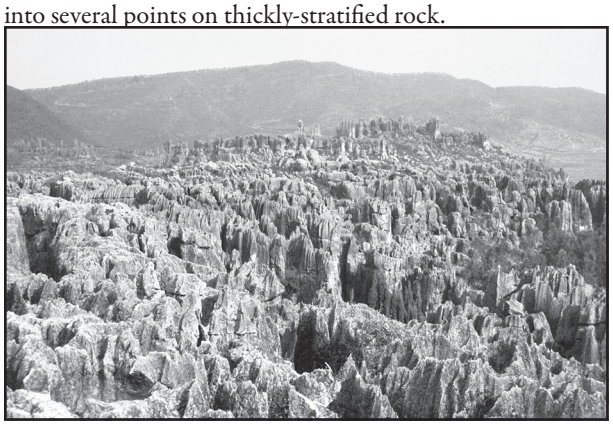

Figure 2: Naigu stone forest.

3.2. Rock strata and its influence on the shape of stone pillars

The rock from which the stone forests developed consists of strata of different thickness and composition. This is reflected in the shape of the stone pillars, particularly in their cross sections, the shape of their tops, and their rock relief. The shapes of pillars that develop on thick and uniformly composed rock strata show hardly any influences but rather reflect a more or less uniform development from subsoil karren to stone forest. The central part of the Lunan stone forests is an example. Narrower pillars have pointed or blade-like tops and relatively flat or subsoil undercut walls. Wider stone pillars, however, often have broad tops dissected into many points with notches between them.

Longitudinal sections of pillars on thin rock strata (e.g., Pu Chao Chun) are often jagged since they are dissected by wall notches occurring along the bedding planes, or their shapes reflect the uneven resistance of the different rock strata to the factors of their formation (Fig. 3). Cross sections of the pillars are of various sizes and shapes. Thinner strata disintegrate faster and therefore the pillar tops are relatively flat and have a typical rock relief. Where the strata are thinner, as a rule, the pillars are narrow. Subsoil tubes along bedding planes can develop into subsoil channels when they occur on the top of a stone pillar or be reshaped by rainwater.

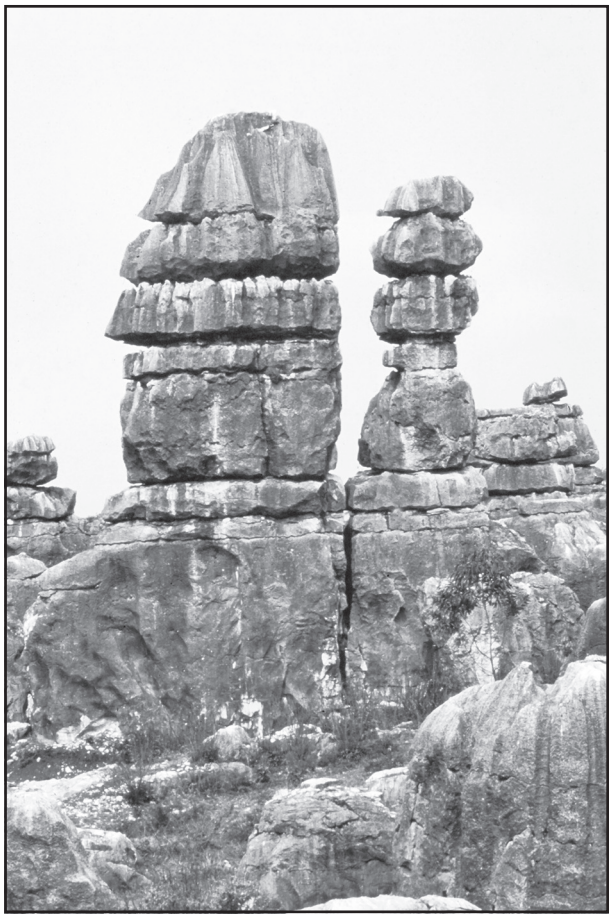

Figure 3: Pu Chao Chun stone forest where rock strata play an important role.

3.3. Rock Composition and its Influence on the Shaping of Stone Pillars

Rock composition, particularly if it is diverse, may decisively influence the shape of the stone pillars, as much their longitudinal sections as the size of the cross sections. Porous strata are often perforated below the ground and disintegrate more rapidly on the surface as a result (e.g., Naigu, Lao Hei Gin). Pillars are most narrow at the level of porous strata (Fig. 4). Above them occur forms typical of overhanging walls and below them, gently sloping walls. The pillars break fastest along these strata. The tops of pillars occurring on such rock are most often of irregular shapes.

Rock strata with less soluble components usually protrude from the walls. If they are at the top, the tops are broader than the lower parts of the pillar and the pillars acquire characteristic mushroom shapes. These are particularly distinct if the pillars occur on rock whose lower strata are relatively more soluble, porous, or disintegrate rapidly (e.g., Naigu).

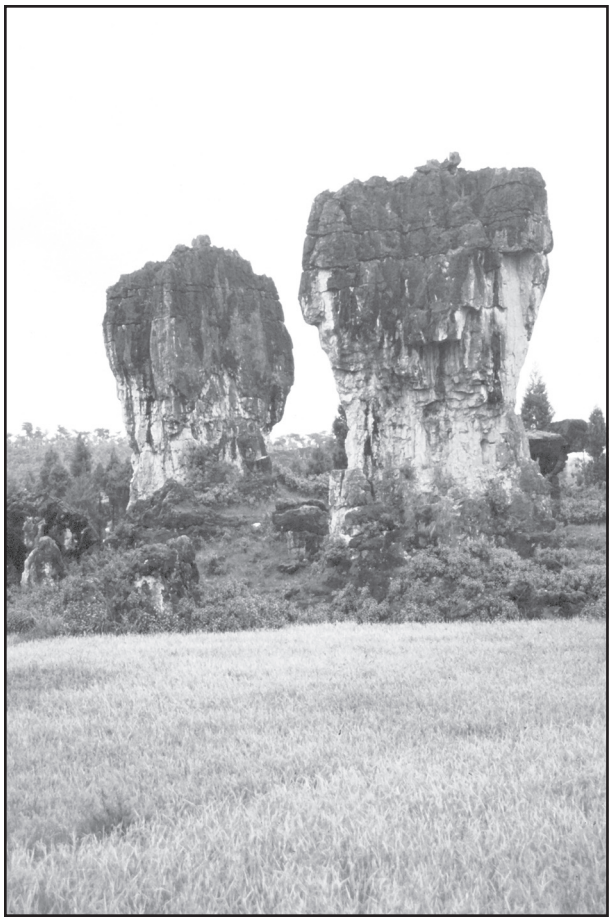

Figure 4: Lao Hei Gin stone forest. Rock composition decisively influenced the shape of stone pillars.

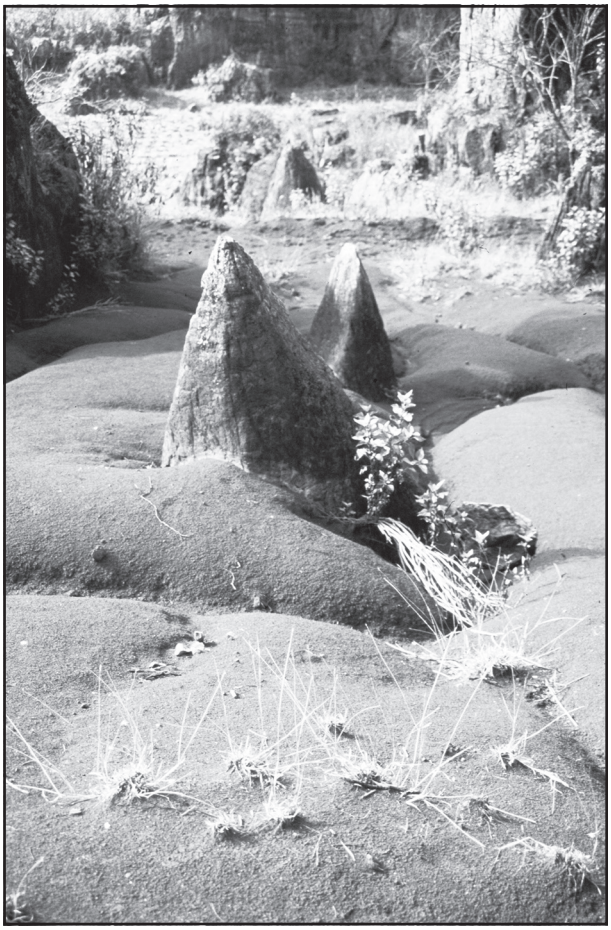

Figure 5: Subsoil factors created the pointed tops.

3.4. Subsoil factors and their influence on the shape of the stone forests

Subsoil factors created the pointed tops of the narrow subsoil teeth - up to 5 m high pillars (Song Lin Hua 1986) -and the channels penetrating the broad teeth (Fig. 5) that caused the undercutting of pillars. At levels where sediment and soil surrounded the stone pillars for a long period, larger notches or half-bells developed (Fig. 6). Below the surface, pillars were most often dissolved along bedding planes and more porous rock strata. Subsoil factors working only on individual parts of the stone pillars, as in cases when their tops are covered with soil and vegetation, most distinctly dissect them vertically when water trickles through the soil and corrodes the rock or when the water flows from the soil down the pillars. Rainwater sharpens the pillar tops, reshapes the traces of their original subsoil formation, and with time also carves unique shapes distinctly reflected in the rock relief.

4. Conclusion

Shilin is a type of stone forest that emerged when carbonate rock, previously covered with sediment and soil, became exposed. Along with subsoil factors, rain, their topographical position and cave development their shape and size were primarily determined by the rock itself. The forests developed in horizontal or gently sloping rock strata cleft by vertical joints and fissures. Diverse examples of stone forests that formed in almost identical conditions show that the shape of the pillars is mainly the consequence of the distribution and density of fissures in the rock, its stratification, and different rock strata composition. The rock forms on the pillars are divided into subsoil forms, composed rock forms, and forms shaped by rainwater. The composition of the rock enables their creation and influences their shape and distribution.

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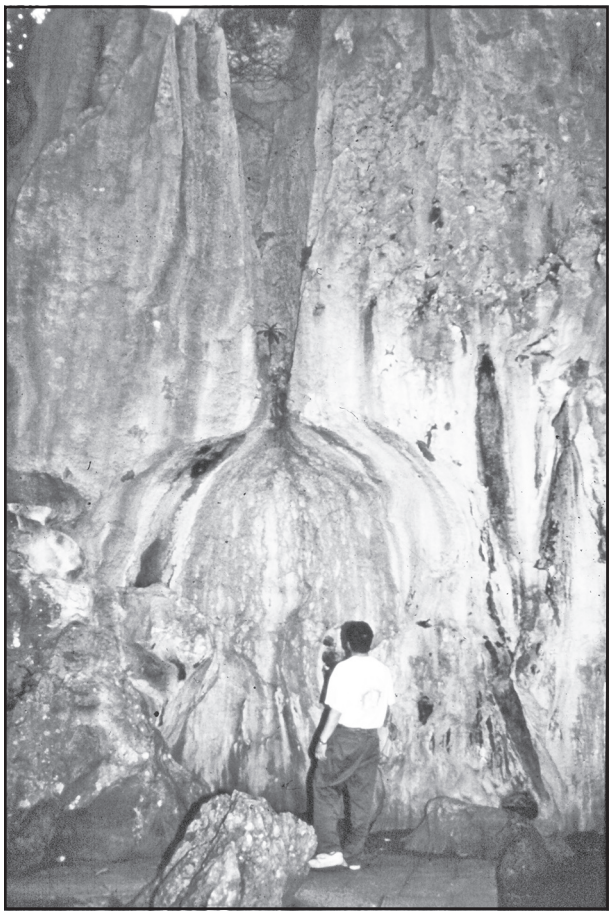

Figure 6: At levels where sediment surrounded the stone pillars, half-bells developed.

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CAVE CONSERVATION ONLINE

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Cave Conservation Online was proposed in October 2007 and launched in September 2008 as a moderated single-focus online course focused on readings from the book *Cave Conservation and Restoration, 2006 Edition*, published by the NSS. The full syllabus includes additional online resources, guest appearances by experts for questions and answers, and is based on a calendar schedule. This online course and others based on the book have the potential to improve communication and cave conservation across the United States and internationally.

1. Introduction

In the Unites States, local caver groups – usually grottos, which are chapters of the National Speleological Society (NSS) and Conservation Tasks Forces, which are recognized as internal organizations of the NSS, are continually carrying out cave conservation and restoration projects. On their own initiative, these local groups develop, publicize, and carry out sinkhole cleanups, graffiti assessment and removal, speleothem restoration, in-cave trail marking, public education/outreach projects, and so on. At the same time, federal agencies and grant-funded academic and agency-based experts have been developing and perfecting science-based management practices and restoration techniques for use in conserving and restoring caves in national parks, national forests, public lands, and other protected areas.

Until very recently, there has been inadequate communication between the two, between the local, common sense-based projects and the academic, agency-based research and applications. As a result, local caver groups have missed out on up-to-date information and techniques that could lead to improved cave conservation outcomes. The academic-agency researchers, in turn, have missed out on the insights and information resulting from low-tech, no-to-low-budget conservation and restoration projects developed by cavers with day jobs as carpenters, masons, electricians, plumbers, personnel managers, and other skills that provide common sense expertise for good cave conservation and restoration.

In the United States, it is the members of local cave clubs and grottos who have the most frequent, direct access to caves across our numerous, widespread karst regions. These cavers have a different potential than agency and academic cave conservators to reach a broad audience and educate local communities, young people, and non-organized cavers how to better protect USA cave and karst resources. These grassroots caving groups need all the cave and karst conservation and restoration information they can get.

Over the past decade, two nodes have emerged in the USA caving community to improve communication between these groups. The first one, of course, is the Internet. Information that in the past would have taken months or years to disseminate from researchers to cavers now moves nationwide within minutes. A good example is the winter 2008-9 flow of updates on White Nose Syndrome incidence and spread among bat hibernacula in the northeast and westward.

The second node is improved use of the NSS's monthly newsletter, *The NSS News,* as a national tool for sharing the results of cave conservation and restoration projects. Each April now brings the annual *NSS News Conservation Issue*, initiated during the 1990s under the leadership of NSS Conservation Division Chair Dave Jagnow and his present successors, Co-Chairs Val Hildreth-Werker and Jim C. Werker. In these pages, local groups and academic cave researchers share their hard-fought efforts. Each article is illustrated with photos and bristling with links to additional information and easy e-mail access to expertise of all types. The Werkers have also pioneered the development of a nationwide network of cave conservation groups that report to the NSS on a regular basis. NSS grottos, conservation groups, and internal organizations are now easily reachable via the online Grotto Conservation Network.

With the 2006 publication of the Werkers' book, *Cave Conservation and Restoration*, the stage was set for local caver groups in the United States and abroad to benefit

from the decades of academic-agency research projects and results, ably and expertly documented in the Werkers' book. This encyclopedic "how to" guide provides step-by-step instructions, with illustrated examples, for every issue and situation cave conservationists may face, from A (Abstract Rock Art) to Z (Ziplock Bags).

In a 2008 review, Spate comments "this is a dip-into reference book but can also be read cover to cover. Fabulously well illustrated and referenced (although with a preponderance of USA references, which is fully understandable...) it addresses so many aspects of cave and karst conservation – plus the restoration component. Many of the questions that have been directed at me over the past three decades are tackled here. ...all caving clubs, management agencies, show cave sites and professionals dealing with cave and karst conservation **MUST** have this book" (SPATE, 2008).

However, publication of this "veritable bible" (SPATE, 2008) does not mean that all the U.S. cavers who would benefit will buy it, read it, and use it. The book's price is daunting for some cavers. While written in a simple, engaging, accessible style, its present thick size and packed, dense format is not accessible to many savvy and smart cavers who just don't like to read. The book's worksheets and dozens of other wonderful tools for project development and implementation are not copyable for caver handouts at meetings, via e-mail, or on the trail to a cave entrance.

In 2007 co-author Lambert suggested to Hildreth-Werker that an online course, Cave Conservation Online, be developed around the book at an introductory level, breaking out a few basic topics and offering worksheets. It was suggested that this approach might open the book's encyclopedic contents up to a wider audience and improve caver communication about cave conservation, leading to healthier caves. An additional benefit of the course would be learning about caver-run projects and case studies for the next edition of *Cave Conservation and Restoration*.

2. Course Implementation

Lambert publicized the upcoming launch of Cave Conservation Online via an article in the 2008 Conservation Issue of the *NSS News,* an announcement on the Karst Information Portal (KIP), and caver forum announcements. The initial call for participation suggested how the course could help cavers better protect their caves of concern:

"Perhaps the most powerful aspect of this online course

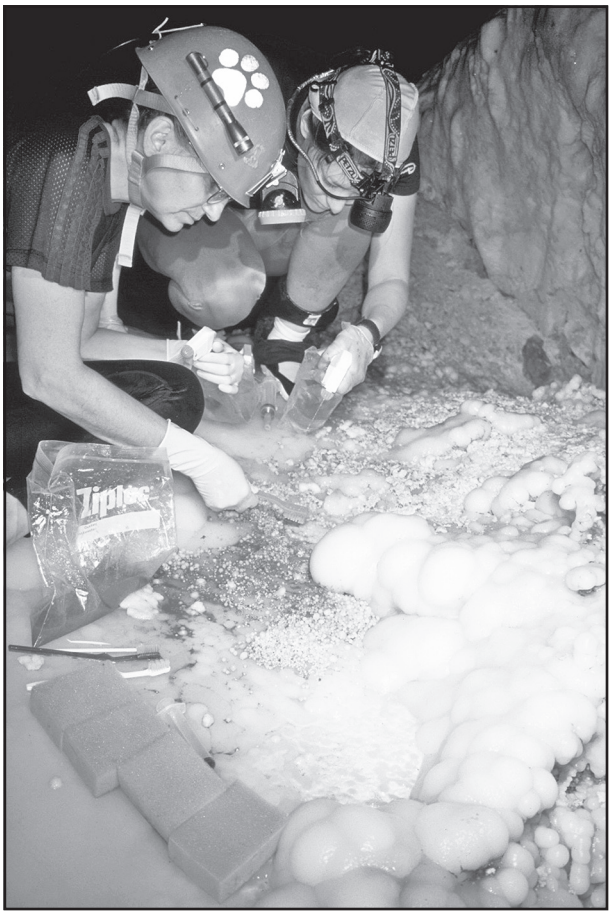

Figure 1: To illustrate the in-depth, step-by-step "how to" approach that characterizes the book's approach to cave conservation and restoration, this photo demonstrates that "The Pellucidar restoration [in Lechuguilla Cave] required clean clothing and careful technique." (Photo by Val Hildreth-Werker.)

is the opportunity for groups to share what they are doing with others world-wide, towards more effective protection, conservation and restoration of cave and karst resources. Locally, many of us are embarked on cave and karst conservation efforts. This course will provide a networked community for participants to meet, discuss, compare, inform, improve and support one another in what often seem like lonely or hopeless struggles in the face of development and rapid change" (LAMBERT, 2008).

The initial run of Cave Conservation Online took place from August to November 2008. Thirty-two people signed up, of all ages and levels of experience. Class participants were clustered in the central USA, with outliers in the mainland's corners. An international participant was in Malaysia. Participants offered varied reasons for their interest.

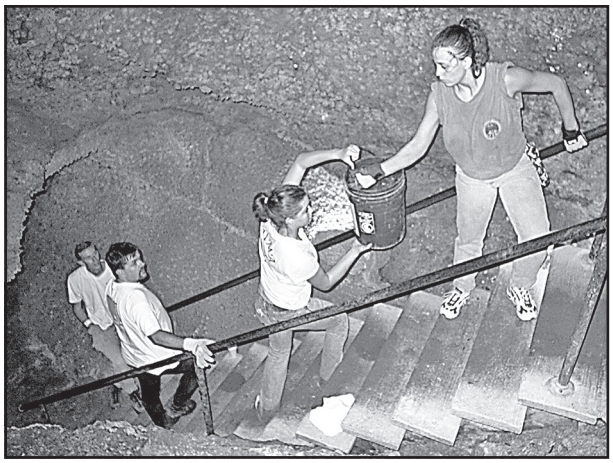

Figure 2: In the Caverns of Sonora (Texas, USA), cave restoration science goes hand-in-hand with willing caver workers, as shown in this of a chain of cavers passing buckets up the stairs. (Photo by George Veni.)

Jeff Cay, Louisville (Ky) Grotto: "My hope is that in taking this course I will better understand the restoration and conservation of caves. Also, I will be able to understand, or at least have some type of working knowledge about the process of cave conservation and restoration."

John Fino, Minnesota Speleological Survey: "I am taking this course partly to learn more about cave conservation in general, but especially to know if there has been any research done about the effects of cave digging on the cave environment, biota, speleothem growth, or the like."

Hymeir Kamarudin, Northern Cave Group of the Malaysian Nature Society & Malaysian Karst Society: "No one in Malaysia I know does restoration of caves although it's obvious this expertise is needed. I would like to learn enough to gain confidence to actually start doing it and perhaps share my experience with others in Malaysia. I am doing several projects where restoration is needed thus I'm hoping this course would allow me to have access to good advice and expertise."

Due to the plummeting economy, the 2008 election, and lack of course credit and grading, overall participant response was a little less than hoped for, but results were encouraging. Readings were assigned by instructor Lambert from the Werkers' book, once or twice weekly. Participants were asked to respond with comments and examples of what their caver groups have been doing regarding the book's many in-depth, expert-authored cave conservation and restoration topics. Assigned book chapters were sent out to participants as email attachments. The wise, helpful and often in-depth participant responses were compiled and shared as e-mail messages and Word documents.

As a sample of the course's depth of experience and interest, following are selected participant comments on why they became cave conservationists.

Todd Hancock, Millfield, Ohio: "I became more conservation minded when I started to manage Rupert Cave in central Pennsylvania. This was in the late 1980s. I managed that cave property for seven years. The cave was bought by some caver friends of mine. They're now the owner/managers of that very beautifully decorated cave. They do a very nice job of protecting her! I just 'fell' into cave conservation because of protecting Rupert from vandalism. I'm a caver first. I've dug open some new caves and now manage/protect them from the masses."

George Phillips, 8 Rivers Safe Development (WV): "...Then I heard about the sewage plant in the same valley. I called Tom Shipley and told him I was coming up for a caving trip that weekend and wanted to know more about the project. Next weekend after the caving trip I met Tom at the Sharps Country Store and he took me on a tour of the project site. He then showed me the Big Spring Fork Spring Complex which is the main spring/resurgence at the lower end of the Big Spring Fork valley. He said the project planned to dig a trench through the 30-foot-diameter spring pool to run the effluent line to the discharge point. I told Tom he was wrong; there was no way anyone would dig a trench through a major spring. He said they didn't even know the stream went dry and had no idea the spring was there. That was all it took..."

Jim Ruedin, Meramec Valley Grotto (Mo):"I don't think there was a defining moment for me. It was more a chain of events that brought me to the point I'm at now. The first big one was several years ago when a number of Missouri caving organizations participated in a US Fish & Wildlife Service project to do a bio-inventory project replicating some of the work that had been done 20 years prior. It sampled some of the caves from the original work. Anyone who participated went through a class taught by Drs. David Ashley and Bill Elliot. That's when I began my real appreciation for cave biology. My background is nothing near scientific...I'm in social service."

Neena Jud, Greater Cincinnati Grotto (OH) and Rockcastle Karst Conservancy (Ky): "Being involved with Great Saltpetre Cave Preserve, Ky. and needing to think about the strategic plan for the property, I realized there was much more to be considered than just mowing, and taking care of

a few buildings, there was also the cave, the historical graffiti in the cave, and the formations in the Russian Dome (some of which I tend to step on when I go into that space). I guess I realized I should use the label "conservationist" when I read the forward to this book one day this August when I happened to see it sitting on someone's coffee table, picked it up and started reading."

Patricia Kambesis, Cave Research Foundation, Western Kentucky University: "At first I thought that Lechuguilla was an exception in terms of the fragility of its delicate mineralogies and speleothems and that I had to be on my "best behavior" only when in that cave ... but then I started noticing caver impact in my "home" caves, the ones that were not as pristine, or as obviously delicate ... . Did we really have to put footprints on every inch of those mud banks? Was it necessary to put muddy gloves on the walls and formations that were in the way of the trade routes? And did we even need to have all of those trade routes? Shouldn't we avoid setting survey stations on speleothems - even if they were already muddy ... and did the photographer really need to walk all over the flowstone to get that beautiful picture. It hit me like a ton of bricks ... that our impact counted not just in the most beautiful cave in the world, but in all caves."

Roger W. Brucker, CRF, Karst Environmental Education & Protection, 8 Rivers Safe Development: *In the late 1960s, The National Park Service built a sewage lagoon on top of Flint Ridge in Mammoth Cave National Park. The Cave Research Foundation objected, but work went forward:* "A few weeks later they bulldozed the wall of the lagoon sending all the raw sewage contents down the valley and into the cave, killing mature trees for years to come. It took more than five years for underground aquatic life to begin to return. The Job Corps build two sewage lagoons to replace the one, and those walls were also leaky gravel. CRF and the Sierra Club and Bill Bishop sued to remove the Job Corps from Flint Ridge. At the last minute the NPS agreed to remove the Job Corps camp "in two years." Two years later there was no sign of movement. The conservative judge summoned the NPS officials and said he would cite them for contempt, a criminal offense, if the camp was not moved forthwith. In about a month the camp was moved and even the asphalt road plowed up. That saga made me into a cave conservationist for life."

3. Conclusions

The authors hope to develop this course further in cooperation with KIP, the Karst Information Portal). Other educational institutions may find this online course offering of interest, and we welcome inquiries. We feel that Cave Conservation Online has the potential to improve USA and international cave conservation communications, discussions, and research, leading to more effective protection of the cave and karst resource base. The course can be tailored for college curricula, agencies, non-governmental agencies, individual cavers, local grottos, and cave clubs. Specialized-topic courses based on the book's many areas of expertise can be developed and delivered along the same lines (LAMBERT and HILDRETH-WERKER, 2009).

Through this and related online courses, the original *Cave Conservation and Restoration* book has the potential to evolve into an easily accessible, teachable, living, growing entity as we collect, index, and archive new experiences, updated know-how, and additional expert opinion. With the inclusion of international course participants, worldwide expertise can be shared.

Please contact the authors for information about course scheduling.

Acknowledgments

Thank you to the patient and experienced cavers, cave owners, and interested others who participated in the inaugural run of this exciting course: Thomas Barr, Leslie Barras, Deb Bledsoe, Roger W. Brucker, Jefferson Cay, Ben Currens, John Fino, Ken Follett, Preston Forsythe, Kevin Glenn, Todd Hancock, Laura Hohman, Neena Jud, Greg Juhl, Hymeir Kamarudin, Pat Kambesis, Mae Kile, George Phillips, Thomas Poulson, Oliver Renwick, Peggy Renwick, Jim Ruedin, Larry Simpson, Scott Sweet, William Tucker, Julie Uselton, George Veni, Fred Wallace, Jim and Gail Wilbanks, and Evan (in Wyoming).

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CAVE PROTECTION ACTS: ARE THEY EFFECTIVE?

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The protection of caves on federally owned land has come a long way since the National Park Service was founded in 1916. Speleologists should have a working knowledge of the National Park Services Act of 1916, Federal Cave Resources Protection Act of 1988, Endangered Species Act of 1973, the Lechuguilla Cave Protection Act of 1993 and the National Cave and Karst Research Institute Act of 1998.

There are twenty-nine states with cave protection laws. The definition of a cave varies widely by state and ranges from a "historic site", as defined in Vermont, to Kentucky's definition of "any naturally occurring void, cavity, recess, or system of interconnecting passages beneath the surface of the earth containing a black zone including natural subterranean water and drainage systems, but not including any mine, tunnel, aqueduct, or other man-made excavation, which is large enough to permit a person to enter."

This paper focuses on the Virginia Cave Protection Act and the enforcement activities taken to protect caves and karst resources. The Virginia Cave Protection Act was first ratified in 1966, with a major revision in 1979, yet Virginia cave and karst resources are still threatened by vandalism, pollution, and poorly planned development.

Over the past 30 years, there have been many important court cases in Virginia as well as countless state and federal actions. The difficulty of apprehension and prosecution of vandals demonstrates the inadequacy of current penalties. More prosecutions and harsher penalties will invariably serve as a deterrent to future potential vandals. Complex Federal and State projects**,** like highway widening and the construction of new prisons and airport**s**, put additional pressures on karst areas. In order to preserve the unique educational, recreational, scientific, historic, and economic values of Virginia caves and karst, the Virginia Cave Board has been authorized to safeguard these resources (Lera, n.d.).

1 Federal Laws

The Federal Cave Resource Protection Act of 1988 (Public Law 100 – 691), enforced by the Department of Interior, defines a cave as "any naturally occurring void, cavity, recess, or system of interconnected passages which occurs beneath the surface of the earth or within a cliff or ledge (including any cave resource therein, but not including any vug (a small cavity in a rock), mine, tunnel, aqueduct, or other manmade excavation) which is large enough to permit an individual to enter, whether or not the entrance is naturally formed or man-made and shall include any natural pit, sinkhole, or other feature, which is an extension of the entrance." The rule establishes criteria to be considered in the identification of significant caves. It also integrates cave management into existing planning and management processes and protects cave resource information to prevent disturbance of significant caves and vandalism.

Long before the enactment of The Endangered Species Act (ESA) of 1973 (Public Law 93 – 205), the US Fish and Wildlife Service (USFWS) and it's predecessor, the Biological Survey, were taking specific actions to save, manage and restore America's imperiled natural resources, including caves. Expanding upon the preceding Endangered Species Preservation Act of 1966, the ESA sought to stop the extinction of many species of wild animals and plants in the United States, other nations and at sea. (Lera, 1978) As a general rule, the majority of species listed are under the authority of the USFWS with a goal to bring about the recovery of listed species so they no longer need protection.

The Lechuguilla Cave Protection Act of 1993 (Public Law 103 – 169) stated that Congress found Lechuguilla Cave and adjacent public lands have internationally significant scientific, environmental and other values, and should be retained in public ownership and protected against adverse effects of mineral exploration and development, as well as other activities presenting threats to the areas. The cave has multiple layers of protection under the Wilderness Act of 1978 (Public Law 95 – 237) and the National Park Services

Act of 1916, as well as the Federal Cave Resources Act and the Lechuguilla Cave Protection Act. (Huppert, 1995)

Another important act is the National Cave and Karst Research Institute Act of 1998 (Public Law 105-325), whose purpose is to further the science of speleology, promote national and international cooperation in protecting the environment for the benefit of cave and karst landforms, and promote and develop environmentally sound and sustainable resource management practices.

The Federal Cave Resources Protection Act (FCRPA) and the Endangered Species Act (ESA) each have provisions for permitting and land acquisition with specific guidelines, and penalties for violations. The FCRPA penalty is a fine up to $10,000 and/or up to one-year imprisonment with subsequent penalties being stricter. For violating the ESA the criminal penalty is up to $50,000 and/or up to one-year imprisonment, and a fine up to $25,000 per violation as a civil penalty.

2. State Laws

There are twenty-nine states with some type of cave protection laws. Penalties for vandalism, removing any materials found in caves, killing or removing plant and animal life, breaking or tampering with doors or gates are classified in every state as a misdemeanor ranging from Class A/Class 1 to a Class D/Class 4. The penalty is either criminal or civil and ranges from $50 to $10,000 and/or up to two-year imprisonment. A subsequent violation either increases the penalty or becomes a criminal felony. Table 1 lists States with Cave Protection Laws and the Penalty for Violations.

Table 1

States with Cave Protection Laws and Penalty for Violations

	Misdemeanor	Misdemeanor	Misdemeanor	Misdemeanor
	Class A or	Class B or	Class C or	Class D or
State	Class 1	Class 2	Class 3	Class 4
Alabama	$2,000	$1,000	$500	$250
Arizona		$750		
Arkansas	$500			
California	$1,000 +1yr			
Colorado*	$750			
Florida	$1,000			
Georgia	$50 - $1,000			
Hawaii	$10,000 - $30,000			
Idaho	$300 + 6 mo.			
Illinois	$2,500	$1,500	$1,500	
Indiana	$250 -$2,500			
Kentucky	$500	$250		
Maine	$1,000			
Maryland	$500 +6 mo.			
Missouri	$1,000			
Montana	$500 - $2,000			
Nevada*	$1,000 - 6mo			

New Mexico	$1,000 - 6mo-1 yr			
North Carolina	$150 - $500			
Ohio	$1,000	$750	$500	$250
Oklahoma	$500 + 12 months			
Pennsylvania	$100 - $1,000			
Rhode Island*	$500			
Tennessee	$500			
Texas	State Jail Felony + $10,000			
Vermont*	$500			
Virginia	$2,500	$1,000	$500	$250
West Virginia	$150 - $500			
Wisconsin	$5,000			
Note: These are maximum penalties and "*" means associated laws protecting caves				

The first Virginia Cave Protection Act became law on March 2, 1966 when House Bill 24 was enacted as Section 18.1-175.1 of the 1950 Code of Virginia. It was the clear the intention of the legislators to protect Virginia Cave resources, especially those found in commercial caverns bringing tourist dollars to the state. With the 1975 recodification of Title 18, The Cave Protection Act was moved to Section 18.2-142 under "Damaging Caverns or Caves" and contained two parts:

(a) It shall be unlawful for any person, without the prior permission of the owner, to willfully and knowingly, break off, crack, carve upon, write or otherwise mark upon, or in any manner destroy, mutilate, injure, deface, mar or harm any natural material found within any cave or cavern, such as stalactites, stalagmites, helictites, anthodites, gypsum flowers or needles, flowstone, draperies, columns, or other similar crystalline mineral formations or otherwise; to kill, harm or disturb plant or animal life found therein; to discard litter or refuse therein, or; otherwise disturb or alter the natural condition of such cave or cavern; or break, force tamper with, remove, or otherwise disturb a lock, gate, door or other structure or obstruction designed to prevent entrance to a cave or cavern, without the permission of the owner thereof, whether or not entrance is gained.

(b) Any violation of this section shall be punished as a Class 3 - Misdemeanor. (Changed in 1975 from a full description to a "Class 3 - Misdemeanor" - A fine not exceeding $500 or confinement in jail not exceeding 12 months.)

In December 1978, The Commission on the Conservation of Caves documented the rapid deterioration of Virginia's caves as geologic, archeologic, biologic, recreational, and educational resources. (Report of the Virginia Commission on the Conservation of Caves to the Governor and the General Assembly of Virginia, House Document No. 5, 1979) The Commission recommended an inventory of archeological resources in Virginia caves be made, a permanent Commission be created, and a new Cave Protection Act giving broader protection to cave resources be enacted. (Virginia Minerals, 1979)

The 1979 Session of the General Assembly, responding to the recommendations of the Commission on the Conservation of Caves, created the Virginia Cave Commission and enacted a new comprehensive Cave Protection Act with two basic objectives. The first was to protect Virginia cave resources from vandalism and degradation; the second, to protect the cave owner's interest in his property. Violations of the Act were designated as Class 3 - Misdemeanors, punishable by a fine of up to five hundred dollars.

The Commission's report stressed caves are unique natural laboratories for the investigation of biologic processes. The Cave Protection Act therefore prohibited disturbing or harming any cave organism.

Under the provisions of this new law it also became illegal to remove, mar, or otherwise disturb any natural mineral formation or sedimentary deposit in any cave without the owner's express, prior, written permission. Although collection of mineral specimens was not completely prohibited, it was the intent of the Commission that future collection be as minimal, selective and scientific as possible. The Act was designed to preserve the beauty of Virginia caves and prevent them from being destroyed by indiscriminate collection and/or vandalism. It also became illegal to sell, or export for sale, speleothems (mineral formations or deposits found in caves). The General Assembly felt by eliminating the market, much of the incentive for theft would also be eliminated.

The pollution of groundwater, as a result of the dumping of garbage, sewage, dead farm animals, and toxic wastes into caves and sinkholes, had been a problem within the State. It now became illegal to dump any litter, waste material or toxic substance in any cave without the express, prior, written permission of the owner.

The new Act protected archeologic resources by requiring a permit from the Virginia Historic Landmarks Commission and written permission from the cave owner, before excavating, removing or disturbing any fossils, historic artifacts or prehistoric animals. It also protected gates, locks, and other barriers designed by the cave owner to prevent or to control access to the cave. It was illegal to break, force or tamper with these barriers or to remove or deface any sign posted by the owner. The cave owner was also exempted from liability for any injury sustained in his cave as long as he has not charged an admission fee.

The Virginia Cave Protection Act was amended several more times, as late as 1989, and better defined the Cave Board and its powers and duties; the requirements for permit issuance for excavation and scientific investigations; vandalism, pollution, disturbances, sale of speleothems and their penalties; and the liability of land owners.

3. Enforcement Actions - Vandalism

In 1995, three young men pleaded guilty to federal charges that they took and destroyed speleothems from Crystal Cave in Mammoth Cave National Park and faced a maximum sentence of 35 years in federal prison, plus fines of $750,000 each.

It was proven the vandals in this case fully premeditated their actions with complete knowledge the cave was protected by federal law, went to great lengths to mine under a gate, and visited the cave repeatedly to remove speleothems to be sold for profit to local rock shops, with complete disregard for the law and the environment. The sentences handed down by the judge were: Perpetrator One - 33 months in federal prison followed by 3 years probation and 550 hours of community service work. Perpetrators Two & Three - 21 months each in federal prison followed by 3 years probation and 500 hours of community service work. (Cynthia Eagles, *The Courier-Journal*, March 1, 1996)

The sentences were much harsher than requested by the U.S. Attorney's Office. The decision became a legal precedent sending a clear message to other courts across the country about how the federal court views this type of criminal activity.

Park officials at Maple Run and Goat Caves near Brodie, Texas, reported vandalism destroyed or damaged at least 50 formations in June or July 1996. In this case no one has yet been apprehended. (Scott W. Wright, *Austin American-Statesman*, Tues., July 30, 1996)

The Virginia Cave Commission / Cave Board has also been involved in several court cases regarding vandalism and have worked with various communities to protect cave resources.

In 1981, local students illegally entered the fenced Barterbrook Spring Cave. The owner had the students arrested, however, rather than go to court, their parents paid for a new fence. (Virginia Cave Commission Minutes, March 29, 1981. Copies of Commission and Board minutes can be obtained from the Virginia Department of Conservation and Recreation, 217 Governor Street, 3rd Floor, Richmond, Virginia, 23219)

In another case, students from James Madison University, who had removed speleothems from Fountain Cave, argued in their defense they did not know it was illegal since there was no sign at the cave. They were sentenced to complete a special project at the University to benefit caves which included publication of an article in the JMU newspaper about the new Cave Protection Act and the importance of preventing cave vandalism. (Virginia Cave Commission, December 6, 1981)

In Southwest Virginia, two students allegedly entered a cave to collect speleothems for a science project. They saw a sign that said in large letters, "THIS" CAVE is protected." They left, found another cave without a sign and collected their speleothems. Again, the judge sentenced them to community service. As a result of this case, the Virginia

Cave Commission changed their signs from "THIS CAVE" to read "ALL CAVES" are protected. (Virginia Cave Commission, June 2, 1984)

Many, but not all, of the cases involved lack of vandalism deterrent signage. Still today, out of 370 significant caves in Virginia, only 100 have cave protection warning signs.

In the fall of 1985, there was a break-in at Madisons Saltpetre Cave in Augusta County, even though there was a Cave Protection sign posted on the cave gate. The vandals were identified, the cave owner prosecuted, and they were sentenced to 20 hours of community service. (Virginia Cave Board, May 10, 1986)

Commercial caves have also had their share of vandalism. In 1981, Grand Caverns in Virginia was closed for two weeks when six Boy Scouts, camping nearby with their troop from Silver Spring, vandalized the Caverns. They were arrested, released on $500 bond, and sentenced to community service after their hearing. Massanutten Caverns had their steel-plated door smashed in, however there were no arrests (Denis Collins, *Washington Post*, July 5, 1981). In 2006, three suspects were arrested in connection with the break-in and vandalism of Wyandotte Cave, Indiana, where they painted the walls, broke formations and injured the bats.

In Missouri under the Archaeological Resources Protection Act of 1979, four men were captured on videotape while looting historic Decker Cave on April 17, 2000, pleaded guilty to misdemeanors, sentenced to probation and ordered to pay restitution.

In October 2007, near Olive Hill, Kentucky, State and federal wildlife authorities investigated the deaths of more than 100 federally endangered Indiana bats at Carter Caves State Resort Park which harbors the largest hibernating population of Indiana bats in Kentucky. Vandals entered a cave at the park and struck a hibernating colony of Indiana bats with rocks on two different occasions. Some bats were crushed, while others died after being knocked into a stream. Violations of the Endangered Species Act can result in a maximum penalty of a $100,000 fine and a year in prison, however, the perpetrators were never apprehended.

And in 1994, vandals attempted to saw out a panel of paintings from the Gottschall rock shelter in Iowa County, Wisconsin, and late in 2004, 1,000-year-old paintings of canoes and birds' feet on a rock face in Larsen Cave in Roche-A-Cri State Park were defaced with spray paint and a five-foot pit was dug in search of artifacts. Protecting these sites has proven difficult and no one was caught in either instance. Perhaps the best alternative might be to heighten public awareness of the value of the caves and their paintings. (Ron Seely, *The Wisconsin State Journal*. August 7, 2007)

In 2006, at the Caverns of Sonora, Texas, one of the rarest and most popular cave formations in the world the butterfly formation was vandalized. To date, the missing piece still has not been returned and no one has been charged in the case. In response, Texas increased the penalty for defacing a cave in the state, giving state and local prosecutors the ability to seek state jail felony convictions in cases involving vandalism. A person found excavating, defacing or removing speleothems or animals from a cave without a permit issued through the General Land Office commits a Class A misdemeanor, which could carry 180 days to two years in state jail and an optional fine of up to $10,000. (David Saleh Rauf, *The Herald-Zeitung*, June 20, 2007)

4. Enforcement Action – Project Review

Between 1981 and 1984, the Commission became involved in a long drawn out discourse with the Town of Grottoes, Virginia, via letters, meetings and hearings, regarding a proposed water tank and pipeline on Cave Hill. Many concerns arose from impending blasting and jack hammering, including potential damage to speleothems in Grand Caverns, collapse of cavities, pollution and siltation of the Cave Hill Aquifer, change in groundwater flow, and failure of the water storage tank due to site conditions. The number one concern was the potential impact on the Madison Cave Isopod, *Antrolana lira,* which was on the Endangered Species List of the Fish and Wildlife Service. During this same review period, a sinkhole was inadvertently filled and Federal funding was delayed. Additional studies were conducted, and as a result, all concerns of the Cave Commission were addressed by the town and their engineers and the water tank was built. (Margie Shetterly, *Daily News-Record*, Harrisburg, Virginia, November 16, 1983, and April 18, 1984)

5. Resource Preservation – American Indian Burial Sites

Bull Thistle Cave, the best preserved example of a burial pit cave known in Southwest Virginia and listed in the National Register of Historic Places, was used by Native Americans for the burial of their dead during the Late Woodland Period (A.D. 900–1700) and contained archaeological remains in an excellent state of preservation. At least 11 individuals were represented among the bones exposed on the surface of the cave. The structure of the talus cone below the pit

entrance suggested more human remains and artifacts were probably buried there, however, no evidence of previous excavations or disturbances was observed. Further scientific study of the cave deposits yielded important new information about the paleo-demographic characteristics and cultural practices of the Virginia Native Americans. The removal of remains from the cave was covered under Section 10.1 – 1003 in the archeological section of the Act, and resulted in the development of a management plan (Virginia Cave Board, September 20, 1986.

In August 2001, there was a break-in at Adams Cave and human remains removed. Local students were apprehended, prosecuted and each sentenced to 10 hours community service. (Virginia Cave Board, September 8, 2001)

In 2002, American Indian remains removed for research purposes from Bone Cave in Lee County were re-interred at a site in Amherst County on land owned by the Monacan Indian Nation. The unexcavated remains are still in the significant and protected Bone Cave. (Virginia Cave Board, November 23, 2002)

6. Resource Preservation – Endangered Species

In 1990, it was discovered that Thompson Cedar Creek and the Batie Creek watersheds in the Cedars Karst Area in Lee County, Virginia, had been polluted for more than three years with sawdust debris dumped by the Russell Lumber Company. The sawdust had accumulated in immense ridges 20 – 30 feet deep and 200 feet across, and acres of forest were covered with it. The surface and subsurface water resources had become a black viscous flow which was sinking into Thompson Cedar Creek and eventually the Powell River.

The caves of Lee County hosted a diverse and abundant fauna of cave-adapted invertebrates. Among them was Thompson Cedar Cave, where, in the 1960s cave biologists John Holsinger and David Culver first discovered the Lee County Cave Isopod, *Lirceus usdagalun*. (Virginia Cave Board, June 9, 1990). Batie Creek was included on EPS's 303(d) list of impaired streams and through the combined efforts of the Virginia Department of Conservation and Recreation (DCR), the Virginia Department of Mines, Minerals and Energy, the U.S. Fish and Wildlife Service, the Tennessee Valley Authority, Curtis Russell Lumber Company, and the Cave Conservancy of the Virginias a recovery plan was developed.

By 2005, the restoration of the Batie Creek Watershed was complete. Accumulations of sawdust which had generated toxic leachate were removed and mixed with lime and fertilizer as a beneficial soil additive on nearby coal mine reclamation projects. Dissolved oxygen levels which had been near zero, returned to normal levels. The Lee County Isopod, *Lirceus usdagalun*, listed as endangered due to its extirpation from the cave in the late 1980's, also recovered although not to pre-impairment levels (Virginia Cave Board, March 19, 2005).

Also in Lee County, new airport and prison plans were in development. These projects impacted significant biological resources including an endemic millipede, several rare cave invertebrates, and rare plants, including a new species of clover found only in Virginia. The Virginia Cave Board wrote letters to the County Board and held meetings resulting in the airport expansion but not the construction of the prison.

In June 1993, Virginia Cave Board recommended a change to the proposed right-of-way for Rt. 58 in the vicinity of Young-Fugate Cave, with over 5,800 feet of surveyed passages considered to be biologically, geologically and hydrologically significant. A number of rare cave invertebrates, including the trechine beetle, *Pseudanophthalmus holsingeri,* a dipluran, *Litocampa cooki*, two aquatic crustaceans and the gray bat, *Myotis grisescens,* had been noted. The proposed right-of-way could well have led to future subsidence and eventual collapse of the roadbed into the subterranean passages. The result of numerous meetings was a re-routing of the right-of-way. (Virginia Cave Board, June 19, 1993)

In 2007, Rocky Hollow Cave, located on the west slope of Powell Mountain in Virginia, and home to the endangered Indiana Bat*, Myotis sodalis,* was vandalized. A gate installed at the cave entrance by the U.S. Forest Service in the late 1990s to protect hibernating Indiana bat populations was breeched via a tunnel near the western end of the cave entrance. Inside were numerous patches of graffiti which included several names in pink, white and orange paint.

Assuming the May 28, 2006, graffiti date was correct, it is unlikely the visit by the vandals caused any disruption or negative impact to the Indiana Bat as it was well past its winter hibernation. The Virginia Cave Board requested the assistance of the Wise County Sheriff in apprehending the perpetrators of these violations.

One individual was apprehended and, based on the recommendation of the VCB Virginia Cave Board, was ordered by the judge to clean up the graffiti, which resulted

in 10 hours of community service. One important note - when undertaking an enforcement action, the statute of limitations must always be considered. In Virginia this statute is one year (Virginia Cave Board, March 24, 2007).

7. Other Board Actions

The VCB continues to work with various State Departments on Environmental Reviews and has participated in discussions on State Regulations regarding the caves and karst and the importance of their protection. The Board has also worked with the Department of Historic Resources in permitting the excavation and removal of any archaeological, paleontological, prehistoric and historic features in a cave; worked with the Virginia Department of Transportation, the largest manager of State-owned caves, on the widening of State highways and the gating of significant caves; and, worked with the Virginia Natural Area Program and Department of Game and Inland Fisheries on preparing management plans for 156 state-owned caves.

8. Conclusions - Future of Cave Protection

The vandalism of caves is a persistent, pervasive problem throughout the world. Prehistoric humans used caves for shelter and self-expression, which ranged from graffiti to sacred art. Presently, cave vandalism occurs in three overlapping categories: (1) Casual vandalism caused by untrained novices who may visit caves to sightsee, then litter, smoke, drink, go to the restroom, disturb bats, build fires, and mark graffiti; (2) Malicious vandalism involves harassment or killing of bats, breaking and stealing speleothems, breaking cave gates, and massive spray painting; and (3) Professional looting of archaeological artifacts is supported by selling the loot at flea markets, gem shows, and on the internet. The overuse of caves, even by well-meaning visitors, gradually degrades the largely nonrenewable cave environment. Many states have no or weak cave and archaeological protection laws, which are rarely enforced, probably because they are poorly known among prosecutors and provide only Class A or B misdemeanor penalties. Felony theft and strong penalties under the federal Archaeological Resources Protection Act and Federal Cave Resources Protection Act may be effective, but may apply only to federal land. The real problem is in preventing vandalism and apprehending vandals. (2001, Cave Vandalism)

It was important for the Crystal Cave, Kentucky, case to set a significant precedent as a deterrent to future cave vandals. Of all the possible outcomes, stiff prison sentences sets the most powerful precedent, and have the highest probability of deterring future cave vandals, particularly when the case and the sentence is widely publicized.

While cave vandalism seems like a victimless crime, there are actually millions of victims, i.e., those who are forever denied the opportunity to experience the cave in something close to pristine condition. To use an analogy, vandals did not impudently break-into, vandalize, and burglarize a small village church, they impudently broke-into, vandalized, and burgled the Sistine Chapel of caves. Thus, it was doubly important that a strong precedent to deter cave vandals be set.

It has been 30 years since the 1979 Virginia Cave Protection Act became law and the importance of the confidentiality of significant cave locations and the difficulty of apprehending vandals continue to be addressed by the Virginia Cave Board. The prosecution of vandals demonstrates the inadequacy of current penalties. The Act should be amended to allow prosecutors to choose between a misdemeanor and a felony charge, similar to the Federal Cave Resource Protection Act. More prosecutions and harsher penalties will invariably serve as a deterrent to future potential vandals (Kramer, 2003).

Virginia cave resources continue to be threatened by vandalism, pollution, and poorly planned development. Unfortunately, many cave owners remain unaware of the immense scientific, historic and economic value of the unique nonrenewable cave resources they own.

As public interest in outdoor recreation continues to grow and land development accelerates, increased pressures will be put on Virginia's limited and fragile cave resources. In order to preserve the unique educational, recreational, scientific, historic, and economic values of Virginia cave and karst areas, the Virginia Cave Board is committed to safeguarding these resources.

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ECOTOURISM MANAGEMENT PLAN FOR "EL SAUCE" CAVERN, PIEDRAS GRANDES, CÓRDOBA, ARGENTINA

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"El Sauce" cavern is on private property and the "Sociedad Argentina de Espeleología" is working with its owner with the purpose of implementing a management plan. We have been carrying out some preliminary activities over five years, including trapping and collecting biological samples. In addition, a thermometer to measure maximum and minimum temperatures and a data logger registers temperature fluctuations, allowing the correlation between tourist activity and the temperature changes.

To ensure visitor safety, it has been necessary to implement an evacuation plan from the cavern for tourists in case an accident takes place. To deal with this problem, we implemented a rescue plan and carried out a drill using rescue equipment and provided a course about speleological rescue. Firefighters from the surrounding areas joined us and both of these activities were sponsored by "Agencia Córdoba Turismo."

The management plan had to always consider the cave's characteristics within a tourist context. Some improvements were added to the guidelines to preserve the cavern and to reach a sustainable tourist development. A monitoring plan and some mitigation alternatives described on the basis of an environmental diagnosis are included in the management plan to address Argentinian regulations of protected natural areas.

The main idea is to declare this area as a Private Natural Reservation with a management plan as a technical document, to regulate the conservation unit, the natural resources administration and the implementation of facilities needed to incorporate other activities within the rural and adventure tourist modalities which the tourist agents in the area require.

Resumen

Caverna El Sauce es una propiedad privada y la Sociedad Argentina de Espeleologia esta trabajando con el propietario para instrumentar su plan de manejo. Los trabajos preliminares ya se vienen realizando hace cinco años y se están efectuando muestreos biológicos, por recolección de ejemplares y capturas en trampas, y además se han colocado termómetro de máxima-mínima y termómetro con data logger para ver las variaciones que puedan influenciar las visitas turísticas sobre las temperaturas. Con respecto a la seguridad de las visitas se ha realizado un taller de instrumentación de rescates y un curso de Espeleosocorro con los Bomberos de las zonas de influencia, ambos auspiciados por la Agencia Córdoba Turismo.

En una 1º parte se expone la descripción de la zona y de la caverna para dar sus características dentro de un contexto turístico. En una 2º parte se proponen algunas medidas para alcanzar la conservación de la caverna y que su desarrollo turístico sea sustentable. En base a un diagnóstico ambiental se describe un plan de monitoreo y alternativas de mitigaciòn, de acuerdo a normas de planes de manejo de áreas naturales protegidas que se utilizan en Argentina. La idea central es que la zona se declare Reserva Natural Privada y con un plan de manejo como documento técnico que regule la unidad de conservación, la administración de los recursos naturales y la implementación de futuras estructuras físicas necesarias ya que se anexaran otras actividades dentro de las modalidades de turismo rural y de aventura que piden operadores turísticos de la zona.

1. Introducción

El espeleoturismo o Espeleismo, como se lo denomina en Córdoba, se realiza en enclaves naturales y por ello necesitan cierto grado de proteccion ambiental. Además hay que darles suficiente proteccion a los visitantes frente a los riesgos que conlleva la práctica de este tipo de actividad. Por estos motivos el propietario de Caverna El Sauce ha permitido que la Sociedad Argentina de Espeleología tome estos temas como objeto de sus trabajos en la provincia. La caverna y el predio circundante son propiedad privada y el acceso a la cueva se halla en una cantera de mármol cuyo actual propietario quería activar.

Durante un curso de Turismo Minero y Espeleologia, dictado en Valle Hermoso Córdoba, para prestadores de turismo, convinimos con él en hacer un proyecto de ecoturismo, ambientalmente sustentable para evitar la destrucción de la caverna. Surge así el trabajo de Tesis de Torres Guevara (2005), "Plan ecoturístico para la zona de la Caverna de Piedras Grandes en el Valle de Punilla Provincia de Córdoba" que presenta en la Universidad de Salta, Subsede Buenos Aires.

El proyecto del propietario fue avanzando con la prevención de los impactos ambientales circunscribiendo la zona turística de la caverna, acotando el circuito exterior y aislando a los visitantes de los lugares con riesgos de derrumbes, efectuó una limpieza total del lugar y coloco un cuidador para evitar la entrada de saqueadores de espeleotemas que venían de localidades vecinas para vender estas concreciones en centros turísticos como "cristales esotéricos" (!). En cuanto al manejo se respeta la capacidad de carga aconsejada, y se comenzó el monitoreo de la temperatura interna y de la erodabilidad de los circuitos. También se comenzó con el muestreo biológico.

Respecto al programa de contingencia se realizaron dos Talleres de espeleorescate para coordinar acciones a tomar con los bomberos de la zona. Para continuar con estos trabajos y los objetivos presentamos ahora algunas acciones futuras que complementen la sustentabilidad del proyecto ecoturistico.

2. Propuesta

Las visitas a la caverna El Sauce son presentadas como una actividad de Turismo Alternativo y complementaria a las propuestas turísticas de la Agencia Turismo Córdoba. En Argentina, en varias cavernas propuestas como objetivos turísticos ya hemos observado, con estudios comparativos, los daños producidos por la actividad antropica (Antonietti et al., 2003). Donde las cavernas se hallan con libre acceso (terrenos fiscales en su mayoría) se deben proponer medidas mas severas de control para evitar que bajo el nombre de Ecoturismo o Turismo Aventura se degraden estos ambientes (Allemand et al., 2003). Por ello, en el escenario actual de degradación ambiental, las decisiones que protejan estos ambientes deben ser adoptados de manera urgente.

Dado que la caverna El Sauce se encuentra en terrenos privados y existe control sobre los accesos a la misma, será más fácil implementar medidas de seguridad ambiental.

El trabajo de Tesis ya diagnosticó y sugirió, a manera de Plan de Manejo, las formas de minimizar los riesgos ambientales y estas nuevas propuestas y acciones son para lograr la continuación de estudios que reflejen el trabajo "conservacionista" que viene desarrollando el administrador del emprendimiento turístico.

La idea es que se declare la zona como Reserva Natural Privada con un Plan de Manejo como documento técnico que regule la unidad de conservacion, el manejo de los recursos naturales y la implementación de las estructuras físicas necesarias. Para la implementacion de estas propuestas será necesaria la integración en una Estación Ecológica de todos los profesionales y técnicos que se necesiten involucrar dada la magnitud del proyecto.

3. Descripción de la Zona

El lugar Piedras Grandes se halla enclavado en el Distrito del Chaco Serrano, donde se desarrolla el "Bosque Serrano" en forma discontinua debido a la actividad agropecuaria. Aun así la biodiversidad, si bien en franco retroceso por la introducción de especies exóticas, puede verse distribuida a lo largo del gradiente altitudinal formando pisos o "zonas de vida".

La geología de la localidad que nos interesa son los mármoles pertenecientes al basamento cristalino de las Sierras Pampeanas Orientales. Una descripción detallada puede encontrarse en Elortegui Palacios (2002). El acceso de la caverna al encontrarse dentro de una cantera de extracción de mármoles, facilita la comprensión de los procesos de sedimentación, metamorfismo y de formación de la caverna haciendo del lugar, junto con el paisaje serrano circundante, una escuela de interpretación de la naturaleza geológica de la zona.

Sus coordenadas geográficas son 31º 05` 08" LS y 64º 33` 09,8" L W a 1102 mts snm. Desde el punto de vista turístico se halla dentro del corredor del valle de Punilla y tiene como localidad de cabecera a la ciudad de La Falda.

4. Actividades Desarrolladas

Ya hemos hecho un diagnostico ambiental (Torres Guevara, 2005) y dadas las posibilidades de que la actividad turística se realice sin afectar a la totalidad del desarrollo de la caverna hemos continuado con una etapa de recolección de datos para tener las referencias base para ver modificaciones en el Plan de Monitoreo que activen el Plan de Mitigacion.

Para ello hemos dejado un termómetro de máxima y mínima y un Datalogger de temperaturas en diferentes sitios para detectar posibles variaciones. El de máxima y mínima ha oscilado entre los 13 y 15 ºC en un periodo de un año. Se han recolectado, por captura directa o trampas cebos, invertebrados como moluscos, opiliones, insectos, crustáceos, ciempiés y lepidópteros que se han derivado a especialistas para conocer su posición taxonómica.

El hallazgo de un grillo del genero Ceuthophilus sp. (Orthoptera, Rhaphidophoridae) se esta estudiando como posible nueva especie (Di Iorio, com. pers.). Toda esta fauna de cavernas a comenzado a estudiarse por la Sociedad Argentina de Espeleología dentro de un programa para conocer la Biodiversidad de Artrópodos en Cavernas de Argentina (Di Iorio et al., 2008).

También hemos recolectado un anuro, un quiróptero de la especie Myotis dinellii (Castilla, com. pers.) y egagropilas del exterior conteniendo restos de mamíferos que nos ayudaran a comprender la red trofica de la zona.

También se ha comenzado con las tareas de topografía. En una primer etapa se topografiò el circuito turístico para determinar los puntos de monitoreo a distribuir según los factores que se seleccionen.

5. Consideraciones de la Propuesta

La Sociedad Argentina de Espeleología, como organización conservacionista, ha conformado un Grupo de Espeleología Ambiental, entendiendo como ambiental aquella rama de la espeleología que estudia los problemas que afectan las cavernas provocados directa o indirectamente por la actividad humana.

En este caso necesitamos brindar a los operadores turísticos herramientas y programas de actividades que garanticen la disminución de los impactos negativos de la actividad turística.

Estas herramientas y programas se contemplan en los Planes de Manejo y nos brindan las estrategias necesarias. El Plan de Manejo contendrá un diagnostico ambiental actualizado que describa el medio físico (Geología, Paleontología, Hidrogeología, Geomorfología, Hidrologia, Edafología entre otros), el medio biótico (Flora y Fauna) y el medio socioeconómico haciendo hincapié en actividades asociadas como el Turismo Rural.

Luego se continuará en la identificación y evaluación de los Impactos Ambientales de todas las actividades, no solo la turísticas, con la propuesta de medidas mitigatorias y un Plan de Monitoreo.

El monitoreo ambiental es una herramienta para el control de las visitas y los parámetros elegidos son aquellos que aseguren la integridad del ambiente, como la composición de su fauna y la formación de espeleotemas (Torres Guevara et al., 2003)

Si es necesario un plan de compensación ambiental, dado que se sacrifica un circuito para el turismo, a manera de resarcimiento se habilitaran otras galerías para estudios científicos y otras para la recolonización por especies desplazadas. En el exterior se propone un Centro de Visitantes o de Interpretación para concientizar a los visitantes sobre la fragilidad de estos ecosistemas.

Dado que prácticamente toda la zona es de propiedades privadas el único procedimiento de expandir un área natural con este tipo de ecorregiòn (que le dará cobertura de proteccion), es la figura de Área Natural Privada. Esta declaración, al nivel municipal y o provincial, no solo beneficiara al propietario con alguna exención impositiva, si no que también le dará status de conservación que se asegure en el tiempo.

El uso de las cavernas para visitas esta teniendo cada vez mayor demanda. La dinámica del turismo y la recreación en áreas naturales requiere de decisiones puntuales flexibles y eficientes. Por ello la gestión del espeleoturismo se debe centrar en un Plan de Manejo desde el punto de vista científico por sobre el turístico al momento de planificar sus visitas y actividades.

Las herramientas técnicas como los relevamientos (Flora, Fauna, Geología, etc.), la zonificacion del área, los programas operativos anuales y el monitoreo, teniendo en cuenta que el proyecto es ecoturistico, necesitaran de profesionales en cada área.

La propuesta de creación de una Estación Ecológica que centre la información y estudios generados podrá monitorear en forma eficiente y desarrollar los planes de

mitigacion necesarios. Esta Estación debería administrar un Centro de Interpretación para los turistas dado que la información debe ser comunicada en presencia del objeto real para revelar el significado del lugar y los fenómenos que visitan.

6. Conclusiones

El turismo es uno de los sectores con mas rápido crecimiento y con un manejo apropiado contribuye al desarrollo sostenible y a la lucha contra la pobreza.

Los visitantes merecen normas que sean aceptadas ampliamente para que distinga lo que es ecológico de lo que se pretende vender como verde. El Plan de Manejo permite agrupar esas normas para que sus prácticas sostenibles sean verdaderas. Asimismo una Estación Ecológica garantizara que el material comercial que el propietario ofrece esta de acuerdo con las herramientas técnicas propuestas en la implementación de practicas conservacionistas.

Si bien la actividad turística se halla controlada es necesario un marco de conservacion que no solo involucre al administrador del emprendimiento y sus asesores sino también a los visitantes y a las autoridades correspondientes para compatibilizar las legislaciones ambientales.

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CLASSIFYING CAVE ENVIRONMENTS BASED ON THE ENERGY FLOW LEVELS (CASE STUDY OF THE CAVE OF SANTANA, SAO PAULO STATE, BRAZIL)

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Abstract

The classification of energy flow levels in Brazilian caves has traditionally followed the 1986 theoretical revision of Timothy Heaton that defines three levels of energy flow. The main indicators of energy level are the water movement and physical characteristics of cave walls and floor. However, some papers published in Brazil have suggested another classification, based on airflow, while not defining criteria and parameters for the findings. This work presents the results of two surveys related to the classification of energy flows from cave of Santana, located in the State Touristic Park of the Upper Ribeira River – PETAR. The objective was to compare classification approaches and to develop classifications for sections of tourist cave, so as to reduce impacts of visitation. In the first phase field studies of geomorphology and hydrology based on secondary data were used to obtain a "Heaton style" classification of the environment. In the second phase experimental monitoring of temperature and relative humidity for a period of thirty days was carried out in order to draw a profile of the original variability of the cave microclimate and its relation to the climate of the surrounding rainforest. The resulting data was analyzed statistically using cluster analysis, correlation matrix, and multiple linear regression. We will discuss trends and assumptions for the microclimatic sections on the cave and compare the results with hydro-morphological data.

TRENDS FOR TOURIST CARRYING CAPACITY IN BRAZILIAN CAVES

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Abstract

On the whole Brazilian territory there are approximately two hundred caves with some sort of tourist attraction, with or without regulation. Of these, around of forty have some kind of control on the daily visitors, with only 11 of them were made technical studies of management. Under this scenario, this work presents some studies related to the behavioral and physical limits for tourism in Brazilian caves, as well as trends in current research on speleoturist carrying capacity. The methods of research were based on surveys including Europe, the United States and Costa Rica examples for any comparisons with Brazilian caves. The result shows two main currents of visitor's control: the rotation rate, a parameter based on management ability of cave manager, and the carrying capacity calculation by the method of Miguel Cifuentes Arias. For the cave sections were also identified another two trends: a division based on tour trails and other one following the methodological guide of the Brazilian Institute of Environment – IBAMA. In some cases, on isolated or small caves, the trail definition and the rotation rate are sufficient to preserve the cave allied to its tourist use. In other cases, caves of greater complexity physical, microclimatic and biotic, it is essential to use methods more focused on the public use limitations based on monitoring of environmental indicators. It was also noted that the correction factors in the methodology of Cifuentes is of little or no utility for cave management. Thus, new speleological indicators and adjustments to this method are also suggested.

COMPLEX SPELEOLOGICAL EXPLORATION OF KAPOVA CAVE (SHULGANTASH) AS BASIS FOR PROTECTION OF ITS UNIQUE PALEOLITHIC PAINTING

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Kapova cave in the South Ural Mountains bears paleolithic paintings that were discovered by A.V. Rymin in 1959. To date, it is a unique site in Eastern Europe. At first, about 50 drawings were found – of mammoths, horses, bulls, and woolly rhinoceros that were studied by archeologists O.N. Bader and V.E. Shelinsky.

Our speleological group first studied the object about 30 years ago, but systematic work began in 1999. We conducted further exploration and monitoring of the following dynamic parameters of this speleosystem: geologic, topographic, mineralogical, geomorphologic, hydrologic, hydrochemical, microclimatic, microbiological, and others. Geoecological parameters, such as radiation fields, radon danger, and gas composition were taken and studied.

New paleolithic drawings were searched for and unclear drawings were read using computer methods of digital information processing. This work resulted with discovery of new drawings. The number of drawings totals 174 to date. Apart from drawings, there are various abstract signs in the cave. They have complex shapes and tend to build a pattern. They might be used for sharing information.

The preservation conditions of drawings in the cave are not always favorable, thus we work on correcting the cave's microclimate. It is planned to plug the dolines above the cave to avoid stream water from soaking into chambers with drawings.

To satisfy the growing interest of visitors, we have planned and built a small excursion path from the entrance to the climatic barrier of the cave. It is built in order to not disturb the inner branches that contain drawings. For protection of the cave, preservation of its paleolithic drawings and better organization of tourist activity, a foundation of a protected museum is planned.

1. Introduction

Shulgan-Tash cave (Kapova) is situated on the territory of the republic Bashkortoshan and nature reserve "Shulgan-Tash" on the Belaya River. It has been known since prehistoric time and during Paleolith was a regional temple. In 1959, A.V.Rymin, a biologist of Bashkirsky reserve, discovered the first paleolithic painting in Eastern Euroasia, what proves the existence of South Ural center of Paleolithic culture, similar to Pirenean-Cantabrian in Western Europe. Archeologic exploration in the cave was conducted by O.N.Bader (1960–1978) and V.E.Shelinsky (1982–1989).

The speleological groups of the Karpinsky Russian Geological Research Institute (VSEGEI) and Russian Geographic Society (RGO) work on exploration of the cave for over 30 years. Since 1999, our work has became systematic. This exploration is conducted under an agreement with the Culture Ministry of Bashkortoshan. Our main tasks are: complex speleological exploration and monitoring of dynamic and geoecological parameters of the cave, correction of the cave's hydrological and microclimatic regimes for long-time preservation of paleolithic painting, and development and control of an excursion route. Also, a concept of a modern federal culture and historical museum and reserve is being developed.

2. Survey Overview

The cave lies in a low-mountain area with elevations ranging from 270 to 500 m, parted by valleys of rivers and streams. The main elements are the limestone massifs, with the Belaya River canyon to the south. East massif and the Cave massif are parted by the Shulgan canyon. It lies close to the

cave and on the north of the area becomes a dry valley. The area is strongly affected by karst processes. There are many caves, potholes, grottos, dolines, dry valleys, canyons, also karst lakes and rock towers present.

Topographic work resulted in a new map of the cave ajoined with a surface plan. The length of the cave is 2984 m, relief 173 m, where 78 m are underwater areas. The cave mainly consists of large chambers and underground canyons, it has four floors, including the flooded area. The karst system has a length of 7 km and includes the yet unpenetrated sumped areas under the dry-ditch that connect Kapova cave with the input area of cave-doline, Oziganovskaya.

To understand the history of cave development, geomorphological research was conducted. According to correlation scheme of terraces of river Belaya, Shulgan canyon, and the cave's hollows, the dating of cultural layer in the Sign chamber turns to be Upper Pleistocene, and the cave itself – over 2 million years old. Possibly, its formation began even discovery of new cave hollows between 335-360.5 m.

The region of the cave is mostly built of Devonian carbonate rocks. It has a blocked structure with intensive breaks of different size and gentle folds. The cave is situated in the central zone of a massive synclinal fold, torn by two large breaks. These breaks control the Belaya River canyon. The formation of the cave was caused by blocked structure and two massive crossing breaks, assisting the concentration of drainage and absorption. The result was favorable conditions for karst formation and development of large caves. In the waterless valley of Shulgan and on the East massif there are ochras and debris that were used by the ancient people for preparation of painting material.

In the cave there are gypsum crystal speleothems and calcite core speleothems of complex shape that form under the water-drops on the slopes of pits in clay. Basing on paleomagnetic study of clay, conducted with V.V. Kochegura, some additional details in change of geomagnetic field at the time of two excurses, that basing on chronological, archeological and paleomagnetical data can be well identified with excurses of Mono and Kargopolovo and, thus, make a more precise paleomagnetic stratotype of South Ural. The results speak for the Pleistocene age of the cultural layer.

Archeologist T.I. Sherbakova helped to conduct a survey of absolute age of coals (C^{14}) in the laboratory of VSEGEI that were taken from a excavation at the east wall of Paintings chamber under the composition number 1. The age of ochre elements seems to be around 17 thousand years old.

Hydrological work has considerable importance for protection of Paleolithic painting, as too much water bears a serious danger for the painting. The exploration includes hydrological monitoring and tracing of water tributaries to chambers with painting, in order to reduce or prevent this water from coming into the cave.

The main water system of the karst system is the Shulgan river, which is swallowed in the north by the pit of Ojiganovskaya cave, runs 2.5 km under the dry valley and canyon of Shulgan, appears for about 150 m in the chambers of the cave, and then comes to surface as a strong vauclusian spring in the entrance grotto of the cave, forming the Blue lake. The second water system –Koran stream, starts as karst spring to the northwest of Cave massif and runs along the Shulgan canyon. Its waters are caught by the moulins. One of them delivers water to the Chaos chamber, where the painting is to be seen. In the cave, there are three lakes and some smaller streams. The most negative effect on painting results from the water coming from the canyon. For protection of painting they need to be cut off.

A considerable meaning for cave's microclimate plays on the temperature regime of water in the cave. We conducted a temperature survey of practically all streams and lakes in the cave. The chemical composition of waters in the region is hydrocarbonate calcite. Mineralization is not higher then 1 gram per liter, medium pH is 7.5, sometimes up to 8. Due to flooding caused by rain regime and high levels of still water, change of pH in water in the cave and at surface vary considerably.

Microclimatic survey is very important for protection of painting, as they point out the main agents that influence its condition. In course of survey, we fixed the meanings of temperature, moisture, and speed of air currents. What is needed to build a model of air-warmth-moisture transition and zones of condensate formation. The temperature survey showed that there is a large transition area from the entrance to the Gorge (200 m) on the first floor, and to the First gallery (190 m) on the second floor. Further into the cave the temperature stabilizes, its fluctuation does not exceed 1^0C and is +6.6 - +7.0^{0}C. In the further part of the cave, a lower temperature is registered (from +6.6 - +5.8^{0}C, and on the shore of Underground Shulgan in the Abyss chamber the temperature raises to 7.0^{0}C. Analysis of the humidity change date showed a serious variation of relative and absolute humidity on the lower floor of the cave, depending

on weather conditions on the surface. During rainy weather, there is some fog on the first floor as far as the Signs chamber, the relative humidity varies from 97 to 100%, the absolute humidity varies from 8.6 to 6.6 g/m^3 , and by hot weather – from 90 to 100%, by absolute humidity from 8.0 to 7.2 g/m^3. On the second floor, the humidity variations depend on weather change as far as the First gallery. The further from the entrance, the lower is the change of relative and absolute humidity (amplitude of relative humidity does not exceed 5-6%) and it does not depend on weather conditions at the surface any more. A double direction circulation of air currents prevails. In summer, the cold air from the cave, forming the lower current, flows out of the cave. In winter, under the cave's ceiling, there is a comparatively warm upper current flowing out, and a lower frosty current flowing into the cave. Sometimes this scheme of circulation breaks up and turns to a single direction scheme.

The conditions of air circulation in the cave are quite complex, and they have to be considered during the work on organization of the excursion path. The survey of air currents allowed us to find an early unknown part of the White Giant system and a crack-like link with the surface through a small cave Tashkeljat. It was fixed that a large part of the air circulates in the entrance area, and only 17 % of this air makes it through the climatic barrier into the cave. Whereas only 2 % flows into the chambers of the first floor and 15 % flow into the second floor. We measured a small reasonable prevail of outcome over income. That can be explained, as there are unknown to us cracks and channels, through which spare air flows into the cave from the surface.

Our exploration showed that small influence of tourist groups on the microclimate of the entrance area does not affect the regime of the inner parts of the cave. On the first floor behind the climatic barrier prevails a stable regime that does not allow influx of infiltration water that flows inside through cracks and channels from the surface. The second floor's hollows depend more on weather situation at the surface. During summer hot weather, which causes intensive circulation, there was some condensation at the ceiling and moistening of walls in the Drawings chamber. Condensate is the most important negative factor affecting the preservation of drawings. Conducted exploration allowed us to minimize this effect in chambers with drawings. In order to do this, we have closed the upper part of the microclimatic barrier with a polymer screen that prevented the income of warm air from the surface.

Thus, the microclimatic characteristics of Shulgan-Tash cave at the moment are unfavorable for long-time preservation of drawings, especially at warm period of the year. The humidification and warming of climate that we have today in the South Ural also causes concerns. It is very unfavorable to conduct excursions into the inner areas of the cave, as it may lead to condensation on walls with drawings, which is highly dangerous for preservation of drawings. Due to this fact special excursions into the closed area of the cave are conducted very rarely.

In winter in the entrance area of the cave, many ice core and sublimate formations. Some of them are quite large – stalagmite candles are up to 4 m high and massive stalagmites up to 8 m high. Sublimate ice crystals are up to 7 cm in diameter and they cover all of the cave's ceiling as far as 50 m from the entrance.

The excursion path in the cave needs a geo-ecological survey, one of these is a survey of radon danger. The cave divides into three zones relative to radon danger. First part, including first floor, terraces of Cascade gallery to the microclimatic barrier and has, with some exceptions, levels of radon lower then 200 Bk/m^3. The second part stretches on the second floor from the First gallery to the Upper chamber. This part characteristically has radon levels from 200 to 530 Bk/m^3 . The level in this area differs in summer and in winter. In winter it is usually not higher then 300 Bk/m^3 and in summer rises over 500Bk/m^3. The difference of seasonal levels of radiation is explained with microclimatic differences of warm and cold year periods. In summer, cold air rich with radon flows from the cave and in winter cold air with low radon flows into the cave. The third area includes all of further part of the cave, starting from the lower part of Brilliant chamber. This area characterizes with radon danger level over 1000 Bk/m^3, and the field instantly raises further, sometimes up to 9000 Bk/m^3. A long-time change of radon field was noted and it is seen as quite reasonable. In the period of high solar activity (from 1995-2002) the level raised intensively every year. In periods of low solar activity and now we survey a slow constant raising of radon field. This effect could be explained by raising tectonic tension, what causes a rise of radon coming from the depths of soil, what might be connected with cycles of solar activity. Some global laws of radon localization in a speleo-system are known. High radon concentration is characteristic for: hollows with constant microclimatic regime (usually these hollows are far from the entrance), for hollows that pass through massive fractures, which act as channels for raising radon. In summer the lower air stream is rich with radon, in winter the upper. Radon is well transported by water streams, sometimes radon is driven by them into the cave, sometimes out of the cave.

For the first time in Russia, we conducted a survey of air ionization in a karst system. We fixed a stable rise of ionization as one moves further into the cave, what seems to be an effect of radon field growth. Close to the microclimatic barrier on the border of upper and lower air currents, sometimes we observed a considerable growth of ionization. In summer below the border of warm and cold currents we observed a maximum of negative ions concentration, and over this border – a concentration of positive ions. It is possible, that to a certain extent, it is explained by the effect of air ionization at the climatic barrier in conditions of intensive condensation.

The survey of gas composition of cave's air showed that in close to entrance areas it does not differ with the surface data. The maximum of CO_2 is fixed in further areas of the cave with constant microclimate (up to 0.7%). In chambers with drawings it reaches 0.1-0.2 %, which does not affect the drawings.

Microbiologic data has a considerable importance for drawing preservation. Microbiologists working with us in our group conducted various survey: I.Y. Kirzidely (Botanic Institute, Academy of Sciences) conducted research of micromizets, and scientists from the laboratory of mycology and microbiology (NIZEB Academy of Sciences), N.G. Medvedeva and Y.A. Gridneva, conducted analysis of microbe air contamination and substrate of different cave areas and found different types of bacteria.

A survey of cyanobacteria and weeds, conducted by ecologist and biologist from Bashkirsky state university Sh.R. Abdullin. On the whole, these research show a definite microbiota danger for preservation of drawings, but at the moment the danger level is not high. A partly anthropogenic influx of microbiota was registered.

3. Drawing Overview

During our work had some interesting and important findings. The first finding was a paleolith palette – a flat palette with a layer of ochre for painting was hidden by an ancient artist under blocks in the Chaos chamber. In Brilliant chamber we had two findings. Our group found ancient wooden plates with carved figures. In the Chaos chamber there are hollows between giant stone blocks, forming stone rooms, that were additionally isolated to close all cracks and leave only small entrances. These hollows could possibly be for people to stay during mysteries or, for instance, initiation ceremonies. In the course of our work we noticed that areas of concentration of drawings also had specific acoustical effects. It is obvious that ancient artists attached special meaning to the acoustic characteristics of a place.

Our research, long-time monitoring, and considerable working experience in complex karst systems allowed us to develop a conception and project of an excursion path in the close-to-entrance part of the cave but not further than the climatic barrier. Thus, the path does not influence the inner areas of the cave and does not affect the safety of ancient drawing. On the wells of the main gallery, an artist-animalist V.Y. Chernoglazov copied the most interesting paleolithic drawings, increasing the intellectual content of excursions. To prevent unapproved access into the inner parts of the cave, two protective gates were constructed. They are placed at the climatic barrier and their construction provides enough space for the arrival and departure of cheiroptera.

Work focused on ancient drawings is seen as very important. Under this fixation we made photographs of painting in different regimes using etalons of color and size and topographical fixation.

While fixing drawings we divide them into several groups.

First - ancient red and close to polychrome zoomorphic drawings (mammoths, horses, bulls, rhinos), most of them outlined.

Second group – red anthropomorphic figures.

Third group – abstract geometrical signs, including specific for Kapova cave trapeziums, (mostly red, sometimes black and of mixed colors).

Fourth group – red and yellow zoomorphic drawings, mostly silhouettic, in rather poor condition.

Fifth group – red ochre spots, it is not known what they represent (relicts of drawings).

Sixth group – black spots and lines (mostly with angles), their identification as ancient drawings is being questioned.

Prior to our project there were 50 drawings known in the cave. At the moment, 174 drawings are known, as a result of our thorough exploration and new computerized methods of photo processing.

The drawing of Kapova cave is quite different from its western analogs. Drawings of animals comprise only 26%

as a large part of all drawings are abstract geometrical signs (38%). Some drawings are not solved, as they are largely damaged and look like fade spots (34%). Out of well preserved drawings, 12 are of mammoths, 8 of horses, 2 of bulls, 2 of rhinos, 1 deer, 1 mountain goat, 3 anthropomorphic figures. Quite interesting are abstract signs, which are different from western analogs as there are more of them and they are more complex, diverse, and tend to build a system. Specific trapeziums that widen to the top are seen only in Kapova cave. They have "ears" on top and inner subvertical ribs, the number of these ribs varies. It is possible, that they act as numeric signs together with zoomorphic drawings, that are totemic animals. It is a pity that only 11% of drawings have more or less convenient states of preservation, whereas 67 % have a poor state of preservation.

We witness considerable differences in specific and stylistic composition of drawings. On the second floor, realistic drawings of animals are widely spread, nearly all of them are outlined and drawn with red ochre, only one geometrical sign is present – a trapezium. It could be that zoomorphic figures were a special totem of this group of people and a trapezium fixed its number of members. It is hardly a coincidence that there are 12 zoomorphic figures in the east wall composition of Drawings chamber and the only trapezium found near them has 12 ribs.

On the first floor, abstract signs are dominant. Drawings of one type tend to build groups on local parts of the walls. Also some drawings are similar to engravings on rocks in Tuva, for instance, that belong to later period – before the bronze age. This could mean that drawings in Shulgan-Tash are not homogeneous and belong to different periods. An abundance of complex abstract signs, similar to hieroglyphs, is characteristic for the post-Paleolithic period, when a human being began to stand out distinctively in surrounding nature.

A part of drawings (about 8%) are possibly later drawings or natural spots. We marked them as problematic and hope that future study would allow us to understand their true origin. If not registered and paid attention, these problemetic drawings could be lost forever.

Many drawings are influenced by membranous moisture and these drawings have to be protected with hydrofob solutions as soon as possible. Also some cleaning work has to be done to clean the drawings from later graffiti and covering them calcite cores. That will be the task for professional restorers.

The drawings found also have to be precisely fixed in the interior of the cave. We tried various methods of topographic fixation. Most precise and adequate in this situation is the method of combined topo-fixation. It is based on topographical survey of hollows and chambers and fixation at evident stationary points (blocks, corners) of axis of rectangular spatial system of coordinates. Drawings are fixed in space using this system of coordinates. Every drawing has its coordinates: X – horizontal distance from zero, Y – vertical distance from axis to drawing, Z – horizontal distance from axis to drawing (to the wall). Also the height of drawing above ground level is fixed.

4. Conclusions

A long time research in Shulgan-Tash (Kapova) cave, conducted by our speleo-group of VSEGEI and RGO allowed gathering of data on it morphology and special regimes of hydrological, microclimatic, microbiological and other systems. Geoecological parameters collected allow us to recommend actions for long-time preservation of Paleolithic drawing, work of a special excursion route that does not harm the cave and ancient drawing, and development a project of a federal specialized speleological reserve and museum.

KARST AND GEODIVERSITY INITIATIVES IN NSW, AUSTRALIA

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The Karst and Geodiversity Unit (previously Karst Conservation Unit) of the New South Wales (NSW) Department of Environment and Climate Change, was established in July 2006 and has the primary aim of *protecting, conserving and promoting karst and geodiversity for the benefit of current and successor generations.* It is the first of its type within the New South Wales (NSW) Government, and is responsible for over 40 publicly-managed karst environments.

A Karst Management Advisory Committee was established under the NSW National Parks and Wildlife Act 1974 to advise the Unit and NSW Government on a range of karst-related matters. This committee, which has a state-wide mandate, consists of representatives from a variety of non-government organisations and industry specialists. The Unit is also provided invaluable support by local speleologists, the Australian Speleological Federation and Australasian Cave and Karst Management Association.

The Unit is strategically located in Bathurst, New South Wales, close to Abercrombie, Borenore, Jenolan, and Wombeyan karst conservation reserves, which contain some of Australia's most significant and well known cave systems. It is also within a day's drive of other features of geological and geomorphological significance including the Warrumbungle Ranges and Mount Kosciuzko, which are two of the state's and Australia's foremost visitor destinations.

The formation of the Unit represents a significant breakthrough for the many karst practitioners, researchers and speleologists who have long supported such an initiative. It also demonstrates a growing awareness and recognition of geodiversity by the people of NSW, in particular, its role in supporting ecological systems and processes, which had often been viewed in isolation.

Consistent with its diverse stakeholder audience, the Unit has both strategic and operational responsibilities. These include the review and preparation of geoconservation plans, policy formulation, community and staff education, providing technical support to operational staff, approving speleological activities (including cave exploration and diving) and assessing applications for karst-related research. This paper outlines the key achievements of the Unit since its inception in July 2006 and outlines future initiatives which will assist the Unit and NSW Government in meeting its karst and geodiversity objectives.

1. Introduction

Parks and reserves managed by the NSW Department of Environment and Climate Change (DECC) contain karst environments of state, national and international significance. In relative terms, these environments (and associated values) remain poorly understood, with the past focus of conservation agencies directed towards more topical issues associated with above ground environments

Recent initiatives of the NSW Government, including the formation of the Karst and Geodiversity Unit (KGU) in July 2006 and constitution of the Karst Management Advisory Committee in November 2006, are helping to redress past imbalances, while ensuring that karst and geodiversity issues are more prominent in strategic and operational planning.

In March 2007, the KGU convened a forum attended by karst managers, practitioners and scientists from across NSW. The Karst Managers Forum, as titled, provided a diverse range of people with the opportunity to raise issues of concern and discuss the outcomes of field inspections conducted by the KGU since its inception in July 2006. In identifying the key issues and impediments to the DECC meeting its immediate and long-term geoconservation objectives, a range of stakeholder views has been considered.

This will hopefully result in mutual benefits to both the NSW Government and community generally and the catalyst for on going dialogue and cooperation between stakeholders, a key aspect of sustainable karst management.

2. Context

Limestone deposits form a broad, irregular fringe around the Australian continent and comprise approximately 4% of the total land surface. Although below the world average for outcropping carbonate rocks, Australia is well represented by a variety of karst features and environments, ranging from expansive soft outcrops, in the order of 2 million years old, to ancient, *hard rock karst* more than 300 million years old. Whilst not the largest or deepest in the world, Australia's karst environments are of immeasurable value. Its relative geological stability, combined with a wide array of past climactic conditions, has resulted in the formation of the worlds most complex and truly ancient karst systems (Gillieson and Spate 1998), and contain the most diverse subterranean fauna yet recorded (Wong et al., 2001).

The majority of New South Wales (NSW) karst environments occur in older, hard rock areas where limestone is recessive in the landscape. These *impounded karsts* are found in over one hundred separate locations, ranging from Ashford, in the State's far north, to Delegate in the far south. NSW karst environments display complex processes of cave evolution and development; they are also the most studied in Australia due to their plentiful array of endemic flora and fauna, intricate origins, rich cultural history and accessibility (Gillieson and Spate 1998), and are visited by over 500,000 people each year.

NSW karst environments which are managed by the DECC contain over 40 individual karst environments. These contain four, of the five *subterranean biodiversity hot spots,* as described by Thurgate et al., (2001), over 1000 identified (or tagged) caves and the oldest open cave system in the world, the *Jenolan Cave System* (Osborne et al 2006). Originally recognised for their outstanding aesthetic and recreational values, DECC karst environments are amongst the oldest protected areas in the world. The Wombeyan Caves were reserved from sale for the purposes of leisure and cave preservation in 1865, followed by the Jenolan Caves in 1866; both preceding the declaration of the world's first national park (i.e. Yellowstone National Park) in 1872.

The DECC manages approximately one third of NSW cavernous karst environments, with the remainder on private land. A percentage of DECC karst environments are contiguous with similar areas off-park. These areas are of potential conservation value and would benefit from further evaluation and protection.

3. Statutory Framework

The framework for protecting and conserving NSW karst environments is provided by the following key legislation:

- Australian Charter for Conservation of Natural and Cultural Heritage;
- Environment Protection and Biodiversity Conservation Act 1999;
- Environmental Planning and Assessment Act 1979;
- IUCN Guidelines for Cave and Karst Conservation 1997;
- National Parks and Wildlife Act 1974;
- National Parks and Wildlife Regulation 2002;
- Native Title Act 1993;
- NSW Heritage Act 1977;
- Protection of the Environment Operations Act 1997;
- Threatened Species Conservation Act 1995; and
- Relevant DECC plans, policies and operational guidelines.

4. Visitor Use and Impacts

Under the National Parks and Wildlife (NPW) Regulation 2002, a permit is required to access caves on designated parks and reserves. The processing and approval of permits is undertaken by DECC field operational units, which impose *conditions of access* based on relevant legislation, stakeholder requirements and their knowledge of caves. Access to caves is also controlled by routine patrols, on-going liaison with stakeholders and park interpretation.

The regulation, assessment and monitoring of visitor access is essential to the conservation of karst environments. Recent inspections of DECC karst environments by the KGU highlighted a range of issues stemming from inappropriate use including damage to speleothems, removal/destruction of fossils, disturbance of fauna, lighting of fires and littering.

Management Initiatives

- Develop a Cave and Karst Access Policy which specifies the extent and nature of cave access and the requirement for a standard approach to processing and approving activity permits;
- Develop a DEC Code of Conduct for speleological and related activities;
- Develop a Memorandum of Understanding

(MOU) with key stakeholders in which the protocols, procedures and underlying tenants for conducting speleological or related activities, are defined and agreed to;
- Develop a framework for monitoring the impacts of visitors on karst and geodiversity values with aspects to be considered including;
- Develop a Cave Gating Policy, which outlines the types of caves to be gated, the purposes for which gates would be installed and key design criteria.

5. Information Management

Historically, researchers (including speleologists) have provided much of DECC's available information on karst and geodiversity; particularly as it relates to cave numbers, location, morphology, structure and significance. Past and current members of the DECC staff have also contributed to the existing information base, by documenting key features and attributes of caves during the course of park inspections. Until recently, a percentage of DECC's karst information was only available in hardcopy and stored in files located in regional/area offices, or the DECC Library. This provided minimal opportunities for resource sharing and increased the potential for valuable information to be lost/damaged.

Management Initiatives

Develop a Karst Resources Database which includes information on:

- number and location of karst environments;
- cave biota and ecosystems;
- Indigenous and historic cultural heritage;
- threatened flora and fauna species;
- surface and groundwater hydrology;
- palaeoecology:
- archaeological records; and
- geodiversity and geoheritage.

6. Education, Training and Awareness

The DECC manages karst environments of local, state and national significance. Day-to-day management of these environments is the responsibility of rangers (in conjunction with regional/area managers), who juggle this responsibility with other duties such as fire management, feral pest and plant control and park interpretation. In many cases relevant officers have limited knowledge of the principles underlying sustainable karst management. This, combined with the absence of karst-specific policy, competing priorities, staff transfers and the remote location of many DECC karst environments, presents an on-going management challenge.

Management Initiatives

- Amend the DECC Park Management Operating Procedures Manual to include key principles for karst and geodiversity management;
- Establish a Karst Managers Network involving researchers, speleologists, cave managers and relevant DEC staff to facilitate information collection and exchange;
- Develop relevant promotional and/or educational material for distribution within the DEC and to the public.
- Include instruction on karst and geodiversity management in relevant training courses (in-house);
- Develop and implement a communication plan for karst, which identifies strategies for increasing awareness of karst issues through media releases, newsletters and promotional and interpretive material etc;
- Promote the role of the KGU in the provision of technical advice to regions/areas.

7. Development on Karst

Under Part 5 of the NSW Environmental Planning and Assessment Act 1979, a *Review of Environmental Factors* (REF) is required for activities on parks and reserves, which have the potential to impact on the environment. These activities include the construction of walking tracks, roads, pathways and minor capital works. Few on-park activities require the preparation of an environmental impact statement (EIS), which only applies when there is likely to be a *significant impact* on the environment.

Field reconnaissance by the KGU indicates that the incidence of poorly conceived or inappropriate development on DECC parks and reserves is currently low, with increased environmental awareness amongst staff and defined procedures for assessing and approving activity proposals, attributed to this result. Notwithstanding, past anomalies, including the establishment of limestone quarries at Wombeyan and Yessabah reserves and the inappropriate siting of services and utilities, indicates the need for further refinement particularly, when considering that current referral and assessment processes do not require comment from the KGU, or other relevant groups/individuals, on significant or contentious developments.

Management Initiatives

- Confirm existing assessment and referral processes including the identification of key units and/or functional areas;

- Ensure that the protection of karst values is adequately addressed in relevant environmental planning instruments and the environmental assessment procedures under Parts 3A, 4 and 5 of the EP & A Act 1979;
- Investigate the feasibility of a karst-specific State Environmental Planning Policy;
- Develop guidelines for assessing the potential impact/s of development on karst values and incorporate into existing DECC development assessment procedures;
- In consultation with the NSW Department of Primary Industries, develop guidelines for restoring or remediating karst environments, which have been adversely impacted by mining, quarrying or other activities.

8. Risk Management

While DECC acknowledges the risks posed by high-risk caving activities, the incidence of serious or fatal accidents is low when contrasted with other recreational pursuits. In Australia, the number of fatalities linked to high-risk caving activities is less than one per year, with the last recorded fatality at Mystery Creek Cave, Tasmania in 1992.

Terms and conditions for conducting high-risk caving activities are currently included in *activity* or *caving* permits issued by DECC operational units. Should users breach these terms and conditions, permits may be revoked, and a fine imposed if any damage to the cave is apparent.

Feedback from DECC regions/areas indicates a reluctance by managers and other operational staff to authorise high risk caving activities of which they have minimal knowledge, and are not supported by policy. The fact that a percentage of speleological clubs/groups are not members of the Australian Speleological Federation (ASF), and therefore not bound by any code/s of conduct, is also considered undesirable and an area for attention.

Management Initiatives

- Develop and implement a Cave Access Policy, which incorporates risk assessment as part of the permit approval process;
- Develop DECC codes of conduct for caving and related activities;
- Develop a Memorandum of Understanding (MOU) with the ASF, in which the protocols, procedures and underlying tenants for recreational caving and related activities are defined and agreed to;
- Amend the National Parks and Wildlife Regulation 2002 to ensure that DECC interests are sufficiently protected in karst environments;
- Review the procedures and protocols for responding to cave emergencies, in particular, the relationship between the NSW Cave Rescue Squad, Police, State Emergency Services and the DECC.

9. Off-park Conservation

DECC karst environments are of varying complexity, scale and significance and are often contiguous with similar environments located off-park. Consequently, activities on adjacent or nearby properties have the potential to adversely impact on karst values. The DECC has recently prepared a *Reserve Establishment Plan* (REP), which identifies short, medium and long-term land park expansion objectives, including greater representativeness of karst systems and processes, and the procedures, protocols and guidelines for establishing a new park or reserve.

In recent years the percentage of lands acquired for the specific purpose of karst and geodiversity conservation has been low, with the majority of acquisitions aimed at biodiversity and wilderness conservation. Moreover, funding constraints within the DECC (and NSW Government generally), mean that inter-departmental competition for land acquisitions remains strong. Cooperative land management arrangements, such as Voluntary Conservation Agreements, provide a valuable backstop in the event that funding constraints curtail acquisitions; they also provide the DECC with the opportunity to influence off-park activities at minimal cost and are the basis for on-going cooperation between park managers and neighboring landholders.

Management Initiatives

- Develop and implement a Karst Conservation Strategy, which identifies acquisition priorities, alternative land management arrangements (including voluntary conservation agreements) and other key issues and considerations;
- Convene workshops with relevant stakeholders (e.g. scientists, DECC staff, speleologists) to determine the criteria for identifying karst acquisition priorities.

10. Research and Science

The framework for conducting research in DECC parks and reserves is provided by the Science Investment and Management Plan (SIMP) 2006 and the Parks and Wildlife

Group Strategic Plan. These documents acknowledge research as an effective means by which the DECC can meet its objective of protecting the state's natural and cultural heritage. Under Section 132C of the National Parks and Wildlife Act 1974, a license is required by individuals/groups that wish to conduct research in parks and reserves.

The Wildlife, Licensing and Management Unit (WLMU) of the DECC, in collaboration with specialty units such as the KGU, has responsibility for assessing and approving research applications and issuing the relevant license. Should proposed research be of a minor scale and negligible impact, the WLMU may waive the requirement for a license, and leave the management of such to the discretion of the relevant on-site manager.

Recent discussions between representatives of the KGU and WMLU indicate that the formal identification of research priorities has yet to be undertaken, with proposals generally considered on a case-by-case basis; they also indicated that support for research is often the result of long-standing associations between the proponent and relevant regions/areas and not linked to any formal research program.

The absence of any formal list of karst research priorities means that DECC's geoconservation objectives have a reduced chance of being realised. There are a number of institutions (tertiary) having expertise in karst that are not partner to any formal research agreement with the DEC. The University of Technology Sydney, University of Sydney, Australian National University and Charles Sturt University all possess expertise in karst and have a variety of students willing to undertake research activities.

Management Initiatives

- Liaise with the WLMU and regions/areas to ensure that proposed research conforms with SIMP principles and accountabilities for karst management.
- Establish the focus and scope of past research.
- Consult with relevant stakeholders (e.g. scientists, DECC staff and speleologists) to identify key research priorities.
- Prepare a Karst Research Prospectus which identifies key areas for focus and which prioritises research.
- Establish formal links or partnerships with relevant institutions/organisations as a means of facilitating cost-effective, targeted and appropriate research outcomes.
- Define the protocols for storing, disseminating, promoting and communicating research findings.

11. Conclusion

The creation of the KGU in July 2006 has provided the resources from which a variety of karst and geodiversity initiatives may be implemented. Furthermore, it demonstrates a growing recognition by the community as to the role of geology and geomorphological processes in shaping and sustaining other aspects of the natural world. The initiatives identified in this paper are consistent with this growing recognition and will provide karst practioners throughout NSW (and conceivably other parts of Australia) with the tangibles means for identifying and attending to issues. They will also ensure that current and successor generations have the opportunity to enjoy and appreciate the State's many karst environments, including the Jenolan and Wombeyan Caves, which have been legally protected since 1865.

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BAATARA POTHOLE SITE: OVERVIEW AND DEVELOPMENT PERSPECTIVES

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The Balooaa Baatara pothole site in Lebanon is unique in the world with its three overlapping natural bridges. The site is commonly visited by people and extreme sports lovers for the beauty of the site and to practice climbing and/or rappelling. The Lebanon Mountain Trail (LMT), which is a hiking trail delineated based on a project by Ecodit, Inc., and funded by USAID, crosses the site and has identified it as one of the main natural landmarks in Lebanon. While the municipality had constructed a skillfully integrated rock trail that allows access to an area adjacent to the central bridge, no safety precautions and no control over site activities have been emplaced despite the number of visitors it attracts. This article is based on a study conducted by the author for Ecodit, Inc., on the Balooaa Baatara site to examine alternative and viable interventions in and around the site in the aim of attracting more visitors and generating more income for the benefit of the community.

Setting up an information booth/visitor center that is empowered with the resources to control site access and activities, and to safeguard visitors was found essential during the summer high season. While the existing municipality rock trail provides access to the plain adjacent to the central bridge, visitor access was not recommended beyond the end of the plain near the pothole edge and onto the central bridge because of the safety infrastructure then needed, which would alienate the site. Proposed vista locations and prohibiting access to the central and top bridges have made possible a visually discreet trail extension that would allow visitors to access the inside of the first 90m shaft and view the three bridges from a lateral entrance. A tentative design of the pothole descent that is based on semi-circular rock terraces and a stairway, which blend with the natural pothole morphology while stabilizing the terrain, was also provided.

1. Introduction

The Baatara Pothole site, also known as the Balooaa Baatara (Balooaa meaning swallow hole), is located in the village of Balaa in the Tannourine area, Lebanon. The pothole has a total depth of 255 m and a surveyed development of 268 m (Fig. 1). The pothole is characterized by three natural overlapping bridges with a total initial drop of 80 m from the top of the first bridge. It can be accessed from the Laqlouk–Tannourine road in the village of Balaa and by taking the bifurcation to the west just 120m before the church; a short road then leads to a small house and restaurant overlooking the pothole. The site is commonly visited by people and by extreme sports lovers while safety measures and proper care of the site are not enforced yet. This article is based on a study conducted for ECODIT, Inc. as part of the Lebanon Mountain Trail initiative funded by USAID, which aimed to provide technical information on the pothole (a brief overview is provided in Section 2), and to identify threats to the pothole (Section 3), recommended options for controlled visitor access (Section 4), and opportunities for site development (Section 5). A conclusion and recommendations are also presented in Section 6. The different caving clubs that are mostly active in this area, namely the Spéléo-Club du Liban (SCL), the Association Libanaise d'Etudes Spéléologiques (ALES) and the Groupe d'Etudes et Recherches Souterraines du Liban (GERSL) were consulted for feedback on the different sections provided in this report.

2. Threats to Baatara Pothole

As proven by dye testing (Karkabi, 1988), surface water that sinks into Baatara pothole essentially reemerges in Nabaaed Dalli spring in Kfarhilda, which is about six kilometers to the west where it is used for fresh water supply. Protection of the catchment area of the Baatara Pothole and that of the Wadi Baatara upstream of the pothole from any polluting activities would contribute to the protection of groundwater quality. Many people visit the pothole, especially during summer, and drop litter around and in some cases into the pothole. With the possibility of visitor numbers increasing in the future, pollution of the site is a credible threat that needs to be addressed. A dirt road east of the pothole and extending from the restaurant to the area south of the pothole facilitates accessibility to the top of the pothole; this

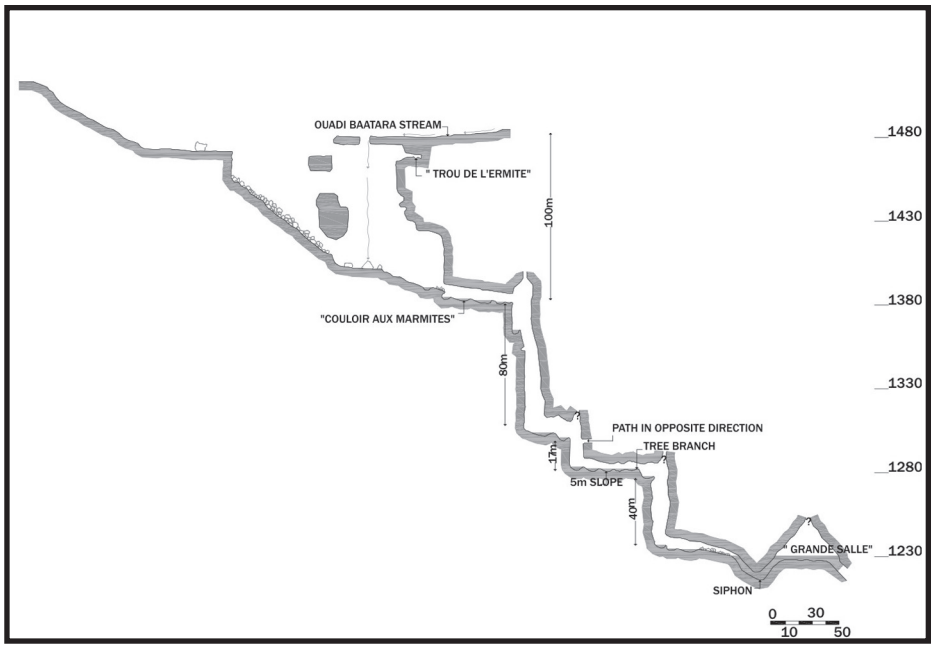

Figure 1: Section of Baatara pothole: dimensions are in meters including elevation above sea level in Y axis (source: Spéléo-Club du Liban archives).

road should be closed to the general public in the future to help protect the pothole site. A law has been recently enacted to protect the site (Yazigi, 2006) whereby an area within a radius of 500 m around the Baatara Pothole falls under very strict regulations. Only small constructions that are built with natural material are allowed after being granted permission from the Ministry of Environment (MoE). Projects in this area also require an Environmental Impact Assessment (EIA) that would be reviewed by MoE.

3. Alternative Options for Visitor Access

Reportedly, visitors' admiration of the Baatara site is due to a relatively limited human intrusion on the site. This aspect served as an important guideline for the visitor access proposal discussed below. Accessing the middle bridge was found dangerous without a handrail, which if placed would aesthetically ruin the pothole. The view of the pothole devoid of visitors and handrails on it whether on the middle bridge or on the top bridge was identified as a key aspect that would work in favor of promoting the site. This would significantly reduce the perception of commercialization of the site and would attract more viewers who are interested in admiring, photographing, or drawing the pothole. A loop walk onto and around the top

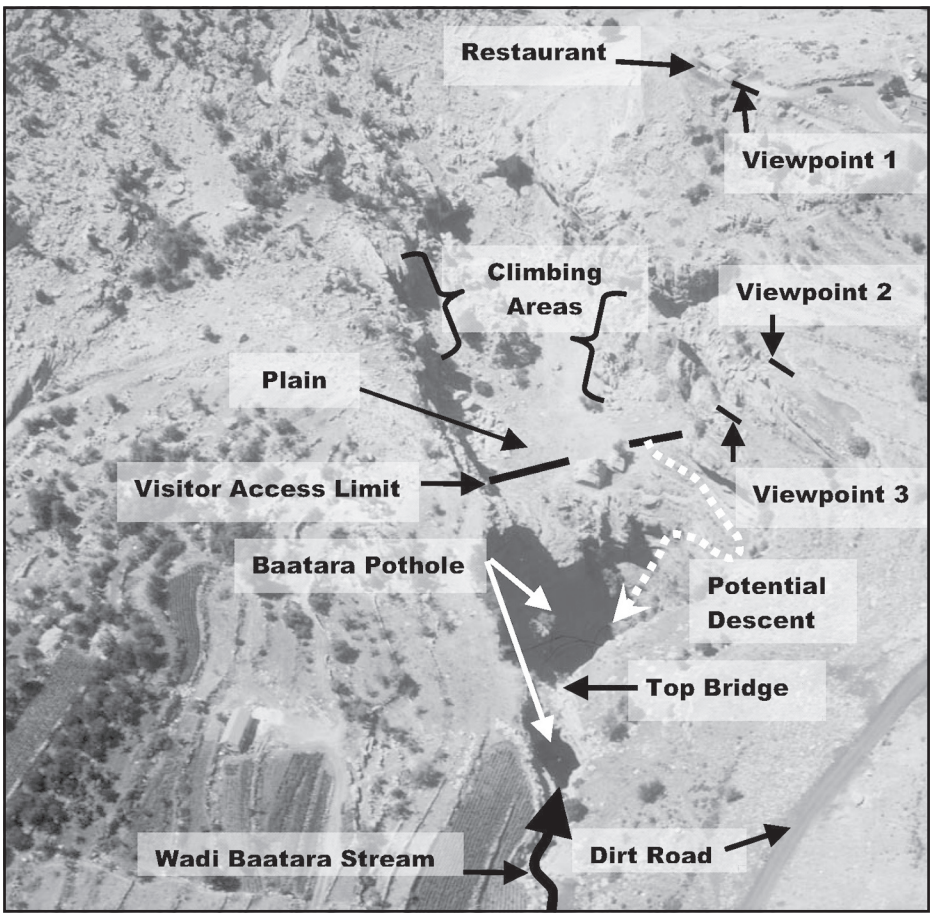

Figure 2: Aerial photo showing viewpoints and potential descent to pothole (dotted in white).

bridge and along the edges of the adjacent cliffs would be dangerous and would entail a similarly unwanted effect and associated safety measures, particularly handrails.

Establishing a small visitor center to control access, to protect visitors and the pothole, and to provide information on the pothole is a necessity if the goal is to attract more visitors. The location of such a center as suggested by the different caving clubs would be at the restaurant location (Fig. 2). All related constructions should have impervious septic tanks that would be emptied regularly due to the high vulnerability of groundwater pollution in the area. It was additionally recommended to remove the small construction just south of the pothole (Fig. 2 –lower left) or to hide it by growing thick trees. Trees may also be used to hide the dirt road extending east of the pothole.

Establishing a visitor parking area next to the restaurant was not recommended because of the air, noise, and visual pollution it would cause to the site. The church just after the bifurcation from the main road leading to Tannourine already has a small parking lot next to it, which may be used and could even be enlarged. If this parking is deemed too far for visitors, a shuttle service (preferably electrically powered) may be adopted, or an alternative parking location could be sought closer to the bifurcation from the main road, just east of it.

The proposed visitor route starts from the church, extends up the main Tannourine road (in opposite direction from Tannourine), and follows the bifurcation that leads to the restaurant where Viewpoint 1 is reached. This would be the closest viewpoint from the main Tannourine road. Although a viewing platform may be established at this point, it would need a handrail and this could be avoided at this site because there are two other viewpoints to the south where handrails would be more visibly discreet. Viewpoints 2 and 3 are characterized by a better view of the pothole and the latter is clearly advantaged by the fact that it is located below a small cliff that hides it from the restaurant area. This was identified as the ideal site for establishing a viewpoint because it has the best view on the pothole and it is well hidden (Fig. 3). A beautifully integrated artificial rock trail, which was built by the municipality, leads down to the small plain near the middle bridge (Fig. 4). A similar trail may be established from the restaurant area to Viewpoint 3. The existing rock trail may also be used by visitors to reach the small plain before the middle bridge (bridge 2) and end at the limit identified by the caving clubs, which may be defined by a line at the level of the huge boulder at the center of the plain (see Fig. 2). Beyond this limit, it becomes dangerous for visitors to venture without constructing handrails, because the edges of the pothole become friable and slippery.

It was observed during the study that the slope leading

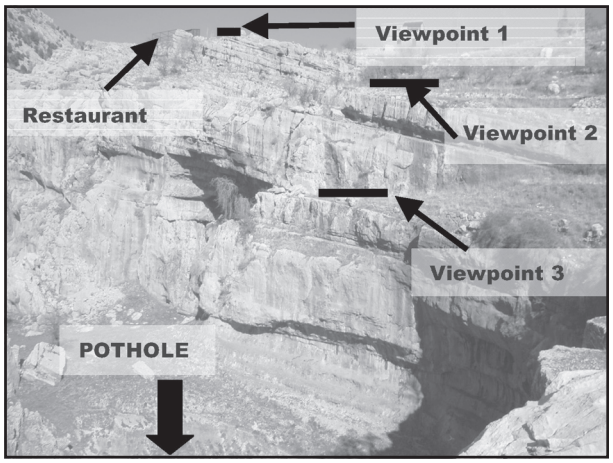

Figure 3: Viewpoints 1, 2, and 3; note how viewpoint 3 is hidden by the small cliff behind.

Figure 4: Existing rock trail.

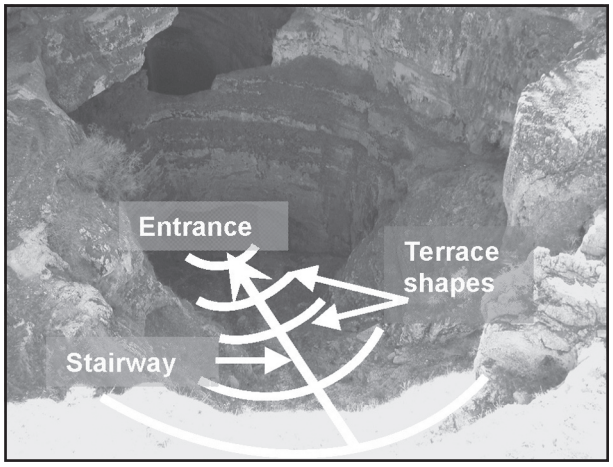

Figure 5: Potential partial descent into pothole and proposed terrace shapes.

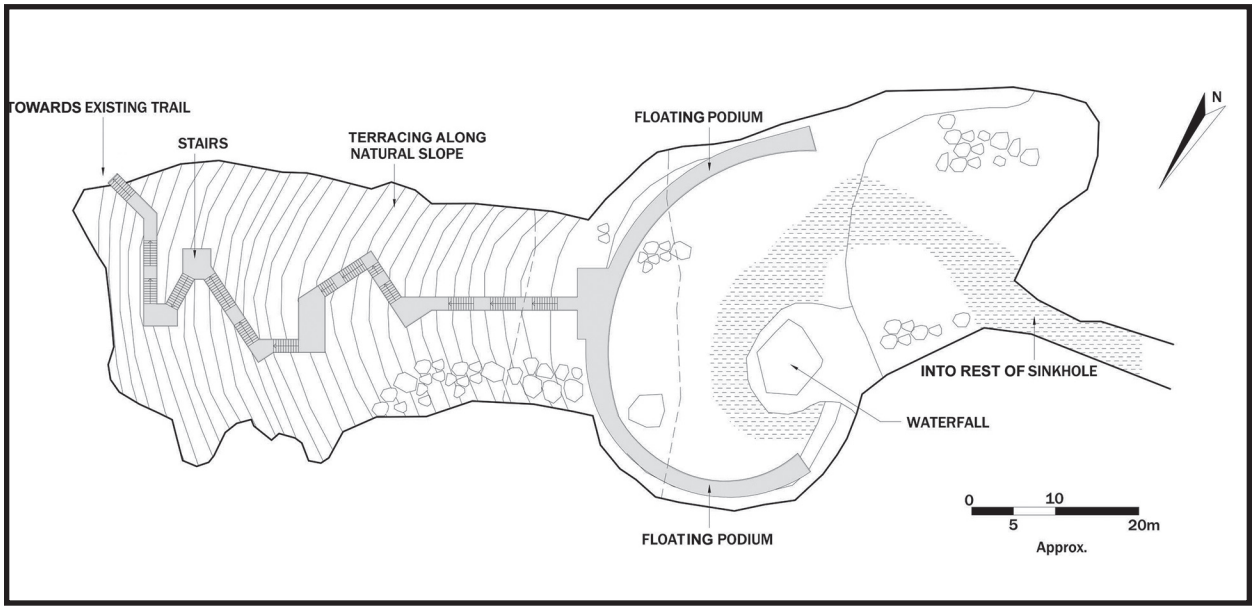

Figure 6: Schematic representation of proposed descent into pothole with stairway path along artificial terraces.

down to the pothole from the northern side where the plain lies is only visible from the center and top bridges, and from the overlooking cliffs (immediately around the pothole). Since it was proposed to restrict access to these areas, a stairway constructed on this slope and leading down to the bottom of the first 80m drop would be relatively hidden to observers from the vistas proposed. This project would also necessitate the construction of terraces along the whole slope to stabilize the terrain as proposed in Figures 5 & 6. Terraces would need to be semi-circular in shape to ensure better support for the slope and to blend better in the circular pothole context. The terraces and the stairway should be constructed with rocks available onsite similarly to the existing municipality trail so not to disrupt the site aesthetics. The stability of the sides would need to be assessed, and measures to prevent rock falls and collapses may be required (such measures should be visually discreet). The stairway should preferably be centered in the middle of terraces to further reduce the risk of any falling rocks. An architect would be needed to design the terraces and the stairway.

The descent allows visitors to admire the beauty of the pothole and its three natural overlapping bridges from inside as shown in Figure 7. Inside the pothole, a semi-circular floating concrete platform may be established as proposed in Figures 6 and 8. This platform would have a handrail and would extend from both sides of the entrance to allow visitors to view the pothole and bridges from different sides. It is worth noting that since the Baatara site is protected by law, a permit from the government would be needed to initiate such a project inside the pothole; a more detailed technical and economic study is also a must prior to initiating such a project, which remains conceptual at this stage.

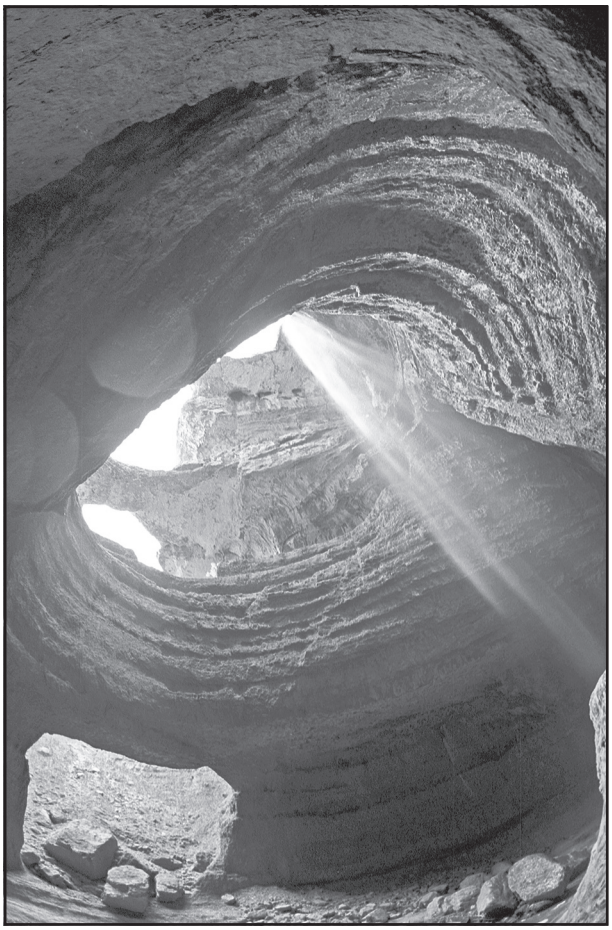

Figure 7: View of pothole from bottom of first 80-meter pitch.

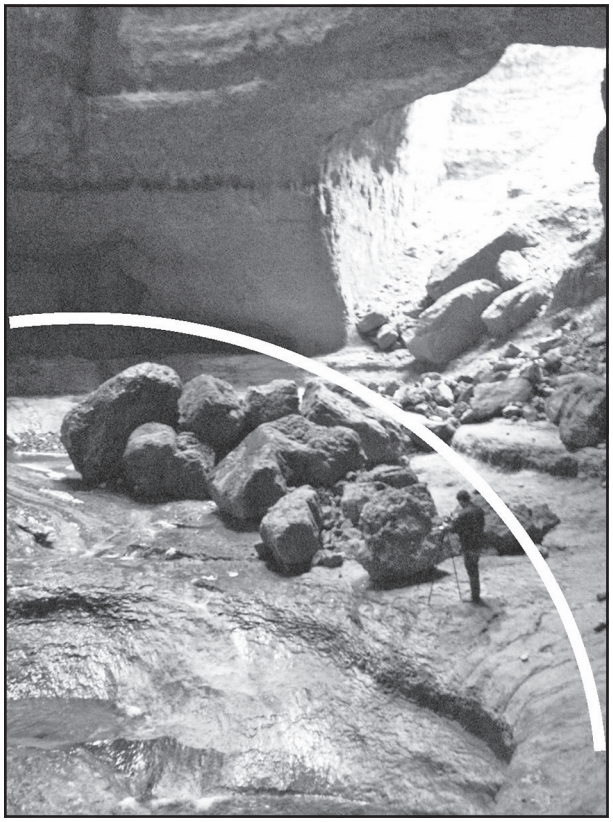

Figure 8: Proposed location of floating concrete platform.

As shown in Figure 9, the bottom of the pothole has witnessed minor but nevertheless clear disturbances between 1986 and end of 2006; new rocks and broken ones may be distinguished. In addition, the walls inside the pothole are moist and affected during winter by repetitive freezing and thawing resulting in small rocks falling; such fragments were observed on the floor. It is thus preferable that visitors going down wear helmets and are accompanied by guides to prevent them from crossing the safety rails and falling down a slippery slope, about 10m lower. The stability of the sides of the proposed descent, which are characterized by fractured and weathered blocks, need to be carefully assessed to ensure safety during and after construction. The cliffs that directly surround the pothole also need to be assessed because collapse of large blocks has occurred, although rarely.

4. Opportunities for Site Development

As suggested by the different caving clubs consulted, activities would best be limited to the area next to the pothole as shown in Figure 2. In addition, activities inside the pothole should only be allowed to professional cavers to help safeguard the pothole and visitors. Figure 2 shows locations that may be used for climbing and rappelling; it was reported that fixed anchors are already present at these locations. A potential Tyrolienne may be stretched between Viewpoint 3 and the opposite cliff across the plain, but this Tyrolienne would need to be tested first and calibrated to ensure public safety, and should later be operated by professionals. Establishing a fixed camping and picnicking location would require restrooms and other sanitary requirements to avoid pollution. Consequently, it was recommended to locate them elsewhere and not onsite. When selecting an alternative site, it was recommended to consider the need to link it to a public sewage network (that may not exist at present but which may be planned for the future).

5. Conclusions and Recommendations

The Baatara Pothole is a unique karst site in the world since it is the only reported site with three natural overlapping bridges. At present, the site comprises a rock trail built by

Figure 9. Changes at the bottom of first 80-meter drop occurring between 1986 (a) and end of 2006 (b).

the municipality from the restaurant location to the small plain at the level of the middle bridge. In order to promote the site and accept more visitors, a small visitor center would need to be established, potentially at the restaurant location. Guides would be needed to control access to the site and to protect the public and the site. The existing trail can be used by visitors to reach the plain but not further; access to the middle bridge should be prohibited to the general public. A potential descent to the pothole along the slope south of the plain may be established, which would allow access to the pothole from the lateral entrance present under the first bridge from the northern side. Such a descent would need further evaluation before seriously being advanced as a truly viable development alternative. The bridges of the pothole and the immediate overlooking cliffs should not be accessed by visitors. Three viewpoints were identified near the restaurant location while it is recommended to use and equip only the best one, which is Viewpoint 3, with safety rails. This proposal would minimize artificial intrusion and preserve the natural beauty of the site; this aspect constitutes a key component in promoting the site and would be appreciated by visitors.

Activities such as rappelling and climbing may be performed on the cliffs overlooking the plain but not on those directly above the pothole. Access inside the pothole should only be allowed to professional cavers with the knowledge of Lebanese caving clubs who are the only qualified Lebanese organizations capable of conducting rescue operations inside caves. It should be remembered that the pothole site is now protected by law and that projects involving any type of construction require permission from MoE. Any works inside the pothole should be executed by highly qualified professionals following a serious selection process due to the uniqueness of the site.

Acknowledgements

Many thanks to the Lebanese caving clubs, namely the Association Libanaise d'Etudes Spéléologiques (ALES), the Groupe d'Etudes et de Recherches Souterrainnes du Liban, and the Spéléo Club du Liban for their time and concern. Special thanks to Mr. Sami Karkabi for his valuable contribution, as always, and for the photos. Thanks to Mr. Carl Estephan for the aerial photos. Special thanks are also extended to ECODIT, Inc. for their interest in soundly promoting the Baatara site and for the opportunity to work on this project.

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KASSARAT CAVE - ANTELIAS: CATCHMENT WORKS HAZARD ASSESSMENT

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Water supply shortage in Lebanon in general and in Beirut in particular has led the Beirut and Mount Lebanon Water Establishment (BMWE) to exploit the water of the underground river passing through the Al-Kassarat Cave in Antelias (Cave of the quarries in Antelias). Catchment works affecting the cave include a conveyor-tunnel, a dam, and an access shaft. A series of artificial and natural events have recently made the catchment works access shaft the only entrance to the cave, whereas it could previously be accessed from two quarry openings and one borehole. Upon discussions with the General Director of the BMWE highlighting mutual interests in safeguarding the integrity of catchment works and in preserving the cave, the Spéléo-Club du Liban (SCL) conducted a field based assessment of potential hazards threatening both infrastructure and the cave and was able to secure continuous monitoring of the cave.

While no imminent danger on built structures inside the cave was observed, a closer inspection of construction rubble accumulated on natural ledges upstream and downstream of the shaft stairway is still needed to better assess their stability. On the surface, the access shaft needs to be completely enclosed to prevent air and water circulation between the surface and the cave. Construction rubble spread along the stream bed constitutes a potential threat on the downstream Toboggan section where water is swallowed into a siphon, later reemerging in down gradient springs. Continuous monitoring of rubble movement was recommended to allow for timely intervention in case of imminent blockage risk of the Toboggan and siphon. It was additionally recommended to protect a borehole and a quarry floor opening that both lead into the cave from rubble and a surface water stream, which could potentially contaminate the underground river and damage the cave. While the gallery that leads to the underground river portion of the cave from the main quarry entrance became blocked by flood deposits, the study did not recommend its reopening at an initial stage because of the potential for air circulation and resulting damage on speleothems. The Spéléo-Club du Liban continues to monitor the cave and to strengthen its collaboration with the BMWE for the sake of sustainable exploitation of the Al-Kassarat Cave underground river.

1. Introduction

The Al-Kassarat Cave in Antelias - Lebanon (Cave of the Quarries) is located about 2 km upstream from the Antelias coast in the valley of Antelias / al Faouar in a past quarry zone known as the Quarries of Antelias. As part of the Beirut and Mount Lebanon Water Establishment's (BMWE) efforts to reduce water shortage in Beirut, the capital of Lebanon, water catchment works have been executed to exploit the underground river of the cave. This cave has had its share of destruction throughout years of civil strife in the country whereby uncontrolled quarrying had wiped out some 300m of cave development including its original entrance in the cave ceiling. Consequently, a new entrance referred to as main quarry entrance in this text was then created at the level of the main gallery leading to the upstream portion that includes the underground river. Furthermore, another opening about 250m downstream and to the West leads into what is today known as the Cave of the Bear while both caves are part of the same development.

Water catchment works include a conveyor tunnel, which extends from an area downstream from the quarries and taps the cave in its wet portion, a dam to divert water into the tunnel, and an access shaft with an approximately seven story high stairway that penetrates the ceiling of the cave in the dam area from the surface to allow for maintenance works (Fig. 1). Associated construction works have resulted in considerable construction rubble inside the water stream

that could potentially clog the siphon in the Toboggan section swallowing the water in the downstream end of the permanent underground river bed. In addition, the almost 3 m high dam has permanently raised water level inside the cave while the shaft has perforated the cave at the start of one of the most beautifully calcite decorated portions of the cave, known as the Galerie du President. No collaboration was requested during the construction stage from the Spéléo-Club du Liban (SCL) who had conducted all discoveries, surveying, underground gauging, and dye tracing; it was dangerous to regularly access the cave during this phase.

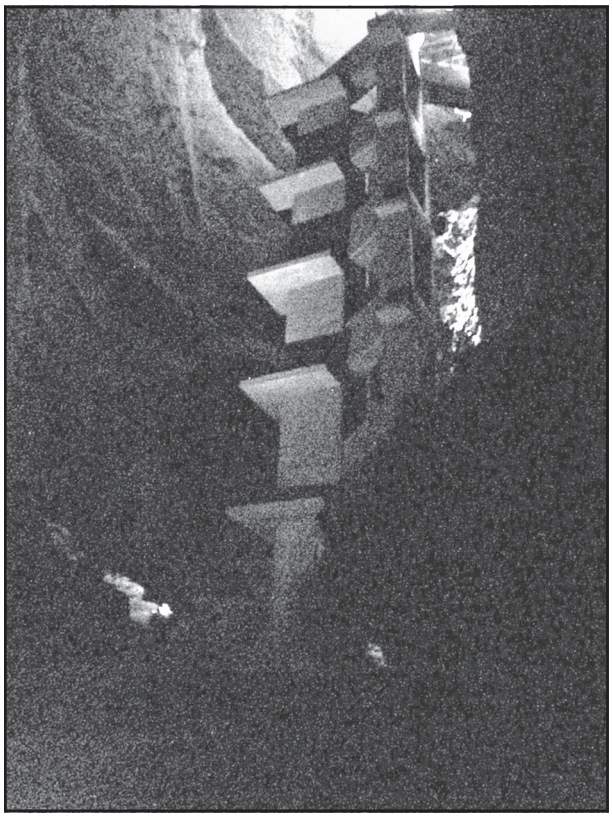

Figure 1: Concrete stairway in access shaft.

Earlier visits and complaint letters submitted to the BMWE jointly by three different caving clubs including the Association Libanaise d'Etudes Souterraines, Wadi al Arayesh, and SCL had resulted in failure. Poor communication and delivery of the wrong message could have contributed to such a failure and to suspension of cave access, especially since the main quarry entrance and passage to the "wet" portion of the cave became clogged with flood deposits thus leaving the artificial access shaft as the only remaining way in.

In 2008 and towards completion of the works and the start of exploitation, the Spéléo-Club du Liban (SCL) approached the Beirut and Mount Lebanon Water Establishment and its general director and highlighted mutual interests in safeguarding the integrity of catchment works and in preserving the cave. Through its general director, BMWE responded favorably indicating its interest in assessing any wrongdoing and conducting necessary corrective activities. The Spéléo-Club du Liban proposed and conducted a field based assessment of potential hazards threatening both infrastructure and the cave. The results of this most recent assessment and corresponding mitigation measures and recommendations are presented below. A map showing the affected cave area is included at the end of this document and can be referred to for better understanding and visualization.

2. Surface Hazards

The main hazards on the surface consist of unstable talus next to the access shaft, and water and air circulation through the stairway shaft, through the old opening in the quarry floor downstream from the shaft, and though borehole 11. These are described below and mitigation measures are accordingly recommended.

The access road to the shaft is built on talus, which may collapse due to erosion; this also applies to the area immediately north of the shaft, which constitutes a slope leading down to the erosive winter stream passing through the valley. The access road needs to be well engineered and reinforced on its sides to prevent erosion and collapse.

Water and air circulation between the surface and the cave through the stairway shaft would result in enhanced weathering and deterioration of the rock walls, the concrete stairway, and oxidation of metal works. This could destabilize the rock walls, which could collapse on the built infrastructure, and would accelerate corrosion and deterioration of concrete and metal elements. Air circulation between the cave and the surface is promoted by differences in air pressure due to temperature and humidity differences between the two environments. The resulting air flow damages the year-round constant microclimate of the cave and results in the deterioration of concretions and death of organisms present inside the cave in addition to the proliferation of exogenous organisms, such as fungus. Such phenomena have been observed in another cave in Lebanon, the Jiita Cave. The shaft entrance should be completely enclosed and sealed to prevent air and water exchanges between the outside and the cave. BMWE seems to have started construction of an overlying access room, and it is recommended that this room contain no open windows to prevent air circulation.

The quarry floor opening predates catchment works but is, unfortunately, impacting the cave similarly to the previous point. This opening overlies a cave passage that extends from the main quarry entrance, which was previously cleared by the quarry owner with bulldozers. This cave passage includes a low lying room called the Winter Lake, which is almost located underneath the quarry floor opening. Winter Lake is now filled to its ceiling by mud deposits due to flooding from the underground river cave section and from surface water being swallowed through the overlying quarry floor opening. The flood deposits brought in from the outside are most likely clogging openings and fractures that contribute to feeding springs located down gradient. It is recommended to set up a fence around the quarry floor opening and a danger sign to protect the public from falling in. The surface water stream, which is bringing in all types of material and pollutants needs to be diverted away from the opening.

Borehole 11 is the 11th borehole drilled while searching for the cave and the one that reached the cave in the "Galerie Sèche" section. It was used by cavers to access the cave in the early expeditions until the main quarry entrance was cleared by the quarry owner. The borehole head is now buried under rubble and not properly sealed (Fig. 2). Given its proximity to the surface and to the surface water stream, water leakage could lead to rock collapse inside the borehole and/or the creation of a water sink for surface water flow. The "Galerie Sèche" is a dry gallery and one of the richest galleries in terms of speleothems inside the cave. Flowing surface water would destroy it. If the borehole head is not adequately protected, this borehole may act as a pollution pathway from the surface to the underground river, which feeds several springs down gradient (Al Faouar, Saltane, and Mqasbiye). The rubble on top of borehole should be removed, and the borehole head should be protected. This borehole may then be used as an alternative emergency entrance / exit if needed.

Figure 2: Borehole #11 buried under rubble.

3. Underground Cave Portion and Infrastructure

The main potential hazards that were investigated inside the cave, which could threaten infrastructures and the cave itself consist of unstable cave ceiling and walls and construction rubble hanging on elevated ledges adjacent to the shaft stairway. The most significant construction rubble accumulations are present, however, in the stream bed.

With the exception of an unstable limestone bed chunk (limited in size) located immediately west of the stairway (Fig. 3) in the ceiling of the cave, the rock walls and ceiling do not seem to constitute an immediate threat to catchment works. Limited damage is expected to occur if the limestone chunk were to fall, especially since it is overlying the downstream side of the shaft stairway. Some collapsed blocks and rubble caused by shaft construction have accumulated on a natural platform located about 8 m higher than the stream bed and immediately upstream east of the stairway (Fig. 4) Although these may not constitute a serious problem to catchment works, a closer inspection is recommended to assess the stability of these deposits. Chicken wire may be used to stabilize them, if necessary, or, alternatively, falling blocks may be cleaned from the basin behind the dam during the dry season. To the west of the stairway, a few accumulations of rubble on a ledge are also liable to slide into the stream but do not present a considerable risk on catchment works given they are located downstream.

Figure 3: Unstable limestone block on the west side of the stairway.

Considerable collapsed rubble and blocks into the stream have been displaced by the water current and spread out along the stream sides downstream from the shaft. A one year old bulldozed rubble track (May 2007) had been completely altered by the force of water into a

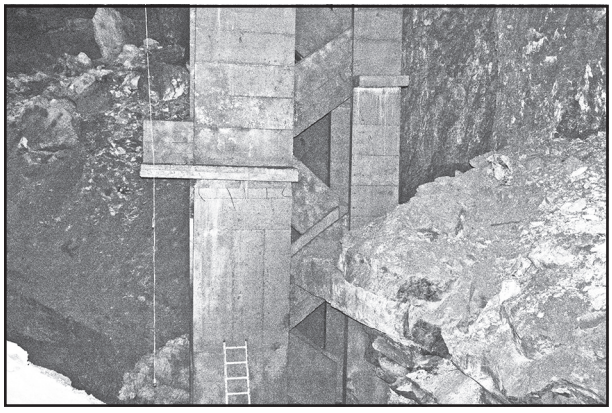

Figure 4: Accumulated construction rubble on natural ledges to the east (top left) and west (right) of the stairway.

rubble mound along side the left bank as shown in the photograph taken in September 2008 (Fig. 5). This rubble material reaches a thickness of about 2 m. Rubble and blocks resulting from the recent shaft construction are easily recognized due to their un-weathered light color and angular sides that contrast with naturally transported pebbles or blocks, which are characterized by a weathered darker yellowish to brown color and rounded sides.

Figure 5: A previous bulldozer track transformed by winter flood waters into an amorphous rubble mound that may reach 2 meters in thickness downstream from the shaft.

Construction rubble and collapsed blocks have been transported as far as the downstream "Toboggan" and siphon (see Fig. 7) as shown in Figure 6 Water flows into the Toboggan and siphon, and reappears down gradient from springs, that are used by locals for irrigation, fisheries, and other purposes. A sump adjacent to the main one was found to host garbage and wood that were deposited by workers working at the access shaft location upstream; water has transported the waste down to this sump over more than 200 m. While blocks and rubble may all eventually reach the Toboggan and siphon in a few years, it is unclear whether the Toboggan and siphon will be able to accommodate the movement of such quantities of rubble. If they become blocked, down gradient receptors such as Faouar Antelias spring could suffer from reduced water flow, which could increase the potential for conflicts between locals and BMWE. In addition, during the wet season, water levels may further rise for longer periods and discharge more quantities through the passage leading to the main quarry entrance, thus causing more flooding and damage on the surface (rising water levels during the wet season cause water to be discharged from the main quarry entrance to the outside making adjacent terrains inaccessible; water then flows into the Bear Cave/Mgharet ed Dib about 200 m northwest resulting in continuous deposition of mud in this cave. This surface flooding problem is worth considering and resolving given the potential expansion of industries and construction projects and/or quarry rehabilitation projects into the quarries area.

It was not recommended at this stage to remove mud from the winter lake, thus reopening this access in order to clear rubble from inside the cave because this would require bulldozers and would promote further air circulation if the up gradient shaft entrance is not properly sealed. Careful yearly monitoring of rubble movement inside the cave is needed however to detect dangerous accumulations of rubble in the Toboggan zone, which can block the siphon and hinder water flow down gradient.

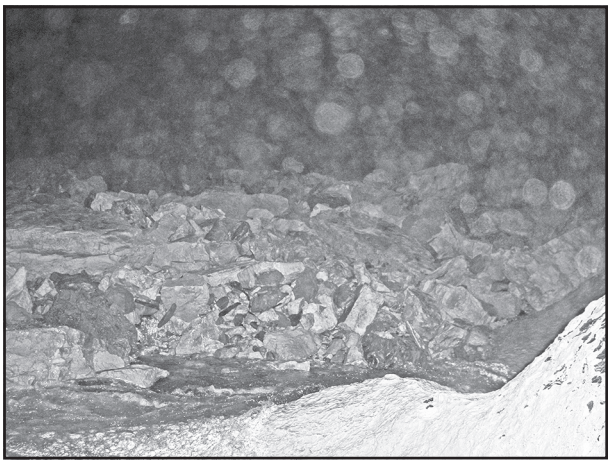

Figure 6: Collapsed blocks and rubble from shaft construction transported down to "Toboggan" section where water reaches the siphon before disappearing and reappearing again in springs down gradient.

4. Conclusions and Recommendations

This study aimed to identify hazards threatening built catchment works and the Al-Kassarat Cvae in Antelias as a result of construction works for the water supply of Beirut.

Potential Hazard	Description	Mitigation Measures
Top of Access Shaft and Environs		
Unstable Talus	Access road build on talus, liable to collapse	Construct well engineered access road with reinforced stream side.
Water and air circulation through the shaft	Weathering and deterioration of the rock walls, the concrete stairway, and oxidation of metal works due to air and water circulation between the surface and the cave. Death of cave organisms and invasion of exogenous ones such as fungus is also likely.	Completely enclose and seal the shaft entrance to prevent air and water exchanges between the outside and the cave (this task seems to be conducted at present by the BMWE).
Water and air circulation through the old opening in the quarry floor downstream from the shaft	Surface water being swallowed through the quarry floor opening is leading to the deposition of deposits inside the cave, which has resulted in blocking the Winter Lake.	• Install a fence around the quarry floor opening to protect people. • Divert the surface stream that is swallowed inside the quarry floor opening.
Unprotected Borehole #11 head	Borehole head is now buried under rubble while it was not properly sealed. Borehole is a potential pollution pathway from the surface to the underground river feeding several springs down gradient.	Clear away rubble on top of borehole and protect borehole head. This borehole could serve as an emergency entry / exit.
Underground Cave Portion and Infrastructure		
Cave Ceiling and Walls	No imminent danger on either infrastructure or cave from unstable ceiling and walls with the exception of a limestone bed chunk hanging from the ceiling west of the stairway. Rubble accumulated on an 8m high platform east of the stairway (upstream) seems to be stable but requires closer inspection. Rubble accumulated on a ledge to the west of the stairway may slide into the stream but does not seriously threaten built infrastructure.	Accumulated rubble on platform east of the stairway may need to be stabilized if deemed necessary upon closer inspection, to protect downstream catchment infrastructure. Yearly inspection of their status and cleaning of river bed from any falling blocks to protect tunnel entrance is also recommended.
Stream Bed	Considerable rubble spread out along stream bed in addition to more than 2m thick accumulations on left bank. Rubble and blocks have reached Toboggan and siphon downstream where water is swallowed before reappearing in down gradient springs. Toboggan and siphon may not be able to accommodate all the rubble and would eventually be choked by it.	Rubble movement should be monitored to detect dangerous accumulations in the Toboggan zone. Monitoring of abnormal changes in water levels inside the cave is also recommended.

Table 1: Summary of hazards threatening the BMWE catchment works and the Kassarat Antelias Cave in Antelias quarries area.

While no imminent danger on built structures inside the cave was observed, a closer inspection and monitoring of construction rubble accumulated on natural ledges upstream and downstream of the shaft stairway is needed to better assess their stability. On the surface, the access shaft needs to be completely sealed to prevent air and water circulation between the surface and the cave. Such circulation would contribute to the quick corrosion and deterioration of metal and concrete structures making up the shaft and stairway, and could potentially destabilize the rock walls.

Construction rubble spread along the stream bed constitutes a potential threat on the downstream Toboggan section where water is swallowed into a siphon, later reemerging in down gradient springs. Continuous monitoring of rubble movement is, thus, recommended to allow for timely intervention in case of imminent blockage risk of the Toboggan and siphon.

A borehole and a quarry floor opening leading into the cave, which are both located in the vicinity of the access shaft,

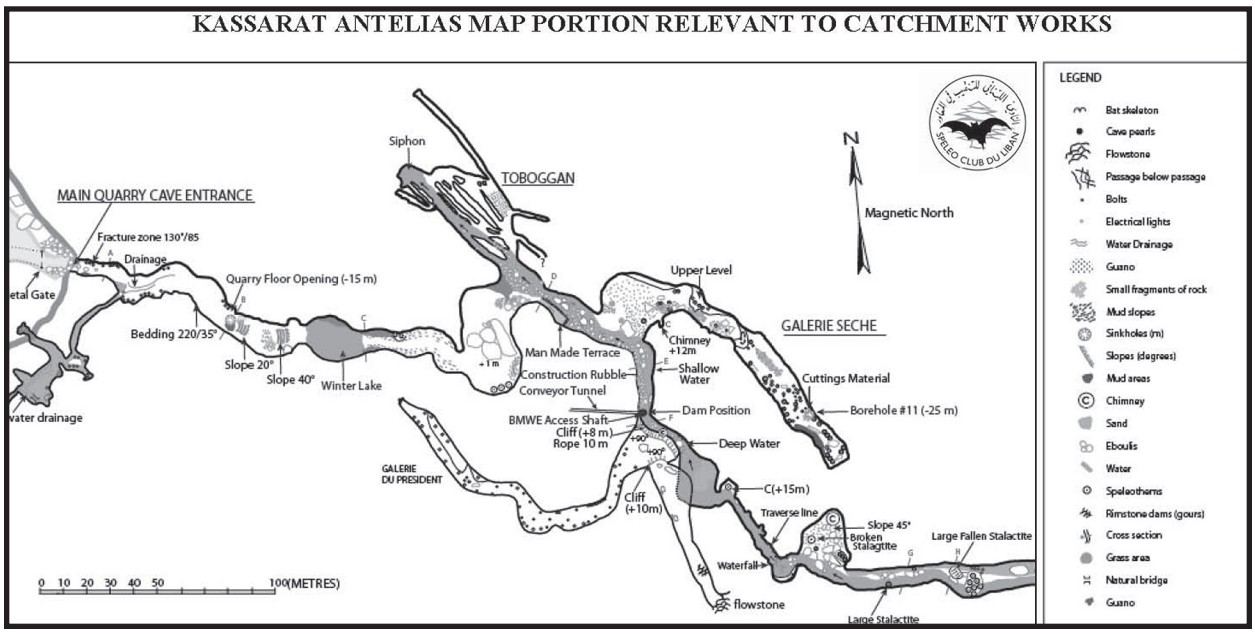

Figure 7: Map of the Al-Kassarat Cave.

would need to be properly protected. It is recommended to clear the rubble covering the borehole head and protect it because of the potential water circulation and consequent pollution pathway and potential damage to the cave. This borehole could also serve as an emergency entry/exit to/from the cave given the stairway access shaft is currently the only access to the underground river portion of the Kassarat Antelias Cave. The quarry floor opening is swallowing a surface water stream, thus bringing in significant amounts of debris and deposits into the downstream section of the cave, which are contributing to burying cave passages and clogging fractures and water pathways. It is recommended to set up a fence around the quarry floor opening and to divert the surface stream away from it. A summary of potential hazards and recommended mitigation measures is provided in Table 1. The Spéléo-Club du Liban will be conducting continuous visits to the cave to secure monitoring and ensure timely intervention, when needed.

Acknowledgments

Mr. Joseph Nseir, General Director of Beirut and Mount Lebanon Water Establishment (BMWE), is thanked for his support and approval to conduct such an assessment. Mr. Raoul Nehme is thanked for his positive initiative and introduction to the BMWE.

ROBBER BARON: RESTORING AN URBAN CAVE PRESERVE

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Robber Baron Cave is located in San Antonio, Texas, USA, in a mixed residential and commercial area developed more than 30 years ago. As the longest cave in the county, it has a large sinkhole entrance, a complex two-dimensional maze of passages, and a long, colorful history. It hosts at least ten troglobitic species, including two endemic and federally listed endangered species. In 1995, the Texas Cave Management Association (TCMA) acquired the cave. The entrance consisted of a large concrete bunker gate that severely restricted airflow and passage of nutrients to the endangered species. The property was a city lot overgrown with non-native plants surrounded by a rusting industrial fence.

In 2003, TCMA and the Bexar Grotto began to undertake a major restoration project to improve and protect the property and cave. Major accomplishments have included: restoring the sinkhole to a more natural state by digging out decades of accumulated trash and fill, improving nutrient flow into the cave by enlarging the entrances and controlling water flow, building an ecologically friendly gate, removing the overgrown vegetation and non-native species from the property, and creating a more inviting park-like environment for the neighborhood. More than 275 volunteers contributed over 3700 hours of labor to complete the project in 2008. Project expenses totaled more than $35,000, including individual donations and grants. This project has not only improved the cave for the resident fauna, but made Robber Baron an educational resource for the community.

1. Introduction

Robber Baron Cave is the longest cave in Bexar County, Texas, USA, with 1,512 m of mapped passages, an unusual geology, a rich history, and several unique biological species. The most well-known and visited cave in the city of San Antonio, Robber Baron, is located in the middle of a dense residential neighborhood that was developed in the 1950s. The cave's prominent 10-meter- diameter sinkhole entrance is located immediately adjacent to a major city street, resulting in frequent unauthorized visitation, vandalism, graffiti, and trash-dumping during the last 70 years. The mud and fill in the sinkhole became so thick that rain would periodically seal and wash open the small crawl-in entrance. Members of the San Antonio Grotto and later the Bexar Grotto began assisting the owner in maintaining the cave in the 1970s. The grottos performed several cleanups of the most egregious debris in the sinkhole in the 1980s. Cavers helped construct several increasingly strong cave gates over the years in an attempt to keep out local youths and others who tried to access the cave, but these were breached in turn. In 1990, a large concrete bunker-style gate was built that was never breached. The cave and the 1,500 m^2 lot around it were fully protected when it was acquired as a preserve by the Texas Cave Management Association (TCMA) in 1995.

2. Significance of Robber Baron

Robber Baron is a multi-level, network maze cave with complex, interconnected passages, lying within the Austin Chalk geological formation, which underlies much of north-central Bexar County, and is above the upper confining layers of the regional Edwards Aquifer (VENI, 1988). The maze likely continues well beyond the mapped cave. The cave has been cited as a prominent example of hypogene speleogenesis, formed by rising groundwater.

Robber Baron Cave was opened as a commercial cave in 1926, with the name dreamed up by Arthur Harp, who managed the cave, to give it an outlaw mystique. The cave was developed with electric lighting and included features such as the "Devil's Kitchen," with a fake skeleton in a coffin illuminated by red lights, and the "Pavilion Room," which was used as a speakeasy during Prohibition for the illegal consumption of alcoholic beverages. To widen the cave's appeal, amenities were added on the surface including a food and drink stand, a playground with a merry-go-round, and a cable ride. An estimated 300,000 people toured the cave until its closing in the 1933. Old-timers from this period relate stories indicating a far more extensive cave than is presently known, with passages having been blasted shut to prevent tourists from getting lost. However, numerous caver efforts have revealed only small amounts of additional passage.

Robber Baron is home to a diversity of fauna including least ten separate troglobitic species along with many other troglophiles. In 2000, two of the troglobitic invertebrates were federally listed as endangered species: *Cicurina baronia*, the Robber Baron Cave Spider, and *Texella cokendolpheri*, the Robber Baron Cave Harvestman. Both have only been observed in Robber Baron Cave. Each of these invertebrates is only a few millimeters long, eyeless, and lacking pigmentation. They have a low metabolism, due to the lack of food, and long legs for efficient travel and to feel their way through the cave surroundings (U.S. Fish and Wildlife Service, 2000).

3. Restoration Project Goals

After acquiring the cave as a preserve in 1995, TCMA and the Bexar Grotto began to consider ways to improve the property with consideration for the preservation of the biology of the cave. During the period when Robber Baron was a commercial cave and in the following years, a great deal of trash, debris and sediment had filled the sinkhole to depth of 3 to 8 meters. The bunker-style entrance gate had a 15-cm-diameter opening which did not allow any organic material or water to enter the cave and only permitted a minimal amount of air exchange (Fig. 1). The bunker sat on top of a 5-meter-tall stack of railroad ties, which were used by visitors to climb down into the cave and also acted as a retaining wall against the fill and debris in the sinkhole. Not only were the chemicals in the railroad ties possibly harmful to the cave environment, but the base of the ties was found to have been undermined by erosion and in danger of collapse. On the surface, the lot was surrounded by an old chain link fence and had a large amount of wild-growing non-native vegetation. After considering many easier plans, the final decision was to attempt to restore the sinkhole to something akin to its original state. Removal of the sinkhole fill and bunker would open up the main entrance as well as a long-blocked side entrance to allow a more natural flow of organic material, water and air into the cave. Further, visitors to the cave would no longer have to climb down the potentially slippery and dangerous railroad ties to enter the cave but could walk directly to the entrance.

Figure 1: Old bunker entrance gate prior to start of the restoration project.

TCMA formed a committee to develop plans for the future of the cave, to improve the cave gate, and modify the

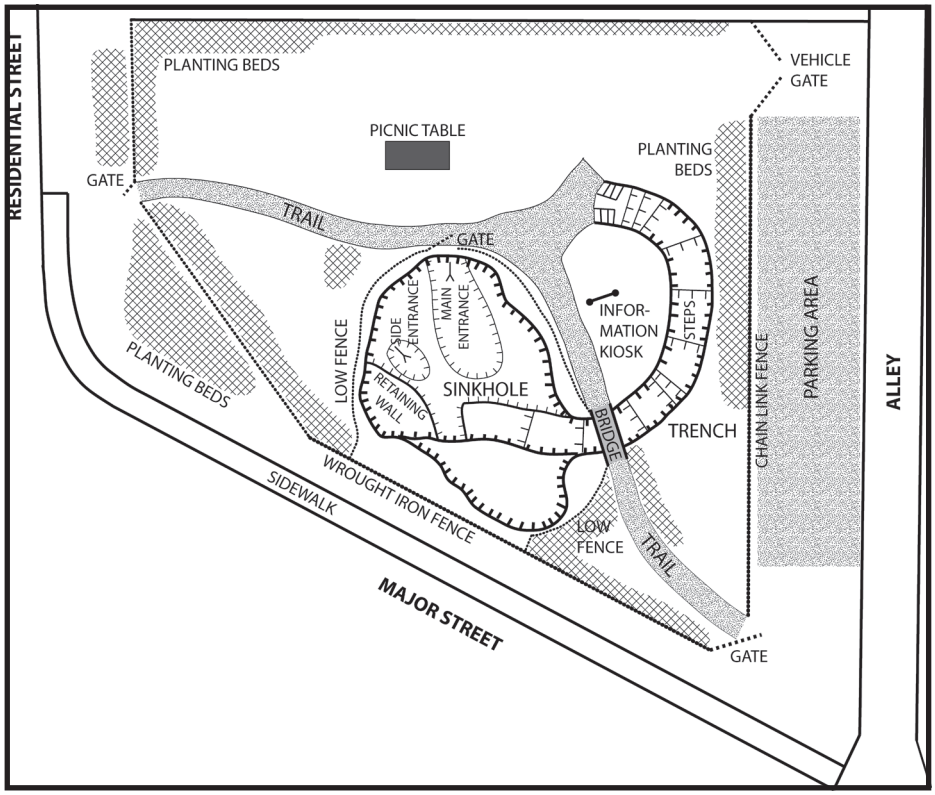

Figure 2: Plan of the surface of Robber Baron Preserve after completion of the project.

grounds for better management of the listed species. After months of discussion, the committee developed a plan to restore the sinkhole and property to a more natural and native state. Five project goals were identified: (1) replace the bunker gate with a more environmentally friendly gate that enhanced the faunal habitat; (2) remove the artificial fill from the sinkhole; (3) re-landscape the sinkhole and property to remove exotic vegetation and restore native plants; (4) promote educational use of the entrance area; and (5) correct and improve conditions at Robber Baron Cave that TCMA inherited from the previous owner. Although the details of the plan changed during the course of the project, the final layout of the property (as shown in Fig. 2) closely conforms to these goals. The project was primarily carried out on designated weekends by volunteers including cavers from all over Texas, groups such as scouts wanting to gain volunteer hours, and families who lived in the neighborhood.

4. Phase I: Excavation of the Sinkhole

The project kicked-off on February 1, 2003, with a survey of the property, removal of some dead and exotic vegetation, and preparation for the beginning of the excavation. The volume of material to be removed from the sinkhole excavation required the use of heavy equipment. Excavation would have a major impact on the property, so surface improvements would have to be deferred to a later second phase. A long trench was designed to give the equipment access to the sinkhole, and eventually, the cave entrance area; the trench would later be converted to a series of steps for access. The very sturdy old bunker gate was difficult to demolish but gave way. To prevent unauthorized access to the cave and possible collapse under the equipment, the old entrance was temporarily filled with sand. A large PVC pipe was placed to allow some airflow and invertebrate movement during this period. Work proceeded with removal of material from the sinkhole using a bobcat and excavator. This proved difficult and slow due to the steep grade, narrowness of the trench, and small work area in the sinkhole. To pull material out of the sinkhole, the bobcat operator would back it up the trench, which was only slightly wider than the bobcat itself, and negotiate a sharp curve while not tipping forward. By the end of the summer, about 200 m^3 had been removed.

Over the next year, the city of San Antonio received a record 112 cm of rain, one and half times its normal amount, bringing the Robber Baron project to a complete halt until mid-summer 2004. During an intense work-week in early August, another 100 m^3 of material was removed from the sinkhole. A couple of weeks later, another long work weekend finally broke through to the natural entrance to the cave. After breakthrough, it was found that the sand used to temporarily block the entrance had been washed away, so a temporary concrete block barricade was quickly constructed. More hard work uncovered the smaller side entrance to the cave, blocked by debris since the 1930's, and removed the last of the fill, reaching the bedrock bottom of the sinkhole. In the end, an estimated 430 m^3 were removed from the sinkhole increasing its depth from about 5.5 m to 9.2 m (Fig. 3). Zara Environmental, which builds cave gates throughout Texas, donated it's time to construct a new gate for the cave. It is composed of spaced angle iron embedded into the surrounding bedrock and deeply buried below the entrance providing a secure gate that still permits airflow and nutrient flow (Fig. 4). A single locking bar is removable to allow access. The small side entrance was permanently gated in the same style to allow airflow and animal access, but not to be used as a human entrance.

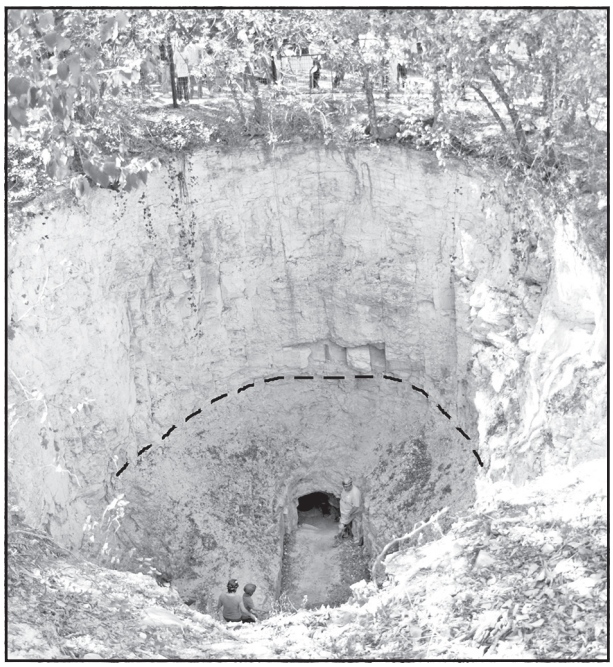

Figure 3: Entrance sinkhole after completion of the project during the open house. The former level of the sinkhole is indicated by the dashed line.

5. Phase II: Surface Improvements

The first portion of the surface work was stabilization of the trench edge and the interior of the sinkhole. During rain events, the trench funneled water directly into the second cave entrance, resulting in erosion and accumulation of fill in the entrances and sinkhole. Committee members developed a solution by turning the trench into a long staircase to slow the water flow, filter out sediment, and provide easier access to the sinkhole (Fig. 5). Starting at the bottom of the trench,

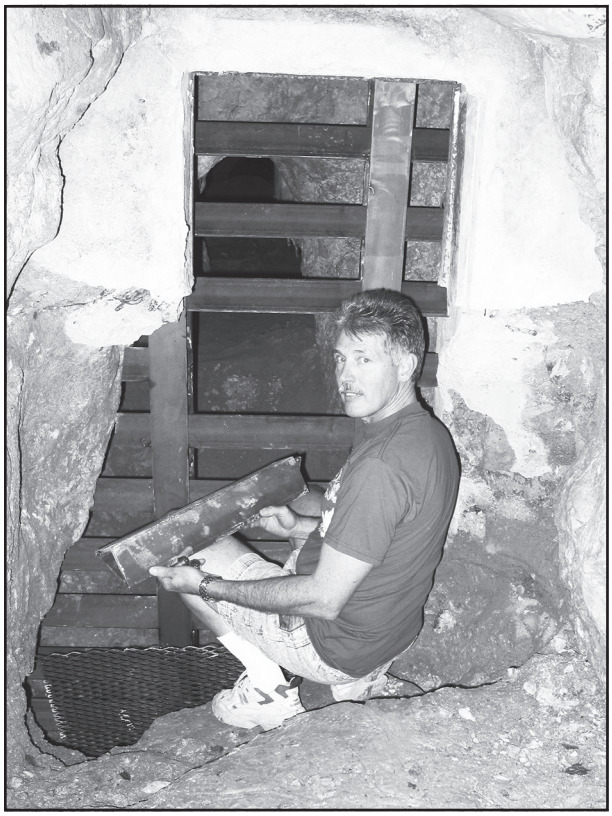

Figure 4: New entrance gate which allows unobstructed flow of nutrients, water, and air.

a series of step-height rock walls were built with fieldstones that were mortared into place. Short lengths of PVC pipe through the walls control drainage through each step. The steps were then backfilled with gravel through which water could slowly percolate. At the top end of the trench, a high rock retaining wall was constructed that diverts surface water away from the trench. Additional erosion control efforts included digging back the soil at the edge of the trench and stacking large rocks as a retaining wall, as well as constructed another rock retaining wall in the sinkhole on the slope above the second entrance. Erosion problems continued to be an issue, as is often the case in urban, developed areas. Because it is especially important to divert surface water from the surrounding streets since it contains numerous oils and contaminates, a decorative, low, stone wall was constructed along the side the sinkhole closest to the adjacent street. Only time will tell if these efforts are successful in finally stabilizing this area.

Another major project was replacement of the old industrial-style fence around the property which had been slowly falling down over the years. Initially, the section along the alley was replaced with a new chain link fence. The most visible section along the two adjacent streets was originally slated to be replaced by a stone wall, but this was determined

Figure 5: Steps in the trench lead down into the sinkhole under the bridge at upper left.

to be too costly and labor intensive. A decorative black wrought-iron fence with two pedestrian gates was chosen instead, which has greatly improved the appearance of the property. The much deeper sinkhole now presented a potential safety hazard which required a second fence that was constructed from wooden posts set in concrete bases with 1.2-meter- high "no-climb" fencing material. It features a gate on the backside of the sinkhole to allow for future hoisting of materials in and out of the cave.

Final project work focused on the remainder of the preserve's surface with the removal of large quantities of non-native ivy and shrubs as well as well as numerous loads of brush and trash from the property. Non-natives including lagustrums and Boston ivy were cut down to provide more light for growth of native plants which will also, indirectly, support the cave biology. A new layer of topsoil was distributed across the surface in preparation for planting. Planting beds were established and over 80 new drought-tolerant plants and shrubs were placed and mulched at various locations. When established, they will make the surface of the Robber Baron not only more ecologically friendly but also a pleasant and attractive place to visit. A key component of the restoration plan was to create a park-like atmosphere on the property, so a trail was constructed that crosses over the trench on a black steel bridge. The trail was built up above ground level with heavy aluminum edging filled in with gravel (Fig. 6). The bridge has also been useful for raising and lower materials during work in the sinkhole. Along the alley, a gravel parking lot was installed providing a better parking area than the former mud bog. A picnic table was built; welcoming entrance signs were installed, and a large information kiosk was designed and installed, displaying extensive information about Robber Baron, cave development, and TCMA (Fig. 7).

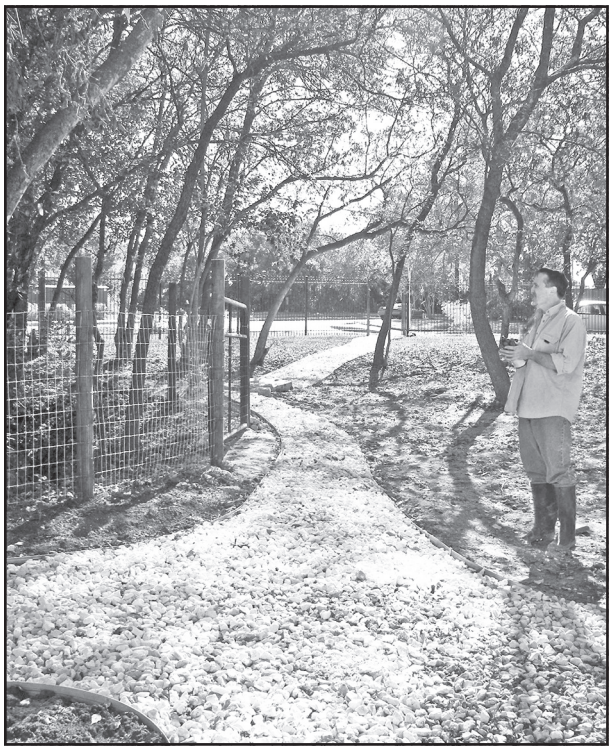

Figure 6: Trail across the property with safety fence around sinkhole at left.

6. Funding and Volunteer Support

TCMA spent over $33,000 for bobcat and excavator rentals, sinkhole excavation and surface grading, costs of hauling away fill and debris to the proper disposal sites, gate material expenses, purchases of fencing and construction materials, and the cost of landscaping materials and plants. Of these expenses, $12,000 was volunteer donations, $5,000 was paid by TCMA and $16,500 was in the form of grants. Three successfully received grants included the Partners Grant from the U.S. Fish and Wildlife Service, which provided $5,000 for work on the gate and entrance area to improve species habitat. The second, $4,500 grant, was from the Magnolia Charitable Trust for general progress, and a Texas Parks and Wildlife Department provided the most recent grant of $7,000 through their Landowner Incentive Program to pay for additional surface improvements such as erosion control.

Figure 7: Visitors examine the information kiosk.

Volunteers were the backbone of the project and performed the bulk of the "cost" of the project with in-kind labor. Over 3,700 volunteer hours from more than 275 unique individuals were logged for a total of $75,000 of in-kind value. Volunteers ranged from children to 80 year-olds, cavers across Texas and beyond, service groups, neighbors, school groups, and others. Five Eagle Scout projects were conducted at the preserve and individual participants from the Boy Scouts of America were present at many work days. The Eagle Projects included the decorative fence that fronts the property, the safety fence surrounding the sinkhole, the parking lot, the trail that crosses the preserve, and a section of fence adjoining the neighbor's property. Members of Texas Master Naturalists were heavily involved in the landscaping of the property, including design of the beds, selection of suitable drought-tolerant native plants, and participating in the soil preparation, planting efforts, and watering required to establish the plants.

7. Community Outreach

Since the preserve is located in a densely urbanized neighborhood, outreach to the community has been important. The immediate neighbors were especially impacted, since at times the preserve resembled a construction site, resulting in a few complaints. Increased communications about activities and plans led to understanding and more willingness to put up with the disruption. By the end of the project, most people surrounding the cave had positive comments about the outcome. A number of the volunteers were people who lived within a few blocks of the cave.

To thank the community, the volunteers, and to mark the end of the restoration project, an open house was held on November 8, 2008. The goal of the open house was to provide the public with a chance to see the completed project, meet with TCMA members, and tour the cave. A very large turnout of over 450 people (somewhat overwhelming) resulted from the fliers distributed in the

neighborhood and newspaper article about the cave. Of these, 345 people entered and toured the cave over a seven hour period. People were willing to wait in lines that at times were two hours long for a chance to go inside. The tours were operated on a semi-self guided basis where cavers were stationed at various key locations in the cave to direct people and answer questions. The San Antonio Express-News also attended the open house day and published a full-page follow up article the following day about the open house that was very positive about the project and TCMA.

The increased awareness of the cave and its value along with the visible property improvements may also be having other positive effects. Vandalism and trash dumping on the property has decreased substantially over the last couple of years. Also, neighbors have reported they have been keeping an eye on the property. Additionally, people in the local community are using it as a park and bringing their children to do outdoor and educational activities.

8. Conclusion

As with any type of restoration project, completing the project is not really the end. The property will require continued maintenance to keep it in top condition. One of the reasons for the restoration project was to enhance the habitat of the endangered invertebrates that lives in the cave. Over the last year, more than six sightings of the *Cicurina baronia* have occurred, along with a noted increase in faunal populations, especially cave crickets. The new gate on the cave is also bat friendly and several eastern pipistrelle bats have been observed. To help protect the fauna living in the cave, fire ants will need to be controlled on the surface. The treatment method for fire ants will be with boiling water to prevent the introduction of pesticides to the cave.

Although the project took far longer and involved much more effort than originally envisioned, this major restoration effort was ultimately successful achieving its goals to improve and protect the property. Major accomplishments have included: restoring the sinkhole to a more natural state by digging out decades of accumulated trash and fill, improving nutrient flow into the cave by enlarging the entrances and controlling water flow, building an ecological friendly gate, removing the overgrown vegetation and non-native species from the property, and creating a more inviting park-like environment for the neighborhood. Although many generous donations and grants have helped support this project, it has been only through the hard work of many individual volunteers that this project has succeeded. Robber Baron Preserve has been made into a centerpiece for TCMA for its unique biological and historical resources, for its educational and scientific functions, as a recreational cave for cavers, and as a place that people can visit for enjoyment and to learn about the world beneath our feet.

Acknowledgements

This project was made possible by volunteers too numerous to mention here, but especially by members of the Bexar Grotto and the Texas Cave Management Association.

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MONITORING OF MICROBIAL POPULATIONS IN KARTCHNER CAVERNS STATE PARK—A COST-EFFECTIVE CAVE MANAGEMENT AND OUTREACH STRATEGY

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Abstract

Kartchner Caverns State Park provides a unique opportunity to investigate the potential role of microorganisms in the development of limestone cave formations and the impact of tourism on the activity of these microbial populations. Although the contribution of bacterial populations to speleothem development in carbonate caves has not been well established the presence of diverse metabolically active populations on cave formations and adjacent rock surfaces has been well documented. A recent study in Kartchner Caverns has documented significant differences in the diversity of bacterial populations present in areas of high human exposure as compared to populations found in areas of low and medium levels of human exposure. In addition, a proliferation of slime producing bacterial populations was also identified from painted fiberglass surfaces that were introduced into the cave to conceal plumbing and electrical fixtures. In response to these studies, Arizona State Parks has implemented a number of strategies to reduce the impacts of cave development and human exposure on microbial populations in the cave. A five-year study has also been funded by the park service to monitor the diversity of bacterial populations on rock and speleothem surfaces at four sites in the cave receiving varying levels of human exposure.

This presentation illustrates how unprecedented cooperation between the scientific research community and a resource management agency like Arizona State Parks, has led to an enhanced understanding of cave ecology and the role it plays on the development of cave formations. Furthermore, the collaboration reinforces why cave management and park planning must remain data- and science-driven activities to be effective in conservation. Due to the demographics, as well as the powerful purchasing and political power that characterize today's park visitors, state and national parks are being courted by progressive universities and colleges as venues for showcasing and conducting leading research and cost-effective science and educational outreach programs.

CAVE AND KARST MANAGEMENT IN GREAT SMOKY MOUNTAINS NATIONAL PARK

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The Great Smoky Mountains National Park (GRSM) encompasses 2,100 square kilometers in the states of North Carolina and Tennessee, United States of America. The park receives over 9.5 million visitors a year, making it the most visited national park in the U.S. GRSM is the most biologically diverse national park in the system, only 12% of the suggested 100,000 species who live in the park have been identified. Karst areas in GRSM account for less than 1% of the total surface land area in the park, but most karst areas receive highly concentrated visitation. For example, the Cades Cove karst area (13 km^2) receives over 2 million visitors a year, more than most national park units.

Six karst areas in GRSM contain 16 known caves with significant biological resources. Several endemic species have been identified in the caves and karst areas. In addition, park caves provide habitat for federally listed threatened and endangered species.

Although much remains to be learned about the specific biology and diversity of GRSM caves and karst areas, in recent years, biological surveys have begun through cooperative relationships with non-profit organizations (e.g., Discover Life in America), universities (e.g., Western Kentucky University) and other federal agencies (e.g., United States Fish and Wildlife Service). Research to date suggests that karst areas in GRSM exhibit significantly high biological diversity.

Management decisions in regards to cave and karst resources in GRSM currently follow general directives and the park's Superintendent's Compendium. Draft cave management plans have been proposed but never implemented. Specific funding has not been directed toward research, management and protection of cave and karst resources in the park.

Currently, efforts are underway to consolidate information surrounding GRSM cave and karst resources. The National Park Service and Western Kentucky University are collaborating to support the development and implementation of a cave and karst management plan specific to the karst resource needs of GRSM.

Caves and karst of GRSM represent unique resources requiring special management in order to effectively protect them. Karst areas attract visitors as popular off-trail destinations and support a variety of rare cave and karst biota. Several GRSM caves exhibit extensive vertical relief. Characteristics such as these exemplify the need to address management of these resources, an effort that will benefit greatly through collaboration with outside entities such as universities, other federal and state agencies and chapters of the National Speleological Society.

1. Introduction

Great Smoky Mountains National Park (GRSM) encompasses 2,109 square kilometers in the states of North Carolina and Tennessee in the United States of America. The park receives over nine million visitors a year, making it the most visited national park in the world. There are 16 known solution caves in six main karst areas within the western portion of the Tennessee side of the park. Current management of cave resources is based on general directives and the park Superintendent's Compendium. The park developed two draft management plans in 1979 and 1989; however implementation of these plans has been limited due to lack of accuracy and completion (GRSM 1979b, 1989). Currently, the National Park Service, in cooperation with Western Kentucky University, is developing a Cave and Karst Management plan to address management and

protection of cave and karst resources.

2. Caves and Karst Management in Great Smoky Mountains National Park

Under the guidance of the Federal Cave Protection Act of 1988, the National Park Service is required to inventory and list significant caves on federal lands, and to provide management and dissemination of information about caves (US DOI FCRPA). Under the FCRPA and CFR Title 43—Public Lands: Interior, Part 37—Cave Management, the NPS observes all caves as significant caves and manages accordingly (Ek 2005 and NPS Cave and Karst Program Website 2008).

NPS resource managers are guided in managing, protecting and conserving resources in their unit by the NPS's Natural Resources Management Reference Manual (RM#77). The guidelines under RM#77 specify the policy and program directives, the authoritative legislation, methods of protection and fulfillment of legislation, as well as an explanation of the roles and responsibilities of those who are in position to manage caves and karst (RM#77).

Within the NPS's RM#77, the Cave and Karst Management section provides guidelines for the management of caves, encompassing the many disciplines needed to protect and perpetuate natural cave systems. Management of caves includes protection of soils, surface landforms, natural drainage patterns and hydrologic systems, and cave microclimate and ecosystems (RM#77).

Currently all caves (both known and unknown) in the Great Smoky Mountains National Park require a permit to legally enter. Permits fall under several different departments depending on the focus of use. Scientific research within caves is permitted through the Resource Management and Science Division. Scientific research is proposed in the application process with detailed descriptions of methods and materials as well as protocols for collection of specimens, etc. The application is reviewed for validity, and suggestions are given to produce a product useful to the researcher and GRSM if possible.

Accepted applicants for scientific study in caves currently receive a protocol for pre and post decontamination of equipment and clothing to be used in the cave environment. This is to minimize the introduction of non-native entities into the cave as well as fulfill the United States Fish and Wildlife Service's concerns with the possible transmission of White Nose Syndrome to GRSM caves.

Non-Scientific permits are obtained through the Law Enforcement Division as either a special use or recreational caving permit. Because park managers do not have a thorough understanding of the carrying capacity and potential impacts to cave resources by permitting recreational caving, the park is not currently accepting applications for recreational caving. Development and implementation of a complete cave and karst management plan will address resource protection issues. In addition, park staff is not trained to assist in cave rescue, and all cave rescue operations are conducted by the Knoxville Volunteer Rescue Squad (KVRS) with above ground logistical support conducted through GRSM.

3. Cooperative Relationships

Early efforts to describe the park's caves were focused primarily on the geology and physical conditions within park caves. Beginning in the early 1930s, verbal accounts of several caves were documented from landowners (GRSM 1936). Through the 1930s and 1940s, the National Park Service began to understand the geology of the park caves and karst areas through publications from various universities in the Journal of the Tennessee Academy of Science (Neuman 1947, Wilson 1935). The 1950s and 1960s brought more systematic cooperative exploration and survey of park caves, with local grottos of the National Speleological Society (NSS) leading documented expeditions into major park caves, and providing documentation of their work and maps to the National Park Service (Haygood 1969).

Upon discovery of hibernating Indiana bats (*Myotis sodalis*), park caves and cave biota became the focus of intensive interagency cooperation with the federal listing of the Indiana bat and subsequent structured monitoring and management efforts between the NPS and United States Fish and Wildlife Service (USFWS) in the late 1970s (GRSM 1979a). Cooperative survey and monitoring of bat populations with USFWS continues to present day. Other park biota was managed tangentially until the continued documentation of an endemic troglobiotic species (*Stygobromus fecundus*). In the 1980s, the NPS contracted an NSS scientist to inventory biota in 11 park caves (Wallace 1984, 1989, 1990). His documentation, in concert with interagency cooperation related to Indiana bat management, lead to the first NPS efforts to manage and inventory the biota of all known caves in the park.

Interest in the study and monitoring of park cave biota continued through the 1990s, with NPS inventory of endemic species (Johnson 1990) and increasing interest

by independent researchers through universities and non-profit research partners, such as Discover Life in America (DLIA 2007). Through cooperative partnerships such as these, significant progress has been made in identifying and describing species associated with caves and karst in the park. The 1990s also brought increased cooperation with training involving KVRS high angle rope and cave rescue crew; NPS personnel cooperate with the KVRS on practice and performing cave rescues. The expertise gleaned by KVRS in park caves has been essential in efficient cave rescue efforts in GRSM. The United States Geological Survey (USGS) also began working cooperatively with the NPS in the 1990s and 2000s in mapping surficial geology of the park and karst topography, and sampling cave and karst amphibians and associated diseases (Southworth et al. 2000, 2003, 2005).

GRSM has benefited immensely from the efforts of outside entities in the understanding and identification of resources in park karst topography. Currently, GRSM does not have a full understanding of the karst resources within it boundary; components such as karst area hydrology have not been systematically researched and documented. Within GRSM caves, meteorology and microbiology have yet to be explored. Although cave and epigean biota continues to be better understood with continued research efforts, there is much work to be done to develop a complete understanding of the karst systems in the park. As progress continues towards a comprehensive source for management guidance for the protection of caves and karst topography in GRSM, partnerships will become increasingly necessary for GRSM in achieving their goals in the management of these resources. Future proactive collaboration with entities such as the NSS, universities, independent researchers, non-profits, and KVRS is essential to fulfilling the mission of the NPS in the protection and understanding of the karst and associated caves of the Great Smoky Mountains National Park.

4. Consolidation of Information Related to Caves and Karst Areas in GRSM

In cooperation with Western Kentucky University (WKU), Great Smoky Mountains National Park is currently developing a comprehensive draft cave and karst management plan. As part of this effort, current management of cave and karst resources in GRSM will be reevaluated to determine more efficient and effective management practices.

To date, there is not a centralized, comprehensive resource related to caves and karst in GRSM. In order to facilitate management decision-making in regards to cave and karst resources in the park, a thorough assessment and compilation of historic and current research of biological, hydrological, geological as well as other components of GRSM cave and karst resources is underway through this cooperative relationship (NPS and WKU) and will allow for more informed, efficient management practices. Creation of a centralized reference location will allow GRSM resource managers to access information surrounding caves and karst, facilitating more consistent and informed management practices.

5. Conclusions

One of the most immediate issues with GRSM cave and karst management is the absence of a formal management document that details the specific management concerns of the resources. Implementation of a Cave and Karst Management Plan would allow for consistent, informed decision-making related to cave and karst resources in the park. This plan will be written in such a way that it can be adaptive to new information and management techniques to effectively and efficiently manage and protect cave and karst systems in the park.

Continued cooperation with other state and federal agencies, non-profits, universities and independent researchers will provide an ever-increasing knowledge base to assist in decision-making related to caves and karst areas in the park. Encouraging cooperative research, through organizations such as Discover Life in America and in conjunction with state and federal agencies, such as USFWS, provides an opportunity for a mutually beneficial relationship to study and protect caves and karst areas.

Exploration and survey of GRSM caves has lead to several great discoveries. GRSM should encourage future exploration while defining proper procedures to address potential threats to the resource. The Tennessee Cave Survey and both the East Tennessee Grotto and the Smoky Mountain Grotto of the National Speleological Society have been historically very active with cave exploration in the Smokies. The park should continue these relationships and encourage participation in cooperative development of procedures and identification of project needs related to exploration and survey.

Cave rescue operations and the involvement of the Knoxville Volunteer Rescue Squad (KVRS) have resulted in a long and positive relationship in GRSM. The park should continue support for their involvement and use their expertise in the development of procedures for specific park cave rescues and

training of park staff in basic cave rescue techniques.

The Great Smoky Mountains National Park has had a long history of exciting discoveries surrounding caves. Reconnecting with historic partners, strengthening relationships with existing partners, and encouraging new partnerships promotes research and protection of cave and karst resources. In addition, these cooperative endeavors provide park managers with a more comprehensive picture of cave and karst areas for more informed and consistent management of these delicate resources.

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THE GUIDES OF VENEZUELA'S GUACHARO CAVE: A HISTORICAL AND ETHNOGRAPHIC STUDY OF LOCALS' CONTRIBUTION TO ITS PROMOTION, EXPLORATION, AND CONSERVATION

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In 1949, the Venezuelan government inaugurated the Alexander von Humboldt Natural Monument, the nation's first, at Guácharo Cave, located near the northeastern mountain town of Caripe. Guácharo Cave is the country's most famous cavern, and the only one with substantial tourist infrastructure. Its descriptions always state two claims to fame. First, Alexander von Humboldt visited the cave in 1799 and produced its first scientific description. He also scientifically named and described its notoriously raucous inhabitant, the nocturnal oilbird, or "guácharo" (*Steatornis caripensis*). The presence of guácharo colonies is thus the second claim typically sited for the cave's recognition. Moreover, although surpassed in length by two other caverns in the country, Guácharo Cave's importance as a site of extraordinary ecological and mineralogical diversity remains unsurpassed.

This paper highlights the important role local guides have played in the promotion, exploration, and conservation of Guácharo Cave. Unlike its many distinguished and mostly European visitors, these individuals remain anonymous to both the regional and national history of this site. Based on extensive archival, ethnographic, and interview evidence, these locals' identities and biographies are presented as poignant examples of how many of the exploratory and scientific successes of visitors could not have happened were it not for the support and active participation of community members.

Particular focus is given to the formalization of guides' education and training during the last 25 years, and these programs' relation to at times competing local interests and the regional and state leadership of Venezuela's Institute of National Parks. Recent government policies have required the guides' reorganization into a cooperative. The implications of these policies and the changes on the ground are examined.

1. Introduction

Guácharo Cave, the most popular cavern in Venezuela, is located in the northeastern town of Caripe, Monagas State. It developed within the limestone of the Inferior Cretacean (Albiense) El Cantil Formation (SVE 1968). This cavern is of great scientific, historic, and cultural importance. Until 1992 it was, at 10.2 km, the country's longest cave. It is currently third behind El Samán Cave in the Perijá Range of Zulia State (18.2 km) and Sistema Roraima Sur in Bolívar State (10.8 km) (SVE 2004). Among speleologists and scientists more generally, Guácharo Cave remains one of the most important caverns in the country since it exhibits the greatest biological diversity and exceptional mineralogical richness (Urbani 1999, 2005). It is also of great historical importance, not just to Venezuela but to world speleology. It was the first scientifically described cave in the Americas (Urbani 2005). It has been site of indigenous rebellions against the Spanish, object of missionary incursions dating to the 1600s, and an attraction for both national and international visitors (many of them prominent naturalists) for over 3 centuries (Urbani 1999, 2005). Moreover, it has played an important role in the cultural life of Chaima indigenous peoples and local farmers, many whom still claim Chaima descent (De Crivieux 1998; Rogelio León 1982). In 1949, the Venezuelan government inaugurated the Alexander von Humboldt Natural Monument, the nation's first, at Guácharo Cave, which remains the country's only cavern with extensive tourist infrastructure and guided visits. In 1975, the monument became the centerpiece of the larger El Guácharo National Park, extending its surface area based on the feeding ground of the nocturnal fruit-eating oilbird, as well as on the distribution a great number of other caverns of the karst ecosystem. A consequence of the creation of the monument and subsequent park was to severely alter the ways local communities could relate to their environment. The capture of guácharos, mostly for

their fat content used for oil was prohibited. Also, in 1967 the government ordered the demolition of houses located right in front of the cavern to make way for the construction of tourist infrastructure (Urbani 1999). Yet, the creation of the monument and park also spurred the growth of tourism in the area, which continues to this day and has joined agriculture as the main sources of income for the town and greater Caripe municipality. It is within this context of Guácharo Cave's importance to the Caripe community that this paper highlights the role local guides have played in the cavern's promotion, exploration, and conservation.

2. Theoretical Orientation and Methods

This research is part of a larger PhD project that examines, from an ethnographic perspective, the history and practice of speleology in Venezuela. The case of El Guácharo National Park is emphasized not only for its scientific, historic, and cultural importance, but also because its exploration was such a critical part of the constitution of institutionalized speleology in the country. One component of this larger study is to highlight the contributions of those more anonymous individuals without whom speleological exploration and science would be much poorer. A theoretical and methodological orientation that understands the practice of science as a social activity that takes place in a particular cultural and historical context informs this project (Latour 1999). From this perspective, understanding the process of production of speleological knowledge regarding Guácharo Cave requires focusing on seemingly trivial daily practices that often get "edited out" of final exploration reports and maps. How does the knowledge of local guides aid the exploration of the cavern? What is the dynamic among explorers and the local community, and how does it impact exploratory practices? How does the new knowledge of the cave system add to, challenge, and/or impact the relation that the local community has with its environment? These questions illustrate the ethnographic approach that informs this broader project which rests on the premise that such insights enrich and may even challenge our understanding and appreciation of scientific practice and its history. It is an *ethnographic* approach in so far as it examines daily social practices in large part by requiring the participation of the researcher.

I (Pérez) conducted the bulk of my fieldwork in Venezuela from May 2007 to June 2008, with time divided between Caracas and Caripe. While in Caripe I lived in the home of a park ranger and his wife, also a park employee. Most days were spent at Guácharo Cave interviewing guides, park rangers, and other employees, as well as volunteering with a variety of jobs. I shadowed cave guides along their tours of the cave. Past guides, park employees, and other Inparques (Venezuela's National Institute of Parks) administrators were also interviewed. Archival research at the Venezuelan Speleological Society (SVE) Library and, in particular, the review of SVE member and geologist Franco Urbani's exhaustive work on the history of Venezuelan speleology, further informs this project.

This paper's focus follows the basic observation that local guides mediate virtually all visitors' experience of Guácharo Cave. Even the famed Humboldt and Bonpland 1799 visit depended on the support and guide of local missionaries and Chaima guides. Based on Humboldt's account, they only traveled 472 m (but according to Urbani 1975, based on his description they most likely reached 422 m). According to Humboldt's interpretation, the Chaima refused to go in any further due to their "pusillanimity," although Humboldt knew of previous accounts describing almost 800 m worth of gallery. All guides that I shadowed during the 1,200 m tourist tour made reference to Humboldt's visit. Most guides, in turn, offered various possible interpretations of why he did not go in further, some suggesting that perhaps it was the Chaima's desire to protect the sacredness of the cave from the incursion of outside visitors. While we may never know precisely why Humboldt and company had to turn back where they did, a guide's own information, tour style, and interpretation of events shape visitors' understanding of the cave's history.

But who exactly qualifies as a guide? The answer requires a historical understanding of how social conditions at the cave have changed. A "guide" is loosely defined as an individual living within the greater Caripe community whose knowledge of the region and cavern serve him or her to accompany first time visitors to the cave. Guides need not be formal employees of the monument or park; in fact, they have rarely been so. Currently, guides are members of an independent cooperative with a contract from Inparques that grants them the permit to work within the monument's premises and charge for their tourist services. Yet, what *has* been a constant is that guides are locals that live in the greater Caripe community. Of course, not all locals are guides, but all guides are locals. In fact, during the formalization of guide training programs in the late 70s and early 80s, the superintendent at the time envisioned a program for local high school students to help them gain work experience and assist in furthering their educational goals. Yet, it is important to bear in mind caution against simplistic stereotypes of so-called locals and local knowledge (Raffles 1999). Certainly, to be of someplace does not endow an individual with knowledge of that place. This

is particularly true for cave regions since knowledge of caves typically requires a focused exploratory effort that goes beyond and breaks from typical daily activities that promote engagement with the environment. Further, precisely who is a local is contextually relative and even contested among the members of the same community. Taking these points into account, the following discussion highlights the contributions of individuals whose lives, in some way or other, have been intimately tied to Guácharo Cave, and whose role as guides has impacted the promotion, exploration, and conservation of Guácharo Cave. The selection of those featured attempts to illustrate key moments in Guácharo Cave's history that show how the conditions of guided visits have changed, particularly during the last 25 years.

3. Role of Local Guides in the History of Exploration of Guacharo Cave

Although Guácharo Cave has been central to the lives of communities living it its vicinity since at least 1,500 A.D. (Perera 1976), historical records suggest most of the cave remained unknown until the mid 1900s. In 1835 Italian colonel and cartographer Agustín Codazzi explored beyond the 759 m Guácharo Gallery and passed into the Room of Silence through a small passageway 680 m from the cave's only entrance. This is the first time the entire actual tourist route was traveled (Codazzi [1835] 1974; Urbani 1999). In his description he notes entering the cave with two assistants, a local indigenous judge called José López, and a group of Chaima. Once reaching the point that Humboldt had, Codazzi pushed forth. He notes evidence that the Chaima entered well beyond the 472 m mark, noting the existence of ladders used to capture oilbirds. Although German geologist Dr. Alfred Scharffenorth is typically cited as having made the next major exploratory breakthrough in 1890 when he reached the cave's famous Wind Pass, it is probable that his companion, Don Ezequiel Gómez, who at the time owned the land where the cave is located, reached that point himself 8 years before (Urbani and Furrer 2007). This narrow and water-filled point of the cave, located at 1,041 m from the entrance, deterred many visitors for more than 50 years. It was in 1946 that Caripe natives Víctor Ciliberto, Francisco Vera, Cirigliano, and Jesús Rodríguez crossed the famous Wind Pass, opening up a new period of cave exploration (De Bellard Pietri 1960; Urbani 1999, 2005). Encouraged, other locals joined in. Between 1946 and 1947, Caripe native Luís Silva Rodríguez with others, crossed the Wind Pass and explored further (Urbani 1999). A 1947 newpaper article signed as L.S.R. (most likely Luís Silva Rodríguez) which pleads for the cave's protection, expressing concern with the effects of torch smoke and vandalism. The article also suggests that the cave become a Natural Monument. On July 15th, 1949, the national government declares the creation of the Alexander von Humboldt Natural Monument (Urbani 1999).

The most famous cave guide during the 40s and 50s was Ramón Alén whose family lived in the *caserío* (hamlet) located near the cave. By 1951, the three men from Caracas that would eventually found the Speleology Section of Venezuelan Society of Natural Sciences (SE/SVCN) in 1952, joined Alén in the cave's exploration. These three men, whose initiative marks the country's beginning of institutionalized speleology, were Eugenio de Bellard Pietri, Juan Antonio Tronchoni, and Roberto Edwin Contreras (De Bellard Pietri 1960; Urbani et al., 2006). For over 10 years Guácharo Cave became the focus of this group's expeditions carried out mostly during holidays since it would take up to 10 hours to drive from Caracas to Caripe. On April 1957, SE/SVCN members Juan Antonio Tronchoni and Mario Vega and the guides Jesús Rodríguez and Ramón Alén reached the end of the cave (De Bellard Pietri 1960; SVE 1971; Urbani 1995).

By the mid 1960s, two other local guides, Ramón Audemer Salazar and Benjamín Magallanes, whose homes were also in front of the cave, become actively involved with the growing and enthusiastic speleological team from Caracas (which in 1967 became the Venezuelan Speleological Society). Locals and cavers alike remember Salazar as the *celador de la cueva* (the cave's warden) whose passion for its protection is legendary, echoed by many people interviewed, local Caripe residents and Inparques officials alike. "He gave his life for the cave," recalled Mario Gabaldón, who was director of Institute of National Parks (Inparques) during the 80s. In fact, the current Guácharo Cave guide cooperative bears Salazar's name. Martín Sarmiento, who worked as park's superintendent for 25 years, recalls that Salazar was not a very educated man, lacking any formal parks management training, but regardless, was entirely dedicated to his job. In fact, the Ministry of Agriculture and Livestock, the organization that managed parks in Venezuela prior to the creation of Inparques in 1973 (Reig 2003), hired Salazar as park ranger, a position he held until his death in a motorcycle accident in 1980.

The exploration and mapping of Guácharo Cave culminated with the SVE's publication of its complete map in 1971 (SVE 1971). Caripe native Benjamín Magallanes, whose family also lived in front of the cave, was the local who most collaborated with the SVE's day-to-day exploratory and cartographic efforts (Urbani 1999), not just in Guácharo

Cave, but in several other caverns in the area, at times making up the second person of a two-person mapping team. His father, Simón Magallanes, had also been a cave guide who was purportedly left blind from a scorpion bite and yet could still lead tourists into the cave (Benjamín believed he could see something). One of Benjamín's brothers actually died while attempting to capture guácharos when his ladder failed him. He eventually became a formal park employee and remains the most senior living El Guácharo park ranger. Both Magallanes and Salazar highlight a recurrent theme among Guácharo Cave guides that is still true today: many community families have several of its members, often across generations, working, whether formally or informally, at the cave. Two of Ramón Salazar's sons currently work at the cave, one as park ranger and the other as guide. While Benjamín Magallanes never had any children, several of his nieces and nephews did.

4. Formalization of Guacharo Cave Guides

The 1970s brought many changes to Guácharo Cave and its surroundings. For one, in May 1975 the national government created the greater El Guácharo National Park. Efforts to alter the area in front of Guácharo Cave to accommodate greater tourist influx was well underway after the 1967 demolition of homes located near the cave. The story here is not unlike others where the creation and growth of a national park requires the clearing of previously settled land. Families were offered money for their homes and farms, but rarely did that price seem right from the perspective of the would-be seller. Harsh feelings towards Inparques often surfaced among those who suffered from what they perceived as both a forced move and a new property regime that kept them from living off their land while on the other hand claiming to making the park public to all. What complicates the picture, however, is that these changes also increased the prospects of more better paying jobs. So, although the Magallanes and Salazar families, for example, had to relocate, some of their family members were also dependent on or gaining entry into the local administrative wing of Inparques. More park ranger positions were created; more guides were needed. The guides, in particular, went through several important transformations. They went from being an informal group that relied on tips to a uniformed group of employed workers. A change in labels indexes this transformation from being a *baquiano* to becoming a *guía* (guide). The term "baquiano" refers to a local expert who knows the environment. Among those interviewed in this study, a *baquiano* is clearly one who is a local expert with native and experiential knowledge. A person cannot study or take tests to become a *baquiano*; this person must be native to the land and engage with it daily, skillfully, in order to achieve such status. Being a *baquiano*, at least in the context of most conversations regarding the history of Guácharo Cave guides, implied none or minimal schooling. A conversation with the oldest (74) living past Guácharo Cave guide, Luis Saffón, stressed the difference between a *baquiano* and a guide, noting that at the beginning, "we were *baquianos*, we did not know about stalagtites." It was once they received formal training that "they became guides." But before that, he continued, "one would pick up his *hacho* (torch) and go right in, we would talk about the figures, but that was it." He notes that his father would sell the wood for the torches right outside of the cave, but he opted to guide visitors into the cave, in part because you could make "easy money" from tips. Once he quit working at the cave, he turned to farming on the land he relocated to once his family was moved, in 1968, from the cave's *caserío.*

The baquiano-to-guide transition occurred in the middle to late 1970s with Inparques' efforts to formalize tourists' Guácharo Cave experience through education and training (for some of this training veteran cavers were contacted to prepare courses on speleological topics). The first efforts towards these aims, as Mario Gabaldón recalled, were met with unexpected obstacles: the printing of training materials were useless since most of those to be trained were illiterate. Martín Sarmiento, the superintendent of the park at the time, recalled coming up with the idea of bringing in students from local high schools, without dismissing or alienating "the older ones." The involvement of students as guides improved, without a doubt, the quality of the tourist experience in terms of standardization among the guides and the quantity of factual scientific information about the cavern. These young guides were better educated, and many took on their work with care and pride. Part of the program's goal was to help finance their higher education, but eventually, they would need to give up their spot to another student. This has only partly worked. To community standards, the guide job brings in a good income especially for work that is, as described by many, very comfortable. So, many have held on to their jobs. Another interesting dynamic related to this point is that most of these young guides either attend university or even have other jobs while working as guides. Most are present at the cave on weekends and vacation, times that have heavier tourist traffic. But what about weekdays or the low season? Here is where the older guides that have remained in their role, even after the implementation of the student program, ensure the daily functioning of the cave. As park ranger Blas Salazar stresses, these men are crucial since they are the ones that show up to work every day, even if they enter the cave

only once with a small group of tourists.

Miguel Fermín illustrates Salazar's point. At 51, Fermín is among the oldest guides at Guácharo Cave and one of the few that shows up to work at the cave everyday. Prior to the very recent transformation into a cooperative, guides, who are not employees of the park and have no fixed wage, would take home an income that was proportional to how many visitors they would guide into the cave that day. To ensure some amount of fairness, guides were organized by the order of a list. If a guide was not present for his or her turn, the next guide on the list would take over. Also, visitors would wait a maximum of 20 minutes prior to being taken into the cave. This prevented guides from waiting too long for more visitors to show up, thus adding to their profit from a single tour. Fermín, who studied up to 2nd grade, began to work at a very early age at the cave selling *alpargatas* (a venezuelan handcrafted sandals). He recalls Ramón Salazar approaching him and suggesting that he try becoming a guide. He trained himself by shadowing veteran *baquianos* during their tours, and soon, at only 13 years of age, he began guiding his own tourists. Fermín recalls that the tips were often extraordinary amounts of money relative to what he was used to making selling sandals. Except for 13 years when he worked in Caracas, he has been a cave guide, thus witnessing many of the transformations that Guácharo Cave has experienced over 30 years.

5. Guacharo Cave Guides Association and Current Situation

Along with the transformations that Sarmiento brought to Guácharo Cave was to allow the entry of women guides. Among the first was Dalidys Dimas de Salazar. One of 13 siblings (6 of which worked as cave guides), Dimas recalls the enthusiasm and commitment shared by this group of young women. Dimas herself went on to become a full time park employee, first dedicated to visitor education and then to working at the ticket booth, a position she has held for over 20 years. Among the key informants of this project, Dimas expressed concern that while the student cave guide program has many positive aspects, many guides tend to become comfortable in their role, and few are motivated to improve their skills. Yulis Márquez, whose grandfather, Ladislao Márquez, was a cave baquiano, supported Dimas's view. Márquez was a young girl when her sister was among the first women to work as a cave guide. Once in high school, Yulis approached the then cave superintendent Leopoldo Pereira and asked to be considered for a guide position, a job she fulfilled for 15 and helped finance her education. In 1996 she lead the initiative to create the Association of Environmental Guides Alexander von Humboldt, in part to gain greater independence from Inparques and to organize initiatives among guides to promote educational and career skills, and to stress their role as environmental stewards. The guides also organized a rescue squad. Guests speakers on speleological, first aid, and conservation themes were invited to give talks with the support of Gloris del Valle Díaz, who was employed by the cave's Environmental Education Department (and had herself been a guide). But both Márquez and del Valle echoed Dimas's concern that it has been and continues to be a challenge to keep a number of guides (and park rangers) motivated to take advantage of educational programs.

These challenges are still with guides today, but so too are individuals eager to take initiative for the sake not just of their jobs, but also for the betterment of the cave. The latest major transformation is the recent creation of the Guácharo Cave Guides Cooperative "Ramón Salazar," formed in response to the national government's push for cooperative-style groups. Govinda Galindo, its president, described the work involved, much of it requiring endless discussions among guides to determine a new standard of fair pay among all, a key of cooperative organization. By January 2009, the guides were working with their new pay regime, although efforts had been hampered by the problems with a computer program that the cooperative commissioned to facilitate the end-of-the-day pay calculations. Yet, the challenges that current Guácharo Cave guides face are offset by new projects to positively impact the national park, greater Caripe community, and beyond. Galindo described an initiative to take guides into Caripe elementary schools to implement a type of junior park ranger program. The flow of scientists to the park continues to rely on the support of guides and park rangers alike. The guides have even assisted communities in other national parks regarding the creation of guide associations and cooperatives.

6. Conclusions

Guácharo Cave is Venezuela's most famous cavern, one with exceptional biological, mineralogical, and historical importance. It has also been and continues to be a central component of the lives of communities in its vicinity. This paper takes a historical and ethnographic approach to highlight the role local guides have played in the cave's promotion, exploration, and conservation. Although the role of the guide has changed through time, from the more informal and less scientifically versed *baquiano* to the more formalized and trained *guía*, what has been a constant is visitors' dependence on their expertise, particularly naturalists, cavers, and scientists. Moreover, many of these local guides have made a critical difference in the promotion

and conservation of the cave. Yet, they are continually met with challenges. While the creation of the monument and park triggered the tourism that is now key to Caripe's economy, many people's lives that were tied to the cave were disrupted. The informal *baquiano* economy was slowly replaced with a more formalized training program that favored more educated individuals. Even for those that remained through the changes, coping with the tension of education vs. expertise is palpable. The formalization of the guides program had other effects, such as incorporating women, several whom have been key promoters of guide educational betterment and cave conservation.

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BOLD NEW RESOURCE MANAGEMENT PROGRAM AT TIMPANOGOS CAVE NATIONAL MONUMENT, A NATIONAL PARK SERVICE CENTENNIAL STRATEGY

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The year 2016 will mark the 100th anniversary of the creation of the United States National Park Service (NPS). In preparation for this occasion, the NPS has launched a Centennial Initiative designed to set goals and objectives for the coming century. The goals are based on themes of stewardship, environmental leadership, recreational experience, education, and professional excellence. While already looked to as a world leader in these categories, the National Park Service will strive to maintain these values and become more relevant to a dynamic United States and world population.

Each unit of the NPS has submitted a Centennial Strategy, outlining how the goals of the overall Centennial Initiative will be implemented within its boundaries and in the surrounding community. At Timpanogos Cave National Monument, the superintendent has outlined a strategy with a new resource management program as its centerpiece.

The Centennial Strategy for Timpanogos calls for the implementation of a bold new resource management program. It will continue to study and protect the cave resources of the monument. In addition, to protecting the cave resources at the park, employees are applying data and techniques learned at the monument to better cave and karst management and education in the community and region creating partnerships with other public and private organizations to increase cave preservation. As the only federally operated tour cave in Utah, Timpanogos is striving to be the regional leader in cave management, stewardship, and education.

Compared to some other famous caves in the National Park System, Timpanogos is a small cave. However, it has a unique position as a showpiece of cave management and protection due to its high degree of preservation and proximity to a large population center of nearly 3 million people. As the flagship of cave resource management in the area, the park strives to be looked to as the local authority on matters of cave science and protection by providing management, project support, and cave expertise.

Timpanogos Cave National Monument will continue to protect cave and karst resources through sound policy, solid scientific research, comprehensive monitoring, and innovative mitigation techniques. The park works to be a regional leader through outreach, education, electronic media, and publications. One of the most important ways the park will ensure cave and karst preservation is by building partnerships. Timpanogos not only fosters partnerships with local businesses, schools, and cavers, but also with area land management partners such as U.S.D.A. Forest Service, Bureau of Land Management, Utah State Parks, and the Utah Trust Land in order to improve cave management and preservation projects throughout the region.

1. Introduction

In American Fork Canyon, Utah Valley resident Martin Hansen discovered the cave that bears his name in 1887. Many local people made the hike up to the cave to see its many formations. Later, miners hoping to sell "cave onyx" destroyed much of its original beauty. Nearby, local boys discovered Timpanogos Cave in 1913. The location of the cave was subsequently "lost." In 1921, Vearl Manwill and friends hiked up to see Hansen Cave that they remembered from their youth. Shocked and outraged by the destruction they found there, they decided to look for the legendary "other" cave rumored to be nearby. They rediscovered Timpanogos Cave and found its decorations to be even more fantastic than those of Hansen Cave. The group vowed to protect this underground wonderland from the fate that had befallen Hansen Cave. They rallied public support

and local people began to lobby the government to protect this cave resource. At the request of the local USFS district ranger, President Warren G. Harding created Timpanogos Cave National Monument in 1922 to preserve and protect the natural resources of Hansen, Middle and Timpanogos Caves.

Today, man-made tunnels connect the caves, and visitors can tour all three along a 600-m long tour route. Passage sizes are small with formations near at hand, providing visitors with an up-close and personal experience as they tour the caves. Delicate anthodites and helictites decorate the cave walls along the path. There are substantial displays of dripstone, and the formations take on hues of yellow and green due to traces of nickel in the calcite and aragonite. The caves are reached by a 2.4-km hike that climbs 324 m up the wall of American Fork Canyon. In addition to an educational experience, the caves provide visitors with a sense of adventure and wonder.

2. Mission

The National Park Service (NPS) will celebrate its centennial anniversary in 2016. In order to bring the NPS into its second century, the service has launched a Centennial Initiative. The Initiative aims to get parks ready and give them the tools they need for "another century of conservation, preservation, and enjoyment." Specifically, the Initiative strives towards keeping the national parks relevant to a changing America. It emphasizes stewardship, environmental leadership, education, philanthropy, and special centennial projects and programs. A key goal of the initiative is to re-engage a growing, changing U.S. population through new technologies and increased outreach.

In conjunction with the NPS Centennial Strategy, Timpanogos Cave National Monument wishes to promote protecting cave resources through policy, research, monitoring, mitigation techniques, with the development and implementation of a bold new resource management program. The resource management division will use research data to reduce the impacts that facilities and tours have on the cave environment. The park not only will continue to preserve the resources within its boundaries, but also will reach out to the greater community and region.

Timpanogos Cave is located adjacent to the Salt Lake City metropolitan area, an urban area of nearly 3 million people. This location provides an opportunity to be a showcase of cave and karst management and preservation for those who may have no previous exposure to it. Visitors are able to observe fragile speleothems and ongoing karst processes and see how NPS conservation philosophy has helped to preserve and protect them. The existence of such a pristine natural environment right in their own backyard has helped many visitors to understand the vital importance of the NPS in preserving natural resources. It is the hope of the park that the cave also helps to reawaken in city dwellers a sense of wonder and connection with the natural world.

As the only federally operated tour cave in Utah, Timpanogos strives to be the regional leader in cave management, stewardship, and education. The resource management division provides a nucleus for cave and karst expertise, helping to further the goal of cave and karst conservation throughout the region. Timpanogos Cave National Monument builds partnerships with local cavers, conservation groups, and other government agencies such as the United States Forest Service (USFS), Bureau of Land Management (BLM), Utah State Parks, and Utah Trust Land.

3. New Program of Resource Management

Timpanogos Cave National Monument has intermittently funded resource management personnel since 1993 through grants and other sporadic funding sources. Variations have included seasonal personnel, a permanent cave specialist shared with Great Basin National Park, a permanent cave specialist with seasonal staff, and term resource managers. These personnel made great progress in the resource field, but the park lacked the continuity of a permanent resource management division. Starting in 2008, building toward the centennial strategy, the park hired a permanent Chief of Resource Management and a term Physical Science Technician. For the first time in the history of Timpanogos Cave National Monument, the park's base budget funds a permanent resource management division. This will allow for stability from year to year in resource management policy and practice. In the summer months, 3 to 5 seasonal technicians will help share the workload.

Resource management responsibilities include monitoring, mitigation, research, and planning for resource issues. Resource Management staff take monthly water quality measurements and daily weather observations. Cleaning the tour route of lint and algae is an ongoing effort. Mitigation of impacts takes place not only in the cave, but on the surface as well. A major example of that is the exotic plant eradication program. While this at first may not seem cave-related, in fact non-native plants can change soil chemistry and affect cave hydrology. Exotics at Timpanogos are hand-pulled to prevent the introduction of herbicides into the

cave environment. Resource Management staff maintain a greenhouse to raise native plants used to replace the exotics that are removed.

Perhaps the greatest threat to the health of Timpanogos Cave is the fact that more than 70,000 people tour the cave each year. The Resource Management staff works with the Division of Interpretation to educate the staff on tour-related resource impact. Limiting the number of people on each tour is vital in order to protect fragile formations as well as providing a quality interpretive experience for each visitor. The Resource Management staff is also dedicated to providing Interpretation with accurate scientific and conservation information so that the tours might have an influence on visitors' appreciation and understanding of fragile cave resources.

4. Outreach and partnership

Timpanogos Cave National Monument was created in response to local requests for its conservation, so it is natural that the park should continue to outreach and seek partnerships with the community. In fact, increased partnership is essential to the directives of the new Centennial Initiative.

Other land management agencies in Utah often look to the park for help with cave-related issues. One area that the park has taken a leading role in is cave gating. Recently, in partnership with the Bureau of Land Management and the Utah Cave Conservancy, Resource Management staff designed, built, and installed a gate in April Fools Cave. Due to a recent publication, treasure hunters were visiting the cave and causing damage to its speleothems and impacts to the mud floors. This is the latest in a series of NPS built gates in western Utah. It represents a continued commitment by the park to share expertise in order to help protect cave resources across the state.

Timpanogos Cave has partnered with the US Forest Service to provide a cave biota workshop for land managers. Structured as a two-day class taught by cave biology experts, the workshop offers karst education and networking for managers of caves from seven different state and federal agencies. The class focuses on the diversity of cave life, management tools to protect it, and ongoing research in the field. Through this workshop, Timpanogos hopes to aid agencies in their understanding and efforts to preserve their own cave resources.

In 2008, Timpanogos Cave partnered with Utah's School and Institutional Trust Land Administration (SITLA) to aid them in protecting and managing Nutty Putty Cave. Nutty Putty Cave has become one of the best-known, undeveloped caves in Utah with an estimated 3000 visitors per year. After a series of accidents, SITLA became concerned about liability and considered a permanent closure. Timpanogos worked with the organization to prepare a cave management plan, and construct a gate at the entrance. Through a partnership with nearby grottos, the visitors are able to again explore Nutty Putty Caves in a more safe and controlled manner.

Timpanogos has a long history of and continues to seek partnership with local cavers. Volunteer cavers re-surveyed the caves in the 1990s at the request of the park and have provided valuable research contributions. Today, cavers are invited to help with cave conservation nights, where lint and algae are removed from the tour route and are able to assist park staff in restoration projects in off-trail areas.

Timpanogos also wishes to capitalize on the large populace near its boundaries to promote cave conservation through educational programming. To enable a greater number of educational institutions to include caves in their curriculum, more than 4600 students were granted fee waivers in 2008 for cave tours and for groups unable to visit the park, rangers have visited classrooms taking cave education to the schools. Additionally, the park has partnered with local museums to provide teacher accredited educational programs to improve outside education on cave resources and conservation and developed "traveling trunks" for teachers to borrow and provide their own cave education lessons.

Resource Managment staff help to produce *Reflections*, the park newspaper and *The Utah Caver*, the newsletter of the Utah grottos. Resource Managment personnel maintain a presence at grotto meetings and activities in an effort to promote a spirit of cooperation and partnership.

5. Conclusion

As the National Park Service moves towards its one-hundredth anniversary, Timpanogos Cave National Monument will continue to be a leader in cave conservation, management, and education. With its new, emboldened Resource Management Division, the park will be better able to protect resources, reach out to the community, build partnerships and work for cave conservation across the region.

URBANIZATION-INDUCEDTRENDS IN SPRING DISCHARGE FROM A KARSTIC AQUIFER - BARTON SPRINGS, AUSTIN, TEXAS, USA

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Barton Springs are the major discharge feature of the Barton Springs segment of the karstic Edwards aquifer of central Texas. There is a unique data set of monthly springflows and monthly precipitation that date back to 1917. Monthly pumpage data from the aquifer are available since the 1930s and were minimal prior to this time. Since 1917, both the aquifer recharge zone and catchment area have changed from a rural cattle ranching environment to an urban/suburban landscape with the greatest rates of change since 1960. The data, particularly precipitation data, show much variability, but general trends can be inferred: (1) periods of high precipitation generally coincide with and slightly precede periods of high spring flows, and (2) there is more total discharge (springflow and pumping) relative to precipitation since the 1960s. We test these observations by plotting weighted moving averages, comparing net total discharge to estimated net natural recharge (related directly to precipitation), and correlagram analyses.

Since 1960, net discharge relative to estimated recharge continually increases and correlagram analyses show a slightly longer delay in peak monthly springflows relative to peak monthly precipitation. These findings indicate another source of recharge and are consistent with independent studies that predict increased recharge from leaky water, sewer, and storm sewer systems and from urban irrigation. The Austin area uses surface water from the Colorado River for most of its needs. In addition, leakage from water detention/retention ponds and through streets and other "impervious" cover contribute more recharge. Common in most urban areas, recharge increases with urbanization. Finally, urbanization of aquifer catchment areas may divert water more quickly into the losing streams that are important recharge sources for the aquifer.

1. Introduction

Barton Springs in Austin, Texas, are the main natural discharge from the Barton Springs segment (Sharp, 1990) of the Edwards Aquifer. They form the basis for an important recreational asset and host a federally-listed endangered species, the Barton Springs salamander (*Eurycea sosorum*). The protection of this aquatic ecosystem is a sensitive issue (Sharp and Banner, 1997, 2000) as Austin has undergone significant urbanization in the last 50 years and political conflicts between stakeholders have been both common and vigorous. Urbanization increases water demand, urban sprawl, and potential contamination and it also modifies both surface water and groundwater systems. Understanding these urban groundwater systems is critical for the development of livable cities and the sustainability of urban groundwater ecosystems.

Garcia-Fresca and Sharp (2005) document that recharge rates in most cities are greater after urbanization. This is most significant in arid climates and in developing countries. Urbanization adds new sources of recharge, including water main, waste water line, and storm sewer leakage; recharge through pavements; septic tanks or on-site wastewater treatment systems; artificial recharge from runoff infiltration basins; irrigation return flows; and aquifer storage and recovery. Natural recharge is subdivided into direct recharge from precipitation, localized recharge through fractures and joints, and indirect recharge from losing streams (Wiles and Sharp, 2008). With urbanization and increase in "impervious" cover, direct recharge may decrease. However, concrete and asphalt pavements are permeable; combined direct and localized recharge can be significant after urbanization Restriction of impervious cover is a zoning requirement for urban development near Barton Springs. In areas where losing streams are present (a common characteristic in karstic systems), pavements and storm sewers may also increase recharge. The effects of urbanization on discharge at Barton Springs are analyzed with the use of water balances and cross-correlation analyses using monthly precipitation and discharge records from 1917 to the present.

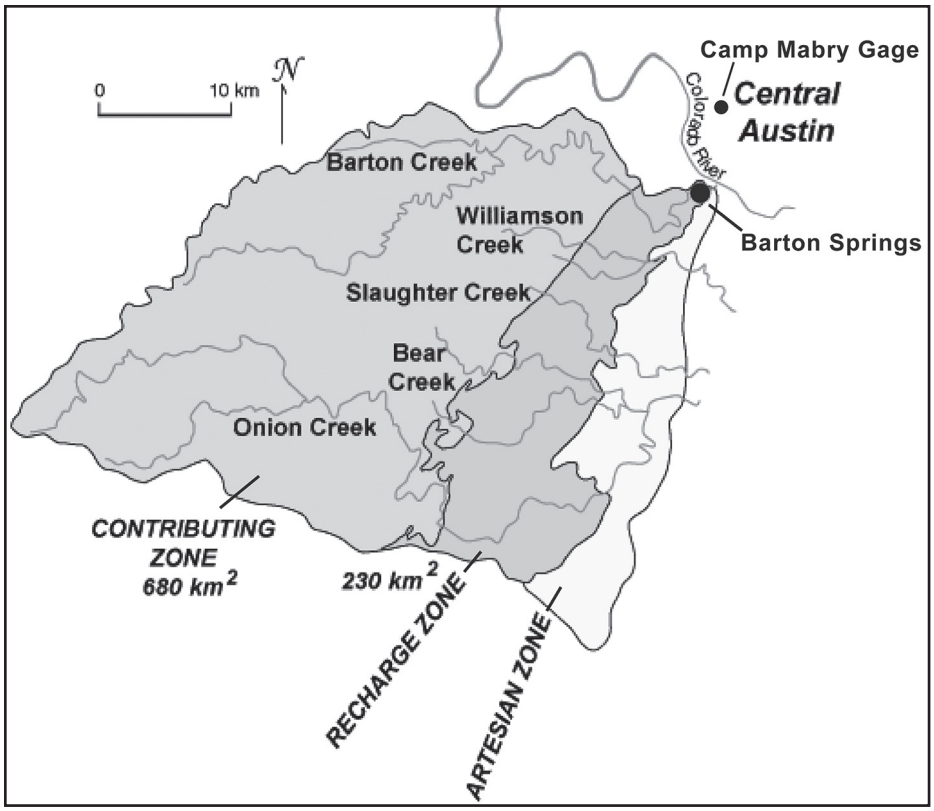

Figure 1: The Barton Springs segment of the Edwards Aquifer showing the recharge and artesian zones. The contributing zones are surface water catchments that discharge to losing streams that flow over the recharge zone. Long-term monthly data for springflow are from Barton Springs and for precipitation are from Camp Mabry.

2. Analysis

Monthly average springflow data in ft^3/s from Barton Springs and monthly precipitation in inches at nearby Camp Mabry (Fig. 1), were collected by the U.S. Geological Survey and the National Weather Service, respectively, and tabulated and provided to us by the Barton Springs/ Edwards Aquifer Conservation District (BSEACD). The BSEACD also collects and provided data on pumpage, which was minimal before the 1960s. Inspection of the time series data shows that months of low or high precipitation precede months of low or high springflow, respectively (Fig. 2). The drought of 1948-1955 is also clear on this time series. We infer from our evaluation of the time series that: 1) over time springflows are greater with respect to precipitation and 2) monthly peaks in precipitation generally, but not always, precede peaks in springflow.

We set the first 60 months of record (1917 to 1921) as a baseline equilibrium state by assuming that cumulative spring monthly discharge (Q) was equal to cumulative monthly recharge, which was related to cumulative monthly precipitation (P) at nearby Camp Mabry. Although Camp Mabry is not on either the recharge or contributing zone, we assume that over the long term, precipitation at Camp Mabry would correlated with precipitation that recharges Edwards Aquifer. Thus, for equilibrium (no change in storage),

$$Q = CP$$

C is an empirical function calculated from the time series that represents the percentage of precipitation falling on aquifer recharge and contributing area that becomes recharge. It is implicitly a function of surface area, slope, precipitation patterns, antecedent moisture conditions, and permeability. When multiplied by time we arrive at a surplus or deficit by calculating Q-CP.

Figure 3 shows Q-CP cumulative differences. Several trends are apparent. First, system is basically in equilibrium until approximately 1960, although there is a slight increase between 1941 and 1945. Since about 1960, there is more discharge from the springs relative to Camp Mabry precipitation. If pumpage is added, this difference is yet more significant. This supports our inferences from about the data presented in Figure 2.

We tested the degree of correlation between monthly springflow peaks and monthly precipitation using cross-correlation algorithms (Padilla and Pulido-Bosch, 1995; Larocque et al., 1998; Budge and Sharp, 2008). These create correlagrams to estimate the temporal correlation between the two time series. Two analyses (Fig. 4) are shown, one for all monthly values prior to 1963 (when rapid urbanization began) and the second for all monthly values after 1963. Before 1963, the lag between the series is one month, which means that peaks in precipitation in one month have the highest correlation with peaks in springflow in the next succeeding month. After 1963, the lag increases to between

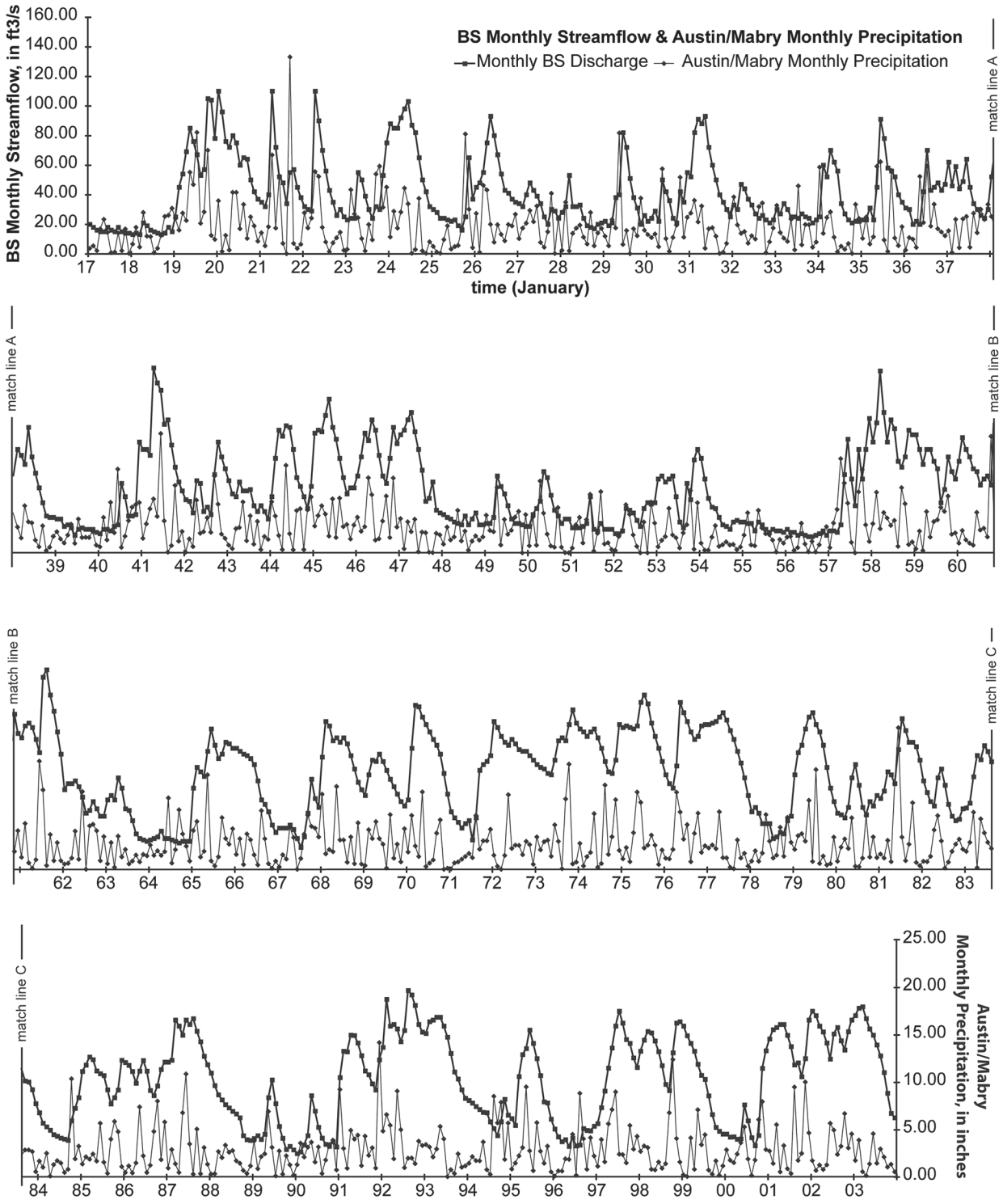

Figure 2: Monthly Barton Springs flow and precipitation data.

1 and 2 months with correlation coefficients being nearly identical. This also indicates that, since after urbanization, there is more springflow relative to precipitation (Fig.4). The correlagrams support our second inference.

3. Discussion

Both analyses are consistent with the hypothesis that another source or sources of recharge have become significant since the 1960s. There are two potential

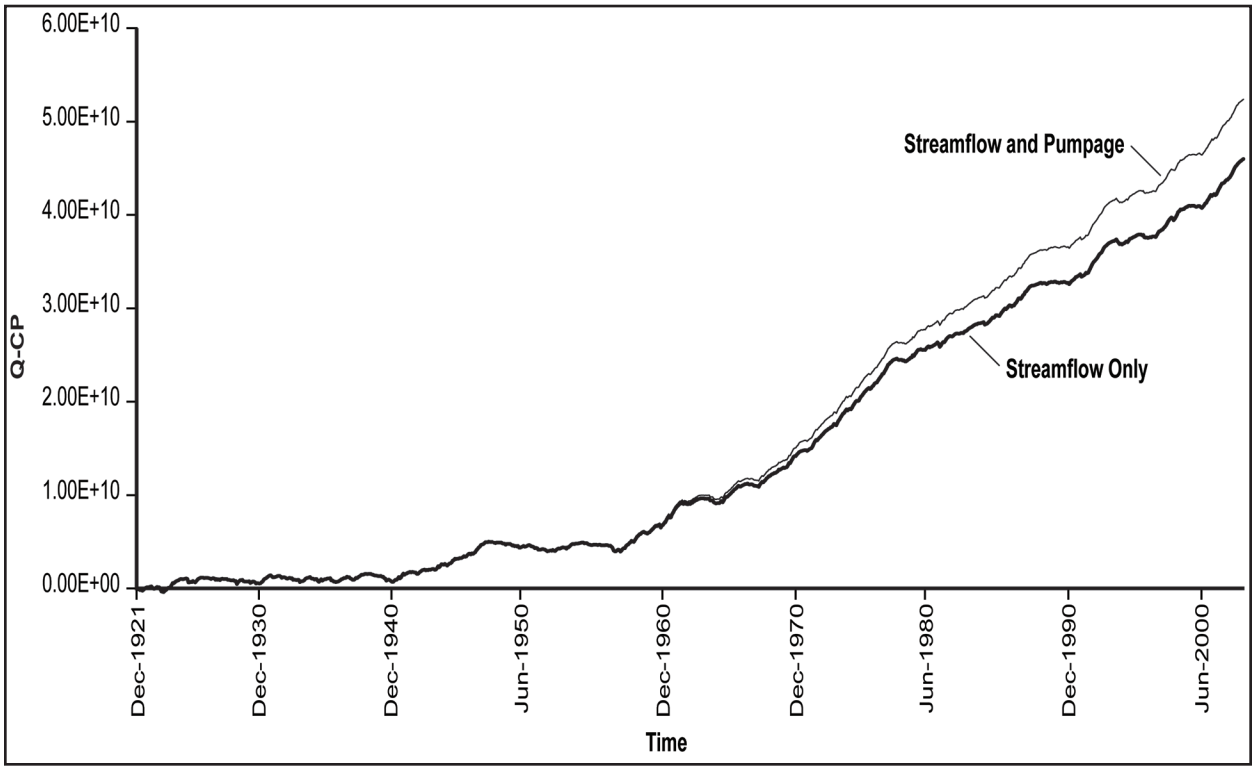

Figure 3: Cumulative Barton Springs flow (and pumpage from the Barton Springs segment of the Edwards Aquifer) less cumulative estimated recharge from precipitation. Note the departure occurring after 1960 that is attributed to urbanization.

possibilities: (1) precipitation over the recharge and contributing zones has become greater than in Austin; and (2) changes in recharge have occurred because other anthropogenic (urbanization) effects. There are no data to support the first possibility. Documented cases of increased rainfall with urbanization (Changnon, 1968; Charton and Harman, 1973; Bornstein and Lin, 2000) show an increase in thunderstorm activity and precipitation downwind from the cities' heat island effects. Here, the recharge and contributing zones are in the prevailing upwind direction from Austin. There are no studies indicating a historical pattern of increasing precipitation over the aquifer's recharge and catchment areas (Fig.1).

However, changes in recharge have occurred because other anthropogenic effects. Garcia-Fresca and Sharp (2005) and Wiles and Sharp (2008) show that recharge in Austin has increased due to urbanization. Garcia-Fresca and Sharp also show that a rapid increase in population and urban sprawl commencing about 1960. Garcia-Fresca (2004) documented difference between the amount of water treated for distribution and the amount arriving at wastewater treatment plants by the City of Austin; this represents the amount of urban water potentially available for urban recharge. She used conservative estimates that at least 7% of all treated drinking water leaks along the distribution system and at least 5% leaks from sewer lines and concluded that groundwater recharge in Austin has increased from 53 mm/a to over 94 mm/a with transition from rural to urban land use. This estimate is probably low because most data show significantly greater percentage losses of water from utility systems across the world (Garcia-Fresca and Sharp, 2005) and it did not include recharge through "impervious" cover. Wiles and Sharp (2008) show that secondary permeability of roads and parking lots is not negligible and recharge does occur through impervious cover and in the storm sewers with leakage rates estimated between 5 and 10% of flow (Wurbs and James, 2002, p. 628). In fact, under some conditions, Wiles and Sharp inferred that adding "impervious" cover increases recharge because it also lowers evapotranspiration.

Consequently urbanization is expected to increase groundwater recharge. We infer that this is the cause for the change in the correlagram and in the increase in Barton Springs flows relative to precipitation that have occurred with urbanization in Austin.

4. Conclusions

Monthly data for springflow from Barton Springs and

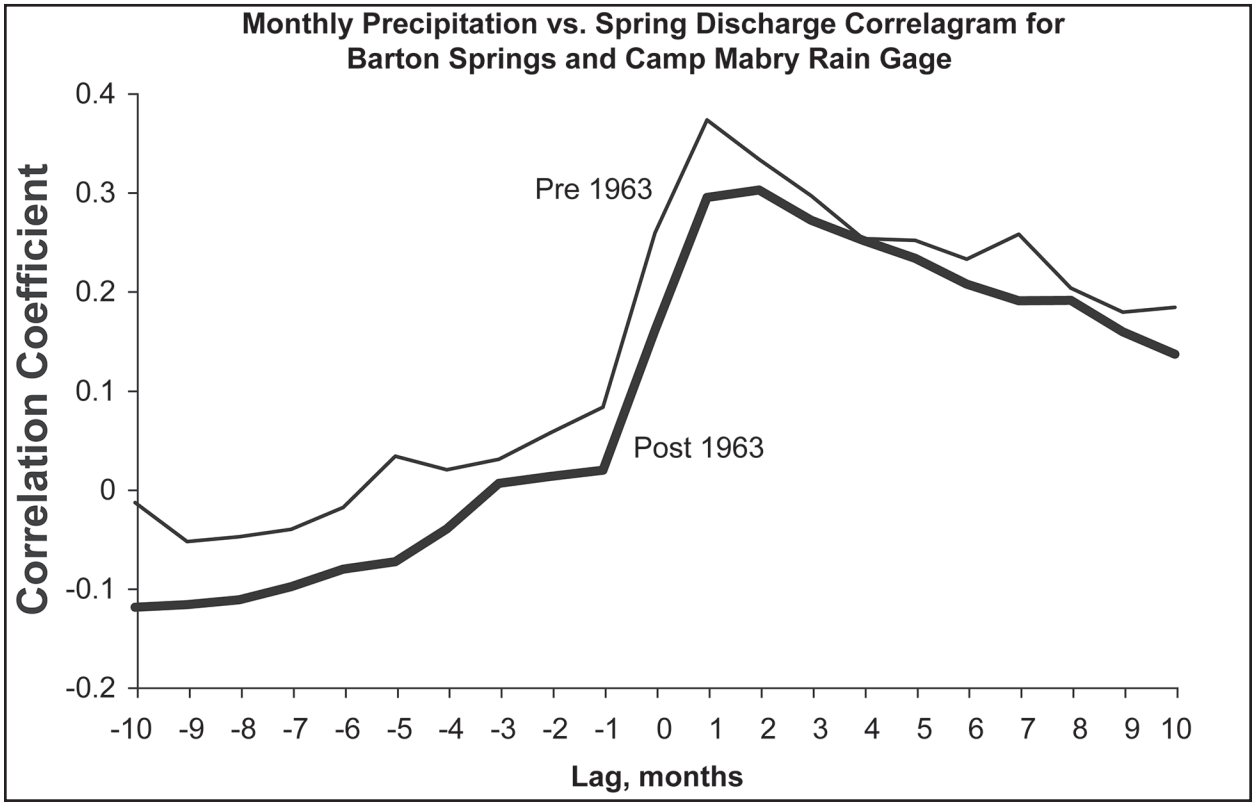

Figure 4. Correlagrams of Camp Mabry monthly precipitation and monthly Barton Springs flows for pre-1963 and post-1963 data. Notice the lag shifts from 1 to greater than 1 month, which correlates with urbanization.

precipitation at nearby Camp Mabry are available since January 1917. The times series indicate that: 1) there is more springflow (Q), relative to precipitation, in years since the 1960s, and 2) months of high or low monthly precipitation (P) are followed by periods of low or high springflow. We observe that Q-CP increases nearly continuously since 1960, where C is an empirical coefficient. This effect is amplified when pumpage data from the Edwards aquifer are added. Correlagram analysis indicates a longer lag between the precipitation and springflow times series since 1962. These trends correspond to the time that Austin's urban population and area (urban sprawl) began to grow. Increased recharge from urbanization is inferred to be the cause of these trends. We propose that these findings should be considered as urbanization proceeds in other areas with karstic aquifers. Increased groundwater recharge may be beneficial in some parts of the urban environment and deleterious elsewhere. For Barton Springs, the result is that springflows are augmented by urban recharge so that discharge is higher for a given precipitation pattern than prior to urbanization.

In other areas, the situation could be different because most of the water usage in the study area is provided by surface water from the Colorado River. If the aquifer was the major supply source, water levels and springflows could decline even with increased recharge increases. Likewise, geotechnical designs to keep the water table deep and foundations dry could also decrease natural springflows. Finally, although Barton Springs has not experienced significant water quality degradation, the effects of urbanization on water quality could be significant in other areas or change with time at Barton Springs. The above findings suggest that urban design practices based upon impervious cover constraints should be carefully examined.

Acknowledgements

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SEDIMENTOLOGY OF PARTICULATE ACCUMULATION AND ITS REMEDIATION, SKULL ICE CAVE, LAVA BEDS NATIONAL MONUMENT, CALIFORNIA, U.S.A.

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1925 in northern California, U.S.A., Lava Beds National Monument is located between 1220 m and 1707 m elevation on the north aspect of Medicine Lake volcano (MLV), a shield-type volcano that exceeds 2440 m in elevation and constitutes the most voluminous volcano in the Cascades volcanic province. Many lava flows emanating from numerous Aerosolic-to-silt-sized sediment thickly coated rock surfaces in upper Skull Ice Cave (hereafter, Skull Cave), a heavily visited lava cave at Lava Beds National Monument on the northeast slope of Medicine Lake volcano, in northern California, U.S.A. The sediment obscured wall and breakdown features, adversely impacting viewscapes and visitors' experiences. In the lower cave, visitors tracked fine-to coarse-grained cinders onto an ice floor. From November 1989 to January 1992, samples of airborne particulates were obtained using a static dust trap external to the cave and arrays of traps below ground in order to characterize the nature, source, and rates of particulate deposition above and below ground and to determine if above-ground sites had the same sedimentary character as did the in-cave sites.

In the upper level of Skull Cave, fine aerosolic to silt-sized sediment coating rock surfaces on walls and the breakdown floor was found to be derived from the trail tread that had been paved with vitric tephra erupted ~950 YBP from Glass Mountain, a nearby young volcanic vent. Rates and masses of dust accumulations correlate directly with distance from the trail tread and directly with visitation as recorded by an automated visitor counting station. The composition of in-cave aerosolic samples was not similar to composition of airborne particulates trapped outside the cave on the basis of visual inspection, microscopic study, and total content of oxidizable components. When this sediment contamination problem was identified to Resources Management, mitigation actions were planned and carried out during the subsequent decade. The old trail-tread composed of Glass Mountain tephra was removed and a new trail composed of basaltic lava blocks obtained from nearby quarries outside the Monument was artistically laid. The dust deposits coating the breakdown and cave walls were removed in result of restoration activities and have not returned.

In the lower level of Skull Cave, conspicuously reddened deposits of basaltic scoria and a clayey paleosol long have attracted the eye (and footgear) of visitors who tour the impressive year-round ice deposits that comprise part of the lower cave's floor. The visitor-mobilized sediment obscured and discolored the ice floor, degrading the visitor experience. We suggested mitigation measures including: (1) grooming the source areas to remove readily transportable sediment; (2) removing readily removable sediment from the ice floor during times when accumulated melt water allowed access to the sediment; (3) installing walkways designed to capture and trap sediment that adheres to footgear prior to reaching the ice; and (4) installing a gate and viewing platform to keep visitors from marring the ice surface, yet still view the ice floor.

The results of the remedial measures and restoration program are strongly positive and enhance the overall visitor experience at Skull Cave. The case history is a fine example where basic scientific study and informed resources management acted cooperatively to preserve key resources at Skull Cave for the benefit of future generations of visitors.

1. Introduction

Established invents during the past 500,000 years or so have built an extraordinary inventory of volcanic landforms; lava tubes as former conduits for flowing lava and different types of lava flows extend for kilometers; types of volcanic ejecta, cinder cones, calderas, craters, including silicic lava flows and associated volcanic ash deposits are well represented (Fig. 1). There have been nine eruptions in the past 5200 years, making Medicine Lake Volcano's (MLV's) Holocene eruption rate one of the highest in the Cascades (Donnelly-Nolan et al., 2007, p 5). The buff-colored vitric tuff erupted about 950 YBP accompanied the Glass Mountain obsidian flow and this eruption figures in our study. Public visitation exceeds 100,000 per year for whom the hundreds of lava tube caves in the Monument are one of several featured attractions. The Monument loans helmets and lanterns to visitors for the purpose of touring the lava caves; interpretive staff give informative tours, and there is a self-guided tour of Mushpot Cave equipped with signage to acquaint visitors with fundamental aspects and features of lava tubes.

Figure 1: Index map showing location of Lava Beds National Monument, northern California, U.S.A.

Skull Ice Cave (more commonly Skull Cave) is a signature lava cave of Lava Beds National Monument (LABE). Most visitors tour it, owing to its easy access and impressive passage dimensions (>25 m wide and up to 20 m in height). In 1989, Cave Research Foundation personnel in cooperation with the National Park Service initiated a series of inventory and monitoring studies at LABE. One of us (Tinsley) noticed that walls, floor and breakdown of many lava caves were so thickly coated with a silt-to-aerosolic sized deposit of loose light-buff sediment that features of the lava itself as well as its dark gray to black color were obscured. As dusty rock appears much less pristine and impressive, it seemed that the visitor's experiences were being adversely impacted.

In addition, in the lower level of Skull Cave, a remarkable ice floor is preserved owing to relatively dense air at subfreezing temperatures sinking into the cave, becoming trapped during winter months, then persisting through the summer months, thereby freezing dripwater that enters the cave. This ice floor was acquiring a coating of pyroclastic cinders and reddish brown mud apparently transported to the ice owing to footgear worn by enthusiastic visitors; the ice was visually and compositionally significantly the worse for wear.

One of us (Tinsley) chose to investigate the nature, origin, and depositional processes controlling the mobilization and deposition of the sediment, including the fine particulates (hereafter "dust") that obscured the bedrock features in several heavily visited caves and the deposits of soil on the ice floor at Skull Cave. As Skull Cave was a signature cave of the Monument and was already equipped with a remotely deployed visitor-counting device, it was an obvious choice for this study. While Valentine Cave also was studied, this report addresses solely Skull Cave.

2. Methodology

Selected sedimentary deposits in Skull Cave were studied above ground and below ground. Above-ground and external to the cave, we collected and partly characterized eolian (wind-borne) sediment at three sites. Rates of eolian deposition and composition of the airborne dust was studied to determine if rates of deposition varied above ground across the Monument and to learn if aerosolic dust from outside the cave could be a significant component of in-cave fine-grained sediment. The underground or in-cave study conducted in Skull Cave was designed to determine the nature of the sediments within the caves and to learn the circumstances of and the rates of deposition of those rock-obscuring materials. All samples were processed in the laboratory according to the same protocol. In every instance,

the objective was to discern the quantity of material collected, information about its composition and particle size distribution, and the probable source of the sediment. From the information obtained in the studies, we expect to learn about several important aspects of the sedimentary processes that occur in the caves and develop a process-based model that can help resource management appraise problems and select practical and effective approached to remediation and restoration.

Above ground, airborne particulates were obtained using a dust trap designed by Marith Reheis that consisted of an angel-food cake pan, 1-cm diameter hardware cloth, 1 cm diameter marbles, three guy-wires that secured a central, 3-corner or I-beam basic fencing post 1.83 m in length and set vertically to support the pan assembly about 1.5 m above the

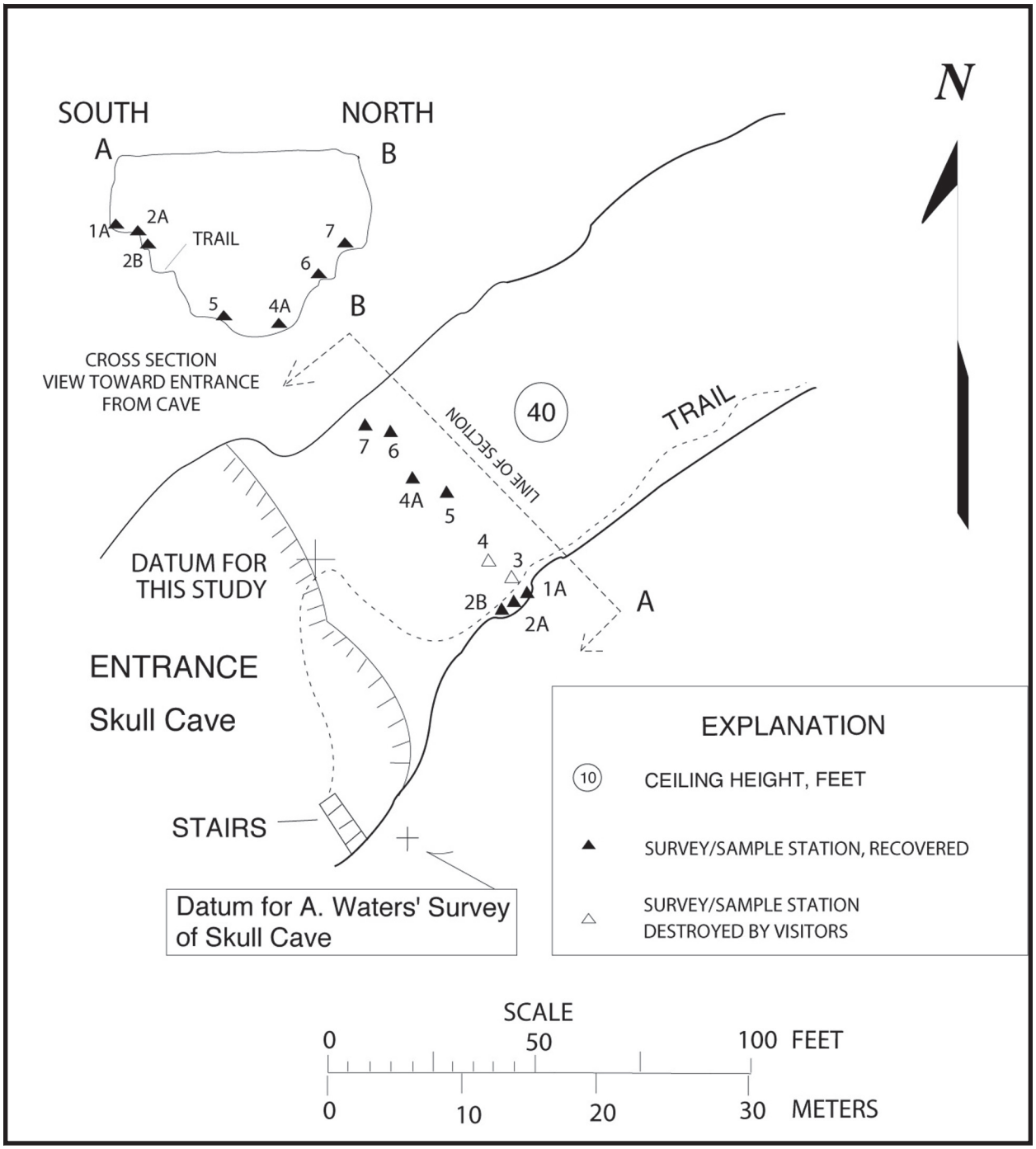

Figure 2: Detailed map showing entrance area of Skull Cave, including plan view and vertical profile illustrating the deployment of the dust traps relative to trail.

ground. The hardware cloth supported the marbles above the base of the pan. Two hoops or bails were attached in short arcs above the pan and coated with a sticky substance to keep birds from perching there and contributing food fragments or feces to the sediment trap. At recorded intervals of time, traps were visited, dismantled and the marbles eluted and washed with distilled water into the pan. Then the pan's entire contents were washed into a sample bag for transport to the laboratory for study.

Below ground in upper Skull Cave, we deployed flat pieces of solid lava, generally devoid of gas bubble cavities (vesicles) that would make them difficult to clean. Prior to deployment as tray-like collectors, the perimeter of each lava block was traced onto paper and its surface area then measured from the tracing using a rolling-block planimeter. Blocks were then washed, dried, labeled with a felt-tip marker and placed in the cave at varying distances away from, above, and below the trail. The location of each station was surveyed relative to the trail using grade V compass and tape techniques. Collectors were initially deployed on 4/8/1990 and were re-acquired and washed off using distilled water into (double) sealable polyethylene bags at intervals of 147, 168, 70, and 252 days; last day of service was January 4, 1992. We also took samples of the trail tread for compositional analysis. Not all collectors survived; in initial deployments two blocks were plucked by visitors and hurled across the cave, where we found them. We became shrewd at placing our collectors (Fig. 2).

Below ground in lower Skull Cave, sediment on the ice floor was swept up and bagged for inspection and analysis. This portion of the study would prove to be quite straightforward.

3. Laboratory Studies

All bagged samples were thrice washed into beakers pre-weighed using a Mettler H-72 single-pan balance and then placed into an oven overnight at 105 °C evaporating each sample to dryness. Dry beakers were re-weighed to determine the mass of particulates in each sample. Beakers were then covered with waxy film to guard against in-lab aerosolic dust contamination. Subsamples from beakers, including trail tread samples were examined with a binocular microscope and a petrographic microscope.

Each sample's mass was normalized against the surface area of each trap to calculate mass of particulates per unit area. The number of days elapsed per deployment and census figures from the trailside visitor counter at Skull Cave were then used to compute the dust flux for above ground and below ground samples. The trailside counters count visitors going in both directions, so counts were halved to obtain a better approximation of actual visitation figures for our calculations (Table 1 and Fig. 3.)

Inspection of all samples indicated that above-ground samples contained significantly more organic fragments than did in-cave samples. To quickly (and roughly) quantify this relation, selected above-ground and below-ground samples were weighed, then treated with 30% hydrogen peroxide solution, re-dried, and re-weighed. The difference in mass was the oxidizable portion of the sample. Surface traps averaged about 33 wt-% as oxidizable organic materials; in-cave traps contained only about 5% oxidizable organics, according to this hydrogen peroxide treatment technique.

Examination of sediment samples from within Skull Cave using a petrographic microscope was conducted to determine the nature of the dust caught on the collectors compared to the material found on the trail tread. Compositionally, the trail-tread materials were virtually identical to the particulates trapped in the cave. These materials chiefly were composed of a vitric volcanic ash or tuffaceous material containing abundant volcanic glass. The trail tread samples also contained occasional pollen (mainly juniper, sage, grasses) and lint from textiles, probably from clothing worn by visitors. The glass component of the tephra is isotropic (extinguished under crossed polarizers) and contains small incompletely crystallized grains of plagioclase feldspar, biotite, and some hypersthene. The refractive index of the oil used in preparing the grain mounts (RI = 1.51) was less than the refractive index of the glass (estimated at 1.525). The particulate samples examined differed most conspicuously in terms of sorting and average particle size. The trail tread material is a match for the Glass Mountain tephra that blankets the land surface about the Monument and thickens towards the Glass Mountain obsidian flow, the youngest eruptive event dated at Lava Beds (Donnelly-Nolan *et al*, 2007).

Using a graduated ocular with the petrographic microscope, 200 intermediate particle diameters were measured on a sample from the trail tread and compared with similar measurements on samples collected at in-cave sites 2A and 6. The trail tread sample contained a great number of rock fragments ranging up to 7 mm or more in diameter. Inspection of the < 2 mm fraction showed a wide range of particle sizes present, from coarse sand size (1-2 mm) to less than 1 micron in diameter. The glassy particles displayed a high measure of angularity, probably reflecting a history of being crushed and comminuted. In contrast to the trail tread

Season	Days Elapsed	No. of Visitors	Visits per Day	Visitor-Days	
Apr-Aug	147	9604	65.3	1411788	
Sep-Feb	168	5392	32.1	905856	
Feb-Apr	70	1558	22.3	109060	
Apr-Jan	252	11625	46.1	2929500	
Collector Number	**Flux (g/m^2/day)**	**Visits/Day**	**Dust g/sq m**	**Flux g/sq m/V-D**	**Log_{10} Flux g/sq m/V-D**
5	0.0481	65.3	7.0707	5.0083E-06	-5.3003071
7	0.0091	65.3	1.3377	9.4752E-07	-6.0234108
2B	0.1368	32.1	22.9824	0.000025371	-4.5956638
5	0.0206	32.1	3.4608	3.8205E-06	-5.4178827
7	0.0047	32.1	0.7896	8.7166E-07	-6.0596521
2B	0.1391	22.9	9.737	0.000089281	-4.0492403
5	0.0283	22.9	1.981	0.000018164	-4.7407811
7	0.0076	22.9	0.532	0.000004878	-5.3117539
2B	0.0584	46	14.7168	5.0237E-06	-5.2989801
5	0.0082	46	2.0664	7.0538E-07	-6.1515791
7	0.002	46	0.504	1.7204E-07	-6.7643631

Table 1: Dust flux and visitation data for Skull Cave. Upper part of table: visitation grouped by deployment; duration of deployment shown as days elapsed. Lower part of table: Dust flux for selected collector stations 2B, 5 and 7. Distance from trail tread increases with collector number. Four deployments are presented here. Units are log10 of dust flux in grams per square meter per visitor day. The trend is obvious from the flux figures with units of grams per square meter.

material, a sample from collector 2A had a mean particle diameter of 25 microns (coarse silt); a sample from collector 6, 12 m away from the trail, had a mean particle diameter of 6 microns (fine silt).

We found that samples from the sediment on the ice floor in Lower Skull Cave were derived in part from the trail tread and, more prominently, chiefly from an area near the end of the cave but beyond the distal position of the trail. In this area of Skull Cave, collapse of the lava tube's lining exposes cinders and a clayey, reddened paleosol that apparently were parts of the paleo-landscape that pre-dated the eruption of the basalt of Giant Crater, the lava flow that contains Skull Cave (see Donnelly-Nolan and Champion, 1987; Waters and others, 1990).

4. Results

Above-ground samples contained five times more oxidizable organic materials than did the in-cave samples. This difference is interpreted to indicate that wind-blown sediment from outside the cave is only a minor contributor to in-cave sediment, and the problem probably decreases as one moves away from the entrance to deeper in the cave. We had only the one profile, so we can neither validate nor quantify this probable trend.

Samples from trail tread and in-cave particulates collected in our array of samplers differ most conspicuously in terms of sorting and average particle size. Most trail tread material is a dead-on match for the Glass Mountain tephra that rests in great abundance on the land surface about the Monument. The mean particle size of the glassy shards decreases as the distance from the trail tread increases, be that vertically above the trail tread or horizontally away from the trail tread.

The dust flux decreases as the distance from the trail tread to a collector site increases (Table 1 and Fig. 3).

The trail tread is clearly implicated as the source of the offending sediment that coats the rocks along the upper trail and environs within Skull Cave. The process is apparently simple: the Glass Mountain vitric tuff composing the trail tread becomes progressively comminuted by foot traffic, then is entrained by visitor-generated air currents, and drifts away from the trail to be deposited on in-cave surfaces.

In lower Skull Cave, sediment from the ice floor was derived in part from the trail tread in the upper cave but chiefly was composed of cinders and reddish clay from the exposed paleosol. The clay easily adhered the cinders to the footgear

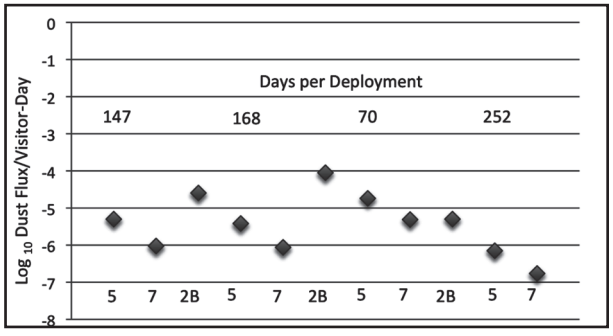

Figure 3: Scatter plot showing dust flux per visitor-day for collector 2B, 5 and 7 for four deployments. Duration of deployment (days) stated in center of graphic. Dust flux decreases away from trail tread. Curiously, the greatest dust flux occurred during the shortest deployment in late winter-early spring months by the fewest visitors.

of visitors, who then tracked the sediment onto the ice.

Our study identified two problems to Resources Management, specifically the need to mitigate sedimentation along the trail in upper Skull Cave and the source of that sediment. The second problem was to mitigate the effect of visitors' boots that was carrying a mixture of trail tread sediment plus sticky clay and adhered cinders acquired in the very back of Skull Cave onto the ice floor.

5. Resources Management's Response

Management digested the results of the Tinsley et al. (1992) study, and then began planning to mitigate identified problems and restore Skull Cave, incorporating most of the recommendations. Fuhrmann (2001) recounts this successful restoration effort with clearly written well illustrated article. Summarizing from Fuhrmann (2001), the offending trail tread was removed (about 862 kilograms of glassy pumaceous sediment) and was replaced with a trail tread composed of basaltic lava blocks obtained from private quarries located outside the Monument. About 900 m^2 of block basalt was laid as flooring to provide a smooth surface of natural materials that would wear well, not impede visitors, and not be a source of sediment. The natural materials used closely resemble the lava of Skull Cave, so introduction of alien chemicals and appearance issues are essentially nil. In the lower cave, old stairs were removed and replaced with new stair treads fabricated of galvanized 12 mm diameter steel mesh. Trays installed below the stair treads collect all sediment dislodged from soles of footgear that dropped through the mesh. Basically, the new stairs effectively clean visitors' footgear while they walk. When needed, trays are pulled from beneath the stair tread; all trapped sediment is cleaned out and is then taken from the cave. A robust gate now keeps visitors off the ice floor while affording a vantage point for photographers. The ice floor was then cleaned. With no visitor traffic to mar it, the ice floor is ever so much better looking than it has been for decades.

6. Conclusions

A low-tech sediment study was designed to reveal the nature of the source and process of in-cave sedimentation problems noted in Skull Cave at Lava Beds National Monument. The study identified a trail tread composed of brittle vitric tuff of Glass Mountain and visitor foot traffic as principal factors in degradation of the ice floor in lower Skull Cave and the source of the fine particulates coating wall rock and other surfaces of Upper Skull Cave.

A receptive National Park Service management at Lava Beds embraced the study and within a decade located funding, designed and implemented appropriate mitigation measures, and has monitored the results, which are quite satisfactory.

The entire restoration effort at Skull Cave required collaborative efforts of Maintenance, Resources Management, Fire Management, and Interpretation divisions at Lava Beds, and the Cave Research Foundation.

Acknowledgements

We thank the National Park Service for sponsoring this study, and especially David Larsen, Resources Manager at Lava Beds, for providing details of restoration and remediation efforts that followed our research.

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RELIGHTING MAMMOTH CAVE'S NEW ENTRANCE: IMPROVING VISITOR EXPERIENCE, REDUCING EXOTIC PLANT GROWTH, AND EASING MAINTENANCE

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During the winter of 2007–2008, Mammoth Cave replaced the tour lighting of the New Entrance section of the cave. The goals of this $82,000 project were to improve visitor safety and enjoyment, to reduce the growth of light-induced algae, mosses, and ferns in the cave, and to reduce maintenance issues associated with the lighting system.

A key hallmark of the new lighting system is the use of specially designed LED bulbs that will reduce exotic plant growth in the cave. These lights were designed to provide most of their light in spectral ranges that are inefficient for photosynthesis. Initial testing of the bulbs under laboratory conditions indicates that they will significantly reduce algae growth compared to the lights being replaced. Further testing of the bulbs is occurring as a portion of a project to examine the growth of algae in caves under various types of lights. Field experiments in this project are taking place at five show caves administered by the U.S. National Park Service.

The LED bulbs were developed through a cooperative effort of enLux Lighting (Dr. D.J. Chou) and Mammoth Cave National Park (Rick Olson). The enLux light engine allows the light color to be manipulated by varying the number of LEDs of various colors. The specific bulb being used in the New Entrance combines 61 amber, 10 green, and 1 blue LED to form a warm white light (color temperature = 2050K). Although the light appears warm white, most of the spectral emission is in the yellow and green wavelengths. Chlorophyll A and B do not use these wavelengths very efficiently, so these lights do not promote plant growth nearly as well as lights that provide more nearly full spectrum white lighting (such as incandescent or fluorescent lighting).

The lighting design was implemented by a multi-disciplinary team that included staff members from Mammoth Cave's Interpretation, Facilities Management, and Science and Resource Management Divisions and the Mammoth Cave International Center for Science and Learning. Interdivisional teams designed lighting for the area by going into the cave with lights then placing them to optimize visitor experience, resource protection, maintainability, and safety. The result was a plan based on sequential mock-ups of the final result. This approach, while more time consuming than simply planning and installing lighting without preliminary set-up in the cave, led to significantly better light placements from aesthetic, resource protection, and maintenance stand points. Combining science-based lighting choices with cooperative project development has provided greatly improved lighting for the New Entrance area. We are continuing this program of replacing lighting which is problematic from an aesthetic, resource management, or maintenance standpoint using this procedure. In areas with lampflora problems, we will continue to use the restricted spectrum lights.

1. Introduction

Installing a fixed lighting system is one of the most important parts of developing a show cave from an interpretive, resource management, maintenance, and cost standpoint. The lighting system fundamentally defines what the visitors will see, so it is one of the most important aspects of developing the interpretive program for a cave. They also provide for safe enjoyment of the cave by visitors and staff. Lighting systems are also one of the primary sources of resource impacts in show caves. They can promote algae growth, alter cave microclimates, and their installation and maintenance may impact delicate cave areas. Maintaining lighting systems

entails continuous work over the lifetime of the system (usually over 20 years). The lighting system is often also one of the largest ongoing costs for a show cave operation, both through replacing and repairing parts and through costs of electricity to run the system.

Because a lighting system is so important for so many reasons, it is important to choose and implement lighting systems carefully. An interdisciplinary team approach and the use of up-to-date scientific information has led to Mammoth Cave National Park installing a new lighting system in the New Entrance that improves interpretation of the area, provides for visitor safety, reduces impact from both installation and maintenance, reduces the growth of lampflora (and thus reduce the necessity to use biocides such as bleach in the cave), provides for increased efficiency in electrical use, and is easy to repair and maintain. This system is an LED based system that uses specialized bulbs to provide good light for tours, but which provides inefficient illumination for photosynthesis. Because the system is largely mounted on existing infrastructure, is also has relatively low direct impact on the cave from installation and is easy to maintain.

2. The New Entrance

The New Entrance of Mammoth Cave is an artificial entrance that descends into the cave through a spectacular series of narrow canyons and fourteen shafts (Fig. 1). In this section, 131 meters of tour trail descend 44 meters from the surface to Grand Central Station in Kentucky Avenue. The trip through the entrance provides visitors with the opportunity to see many of the most interesting vadose features such as domes, pits, canyons, fluting and shafts. The entrance was installed by George Morrison in 1921 so that he could run a cave tour to compete with the Mammoth Cave Estate tours in the Historic Section of the cave. When Morrison opened the entrance, he installed wooden stairways and catwalks for people to descend on. He also installed an electrical lighting system in the entrance (Corrie, 1995). It was one of the first areas of Mammoth Cave with an electrical lighting system. Morrison's wooden stairs and catwalks were used until 1967, when the entrance was closed due to safety and environmental concerns (Blanton, 2004). The wooden stairs and lighting infrastructure were later removed. In the 1980s a new set of stainless steel stairs and catwalks were put in with a new lighting system. The new lighting system consisted of mainly 150-watt incandescent bulbs in "jelly jar" enclosures (Fig. 2). These lights were placed on posts at about two meters in height along the catwalks. The New Entrance was reopened with the newer infrastructure in 1987.

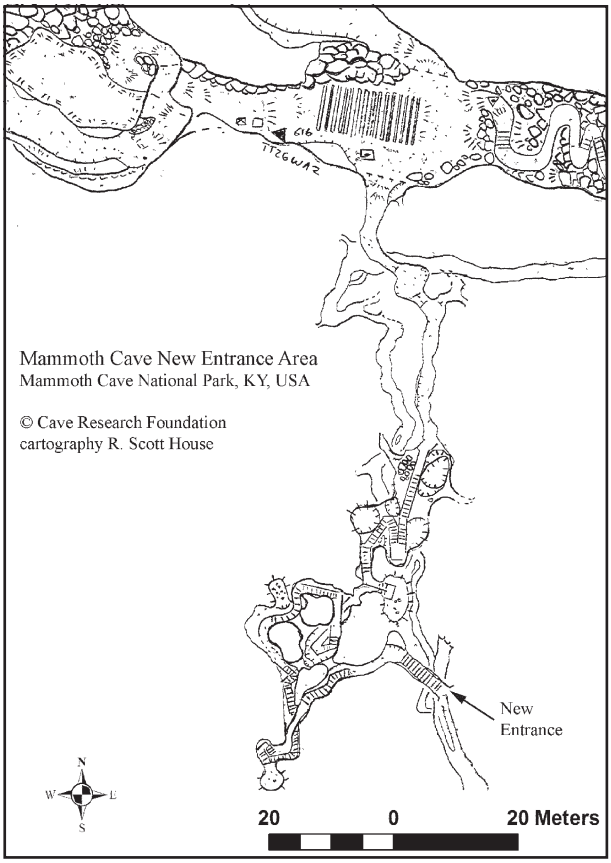

Figure 1: Plan view of the New Entrance shaft complexes and connecting passages to "Grand Central Station" seen at the top.

Figure 2: "Jelly Jar" style fixture used in the 1987 re-lighting of the New Entrance and replaced in the current project. Equipped with a 90-watt clear incandescent bulb, these lights grew algae, moss, and even ferns. They also subjected visitors to glare.

The lighting installed in 1987 had several limitations. Because of the close quarters in the canyons and small shafts and the wet conditions in the New Entrance, the "jelly jar" lights, like the original lighting system, had a tendency to

grow luxurious lampflora. The lights provided illumination for travel, but provided little light directed in ways to see cave features. They also subjected the visitors to significant glare from the bulbs, which impaired visual accommodation to the cave environment and potentially reduced safety. Eight TIR Destiny CW LED panel lights were later added to light selected features. However, these lights had limited capacity to light individual features, and they frequently failed in the high-humidity, dripping cave environment. The bulbs in the jelly jar fixtures were replaced with lower wattage Sylvania "Super-Saver" 90-watt clear glass bulbs.

3. The Relighting Project

The New Entrance re-lighting being described here was part of a much larger project upgrading and replacing the electrical system of the toured portions of Mammoth Cave. This project took place from March 2002 through January 2008. The primary contractor for the entire lighting project was Chappy, Inc. Overall, the goals of the re-lighting project were to replace the aging electrical and lighting infrastructure in the cave to (1) provide a safe and satisfying visitor experience, (2) improve the energy efficiency of the electrical system,(3) protect cave resources by reducing impacts of the lighting system (particularly through reducing the growth of lampflora and removing lights from delicate areas), 4) increase safety for staff members working on lights or replacing bulbs, and (4) reduce maintenance needs associated with the electrical system.

In the New Entrance in particular, implementing those goals resulted in several important choices in the relighting. Because the area has been prone to algae growth in the past, bulbs were specially chosen which would reduce the efficiency of algae growth, and which would hopefully thus reduce or prevent growth. To reduce the impact of the physical placement of the lights and to ease maintenance of the lighting system, lights were attached to existing cave infrastructure wherever possible. We also attempted to light the area in a way which allowed visitors to see major portions of the canyons and shaft complex, rather than simply relighting the stairs and catwalks for travel.

The New Entrance is a very complex area from a lighting standpoint. Because the tour winds its way down through the shafts, the lighting is a complex three-dimensional system where lights from different levels may be visible several times during a tour. This also means that angles that may produce glare cannot always be reliably predicted. Because of this complexity, we chose to mock-up all lighting in the area, before finalizing design. In this process, teams of experts from Science and Resource Management, Interpretation, Maintenance, and the Mammoth Cave International Center for Science and Learning took sets of specially rigged fixtures, bulbs, and electrical cords into the cave. They would then place the fixtures in potential locations. The existing lighting system would then be disabled and the proposed new lighting placements would be evaluated from all levels of the trail and from a variety of visitor heights. The presence of experts from the various divisions insured that all important aspects of the proposed lighting layout were adequately evaluated before a layout was accepted. When a layout was finalized, the positions for the lights were flagged and the fixtures, bulb types, aiming were noted on a map for reference (Fig. 3). When Chappy, Inc. employees installed the fixtures, the team returned to finalize aiming of the lights. The New Entrance portion of the re-lighting project took place from November 2007 through January 2008.

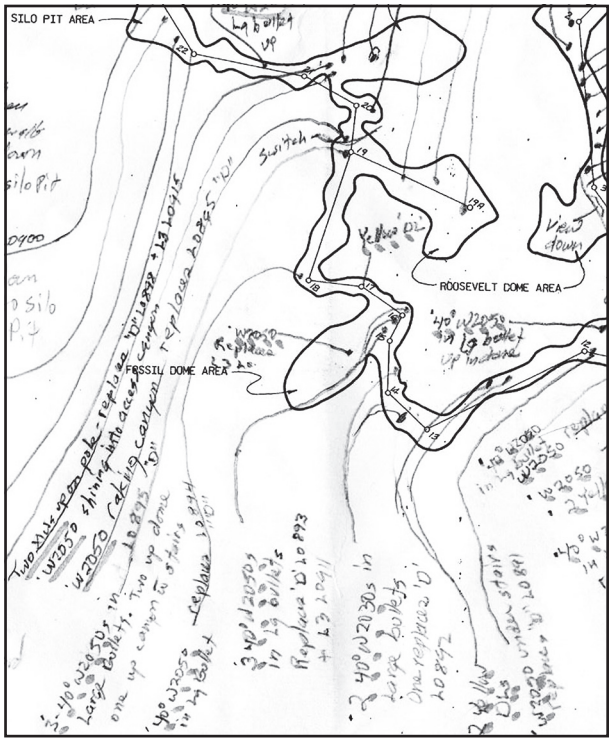

Figure 3: Portion of the field map denoting what fixture and lamp combination had been shown to be effective during the mock-up process.

4. Fixtures and Lights Selected

The wet, humid conditions, close quarters, and potential for glare from lights, constrained the type of lighting fixtures used in the area. Bullet-shaped fixtures (Fig. 4) made of composite polymers were chosen for most locations for several reasons. Metal fixtures (including brass and aluminum) are subject to oxidation in cave conditions. This oxidation contributes to both the premature degradation

and replacing of the fixtures and allows potentially toxic metals to contaminate the areas around the fixtures. These composite, bullet fixtures can be either fully enclosed for use in wet areas, or they can be open to allow better air circulation. In addition, these fixtures provide for significant glare control through depth, aiming, and the potential to add snoots to them. Specifically, we used bronze colored, composite fixtures from Hadco Lighting. These fixtures are designed for outdoor use, and are appropriate for use in the cave.

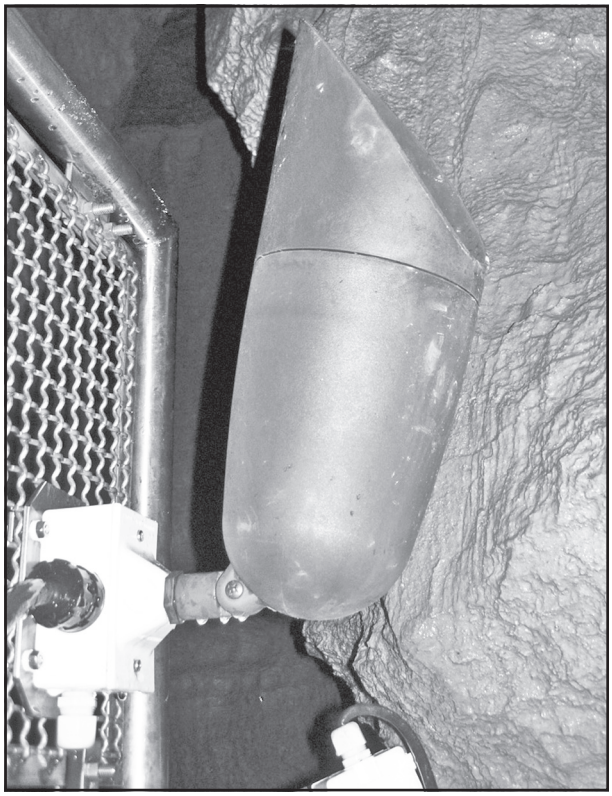

Figure 4: Large Hadco bullet fixture mounted to the railing grille with a plastic junction box. Note the angled snoot on the top to direct the light and prevent glare.

The fixtures were mounted using a Carlon plastic junction box secured with stainless steel screws. The strain reducing couplers were also polymer. These choices reduced the potential for corrosion of any of the elements. Individual fixtures are linked to the power cables using water-resistant electrical sockets and plugs to facilitate easy exchange of fixtures as needed.

The most common lamp used in the New Entrance re-lighting was a custom bulb, designated as the W2050, designed for cave use by Dr. D.J. Chou and produced by enlux Lighting. The W2050 is a modification of the standard enLux R30 Floodlight. This is an LED lamp with a standard medium Edison screw base; it runs on 120V / 220V line voltage (120V in the case of Mammoth Cave). The enLux bulbs produce light through use of a light engine. The enLux light engine uses advanced technology to pack 50 to 100 LED power chips to a small substrate using COB (Chip-on-Board) technology (enLux Lighting, 2009). In the case of the W2050, there are 72 power chips (Fig. 5). The power chips can have different wavelengths (colors), so that the light engine can produce a very wide variety of light colors.

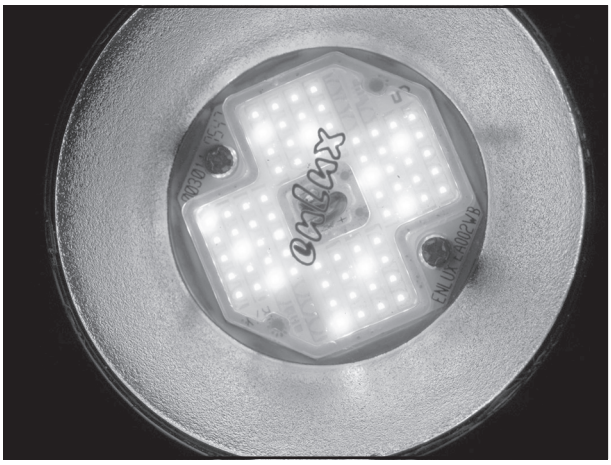

Figure 5: Face of EnLux W2050 bulb showing light engine. The W2050 face has 61 amber, 10 green, and 1 blue LEDs to generate a warm-white light with a color temperature of 2050°K. The brighter LEDs in the picture represent the 10 green LEDs. The width of the light engine is approximately 3 cm.

For use in the cave, Dr. Chou and Rick Olson worked to develop a light engine that would produce light that would show the cave well, but which would not support algae growth. Olson (2006) notes that one approach to reducing lampflora growth is to provide light using wavelengths that do not efficiently support photosynthesis. For the two dominant photosynthesis pigments (chlorophyll A and B) this range is mainly wavelengths between 475 and 600 nanometers, e.g. blue-green, green, and yellow. The enLux W2050 utilizes one blue, 61 amber, and 10 green power chips to create light with a correlated color temperature of 2050°K (a very warm white). With this mix, most of the spectral emission is within the range that is not efficiently utilized by chlorophyll A and B (Fig. 6). These lights may not completely eliminate lampflora growth, because cyanobacteria and plants have secondary pigments that can use these wavelengths. However, it is likely to very significantly reduce lampflora growth. The wattage of the lamps was also reduced to 13 watts, so that they could be placed in enclosed fixtures in wet areas. The W2050 light engine is available in spot (40°), flood (80°) and wide (160°)

dispersions. In lighting New Entrance, we used 29 W2050 flood lamps and 30 W2050 spot lamps in composite bullet fixtures.

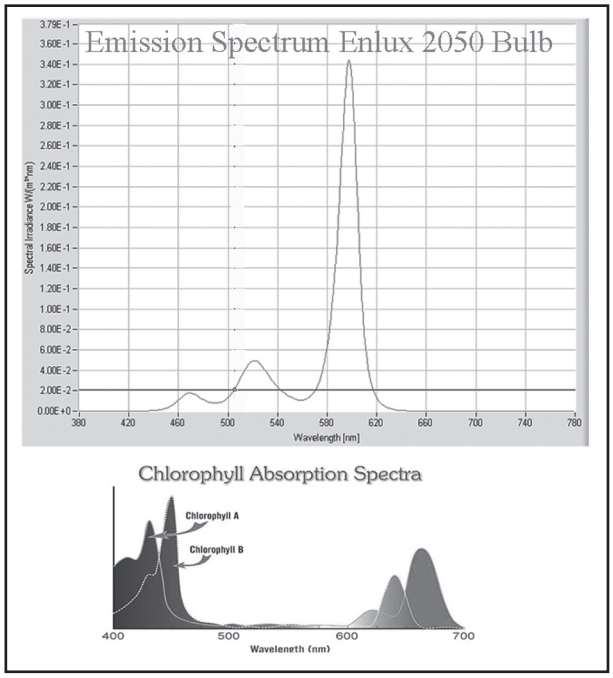

Figure 6: Emission spectrum of the EnLux W2050 bulb (top) and the absorption spectra of Chlorophyll A and B (bottom). They are aligned with each other along the wavelength axis. Note that most of the light from the En-Lux bulb occurs in wavelengths that are not very effective at driving photosynthesis. This is a light designed to not promote plant growth.

In addition to the enLux W2050s, the relighting of the New Entrance also used two other types of LED bulb. Five Ledtronics R30-123 XIW series bulbs were used in bullet fixtures to spotlight upper parts of several domes. Sixteen Wattman amber LED step light retrofit lamps were used in confined areas in which additional light was needed for safe travel. Two "jelly jar" lights were retained in the entrance tunnel; however the incandescent bulbs have been replaced with 10.8 watt Ledtronics LED bulbs.

5. Conclusions

The relighting of the New Entrance has reached or exceeded several of the goals of the project to upgrade the electrical system. Visitor experience, safety, cave resource protection, and efficiency were all improved significantly.

The new lighting provides an improved visitor experience by lighting many of the dramatic features in the shafts, while providing illumination for safe travel on the steep, often wet metal stairs and catwalks. Cave guides and visitors have commented positively on the more attractive and safer illumination.

The new lighting improved resource management by addressing a serious lampflora problem and reducing maintenance impacts. The development and use of lamps that will not support efficient lampflora growth, but which provide aesthetically pleasing illumination is a large step toward controlling the exotic plant growth in the New Entrance (formerly an area with the park's most severe lampflora problem). The use of LED technology reduces the frequency of replacement or service, combined with placing most of the fixtures on existing infrastructure, this reduces potential maintenance impacts to the cave.

The use of LEDs as the basis for the new lighting system greatly increased the efficiency of the system, while allowing us increase total illumination. The system that was replaced had 23 90-watt incandescent lights and eight 106-watt TIR Destiny CW LED flat panels. So, the total rating for the original lights was 2918 watts. The new system consists of 59 13-watt enLux W2050 lamps, five 4.5-watt Ledtronics R30s, 16 1-watt Wattman step lights, and two 10.8-watt Ledtronic LED bulbs. The total rating for the new system is 827.1 watts. That represents a 72% reduction in the power consumption for the area.

The use of interdisciplinary and interdivisional teams of experts insured that interpretation, resource management, and maintenance issues and opportunities were adequately addressed in the planning. Mocking-up the lighting before making final decisions for installation prevented many potential bad lighting placements and actually encouraged finding interpretive opportunities that had previously been unutilized because the features were not lit.

Acknowledgements

Chester Guy (Mammoth Cave, Facilities Management Division) and Dave Spence and Johnny Merideth (Mammoth Cave, Interpretation Division) were part of the lighting mock-up team for the New Entrance. Lydia Creager (National Park Service – Denver Service Center) acted as project manager. Chappy, Inc. installed the lighting. Dr. DJ Chou (enLux Lighting) and Peter Weinreb (Light Southwest) provided valuable technical expertise.

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MAMMOTH CAVE INTERNATIONAL CENTER FOR SCIENCE AND LEARNING

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The Mammoth Cave International Center for Science and Learning (MCICSL) is a cooperative venture of Mammoth Cave National Park and Western Kentucky University. Funding, logistical support, and governance of MCICSL are shared equally by both entities. MCICSL is part of a national network of research learning centers located within the National Park Service.

The goals of MCICSL and the other research learning centers are to:
I. Facilitate the use of parks for scientific inquiry.
II. Support science-informed decision making.
III. Communicate the relevance of and provide access to knowledge gained through scientific research.
IV. Promote science literacy and resource stewardship.

MCICSL has only been operational since the middle of 2005, so it is still building programs. Current staffing consists of a Research Director (Toomey) and a part-time Education Program Specialist (Trimboli). Despite limited funding and staff, it is actively involved in numerous natural and cultural research and education projects at Mammoth Cave National Park.

The center coordinates scientific research at the park and consults with the park on scientific issues. MCICSL staff serves as the primary or co-primary investigator on several research projects involving NPS caves both within Mammoth Cave National Park and at other national parks. These projects include a multi-park lighting research project, research to address on-going E. coli issues in cave waters, and a project to improve monitoring of backcountry caves. MCICSL has also consulted with park management on various resource protection issues and assisted in relighting several areas of the cave to improve visitor experience and reduce exotic plant growth.

MCICSL leads or participates in many educational activities that highlight research at the park. It provides a variety of research-based formal and informal educational and outreach opportunities to diverse internal and external audiences. Each year, numerous professors contact MCICSL to schedule customized research-focused field opportunities for their students. In addition to their work with students, MCICSL hosts, or co-hosts, science and research-based workshops for teachers and the general public. MCICSL also produces written internal and external research summaries and is serving on the exhibit committee for Mammoth Cave's new Visitor Center. Most of the center's educational activities are focused on learners that are secondary school age or older (high school, college, or adult learners).

1. Introduction

Research learning centers were developed by the National Park Service to facilitate research within the national parks and to provide better communication of research results to managers, partners, and the public. Originally 32 research learning centers were planned, each one serving a network of parks. The first research learning centers were funded in 2001, and in 2003, Mammoth Cave National Park was slated to receive funding to develop a research learning center. However, funding for additional centers was discontinued before Mammoth Cave's funding was received.

When funding for new research learning centers was suspended, Mammoth Cave National Park and Western Kentucky University proposed a cooperatively run and funded center. Funding for the Mammoth Cave International Center for Science and Learning was provided through two, one-year (2004 and 2006) Congressional line item appropriations. In 2005, a full-time research director, Rick Toomey, was hired to run the research learning center. In 2007, he was joined by a part-time education program specialist, Shannon Trimboli.

Despite limited funding and staff, MCICSL is actively involved in numerous natural and cultural research and education projects at Mammoth Cave National Park. The center coordinates scientific research at the park and consults with the park on scientific issues. In addition, MCICSL leads or participates in many educational activities that highlight research at the park. Most of the center's educational activities are focused on learners that are secondary school age or older.

2. MCICSL's Goals and Activities

Facilitate the use of parks for scientific inquiry (Figs. 1 and 2).

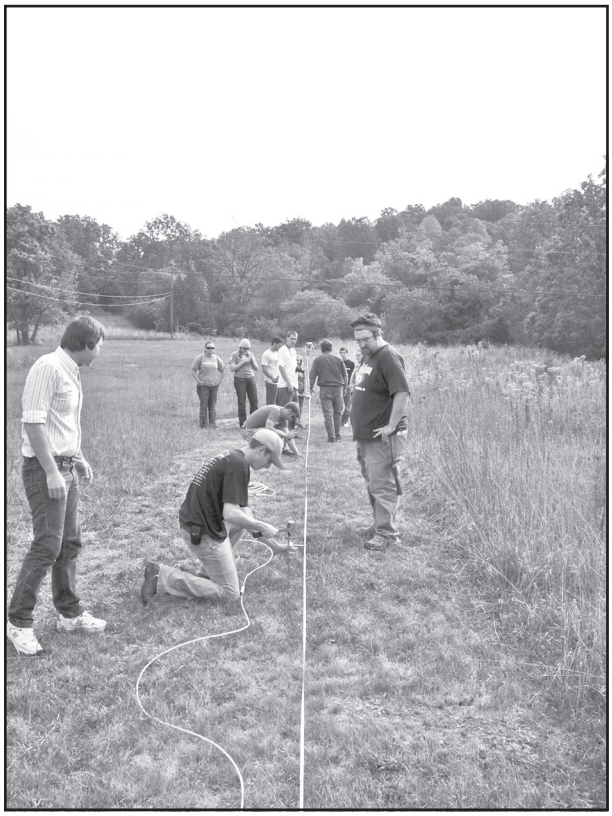

Figure 1: Wittenberg University geology students use Electrical Resistivity Ground Imaging to look for cave passages near Mammoth Cave National Park. MCICSL staff helped coordinate the activity.

MCICSL coordinates the research for Mammoth Cave National Park, including overseeing the research permit applications process. Through permitted research and research projects managed through agreements and other mechanisms, MCICSL facilitates research by state and federal agencies, non-governmental organizations, private researchers, and numerous universities. MCICSL staff also assists the researchers in obtaining lodging, working with park staff and volunteers, and other logistical needs.

Figure 2: Tennessee State University students test the parking lot filter system in preparation for a larger project looking at parking lot runoff around the Mammoth Cave Historic Entrance.

Support science-informed decision making (Figs. 3 and 4). MCICSL staff serves as the primary or co-primary investigator on several research projects involving NPS caves both within Mammoth Cave National Park and at other national parks. These projects include a multi-park lighting research project, research to address on-going *E. coli* issues in cave waters, and a project to improve monitoring of backcountry caves. MCICSL has also consulted with park management on various resource protection issues and assisted in relighting several areas of the cave to improve visitor experience and reduce exotic plant growth. In addition, MCICSL staff assisted Mammoth Cave National Park Superintendent Pat Reed with the preparation of a paper entitled "Science-Informed Decision Making at Mammoth Cave National Park: A Park Superintendent's Perspective." Superintendent Reed presented the paper in October 2008 at the National Congress of the Asociación Cuevas Turísticas Españolas (Association of Spanish Tourist Caves) in Santander, Spain.

Communicate the relevance of and provide access to knowledge gained through scientific research (Figs. 5 and 6). MCICSL offers a variety of research-based formal and

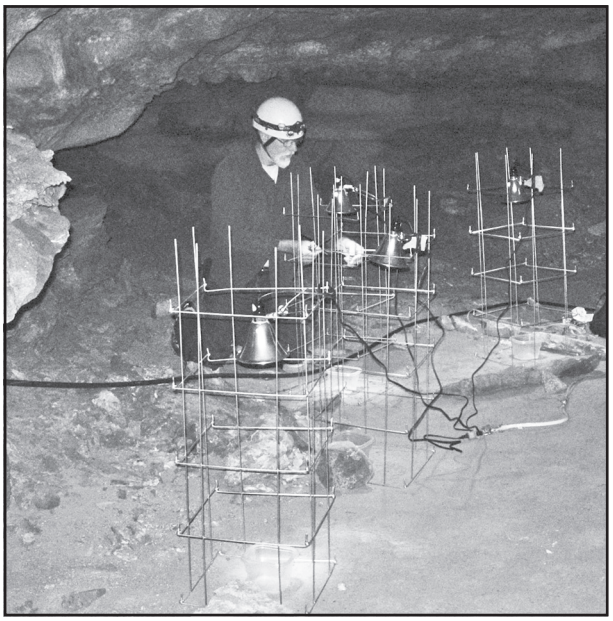

Figure 3: Mammoth Cave ecologist, Rick Olson, sets up an experimental apparatus to measure the amount of algae growth that occurs under different lighting conditions. MCICSL is co-lead on this project, which is also taking place at four other national parks.

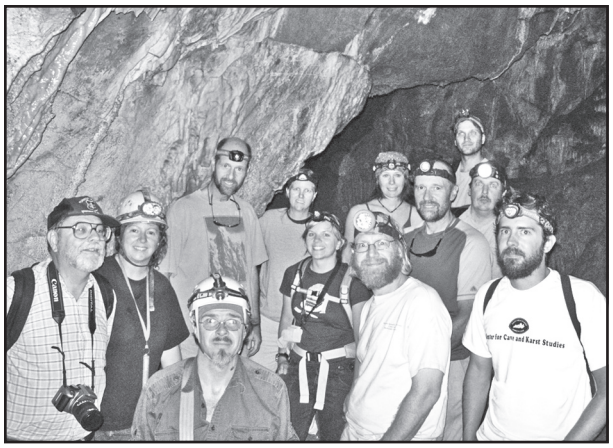

Figure 4: During the summer of 2008, MCICSL co-hosted an intensive, week-long Cave and Karst Resource Management workshop at Sequoia / King Canyon National Park. This workshop was attended by cave resource managers from across the country.

informal educational and outreach opportunities to diverse internal and external audiences. These opportunities include customized research-focused field opportunities for numerous college classes. In addition to their work with students, MCICSL hosts science and research-based workshops for teachers and the general public. MCICSL also produces written internal and external research summaries and is serving on the exhibit committee for Mammoth Cave's new Visitor Center.

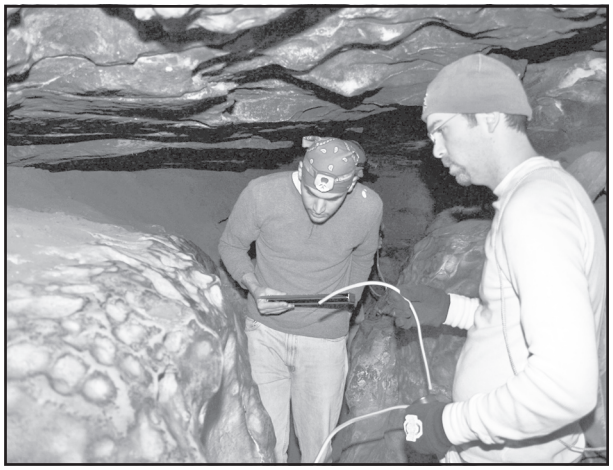

Figure 5: Ohio State University geology students measure scallops to determine the speed and direction of the ancient cave rivers that formed Mammoth Cave.

Figure 6: In October 2008, MCICSL co-hosted Mammoth Cave National Park's Max Kämper Centennial Symposium & 9th Science Symposium: Cultural History and Research. The symposiums focused on Max Kämper's contributions to Mammoth Cave's history as well as other cultural research associated with Mammoth Cave National Park.

Promote science literacy and resource stewardship (Figs. 7 and 8).

For the past several years, MCICSL has collaborated with Mammoth Cave's Environmental Education Division and the National Association of Geoscience Teachers to offer summer internships for local teachers. The teachers gain hands-on exposure to the variety of resources found at the park while working alongside researchers. Several advanced high school classes have also participated in research-focused outdoor learning experiences with MCICSL staff. In addition, MCICSL and Tennessee State University

have partnered on a National Science Foundation grant encouraging minorities to pursue science, technology, engineering and math careers. The partnership is using cultural connections to the park as a way to connect the students with the park's geoscience and environmental resources.

Figure 7: A Geoscience-Teacher-in-the-Park intern assists park scientists by recording the GPS coordinates of a newly discovered cave entrance.

3. What Does the Future Hold?

With the continued support of park management and Western Kentucky University, MCICSL plans to continue facilitating research and research-based education and outreach within Mammoth Cave National Park. Securing permanent funding for MCICSL is an ongoing need that is being actively pursued by MCICSL and its partners. In addition, opportunities for additional grant-based funding are being sought until permanent funding can be obtained. MCICSL is also actively involved in the development of a national Research Learning Center network strategic plan and other network activities.

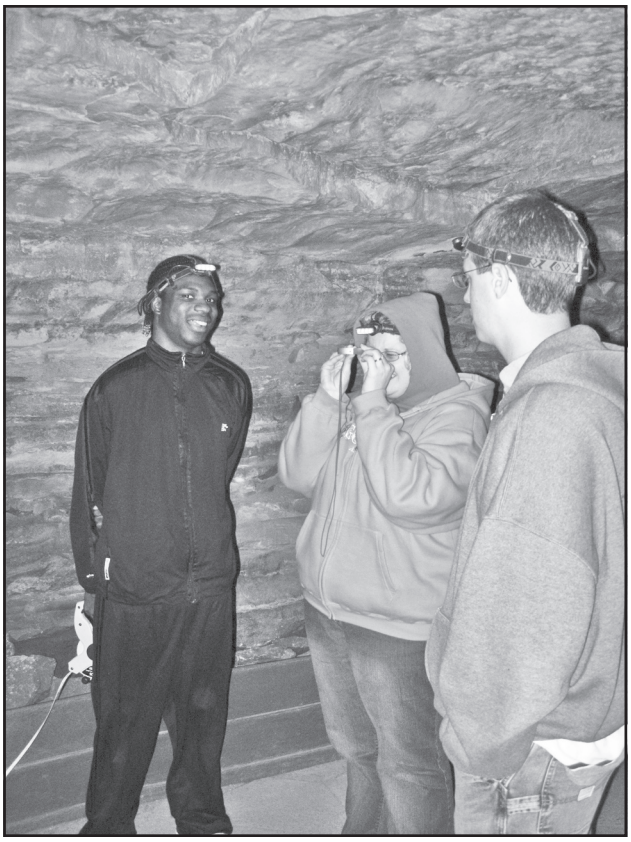

Figure 8: A Special Topics in Biology II high school class learns cave mapping techniques and how cave mapping is used as an important scientific tool in the management of cave resources.

4. Partners

To learn more about the following partners, please visit their Web sites.

Mammoth Cave National Park: www.nps.gov/maca

Western Kentucky University: www.wku.edu

The Research Learning Center Network: www.nature.nps.gov/learningcenters/

Acknowledgements

Thanks to everyone at Western Kentucky University and Mammoth Cave National Park who provide so much support and encouragement. Thanks also to our many partners who make the individual projects in which they are involved possible.

SAVE THE HOLE WORLD CAMPAIGN – CAVE PROTECTION IN THE EUROPEAN PARLIAMENT

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"Save the hole world" was the first campaign of European speleological societies for cave and karst protection in the European Parliament. The written declaration WD 66 about caves and karst as cultural, natural and environmental heritage was to invent and to be recognized. Every speleological federation in Europe supported the campaign. The declaration was brought in the European Parliament on 1September, 2008. The signatures of the majority of the deputies were required by 4 December if the declaration were to be supported. To inform the parliamentarians. a stand with posters, flyers and more informative material was set up in the European parliament building. In the end, the declaration got only 140 votes and vanished. This experience has led to new projects with the European Union.

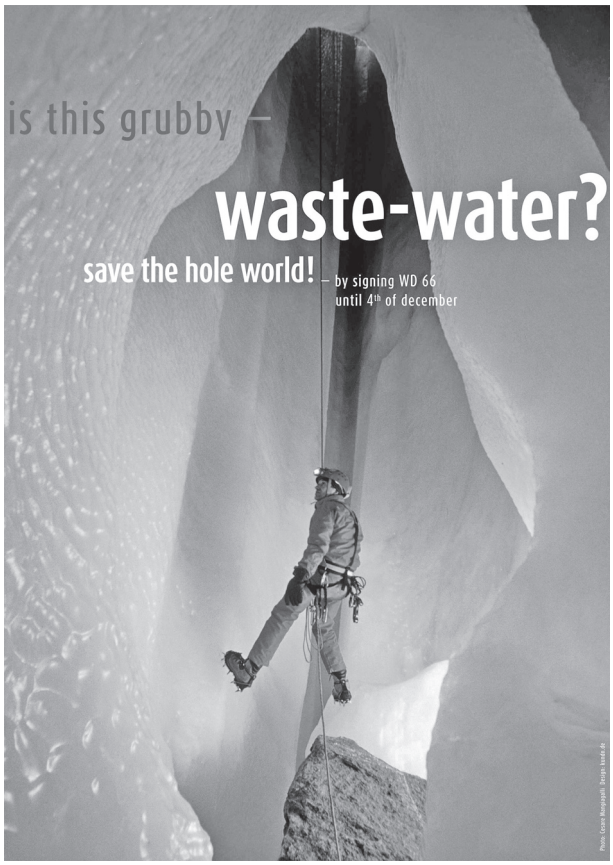
Posters presented to the European Parliment.

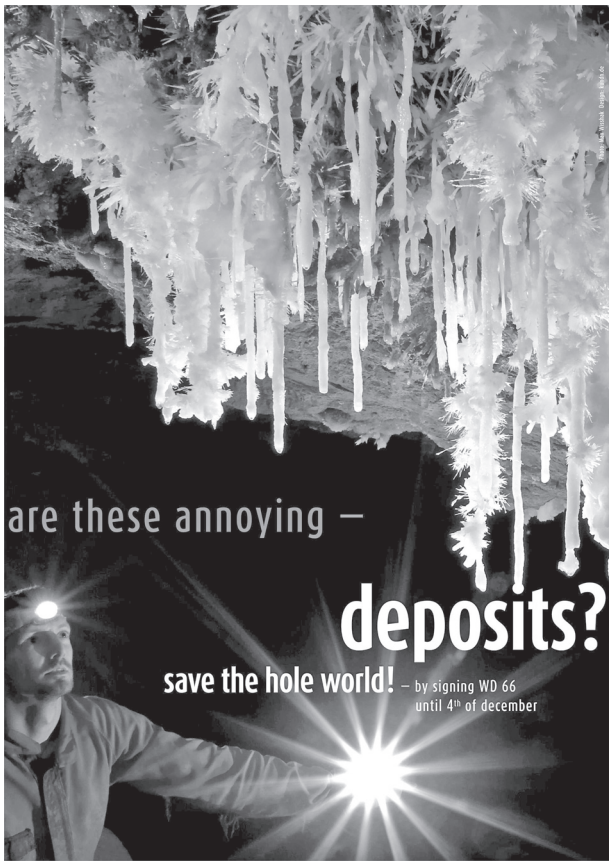
1. Introduction

In November 2007 Mikel Irujo Amezaga, deputy from Spain in the European Parliament, was trying to support the protection of the Praileaitz Caves near Deba, Basque Country. In these caves, findings of the Upper Palaeolothic period had been excavated. Unfortunately the caves are located next to a quarry. In 2007 the Basque Government adopted a decree that established a 50 meter protective area around Praileaitz. For some parts of the caves, it was too late and not sufficient. Wishing to support cave protection Mikel Irujo Amezaga, MEP, acknowledged that there is no directive or guideline for the protection of caves and karst in the European Union.

2. Working Group in the European Parliament

To get closer to the subject, Mr.Irujo invited speleologists





Posters presented to the European Parliment.

and archaeologists for a round table discussion. By chance, the secretary contacted the German Speleological Federation. Then contacts with FSE and UIS were established. Finally the fist meeting was held on 23 January 2008 in the parliamentary building in Brussels. A parliamentary working group was founded, consisting of more than 5 experts from different member states.

In behalf of speleological societies, Jean-Pierre Bartholeyns , President of the UIS Protection and Management Department, Christiane Grebe, FSE Head of the European Cave Protection Commission and Baerbel Vogel VdHK President of the German Speleological Federation took part; three archaeologists and the mayor of Deba were also invited. Everybody agreed that caves can only be protected by appreciating the whole ecosystem. So the idea of initiating cave and karst protection in the European Parliament was born and a second meeting for summer was planned.

3. Trade of Speleothems in the European Union

Furthermore, the speleologists asked the MEP for support against the trade of speleothems. He agreed and asked an official question to the European Commission. The answer was given by the Mr.Dimas, Commissioner for Environment. The European Commission has no information about the trade or trade-related certifications and this does not fall within the jurisdiction of the Community. So he raised a second parliamentary question and pointed out that in the USA the trade of speleothems has been forbidden since 1988. Mr.Dimas answered that this is subject to the legislation of the individual EU Member States.

4. Context of the Written Declaration WD66

The initial conception of the written declaration was developed by the bureau of Mr. Irujo MEP and sent in the middle of February to the members of the working group. Some remarks were made and everybody was happy with the progress in the case. Actually no scientific member of the working group was experienced in parliamentary procedures and nobody really knew about the consequences of written declarations for legislation in the EU. But it was the first time speleology had submitted an official paper in the European Union Parliament with the support of a dedicated deputy. From February to July we had no news from Brussels. Christiane Grebe, head of the European Cave Protection Commission (ECPC) and member of

the working group invited Mr.Irujo and his secretary Iria Epalza to the ECPC meeting during the European Speleological Congress in Vercors in August 2008 to present the declaration. In July Iria Epalza informed the team about changes in the declaration because they had had to reduce it to 250 words. Two other deputies (Mrs.Rebecca Harms, Germany, and Mr. Csaba Sándor Tabajdi, Hungary), also from the Green Party , were found to represent the declaration as well. It was a shock when it was learned that one of the mort important words for speleology was missing in the new document: in the list of specialists, speleologists had been eliminated. The decision was made not to support the declaration anymore, but rather to include it again. This was to be discussed during the meeting in Vercors.

By the end of August Iria Epalza reported at the meeting in France that the word speleologists had already been included and the declaration now had its official name: Written Declaration 66 (WD66) could be signed from deputies of the EU Parliament from 1st of September until 4th of December 2008. So WD 66 was supported by the general assembly of the FSE.

5.Text of the Declaration

EUROPEAN PARLIAMENT1.9.2008 0066/2008 WRITTEN DECLARATION

pursuant to Rule 116 of the Rules of Procedure by Mikel Irujo Amezaga, Rebecca Harms and Csaba Sándor Tabajdi Lapse date: 4.12.2008

Written declaration on the protection of caves as a cultural, natural and environmental heritage

The European Parliament,

– having regard to the UNESCO Convention concerning the Protection of the World Cultural and Natural Heritage,

– having regard to Rule 116 of its Rules of Procedure,

A. whereas there is at present no European law or directive on the protection of caves and their contents,

B. whereas caves represent unique geotypes in the European heritage, which can only be preserved by protecting them and their surroundings,

C. whereas conservation of archaeological and speleological heritage elements provides a foundation for further social and economic development, enhancing European integration,

1. Calls on the Commission to implement effectively cultural protection, as stated in Article 151 of the EC Treaty, with regard to karsts and caves as natural sites, and cultural settlements, in order to ensure that measures to promote them are embodied in all EU policies;

2. Considers that measures to develop these areas must include:

(a) a systematic survey of caves and their surroundings, and their environmental and archaeological heritage;

(b) the establishment of a legislative framework to guarantee their protection, and measures to ensure that new buildings and industrial activities are compatible with the nearby environmental and archaeological heritage;

(c) incentives for conservation of caves, ensuring that they will be studied by specialists like speleologists, geo(morpho)logists, archaeologists, biologists, climatologists, etc.;

(d) financial assistance for projects, conservation and restoration;

3. Calls on the Member States, in cooperation with the Commission, to promote the protection and conservation of caves and their archaeological heritage;

4. Instructs its President to forward this declaration, together with the names of the signatories, to the governments of the Member States, and to regional and local authorities.

6. Realization of the Public Campaign for WD66

Bärbel Vogel and Christiane Grebe worked out a "to do" list with Iria Epalza in Vercors. The facts were clear: the WD 66 was already under way, the time was very short, both to develop a big public campaign and a campaign inside the speleological federations in Europe. The archaeologists of the working group weren't very active after the meeting in

January so help could not be expected from this side.

Within five weeks the whole campaign had to be realized. Emails were sent to every speleological federation in Europe. The designers Stefan Klein and Olaf Neumann, Germany, were responsible for posters, flyers, postcards and stickers with support of speleo photographers from Italy, Switzerland, Germany and Bosnia. Steff Naeff from Switzerland set up the homepage www.cavedeclaration.eu and is still in charge of it. The noodle company AlbGold sponsored little packages of macaroni as gifts.

7. Public Campaigns of Speleological Federations

Personal letters and emails were sent by federations, caving clubs and cavers to every single one of the 785 deputies, asking for their signature on the written declaration WD 66. A cave protection trailer was produced by Italian speleos and integrated into the homepage. By the end of October, 12 federations were already actively involved. Supporting letters from Friends of Nature, the National Cave and Karst Research Institute and the IUCN / WCPA Task Force on Caves and Karst arrived.

8. Information Stand in the Parliament

In the week from November 10 to 14, 2008, a team of 14 cavers from seven European countries informed people in the European Parliamentary building with an information stand, they visited the offices of deputies with informative material, and had a press conference and a meeting with the European Commission. They gave away 2000 campaign postcards, 1000 flyers and 1,000 packages of "cave" macaroni to show that, like speleothems, noodles are also breakable.

It was a great success. The stand was well visited, and many people were very interested in the underground theme. Because of lack of money it was not a designer booth, but it was about something that most of the people didn't already know, and with its big and wonderful posters it turned out to be to a point of interest. It was clear to see that WD66 was not launched by big lobbyists, but by people who work with their heart's blood in their free time for the protection of nature.

9. Meeting with the European Commission

For the meeting with Mr. Ladislav Miko, Director for Protecting the Natural Environment in the European Commission, four speleologists (Paolo Forti, University of Bologna; Christiane Grebe, ECPC; Iona Meleg, biospeleologis;t and Alexey Zhalov, FSE specialist on European cave protection laws) were invited. They didn't have to convince Mr.Miko. He was well informed about caves and karst and wished to help cave protection on its way in Europe.

A workshop is to be planned for the new EU Commission after the elections in June 2009. As a basis for future work, a database about caves and karst in Europe within its nature protection is needed. This should be realized as a GIS project with the data from the EU Natura 2000 to review how caves and karst are already protected and what has to be done in the future.

10. Signatures of WD66

Written declarations in the European Parliament do not have legislative power. Therefore many deputies told us that they did not sign declaration as a question of principal.

country	signatures	total number	%
Belgium	4	24	17%
Bulgaria	12	18	67%
Czech Republic	1	24	4%
Denmark	3	14	21%
Finland	4	14	29%
France	9	78	12%
Germany	16	99	16%
Greece	10	24	42%
Hungary	6	24	25%
Ireland	3	13	23%
Italy	13	78	17%
Latvia	1	9	11%
Lithuania	3	13	23%
Luxembourg	1	6	17%
Netherlands	2	27	7%
Poland	11	54	20%
Portugal	7	24	29%
Romania	11	35	31%
Slovakia	2	14	14%
Slovenia	6	7	86%
Spain	5	54	9%
UK	10	78	13%
* no signatures from Sweden, Austria, Estonia, Cyprus, Malta			

Table 1: Signatures of members of the European Parliament for the Written Declaration WD66.

Nevertheless, 140 signatures were supplied, but 393 would have been needed to get it passed (Table 1).

11. Timetable Overview

Nov 07 first email contact with Mr.Irujo MEP
Jan 08 first meeting with Mr.Irujo MEP in Brussels
Jan 08 ECPC member of the European Commission Groundwater Working Group
Jan 08 first parliamentary question of Mr.Irujo MEP to the European Commission about the trade of speleothems
Feb 08 first concept for the declaration by Mr.Irujo MEP
Jun 08 second parliamentary question of Mr.Irujo MEP to the European Commission about the trade of speleothems
Jul 08 changes in the declaration text
Jul 09 Rebecca Harms MEP and Csaba Sándor Tabajdi MEP support the declaration
Aug 08 support of the FSE general assembly
Sept until Dec 08 WD 66 to be signed in the EU Parliament
Sept 08 speleologists start public campaigning
Oct 08 home page www.cavedeclaration.eu goes online
Nov 08 information stand and press conference in the EU Parliamentary building and meeting with the European Commission
Dec 08 lapse of the declaration

Feb 09 ECPC contact with the European Commission to set up an European karst GIS project

12. Special Thanks

The time was too short for develop the campaign adequately. Thanks a lot to everybody who supported it!
Special Thanks to the sponsors
The Greens | European Free Alliance www.greens-efa.org for financial support of the flyers.
Metzgerdruck GmbH www.metzgerdruck.de for printing postcards and posters.
Edition Reuss www.editionreuss.de for donation of 10 books “Inside Mother Earth” by Max Wisshak and the support for our information stand in Brussels
Klein und Neumann www.kundn.de for designing the campaign
Od*Chi Urwurz www.urwurz.de for the cave music in our presentation
Alb-Gold www.alb-gold.de for the donation of ‘cavespagetti’ as a culinary contribution

Thanks a lot to the cave photographers for their beautiful pictures
Urs Widmer www.speleoprojects.com
Max Wisshak www.speleo-foto.de
Peter Stargalla www.hoehlenfoto.de/Galerie/Gastfotografen/Peter/peter.htm
Andreas Schober www.hoehlenfoto.de and for his wonderful calendars
Cesare Mangiagalli www.fotocommunity.it/pc/pc/mypics/907100
Prof Saxx commons.wikimedia.org/wiki/User:Prof_saxx
Dietmar Nill www.dietmar-nill.de
and to the best webmaster Stefan Naeff for www.cavedeclaration.eu

13. Conclusion:

The European Commission will only be acting in case of the trade of speleothems if several EU Member States bring this theme up. Speleological Federations in Europe should contact their Ministries of Environment to push it forward.

International help can be very useful.

The lapsed declaration in the parliament can be the basis for target-aimed conversations with deputies of the Committee on the Environment and the European Commission. Support of every EU member state is essential to protect caves and karst in Europe as a cultural, natural and environmental heritage.

For the GIS project in cooperation with the European Commission, financial support is needed, as well as support of speleological federations in Europe. The linkage of this project with other projects in the world should be our goal. All in all, the campaign was very successful. Many positive reactions gave the feeling that it was worth doing it and helped provide more links now to continue the work for cave protection in Europe.

PROTOTYPE SITE FOR INTEGRATED SPELEOLOGICAL RESEARCH: LA CUEVA DE LAS BARRANCAS

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PO Box 207, Cuna Cueva Hwy 27, Hillsboro, NM 88042 USA, werks@zianet.com
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801 Leroy Place, Socorro, NM 87801 USA
Associate. Director, National Cave and Karst Research Institute, Carlsbad, NM USA, pboston@nmt.edu

Barrancas, a deep cave in southeastern New Mexico, is managed as a pristine laboratory site for integrated speleological research. Discovered as virgin passage in 1991, geomicrobiological and biomineralogical studies in La Cueva de las Barrancas are supported by grants awarded through NASA. Science in Barrancas has progressed from initiating investigations of subsurface microbial life in 1999 to establishing the site as a prototype environment for subterranean studies on Mars and other planets.

An innovative cave management prescription facilitates sensitivity-ranked research. Sampling and investigation for microbial life is initiated in each new passage before other scientists or cavers are allowed to enter. To preserve pristine conditions, the Barrancas Cave Management Plan inverts traditional strategies for exploration, mapping, and study by allowing science to go first. The foundation of this model system emphasizes low-impact *in situ* studies of microbial communities in highly sensitive, extreme environments.

Barrancas also serves as a test environment for the development of low-impact human operational logistics with particular attention to planetary protection issues. Limits of acceptable change and avoidance of cross-contamination guide the well-defined protocols for exploration, survey, and research.

La Cueva de las Barrancas presents a rare opportunity for scientists, cavers, and the USDA Forest Service to establish baseline data on a pristine cave environment. Barrancas is a unique spelean testing ground for speleologists and astrobiologists to develop study techniques. The efforts in Barrancas will serve in advancing studies of other cave sites, exploring the potential for life on other planets, and protecting other fragile environments of Earth's surface and subsurface.

1. Introduction

The collaboration of science and cave management in La Cueva de las Barrancas provides a unique model for science, cavers, and federal agencies to establish baseline data in pristine environments. Because Barrancas shows no evidence of human entry prior to 1991, it serves as an ideal spelean research environment. The cave management plan inverts the traditional exploration and survey strategy. The plan is specifically designed to preserve this site for investigation of isolated microbial communities and development of planetary protection protocols. Through a unique, innovative cave management agreement, Barrancas is protected as a deep, pristine, prototype spelean laboratory for integrated studies in speleology, biomineralogy, and astrobiology using a multigenerational science model with long-term research protocols and cycles, sensitivity-ranked studies, and the concept of site banking for future advanced studies. Barrancas has special scientific value as a biologically uncompromised, pristine-protocol model for terrestrial caves, extraterrestrial caves, all pristine sites, and low-impact techniques.

2. Descriptive Overview

Access to La Cueva de las Barrancas is limited by rugged desert canyon terrain in southeastern New Mexico and requires four-wheel drive with a moderately strenuous hike. The cave is entered through a solid steel gate that acts as an airlock. After a tight 5m crawl-way, the passage drops down a 115m pit. The descent is divided into three rappels and permanent bolts are set for anchors and rebelays. Airflow at the entrance, often in excess of 60 km per hour, indicates the potential for Barrancas to be a large cave. To date, teams have entered less than 3 km of passage on six levels.

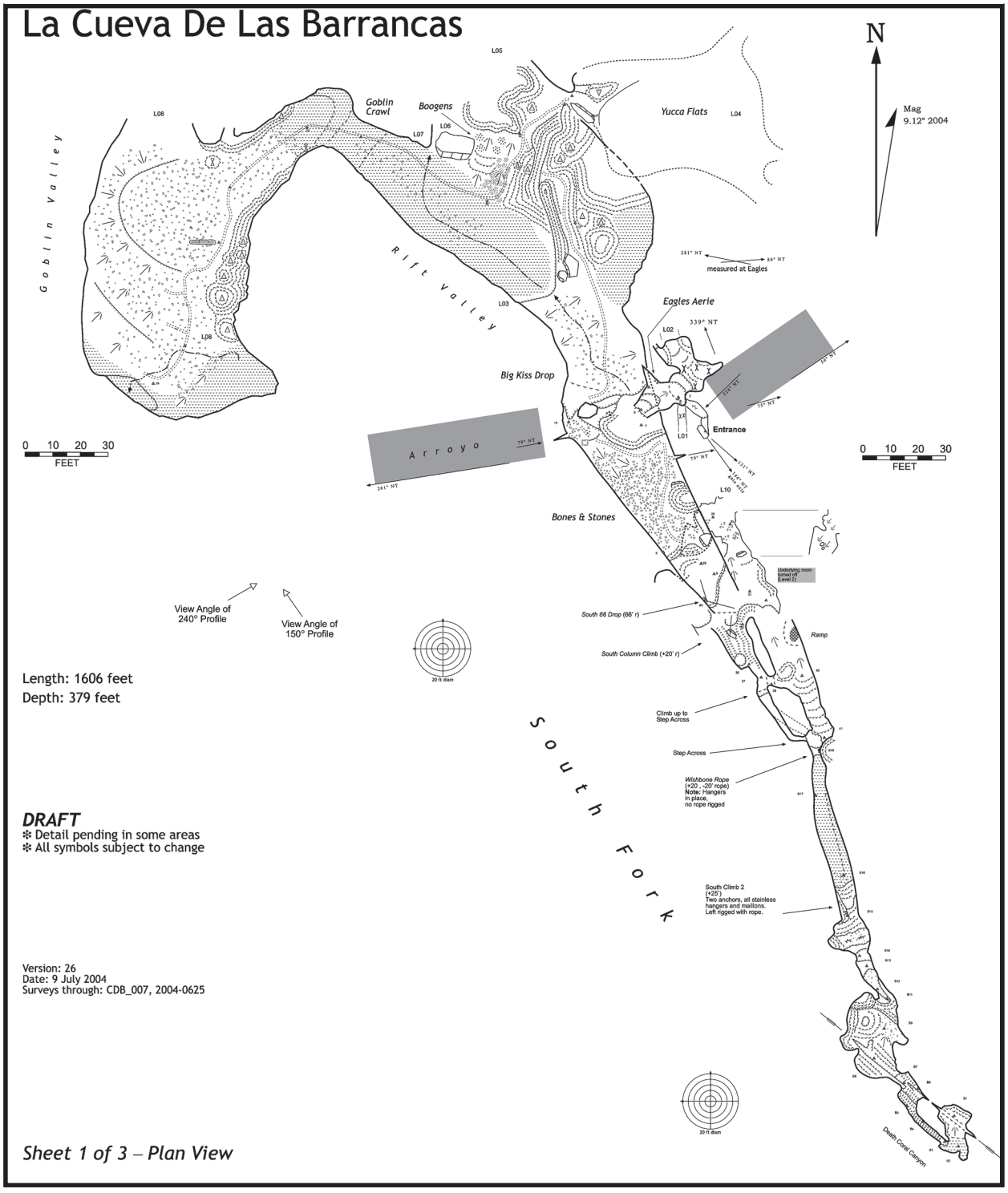

Figure 1: Map of La Cueva de las Barrancas, 2009.

Barrancas is pristine, large, complex, and possesses many geological and microbiological sites of interest including tiny pools, moist flowstone, moonmilk in various stages of development, fungal filaments on speleothems, unique mud formations resembling miniature villages of onion ziggurats and pagodas, at least one detection of H_2S coming from deeper levels of the cave. Some of the known cave passages have two-foot thick mud layers. Deposits are stratified with mud and sand. Many of the cave formations are mud-coated and some speleothems show unique patterns of solutioning and redeposition. Unusual mud formations are scattered through the known passage. Abundant bone fragments

coated with calcium carbonate rest on a rocky slope at the second landing.

Because of the scientific potential offered by the pristine passages of La Cueva de las Barrancas, extensive exploration is initiated slowly, section by section. Survey and cartography of known passages is accomplished by staying on the main trails and using distometers to avoid marring and tracking surfaces covered with possibly very antique mud that may preserve climate signal. The first entry into any virgin section of Barrancas is strictly reserved for microbial sampling, analysis, and culturing.

3. Discovery, Vision, and Initial Protection

Barrancas was discovered on November 27, 1991 (Hildreth-Werker, 2001). Mike Reid and Jim Werker were ridgewalking and looking for caves when they found a fist-sized hole making loud whistling sounds as it sucked in air. They heard the noise from several hundred feet up the canyon. The hole itself, with a 10 cm diameter, was so small they walked past it and had to backtrack. On most weekends for four months, a small crew backpacked to the entrance and mined the bedrock by hand until the entrance slot could accommodate human passage. Before digging, the volume of airflow through the initial fist-sized opening was documented. The later gate design duplicates the original, natural air exchange (Werker, 2006). A solid, octagon-shaped gate, 45cm by 60cm, was designed by Werker and constructed by Reid of 1.5cm solid steel plate. Its finished weight was 40kg.

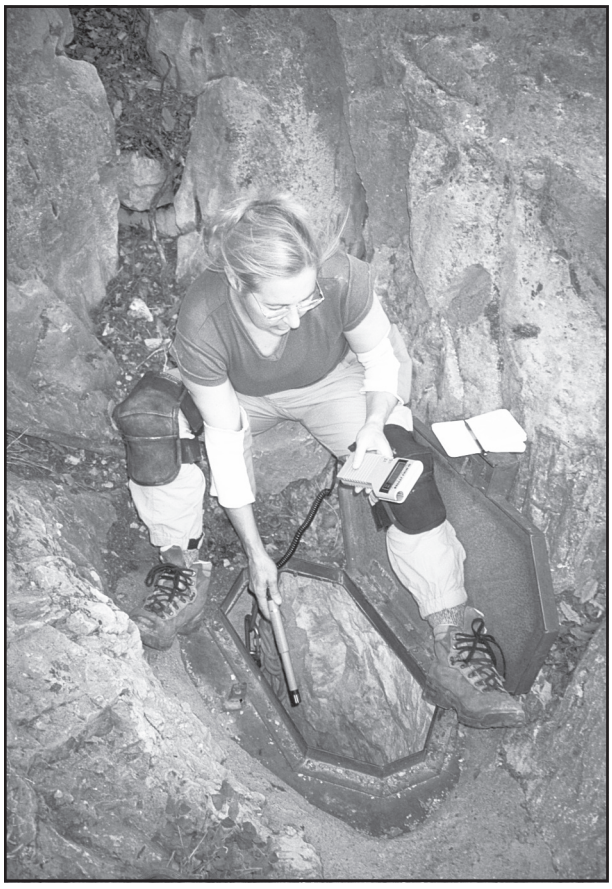

Figure 2: Val Hildreth-Werker recording airflow and meteorological data at the Barrancas entrance gate. Photo by Jim C. Werker.

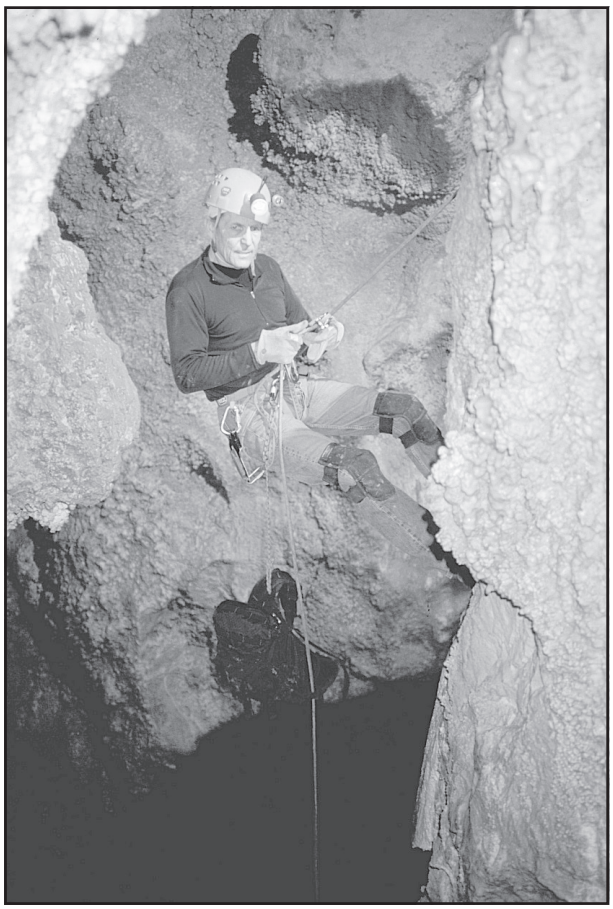

Figure 3: Jim Werker on rope descending Big Kiss Drop in Barrancas. Photo by Val Hildreth-Werker.

Squeezing through the entrance slot, then through a natural 5m crawlway, cavers peered down the drop into a 115m depth of dark, virgin, vertical passage. At the bottom of the rappel, the team found various forms of mudflow covering the floors of cathedral-like rooms decorated with speleothems revealing sequential patterns of corrosion and deposition from drip, airflow, and possibly, microbial activity. Werker realized the unique potential offered by this deep virgin cave and envisioned establishing Barrancas as a preserve for microbial studies and speleological research. Silence was the first route of protection for Barrancas. Before starting the dig, the small team agreed to keep quiet about the find. Careful design and installation of the gate furthered the goals of protection and security.

The US Forest Service agreed to keep Barrancas closed until a cave management prescription was written and implemented. Cavers entered only for initial administrative tasks. The discovery team initiated no extensive exploration. The caving community was beginning to recognize that cave exploration should be carefully orchestrated to be compatible with cave conservation. Especially in the case of geomicrobiological studies, important scientific information can be inadvertently destroyed as easily as the fragile aesthetics of virgin cave passages can be damaged. By carefully considering actions before moving full-bore ahead, Werker hoped to establish this cave as a protected laboratory and test-site for more prudent exploration. We were willing to proceed slowly in Barrancas and develop concepts for protecting it for the future.

Long before the management plan was established, limits of acceptable change in Barrancas were designated. During less than a dozen initial administrative trips, teams entered only the main passages. From the beginning, cavers established trails with continuous lines of flagging tape delineating both sides of the pathway and initiated photomonitoring. We defined safety, bolts and rigging, rope and rig maintenance, and rescue preplans. Teams performed the first cursory inventories, taking care not to step beyond the trail boundaries. Cavers did not enter rooms and passages visible from the trail; we left virgin chambers untainted for baseline microbial investigations.

3. Why Establish Microbial Preserves in Caves?

Microbial data collected from cave passages that show no evidence of prior human visitation yield results that are more representative of the communities in nature than data from human-affected caves (Moser et al., 2001). Wherever we go as cavers, we introduce a steady stream of surface microbes that constantly fall from our bodies. These microscopic organisms live with us and on us, forever feeding on anything organic—from our dermal matter itself to the normal flakes of debris that cling to our hair, skin, and clothes.

In the early 1990s, microbiologists were developing techniques for advanced exploration of subterranean microorganisms on Earth, studying the potential for microbial life on other planets, and looking for microbes in space. New information about the diversity and abundance of microorganisms was imminent. Deep subsurface drilling studies were being conducted through projects sponsored by the Department of Energy reaching deep below the surface to collect underneath the Antarctic ice and inside deep-sea ocean vents (Fleirmans and Hazen, 1991). Such exploration demands expensive and specialized equipment. Virgin cave passages, more easily accessible to humans, were attracting new attention with a dawning recognition of their relevance to space science, medicine, microbe/mineral interactions, and origins of microbial life on Earth (Boston et al., 1992, 2001; Rusterholtz & Mallory, 1991; Chafetz & Buczynski, 1992; Cunningham et al., 1994; Northup et al., 1997). We applied the lessons learned through studies in *geomicrospeleology* to the conservation and management of Barrancas. By the time scientists recognized the significance of geomicrobial organisms in caves, prime pristine areas within most caves had already received recurring human visitation. Werker realized that Barrancas, as an unspoiled study site, offered unique opportunities for this rapidly developing science. The concept of protecting cave passages as microbial preserves was new on the horizon of cave conservation (Northup et al., 1997). Over the years between

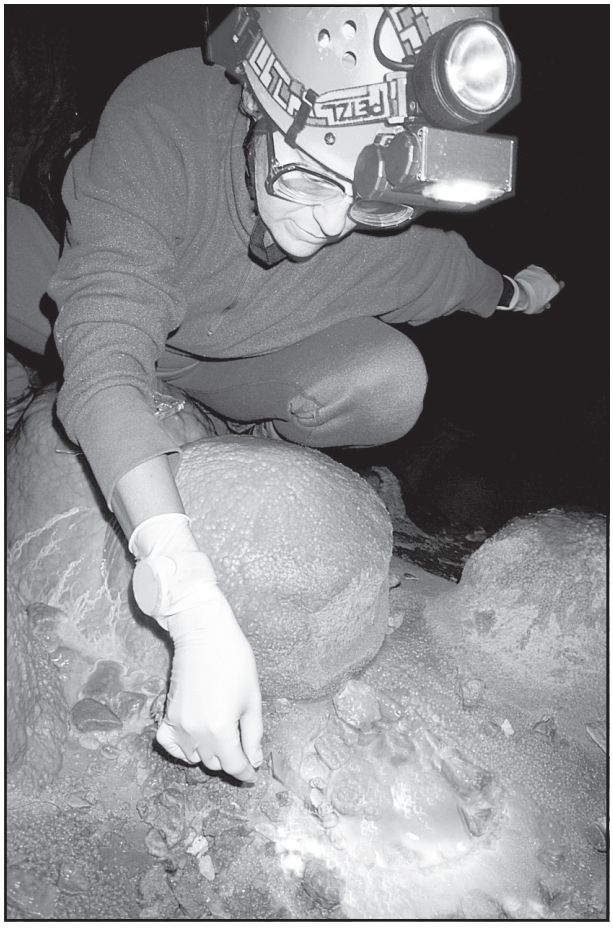

Figure 4: Penny Boston carefully places a sterile glass slide in a virgin pool. Long-term microbial studies remain in situ for several to a number of years before retrieval for laboratory analysis. Invisible biofilms on flowstone and other moist cave surfaces are enough to support cave-adapted invertebrates in La Cueva de las Barrancas, New Mexico. Photo by Val Hildreth-Werker.

1991 and 1999, cave microbiology progressed and Werker's vision matured into concepts for protecting Barrancas as a virgin cave laboratory with exploration standards that allow science to go first and conservation strategies that encourage minimum negative impact.

4. Innovative Cave Management Plan

The Forest Service supported Werker's vision for Barrancas and helped create a new type of cave management plan. In February, 1999, eight years after the noisy fist-sized hole was discovered, the Forest Service approved the management prescription for La Cueva de las Barrancas. Because of the novel concept for cave exploration, it took years of persistence to work out the details and years of collaboration to finalize the plan. Jim Werker started writing the cave management plan in 1992. Several years later, Ransom Turner of the Forest Service, added to Jim's initial work. In 1997, Jim and Val Hildreth-Werker began to further develop the cave management document for Barrancas and requested additional review by USDA Forest Service personnel. Approved in 1999, the first Barrancas management plan, *Cave Implementation Schedule: La Cueva de las Barrancas,* is included in the appendix in the NSS publication *Cave Conservation and Restoration* (Hildreth-Werker and Werker, 2006).

Through a Memorandum of Understanding (MOU) with the Forest Service, we administer the science, exploration, and mapping in Barrancas. The cave management plan defines limits of acceptable for the cave. As Barrancas is carefully studied and explored, the search for new knowledge is balanced with precautions to prevent unnecessary biologic changes in the cave's ecosystem. Important baseline monitoring information is documented through meteorological records, photographs, and ongoing microbial sampling in each new area of the cave. Photomonitoring stations help us record changes in the cave over time. We perform inventories of geological, mineralogical, and paleontological resources with minimal disturbance to biologic resources. All study methods and human operations are designed toward preservation of native biota in the cave. Those who enter Barrancas follow a strict code of conduct, *Minimum Impact Code of Conduct* and *Policies and Guidelines for Entering La Cueva de las Barrancas.* (Hildreth-Werker and Werker, 2006). The complete cave management plan for Barrancas is also accessible on the Karst Information Portal, karstportal.org/.

5. Sensitivity-Ranked Science in Barrancas

In tandem with the inverted exploration strategy that allows microbial science first entries into virgin zones, other scientific studies in Barrancas are prioritized according to sensitivity-ranking (Table 1). To maintain the unique

Sensitivity-Ranked Repeating Science Cycle					
	Year 1	Year 2	Year 3	Year 4	Year 5
Microbiology	DNA, traps, culturing	DNA, traps, culturing	Nutrient processes	In situ tracer studies	
Microscopy	SEM, ESEM, TEM	SEM, ESEM, TEM	SEM, ESEM, TEM		
Biomineralogy	EDS, XRF, EELS	EDS, XRF, EELS	EDS, XRF, EELS	TIMS dating	TIMS dating
Climatology	Baseline Temp., Rh	Baseline Temp., Rh	Baseline Temp., Rh	Advanced studies	Advanced studies
Chemistry	Exoenzymes, organics	Water & air chemistry	All chemistry	Inorganic chemistry	Inorganic chemistry
Geology			Paleomagnetic studies	Speleology, paleontology	Geochronology
Mapping	Preliminary survey			Sectional mapping	Map production

Table 1: Sensitivity Ranking. Cave management and science planning strategy that allows sampling for various analyses in descending order of sensitivity to perturbation and interference by the very acts of studying, mapping, and exploring. Sampling for native subterranean microbes is the first step as the most sensitive science to human contamination. Other scientific investigations in geology, biology, paleontology, climatology, and photomonitoring come subsequently, with survey and cartography as the last step in the repeating cycle.

uncompromised biologic value of this cave as a pristine protocol model, all scientists and explorers, regardless of their particular area of study, are bound by the Barrancas Code of Conduct to exercise specific minimum-impact protocols. Following microbial analysis, other studies are phased in. survey follows the disturbance-sensitive sciences. There is a clear "go slow, no rush " policy for this model of a cave laboratory site. The sensitivity-ranked science cycle repeats as we explore each new virgin zone with limited reconnaissance, initial sampling for microbiology, and simplified photoinventory for documentation. Prioritized sciences follow: microscopy, biomineralogy, micrometeorology, paleontology, climatology, chemistry, physics, geology, survey, and cartography.

6. Barrancas Science and Monitoring Projects

Serendipitous events in cave science and the approval of this plan resulted in a variety of Barrancas research projects initiated by 1999. Initial investigations of subsurface microbial life has led to establishing the site as a prototype for subterranean studies on Mars and other planets (Boston et al., 2003, 2004). Barrancas is a test environment for developing low-impact operational logistics and no-impact *in situ* techniques for investigations of microbial life. These efforts will advance the study of other pristine or previously impacted cave sites as well as the study of fragile surface environments.

Protocols and technologies include imaging at low and ultra-high resolutions, analyses of the minerals contained in cave materials, and a variety of biological analyses aimed at identifying the major microbial inhabitants of various materials. Minimum-impact microbiological studies are ongoing and provide useful baseline data for monitoring programs. We conduct microbial experiments *in situ* when feasible, because cave organisms are relatively sensitive to tiny perturbations in their environment. When procedures cannot be done on site, we stabilize specimens before removing from the cave. Assays for organic and inorganic nutrients are conducted. Imaging of mineral and microbial materials is accomplished using Scanning Electron Microscopy (SEM) and microprobe analysis. Microbial and mineralogical studies are aimed at distinguishing abiotic from biologically influenced processes of speleothem formation. SEM and other techniques are also used to investigate fossil microorganisms and other textural or fossil materials. For example, we have discovered that the protecting tiny capstones which enable the formation of mud pagodas and ziggurats are frequently more resistant microfossils like *Formaminifera* which are eroded from the bedrock of the cave.

Technological developments in the cave have involved robotics research including tests of a robotic collection and data communication system preparatory to implementing a self-deploying multi-unit robotic swarm. Part of the driving rationale for developing robotic units is concerned with developing sterilizable components to conduct aseptic (non microbially contaminating) reconnaissance studies both here on Earth in biologically sensitive environments and for extraterrestrial life detection missions.

7. Barrancas: Prototype Site for Mars Studies

In cave passages that are isolated from the surface, microorganisms have evolved through many generations of adaptation to subterranean conditions that can be radically different from any that we find on Earth's surface. The pristine passages of Barrancas provide a place to practice for future missions when we look for alien lifeforms in the subsurface of Mars or other planets (Boston, 2000, 2001). NASA is interested in caves on Earth and other planetary bodies as scientific targets for future missions and as potential resources for human use at extraterrestrial destinations (e.g., a research base might be placed in a natural subterranean void on Mars). Barrancas is a suitable study site for protocol development toward future human Mars missions. The Barrancas team played a significant role in NASA Institute for Advanced Concepts (NIAC) Phase I and Phase II grants to work on the concepts and developments necessary for implementing Mars prototype studies (Boston et al., 2003, 2004).

Planetary protection refers to the need to protect possible organisms on another planet from contamination by Earth microbes while we study and explore but it can also be seen as a requirement for biologically sensitive extreme environments here on Earth like deep pristine caves. At the same time, we must also protect Earth from any contamination by possible alien species. As a pristine geomicrobiology site, Barrancas provides an ideal test environment for these challenging and competing goals The grueling challenges of exploration, research, and protocols to avoid contamination require on-site resourcefulness. Of paramount importance, the investigations must be performed without compromising the scientific value or ecological soundness of the cave microbiota—any lifeforms discovered must be preserved. We are developing methods to prevent our own human activities from contaminating the isolated environment.

8. Conclusions

La Cueva de las Barrancas is a unique spelean testing ground where the speleologists and astrobiologists of the 21st

century can develop study techniques. The foundation of this research is the Barrancas cave resource management plan for preservation through pristine site protocols. We are in no way advocating this type of management structure for every cave. Cave environments can hold a variety of fascinating assets—some management prescriptions are written to protect specific resources, others are written to protect the people who visit a cave site, and many management plans are written to protect visitors as well as natural and cultural resources within. Our repeating sensitivity-ranked science cycle lays the foundation for tackling a long list of necessary investigations and feasibility studies to give credence to extremophile environments on Earth and extraterrestrial cave use and study. Efforts in La Cueva de las Barrancas will serve in advancing studies of other cave sites, exploring the potential for life on other planets, and protecting other fragile environments of Earth's surface and subsurface.

Acknowledgements

We extend many thanks for the lengthy cooperative effort that contributed greatly to the approval of the cave management plan for La Cueva de las Barrancas and the subsequent Memorandum of Understanding between the USDA Forest Service, Jim Werker, and Val Hildreth-Werker. Forest Service personnel who helped bring the Barrancas dream to reality are Jose Martinez, Forest Supervisor; Johnny Wilson, Forest Recreation Staff Officer; Jerry Trout, FS National & Regional Coordinator/Cave Resources; Brent Botts, FS Regional Deputy Director of Recreation; Jim Miller, Dispersed Recreation & Trails, Washington Office; Mike Baca, District Ranger; Richard Carlson, District Recreation & Lands Staff; Larry Paul, District Wildlife Staff; and Ransom Turner (deceased), District Cave Specialist. Particular thanks goes to the cavers and scientists who have worked many expeditions in Barrancas: Penny Boston, Mike Spilde, Steve Welch, Rick Toomey, John Ganter, Harry Burgess, Dave Hamer, Phyllis Hamer, David Joaquim, Dennis Hoberg. During the past decade, their commitment to the vision for Barrancas and their unified efforts have facilitated the development, approval, and implementation, of this unique cave management and research prescription and funding of these unique cave studies. We extend gratitude to the NASA Institute for Advanced Concepts and to the National Cave and Karst Research Institute for extensive funding. Some of the work has been conducted under National Science Foundation grants*, P. Boston PI,* EAR 0719669 (*Collaborative Research: Biogenic Cave Carbonates: Identifying Surface Carbon Input to Subsurface Ecosystems*), EAR 0311990 (*Collaborative Research: Identification of Microbial Signatures in Biogenic Cave Ferromanganese Deposits*), and DEB 9809096 (*LEXEN: Geomicrobiological Interactions of Microbial Communities in Cave Deep Subsurface Environments*).

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SPELEOTHEM REPAIR: REHANG LARGE BROKEN STALACTITES

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A visitor tripped while descending an old stone stairway in Colossal Cave State Park, Arizona, USA, and fell into a 1.5-meter-long stalactite, breaking it into two pieces. The stalactite weighs over 100 kg. To ensure visitor protection during the restoration of the large speleothem, we constructed and placed sturdy support structures. We secured both broken pieces of the speleothem with stainless steel all-thread support pins and Shell Epon 828® epoxy with Shell Epi-cure 3234® (TETA) hardening agent. A wood support and metal jack system raised the larger 84-kg piece to a tight fit and the support apparatus remained in place for several weeks to allow time for thorough curing. Because the visitor trail runs alongside this sizeable stalactite, we reinforced the repair by installing additional stainless steel pins up through the speleothem and into the ceiling. Threading stainless wire between small holes drilled completely through both sides of the repair provided additional reinforcement for the joint. Between the holes, we carved grooves to receive the wire ends and then concealed all holes and grooves with a rock dust and epoxy mixture. After pinning the lower 18-kg piece into position, wood blocks and shims provided support while the epoxy cured. Removal of supports, additional color-matching, and cosmetic touch-up work completed the successful repair of the long, heavy stalactite. The techniques developed for this repair may serve in other caves to restore large broken speleothems to their original positions.

1. Introduction

A large broken stalactite weighing 102 kg is again hanging on the ceiling of Colossal Cave, located in Colossal Cave Mountain Park in the Sonoran Desert south of Tucson, Arizona, USA. Native Americans from several tribes used the cave for centuries before Solomon Lick rediscovered it in 1879. Colossal Cave State Park is on the National Register of Historic Places. Rich with legendary events from southwestern US history, the first tour groups in 1923 used ropes and lanterns through unimproved passages (Maierhauser and Cockrum, 2000). In this abundantly decorated and historic show cave, the Civilian Conservation Corps constructed durable stone stairways and pathways during the mid-1930s. The 4.3 km of hand-set flagstone walkways continue to be a functional asset for visitor traffic. Many large stalactites and stalagmites are located near the visitor path throughout the cave. In the Drapery Room, an eight-step stone stairway leads down to an especially vulnerable, long stalactite. In 1995, a visitor tripped while descending the stairs and fell into the 1.5-m long stalactite. Fortunately, the visitor walked away unharmed. However, the long, stately calcite stalactite broke off near the ceiling and crashed to the floor breaking into two large pieces. The State Park contacted us to evaluate the break for potential repair. In 2003, we designed safety measures and initiated reconstruction of the grand stalactite. Several Arizona cavers helped us successfully reattach both large pieces and complete the repair.

2. Speleothem Repair Materials: Adhesives and Stainless Steels

We recommend using only proven archival-grade epoxies and adhesives in cave environments. The epoxies, bonding agents, and quick glues found in neighborhood dime stores and variety outlets may create more harm than good. Most hardware store epoxies and quick-glues break down rapidly and may add unwanted toxins and nutrient sources that will harm or destroy cave biota and habitat. All glues break down over time, but archival products are formulated to do less harm than those on the general market. Before choosing epoxies, hardeners, cyanoacrylate adhesives, solvents, or metal fixtures, research and understand the characteristics of the materials. Always carefully test products before using them for cave applications. Never trust cave resources to the marketing claims of wonder products.

Arrange for a cave-savvy chemist, a materials engineer, and/or a research biologist to evaluate how the long-term degradation characteristics may interact with naturally occurring chemicals and minerals in the specific cave environment where product use is proposed. Research the physical components and short-term effects of proposed products. Determine how the degradation and outgassing characteristics of the compounds may affect cave-dwelling biota, ecosystems, chemistry, water quality, and minerals in the cave system. Also, get the manufacturer's data sheets and the Material Safety Data Sheet (MSDS). Understand the recommended safety precautions.

We have successfully used Shell Epon 828® epoxy in underground environments and speleothem repair for decades. Epon 828 and Versamid hardeners were lab tested for long-term underground use at the U.S. Department of Energy Nevada Test Site and have proved successful for speleothem repair during several decades of use and observation (Werker, 1996). Currently we recommend Shell Epi-cure 3234® (TETA) as the curing agent for speleothem repair. (In the past, we used Versamid® 40 hardener for moist environments and Versamid® 25 for wet environments or dripping surfaces—however, these products are no longer available.) The Shell Epi-cure 3234 hardener is a highly concentrated curing agent with bonding properties and archival characteristics similar to Versamid. Epi-cure 3234 is easier to use, can be mixed in various concentrations, and meets a greater range of humidity requirements. Epon 828 is typically mixed in a 12:1 ratio, twelve parts Epon 828 to one part Epi-cure 3234. (Adding more curing agent to the mix will cause the epoxy to harden quicker, but the bond will be weaker.) The combined epoxy and curing agent becomes a creamy white color and a viscous consistency—when dry, it is colorless or a slightly shiny, translucent yellow. Curing time can take 24–72 hours and sometimes longer in moist cave environments. Shrinkage is minimal. The bond is resistant to a broad range of chemicals. These products are designed for archival and long-term research applications. Epon 828 and Epi-cure 3234 are available from the Shell® Chemical Company and through regional chemical or plastic product suppliers (Werker and Hildreth-Werker, 2006).

Chromium–nickel austenitic steels, commonly known as stainless steels, are more suitable than other products for speleothem repair. Stainless is tough and highly resistant to corrosion. Longevity is ten-fold that of mild steels. Stainless steels that are not austenitic will degrade more rapidly in most cave environments. Metals that work best underground include high austenitic stainless steels, particularly types 304L, 316L, and 321.

Stainless steel all-thread is the choice material for pin-stabilization of broken speleothems. The ridges of all-thread grab and adhere better, providing greater shear strength than pins made from regular round-stock stainless. Suppliers stock most stainless all-thread materials in assorted diameters and will cut it to the required lengths.

Consider the expansion characteristics of any material before using it to pin broken speleothems. Over time, corrosion will cause expansion, even when stabilization devices are epoxied inside of speleothems. Structural steel (also called mild or cold-rolled steel), aluminum, plastic, fiberglass, wood, and nylon rods tend to expand and break apart the repaired cave formations when epoxied into the centers. Stainless is more corrosion resistant than most other materials. The corrosion-resistant characteristics of high austenitic stainless steels minimize the potential for breakage from material expansion.

Select pin diameter and length to fit the characteristics of the project. Determine the size of the pin according to the size and shape of the formation repair. If you lack experience in bolt sizing, seek help in deciding the pin dimensions. Length depends on the application. We have used pins ranging in length from 5 to 30 cm. The smallest pin we have installed is 2-mm diameter. The largest is 20-mm diameter. If a speleothem is *not* likely to break again, use a short pin. The only real benefit provided by a short pin is prevention of sliding from shear load while the epoxy cures. A longer pin provides additional strength (Werker and Hildreth-Werker, 2006).

In practice, stainless steel wire is difficult to bend and conform to the shapes of cave formations. However, if the wire is installed as a permanent material in a repaired speleothem, it may be worth the time and aggravation to use stainless wire.

We use other softer wires, usually copper, for temporary support in repairing speleothems.

Stainless is the best all-around metal choice for long-term applications in caves. Stainless materials and archival adhesives are highly resistant, durable, and readily available. For detailed information on materials and methods for speleothem repair, see the repair chapters in the NSS publication, *Cave Conservation and Restoration* (Hildreth-Werker and Werker, 2006).

3. Stalactite Repair Overview

Two large pieces of the 1.5-m long stalactite needed reattachment. The upper piece, weighing 84 kg with an elongated drapery-shape, broke off a few centimeters from the ceiling. Working after visitor hours in the show cave, we cleaned and dried all breaks and set up the tools. First, we ink-marked the drill-spot on both sides of the upper break joint, then drilled the thicker, rounder part at the ceiling break and epoxied in a 20-mm diameter stainless steel all-thread 30-cm long stabilizing rod (see photo sequence). In the break of the mating piece, we drilled a slightly larger hole, filled it with archival epoxy, spread a thin layer of the same epoxy on both surfaces of the break, and raised the 84-

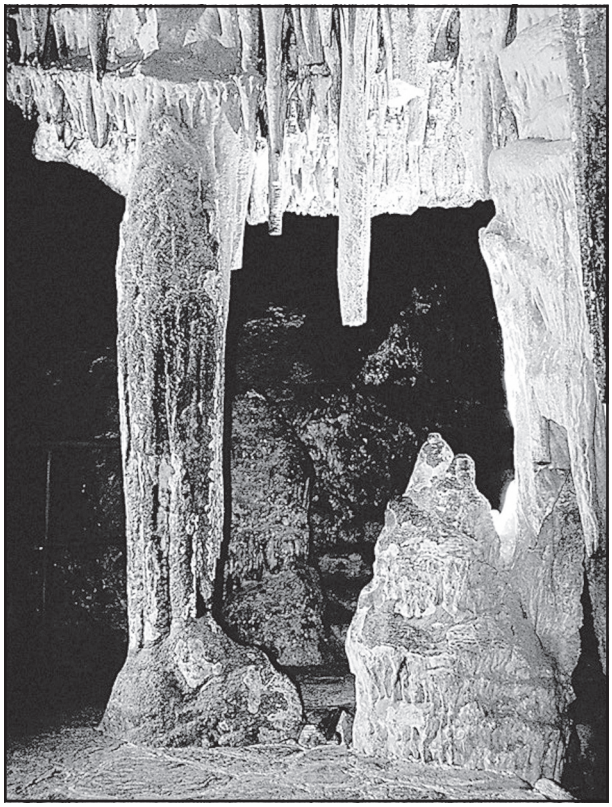

Figure 1: (Before) This sequence shows the steps in the reattachment of a 102-kg stalactite in Colossal Cave, Arizona. Photo by Val Hildreth-Werker.

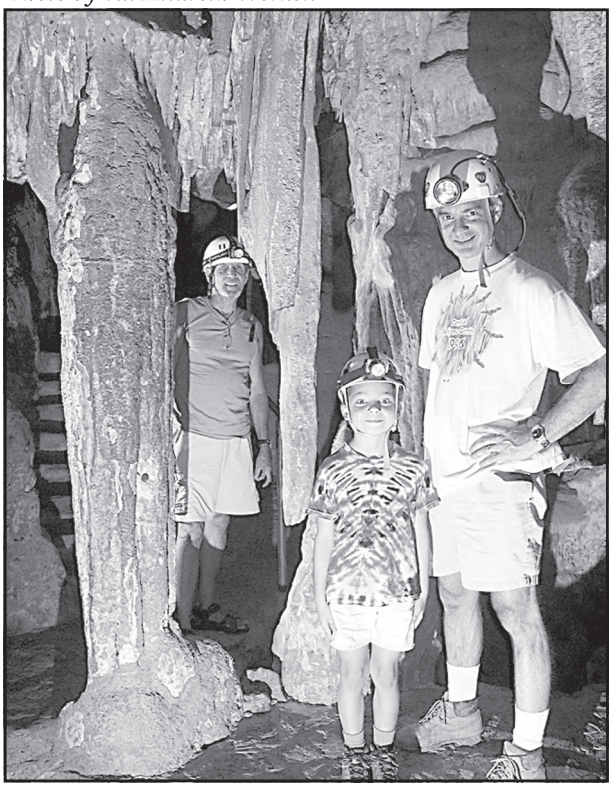

Figure 2: (After) Jim Werker (in back), Ian Joaquim, and David Joaquim, stand beside the completed repair of the long, heavy stalactite. Photo by Val Hildreth-Werker.

kg piece to snap-fit in place with a screw-jack support system (Werker, 2006).

To assure visitor safety and a point of interest for the guided interpretive tours, we cordoned off the area and left the jack and support system in place for several weeks, allowing more than enough time for complete curing of the epoxy. Because the heavy stalactite is positioned directly in the fall zone of the historic stairway, we reinforced the upper repair using

Figure 3: Jim Werker uses Shell Epon 828Ò epoxy with Shell Epi-cure 3234Ò (TETA) curing agent to install a stainless steel all-thread stabilization rod into the upper break. Photo by Val Hildreth-Werker.

two techniques. We installed additional 6.5-mm diameter stainless steel pins up through the formation and into the ceiling to assure stability of the long, heavy piece. Then we also drilled small holes completely through both sides of the upper repair and threaded stainless wire through to provide additional wraps of reinforcement for the joint. For surface cosmetics, we carved grooves between the small holes to receive the wires and then concealed all holes, grooves, and seams with a color-matched rock dust and epoxy mixture.

In the lower 84-kg piece, we epoxied a 12.5-mm diameter

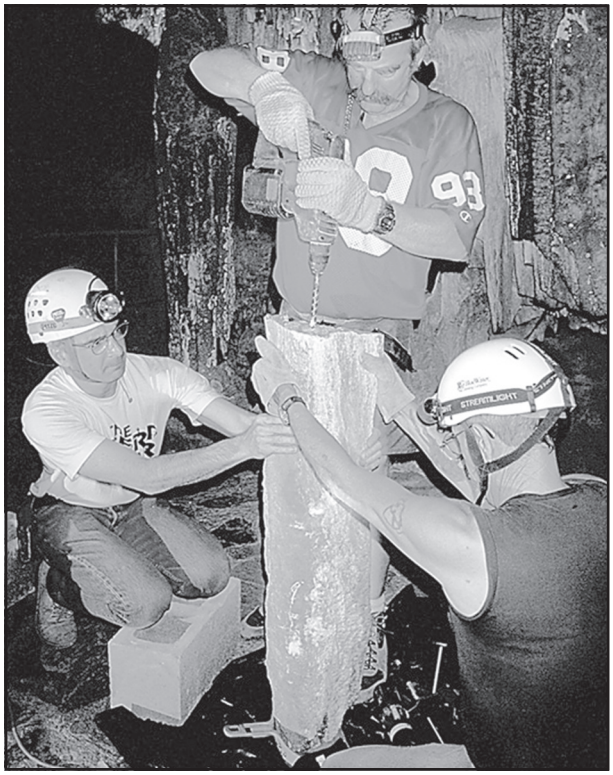

Figure 4. Dave Hamer drills a slightly larger hole in the large bottom section of the broken stalactite to receive the upper stabilization pin. David Joaquim and Jim Werker assist by holding the 84-kg piece of speleothem steady. Photo by Val Hildreth-Werker.

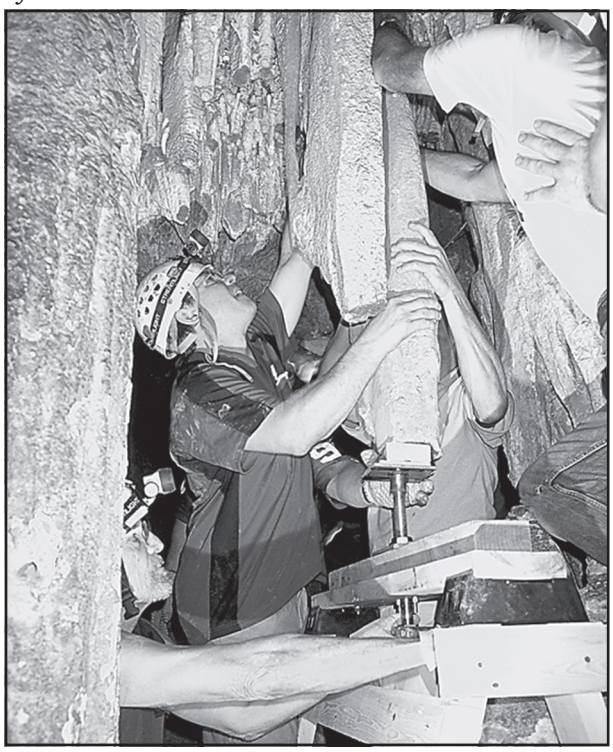

Figure 5: Dennis Hoberg and others position the large stalactite while Jim Werker adjusts the screw jack support structure. Photo by Val Hildreth-Werker.

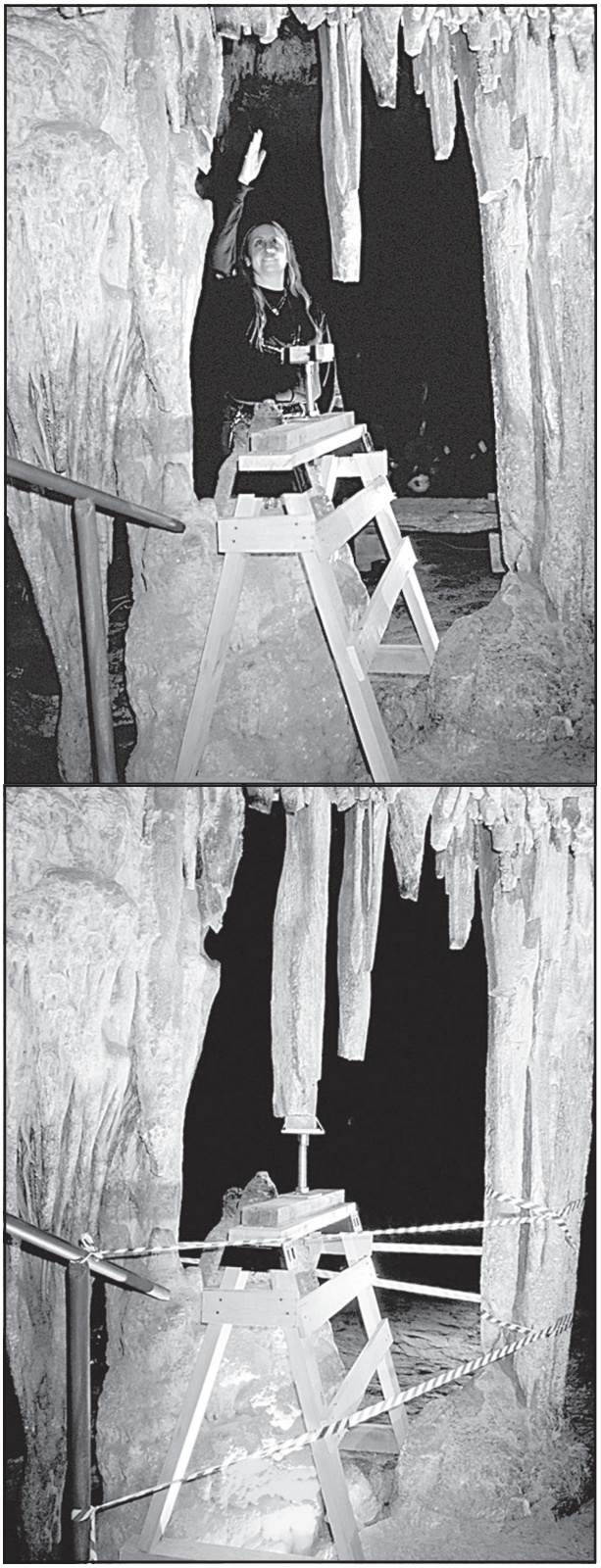

Figure 6a: (Before) and Figure 6b: (Midway through the repair) In the second image, after the reattaching the upper piece to the ceiling, we cordoned off the support jack for visitor safety and left it in place for several weeks to assure proper curing of the archival epoxy. Photo by Val Hildreth-Werker.s

Figure 7: To reinforce the pin and epoxy repair, stainless steel wire is threaded through small drill holes above and below the upper break-joint. Alongside the wire, there are additional stainless pins installed at an angle up through the break-joint and into the ceiling.

Figure 8: A mixture of rock dust and approved epoxy conceals the drill holes, grooves, and wire supports. Photo by Val Hildreth-Werker.

Figure 9: After allowing several weeks for the upper piece to thoroughly cure, we pin and epoxy the lower piece of broken stalactite into position. Photo by Val Hildreth-Werker.

stainless steel all-thread, 20-cm long support pin. Wood blocks and shims held the lower piece in place. We again left the joint to cure for several weeks before removing the supports, then completed the joint repairs with a color-matched, touch-up epoxy and rock dust mixture. For final texture-matching, we first dabbed the semi-dry epoxy mixture with various tools, then used a Dremel® tool after the epoxy completely cured (Werker, 2006).

4. Repair Sequence for the Long, Heavy Stalactite

- Stainless steel all-thread support pins and Shell Epon 828® epoxy with Shell Epi-cure 3234® (TETA) curing agent provide the main support for both pieces of the sizeable stalactite.
- In stalactites, we drill and epoxy the stabilization pin into the upper section first and allow time to cure. Then we drill an oversized hole in the lower mating piece to facilitate snap-fit alignment, half-fill the hole with epoxy, spread a thin layer of epoxy on the broken surfaces, and secure the piece in its original position while epoxy dries.

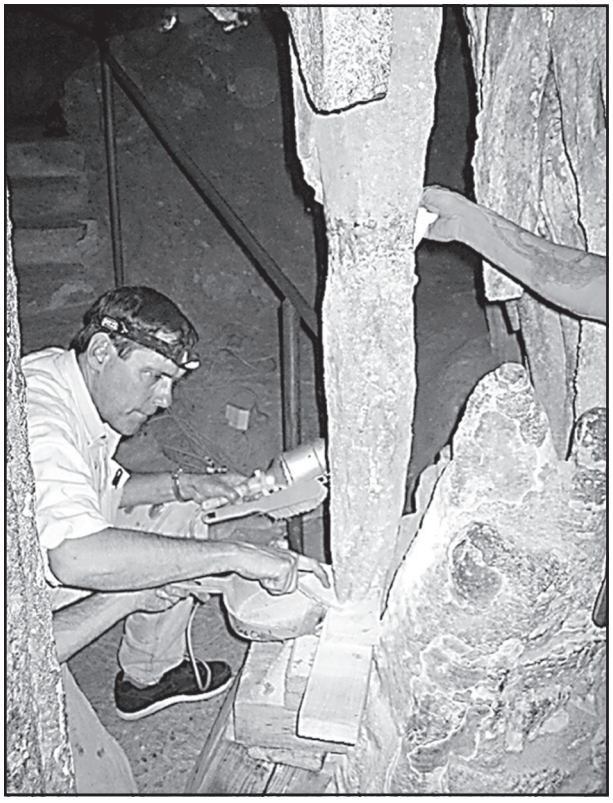

Figure 10: Steve Smith places wood blocks under the lower piece of the completed stalactite while others clean up the lower epoxy seam and the drill-dust. Later we remove the bracing supports after the epoxy cures.
Photo by Val Hildreth-Werker.

- A wood support and metal jack system raise the larger 84-kg piece to a tight fit and the support apparatus remains in place for several weeks to allow time for thorough curing.
- Because the visitor trail runs alongside this sizeable stalactite, we reinforce the repair by installing additional stainless steel pins up through the formation and into the ceiling.
- Threading stainless wire between small holes drilled completely through both sides of the upper repair provides additional reinforcement for the joint.
- Between the holes, we carve grooves to receive the wire ends and then conceal all holes and grooves with a rock dust and epoxy mixture.
- After pinning the lower 18-kg piece into position, wood blocks and shims provide support while the epoxy cures.
- Touch-up, texturing, and additional color-matching work completes our successful repair of the long, heavy stalactite.

5. Conclusions

Based on current best practices in caves, coupled with lab analysis, contemporary understanding, and several decades of practical observation in subterranean environments, the materials listed in this paper are *cave-safe*—reasonably safe for cave habitats and speleothem repair (Hildreth-Werker, 2006). Make informed decisions about speleothem repair products, materials, and practices. Use educated common sense and gather information about current best practices before embarking on repair projects. Archival-grade adhesives and austenitic stainless steels are some of the best options. Refer to the repair chapters in the NSS publication, *Cave Conservation and Restoration* (Hildreth-Werker and Werker, 2006) for other options. Contact trained interdisciplinary speleologists for review when other products or materials promise cave-safe qualities. State-of-the-art techniques and materials for speleothem repair will change as knowledge advances. It is important to stay current and exchange information with others who repair speleothems.

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HYDRO-ELECTRIC POWER PROPOSAL, IRALALARO-PAITCHAU KARST, TIMOR-LESTE

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The Iralalaro-Paitchau Mountains area of Timor Leste is a karst region that contains a wide range of karst-related landforms and features. These include a large polje, collapse dolines, sinkholes, blind valleys, karren and caves. A substantial component of the hydrology is underground and the area relies on underground water for a significant part of its water supplies. The area has significant surface and underground geodiversity and biodiversity. The karst has not been subjected to a thorough and detailed study, and the implications of the karstic nature of the terrain are poorly understood.

The proposed Iralalaro hydroelectric scheme would divert water from the Irasiquero River upstream of the present swallet in the Mainina sinkhole by a tunnel through the Paitchau Mountains to a power station on the coast. Timor Leste has serious problems in regard to the provision of sufficient power generating capacity and has done little to protect or manage its karst. The scheme appears to have a number of significant limitations and risks, especially relating to the costs and potential difficulties of drilling, tunneling and dewatering in karst. There is little understanding of the relationship of the lake and the water table, with consequent implications for maintaining regional water supplies and sustainable power generation from the scheme.

1. Introduction

The Iralalaro-Paitchau Mountains area of Timor Leste is the site of a proposed hydroelectric scheme which would divert water from the Irasiquero River upstream of the present swallet in the Mainina sinkhole via a tunnel through the Paitchau Mountains to a power station on the south coast (Fig. 1). This area is a karst region that contains a wide range of karst-related landforms and features including a large polje previously not identified or described. Investigations undertaken in August 2005 in conjunction with the Australian Conservation Foundation and the East Timorese Haburas Foundation indicated some serious deficiencies

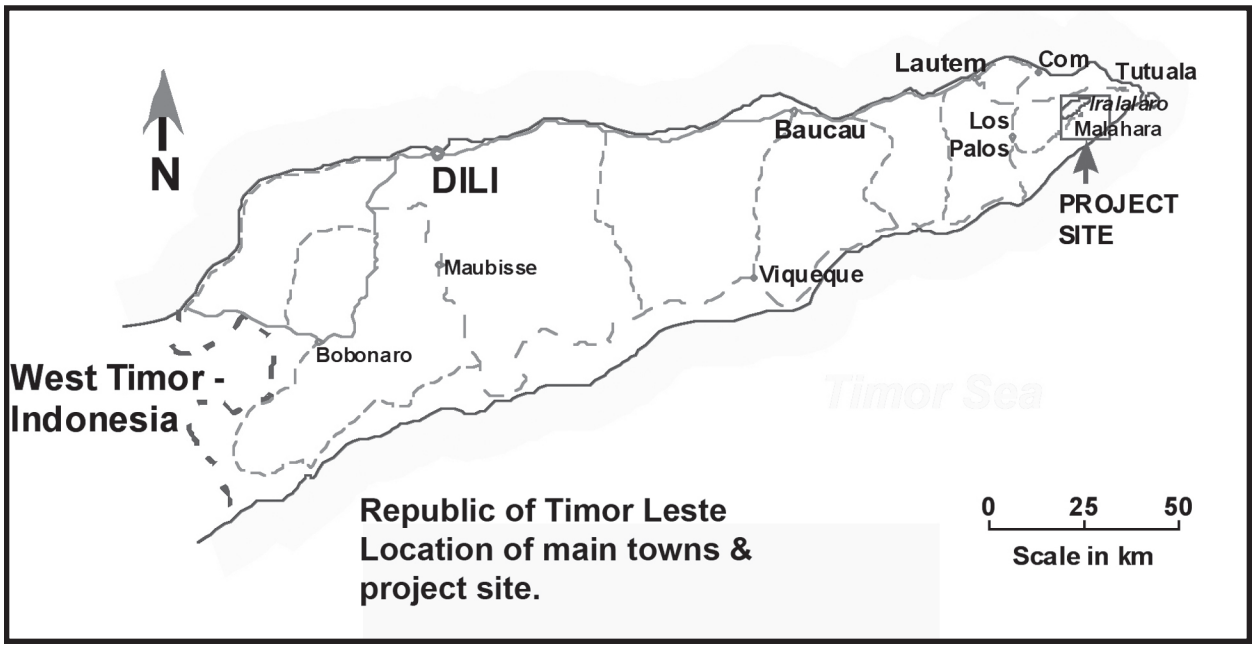

Figure 1: The location of the Iralalaro hydro-electric scheme, Lautem district, Timor-Leste.

in the understanding of the karst geomorphology and hydrology of the area with potential serious consequences for both the long-term viability of the scheme and its impact on the karst and the region.

2. Climate

The eastern end of Timor-Leste has a wet tropical monsoonal climate characterized by a hot summer, distinct monsoonal wet and dry seasons, and relatively small temperature variation. The Lautem district is the wettest in East Timor, with a mean annual rainfall of ~1900 mm concentrated in the wet season, monthly average temperatures range from 28.9 to 18.8°C (Nov and Aug), humidity from 82.2% (May) to 73.2% (October) and an estimated evaporation of 1033 mm p.a. (Los Palos). Evaporation exceeds rainfall for the dry season and the more limited rainfall records from Malahara and Maupitine, east of Los Palos and to the south of the lake, indicate significantly lower rainfall than Los Palos although the evaporation would be similar (EPANZ Services 2004). With this relatively limited data any lake and aquifer recharge calculations have severe limitations.

3. Regional Geology

The geology of the eastern end of Timor Leste is predominantly limestone: only the Permian Cribas Formation and the Recent Suai Formation are significantly non-carbonate (Fig. 2). The several theories attempting to explain the tectonic and formational history of the island all agree that the island is composed of contributions from the Australian continental plate and the highly deformed rocks from the Banda Terrane (Audley-Charles 1968).

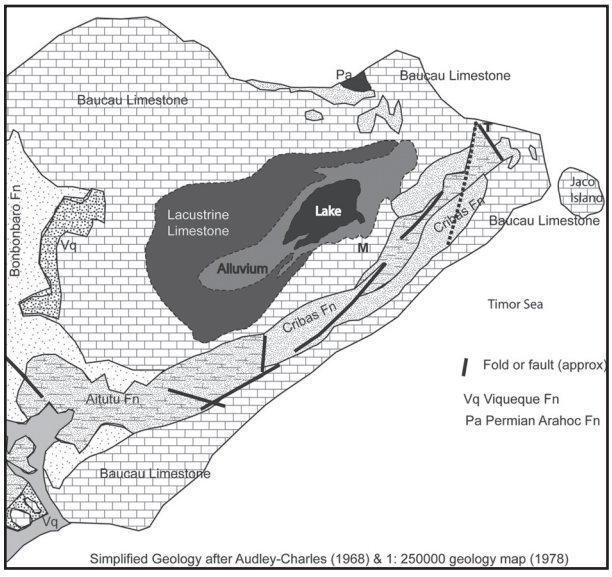

Figure 2: Simplified geology eastern East Timor (after Audley-Charles, 1968).

The insoluble Permian Cribas Formation comprises fossiliferous shallow water non-carbonate sediments derived from elsewhere, possibly from the erosion of northern Australia (Audley-Charles, 1968). Limestone occurs commonly at the top of the unit, but the contact with the overlying Triassic Aitutu Formation is not clear. The Cribas Formation may form an aquiclude where it underlies limestones. It is present as upthrust sections in the Paitchau Mountains south of the Iralalaro polje and along the north coast. Overlying the Cribas Formation is the 1000 m thick highly soluble Triassic Aitutu Formation which is a shallow marine, calcite or aragonite mud. It is present as uplifted sections in the Paitchau Mountains (UNESCAP 2002). This is followed by a large time gap (over 200 Ma) in the geologic sequence, from about 210 Ma (late Triassic) to about 1.6 Ma (early Pleistocene) when the Baucau and Poros Limestones are deposited.

The area was subjected to tectonic activity including folding up until the Pliocene. Except for the upthrust Permian and Triassic sediments of the Paitchau Mountains, the post-Pliocene sediments, e.g., the Baucau Formation, blanket the eastern end of the island and are assumed to unconformably overlie older folded and/or faulted sedimentary rocks (UNESCAP 2002). Lack of data seriously constrains the geologic understanding of the eastern end of the island including the lithologies and structures underlying the Iralalaro polje.

The widespread Baucau Formation is a hard, vuggy, cavernous, massive, white fossiliferous reef limestone (maximum thickness of ~100 m.) occurring as a series of terraces (representing raised beaches) (Audley-Charles 1968) (Fig. 2). The terraces record the continued uplift history of the area to recent times and controls the topography of the Baucau and Lautem plateaus. The lacustrine Poros Formation occurs only east of Los Palos on the Lautem Plateau and was deposited after the Baucau Limestone, on which it rests, had been elevated above sea-level. The bed of the Iralalaro polje is a Quaternary heavy black clay alluvium. It may be the relative impermeability of this clay, which allows the lake to hold water.

4. Karst of Iralalaro-Paitchau Mountains Area.

The karst-related landforms include a large polje, collapse dolines, sinkholes, blind valleys, karren and caves. An indication of the paucity of the earth science studies so far carried out in connection with the proposed project is that prior to our visit (in August 2005) no one had recognized that the feature marked on some maps as the "Fuiloro Plateau" and referred to by some consultants as "the Ira

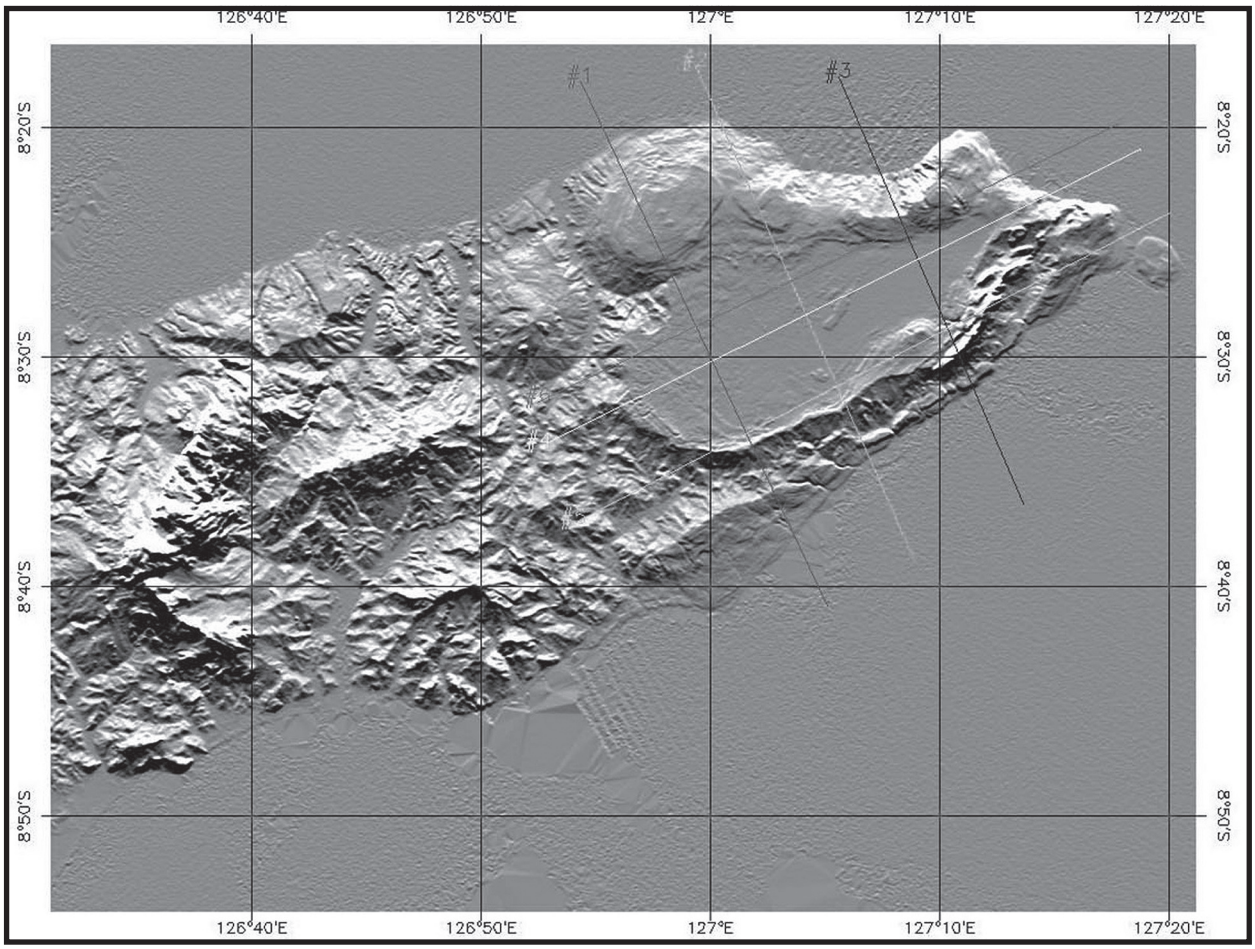

Figure 3: Digital terrain model of eastern region of Timor-Leste, clearly showing the huge polje, which contains the Iralalaro Lake [generated from SRTM 3-arc second data from USGS].

Lalaro depression" (ELC-Electroconsult et al. 1989, p. S-2) and by others as "a large karstic plateau" (EPANZ Services 2004, p. 8) is, in fact, a large base level polje. This polje is the most outstanding single landform of the region and contains the fluctuating Iralalaro Lake. It is clearly seen in a digital terrain model of the region (Fig. 3) and is also quite evident at ground level (Fig. 4). Except for the limited description in our reports (White, et al. 2006, Middleton et al, 2006), it is completely undescribed.

The area of the Iralalaro polje is estimated to be ~100 km2, with 406 km2 entirely contained as internal drainage. The lake fluctuates between 10 - 55 km2. Associated with the polje are a number of small dolines, some of which had water at their lowest points (August 2005). A small number had vertical sides and were filled with water to within a meter or so of the surface. They provide an indication of the level of the water table below the polje floor, especially during dry conditions. The principal drainage from the polje

Figure 4: View north across the flat-floored Iralalaro polje from foothills of Paitchau Range (Photo G. Middleton).

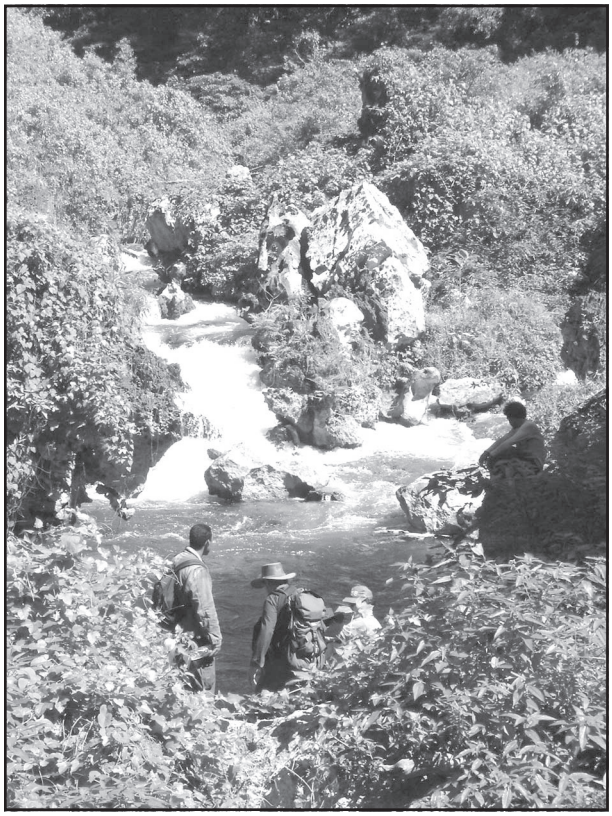

Figure 5: Mainina sinkhole or swallet
Photo G. Middleton.

is via the Irasiquero River south to the Mainina sinkhole or swallet (Fig. 5).

The Mainina sinkhole is a large and impressive feature at the southern end of a blind valley cut into the foothills of the Paitchau Range (Fig. 5). The water sinks into a restricted swallet around a meter in diameter in the riverbed, and drains through holes only about 10 cm in diameter. Investigation of the swallet is difficult due to high velocities of flow, even in the dry season. The Irasiquero River flows for 3.5 km though a blind valley, with a high head wall and a large boulder slide. The boulders are large (some over 5m diameter) and angular and show limited solutional modification. Small boulder caves are present in the boulder slide. It is unclear as to whether the collapse slide is due to the collapse of a previous swallet and cave or just undermining of the head wall. Investigation failed to find any access to abandoned (dry) passages connecting with the present underground flow. The valley periodically floods up to a level of ~20 m above dry season river level, as indicated by the absence of forest below that level. The swallet is unable to easily drain the high discharge of the Irasiquero River during the wet season, and the water dams back.

The area on the south side of the polje has a disrupted drainage pattern. Superficial runoff in the wet season probably drains underground through a range of small sinks, which are obscured by the forest cover. Except for the Irasiquero River and the polje, there is very limited surface water in the dry season.

Very little documentation of caves in the area has yet been carried out. Prior to 2005, the only known records were of archaeological sites to the east of the polje, between Tutuala and the coast, and to the west around Baucau, e.g., Lene Hara cave.

Solutional caves do occur on the raised terraces of Baucau Limestone around the polje, e.g., Noi Noi Kuru near the village of Malahara. This cave is a northeast-southwest series of roughly horizontal passages, indicating strong joint control, 320 m long with significant areas of roof spongework. The cave has abundant speleothems, large chambers (up to 4m high) and with an almost flat floor throughout. The floor of this cave consists of fine silt in many places, and it may contain pollen or other datable material. No doubt a minimum age for the cave could be determined by dating of a suitable speleothem, but as the Baucau Limestone is itself Quaternary, this cave can be no more than 1.5 Ma old. Despite the use of the cave for refuge by the local people at times of invasion and civil strife, there were few signs of damage. Broken pottery indicated occupation but this may have long predated 1975. There was only one obvious modification: a rubble stone wall built most of the way across the passage below the entrance. It is notable that Lene Hara cave also has a stone wall, in that case across its entrance/main chamber.

It is clear that there is considerable karst, including cave, development of the Baucau Limestone. Although no large caves were observed in the limestones of the Aitutu Formation in the Paitchau Range, there were abundant surface karst features (karren) and one small cave was noted. The lack of knowledge of caves in the Aitutu Formation is no indication that significant karst features are absent, as no exploration has occurred. Other caves on the southern slopes of the Paitchau Mountains have been reported to have been used by Fretilin during the guerrilla campaign against the Indonesians. There is potential for significant cave development in the area.

Little information is available on the groundwater and hydrogeology of the area. Substantial development is being planned in the absence of detailed hydrogeological data and the assumptions on which the water volumes have been based are at best unproven. If incorrect they would

have serious consequences for the viability of the planned hydroelectric scheme. Limited water tracing has occurred using tracer material into the Mainina Sinkhole which showed hydrological connection, through to both the north and south coasts. The highest response was to two sites on the North coast although the connections to the south coast were identifiable amounts above background level. The karst aquifer connections beneath the polje and the lake are more complex than were originally assumed. The description of the hydrology in the Scoping Report (EPANZ Services 2004) cannot be accepted with any confidence. The failure to identify the polje and thus understand its close relationship with the groundwater, absence of hydrogeological data and the failure to initiate its collection, and the lack of clarity as to the fate of water disappearing into the Mainina Sinkhole, both in geographical terms and as to quantities at different seasons show that the proponents seriously misunderstand the nature of the area.

5. Hydro-electric Proposal

The scheme would involve the diversion of the entire flow of the Irasiquero River, the only surface outlet from Iralalaro, the country's largest lake/wetland area, away from its sinkhole at Mainina into a tunnel drilled under the Paitchau Mountains. The tunnel would feed water through the range to a powerstation at sea level on the south coast, a fall of about 300 meters (Fig. 6). It is based on feasibility reports dating back to the late 1980s with updates in 2003 and 2004 (Adeler et al. 2003, EPANZ Services 2004). The scheme was developed on inadequate information, including little if any mention of karst, and with no comprehension of the consequences involved in such development on karst. Thirty years later the situation has not significantly improved. However, despite the acknowledgement in the later reports of the significance of the karst and the potential vulnerabilities associated with development on karst, no detailed study of the karst appears to have been undertaken by the proponents. This leaves considerable risks in both constructional and environmental areas. The issue of the costly and risky nature of construction in intensively karstified areas continues to be ignored.

6. Karst management issues and Potential Environmental Problems

The earlier reports barely mention the possibility of problems for this major tunneling project arising from the nature of the karstified rocks through which it must pass. The limestone is seen as competent crystalline limestone and therefore good for tunneling. The major tunnel would run from the sinkhole and pass under the range at a very low gradient; what it passes through depends on the unknown relative relationships of the Cribas and Aitutu formations, the significant faulting in the area and the hydrological relationships of the Cribas Formation. The assumptions that the project did not present especially complex technical problems appears to totally dismiss the very real difficulties, which tend to be the norm, rather than the exception, when undertaking engineering projects on, and especially under, karst terrain. The glib dismissal of any likely problems in the 1989 study and failure to address it in the 2004 report is in stark contrast to the attitudes of those with experience in karst engineering such as discussed in Milanovic (2000).

One of the first points conceded in the 2004 'Environmental Assessment' (EPANZ Services 2004, p. 1) is that "The fate of this water [that entering the Mainina sinkhole] has not been established." It seems remarkable that any environmental assessment of this project did not rate the answering of this question as a top priority. The limited dye tracing undertaken ask more questions than provide answers, and it is not known if any flow times were determined or if there is any real quantitative data on flows. Without such details and the construction of a fully documented water budget for the drainage basin any decision to divert this water to another use would be irresponsible.

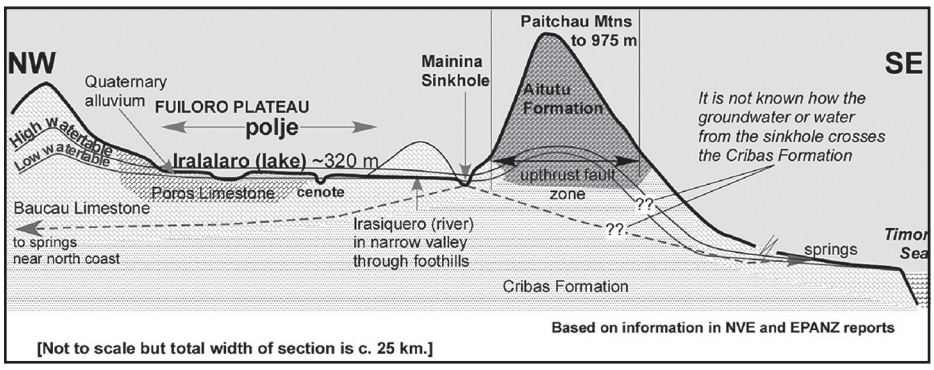

Figure 6: Schematic cross section through Iralalaro (lake) and Paitchau Mountains, Lautem District, Timor Leste.

Possible effects on the structural stability of the area should the flows diminish are acknowledged (EPANZ Services 2004). Any subsequent collapses that may occur within the system could have other compounding effects with regard to the ability of floodwaters to be carried away via the Mainina

sinkhole. While the surface consequences of any collapse deep within the Paitchau Range seem unlikely to be significant, the nature of karst drainage is such that effects potentially may be felt over a much wider area. On the other hand, the existing flow into the Mainina sinkhole varies significantly throughout the year, and there is no evidence of this having led to collapse within the karst. The possibility exists, however, that removing all, or most, of the last 5 m3/sec and the permanent lowering of water levels could be the trigger which destabilizes the system.

Proposals to provide protection to the special environmental values of the Iralalaro-Paitchau area are long-standing. The district contains the major block of 330 km2 dense lowland tropical and monsoon forest on the island of Timor and includes the heavily forested Paitchau Mountains. It has great ecological value and complex biodiversity and has enjoyed some level of protection either as a natural conservation reserve (1975-99), or 'Protected Wild Areas' from 1999. This protection, on paper at least, prohibited logging and other forms of extractive activity within its boundaries McWilliam (2003). There has been attempts since 2002 to establish a National Park and currently the Government is seeking to establish a mutually agreed framework for management with local communities bordering the forest area and is now considering a reserve category more in accord with IUCN's Category V (IUCN 1994), which permits a range of traditional practices to continue (McWilliam 2003), or IUCN Category VI where multiple use is not as big an issue.

A full inventory of the caves and other karst features of the region (especially pits, dolines, sinks, springs and dry stream courses) and their ecological, geological, archaeological, paleontological, and other values should be undertaken without delay as a first step in analyzing the karst networks and connections. Such an inventory would serve as the basis on which plans could be developed for the proper management of these resources.

There is a sizeable local human population, which derives its livelihood from agriculture in and around the lake. There is a serious concern that if the hydro-electric power scheme is built, over time the groundwater level in the polje may be systematically and permanently lowered. If this were to occur the livelihood of the Malahara community and other communities dependent on the lake, the groundwater as well as the associated ecosystem, would be jeopardized.

The Iralalaro area has excellent potential for interesting and significant research. The area has experienced little research except perhaps archaeological work and the biological surveys associated with the hydro-electric proposal. There is potential for significant research in the earth science area such as karst for research into understanding karst in tropical areas of Australasia and the role karst has in landscape evolution in recently uplifted areas. The understanding of karst and its relation to groundwater is fundamental to the future management and appropriate development of this part of Timor-Leste. A thorough understanding of the hydrological relationships of the system would assist in ensuring the sustainability of existing communities and in assessing impacts of proposed developments.

7. Conclusions

The viability and the impacts of the proposed Iralalaro hydro-electric scheme are of real concern. There are serious gaps in the site studies and serious limitations on the understanding of the area by the consultants designing the scheme. In conclusion, the scheme, in so far as we have been able to understand it, appears to have a number of very serious limitations which, unless they are addressed, could seriously undermine the scheme's viability, or at least cause significant cost overruns. Additional studies may address some of these concerns but there appears to be a reluctance to undertake studies on the fundamental nature of the area's karst.

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FUNGUS AND CAVE MANAGEMENT

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The emergence of white-nose syndrome (WNS) in multiple species of bats in the North Eastern States, USA has brought into stark relief our knowledge gaps when confronted with such threats to cave biota. The presence of cave bats in our environment is a given. There have been numerous occurrences of bat mortality due to insecticide use. It was initially thought that the fungal infections seen in affected bats of WNS were symptomatic rather than causative but it is now apparent that the fungus itself may be the reason for the mortality. It is imperative that cavers, speleological researchers and bat researchers not contribute to the spread of this syndrome between caves and to other localities.

To prevent fungal spread by cave visitors, stringent infection control procedures are needed. Fungi produce spores that survive for long periods in adverse conditions and are resistant to many biocides. It is vital that human movement between bat roosting sites is not the cause of spread of an infectious agent such as a fungus. It is quite feasible to use disposable overboots, gloves and overalls when one is part of a bat research team but what of the pencils, notebooks, helmets and lights that are needed for the next cave? What of the ropes and hardware needed for a vertical cave entrance in which there is a bat colony? Can one devise protocols for cleaning cave equipment such as fabric, ropes and metal? The containment and decontamination procedures recommended for preventing the spread of the white-nose fungus will be examined.

The fundamental dilemma for cavers is do we forego caving, or are there behavior modifications which we should undertake to prevent the spread of WNS to other areas of North America or for that matter internationally? What access restrictions to caves should cave managers' exercise to prevent the possible spread of WNS and should this be seasonal or year round? The consequences of the white-nose syndrome as an example of the spread of an infectious agent reminds us as cavers and managers of the complexity of the cave resources which we study and share with the public.

1. Introduction

The sudden appearance of the white-nose syndrome (WNS) in bats in winter 2006-7 demanded immediate attention to discover what was causing the high mortalities across a number of species and genera of bats using hibernation sites in caves or mines in New York State. The spread of the syndrome to neighboring states in the following year 2007-8 put the cave community, bat community and wildlife agencies on notice that continued spread would put bat populations at risk of regional extinction with the possibility that the endangered Indiana Bat would be at risk of extinction (USFWS 2008a).

At the start of any new wildlife disease episode, scientists start looking for a cause. In the case of bats, insecticides have caused deaths in the past. After the winter of 2007-8 it was apparent that there had been spread of WNS to new sites (USFWS 2008a). This pointed to an infectious agent spread either between bats or by human activities such as caving.

The NE Cave Conservancy, NY Department of Wildlife Conservation and the US Fish and Wildlife Service all initiated control procedures based on research to determine the causes and extent of the disease, access controls to sites and put in place hygiene and disinfection protocols to minimize the risk of researchers spreading the disease from site to site (USFWS 2008a and b).

This paper will now reflect on what is now known and examine the risk measures undertaken to control the spread of the disease. This may give a better understanding of the complexities of human interactions and their affects on caves and the biota, in this case bats which rely on the caves for their normal lifecycle. It will also examine the management and legal responsibilities of landowners, legislators and wildlife agencies when charged with protection of endangered species. This needs consideration because appropriate funding and skills are needed to successfully manage listed endangered species and the habitats on which they are dependent.

2. Epidemiology

The first descriptions of the syndrome identified several important factors. These were that bats in the over-wintering sites were behaving abnormally and were dead or in very poor condition and had surface fungal growths particularly around the nose. Multiple species were involved which would normally rule out viruses but could include bacteria or fungi. A viral agent has not been isolated from specimens using methods that would normally retrieve viruses (Tuttle, 2008). Alternatively, the syndrome could have been induced by climatic factors or from introduced chemicals such as insecticides or other toxic agents. Some of these factors have now been ruled out and it appears likely that it may be a particular cold loving fungal species (Blehert et al., 2008). It is still premature to say the *Geomyces sp* is the causative agent as Koch's postulates have not yet been fulfilled. Koch's postulates require that the presumptive infectious agent be put back into bats and cause the disease (Stajich, 2008). This research is now underway. If it is this fungus there are still a number of anomalies to be explained; why has it emerged now and why does it have such a high mortality? Normally most infections are not associated with such high mortalities and this has been explained on the basis of it not being a good Darwinian survival strategy (for the infectious agent) to kill off all the host population before the host population has a chance to reproduce. The high mortalities observed at the hibernation sites may lead to regional extinctions of the bat species concerned. Some post mortem observations are of significance (Blehert et al, 2008). The affected bats have much reduced fat reserves and fungal lesions associated with wing damage. It may be that the high mortality is because during hibernation there is lowered immune responsiveness which allows the fungus to get a hold and disturb the resting metabolism leading to fat store depletion as well as more epidermal invasion than would normally be the case for a skin infection with a fungus. These are factors that can only be answered with further research.

It appears that WNS is an infectious disease. It was retrospectively identified from a photograph taken in the 2005-6 winter. Observations in winter 2006-7 first drew attention to the syndrome and its significance. During the 2007-8 winter the disease was observed over a wider area and beyond New York State (USFWS 2008a. In January to March 2009, evidence of further geographic spreading has occurred with Pennsylvania, New Jersey, Virginia and West Virginia wildlife officers finding evidence of the infection at sites in their states (USFWS 2009).

There are good reasons to think that the fungal spores might be easily spread between bats by normal behaviors such as colonial living, cross infection at roosting sites or direct transfer during mutual grooming. If spread is from bat to bat then cross infection may extend to roosting sites used during all seasons and not just hibernation sites. Regardless of the role of bat to bat transmission, humans may also be contributing to the spread of WNS. There are indications that spread is associated with human assisted fungus transfer and the US Fish and Wildlife Service has now issued a Cave Advisory requesting a moratorium on all caving in affected states (USFWS 2009).

It is important that more research is undertaken on the geographic distribution of the fungus. At this stage it is only known that it is grows optimally at low temperatures such as occur in the hibernation caves and mines. Should the fungus have a wide distribution then the questions that need answering are why and how did the fungus get into these populations in the first place and why now? It may be that the fungus affecting the bats has acquired virulence factors represented by genes that allow cell and tissue invasion not represented in the rest of the fungus population. Answers to the question of geographic distribution and genetic variation amongst isolates will help answer some of these questions. Alternatively, the fungus affecting the bats could have been introduced by human agency from some quite different source not related to bat habitat in caves and mines.

3. Cave Visitors and Disinfection

Presumptively the infectious agent associated with WNS is a fungus (*Geomyces sp*) (Blehert et al., 2008). Fungi may have both sexual and asexual spores both of which contribute to fungus spread. In this case, spores have been seen in fruiting bodies on the surface of affected bats (conidia). Spores typically have toughened walls that are resistant to inactivation. This fungus does not appear to have caused human infection. The prevention of spread of WNS is based on cavers, cave biologists, and others not contributing to the geographic spread of the disease to other sites where bats can be infected.

Disinfectants can only work if they penetrate the infected material for sufficient time at a sufficient concentration to kill or inactivate the organisms concerned. Higher concentrations of chemical disinfectants are needed if there is a high biological load. Surface scrubbing and cleaning of excess mud from boots and clothing is appropriate prior to using a disinfectant.

Disinfection protocols were devised and published by the US Fish and Wildlife Service NE Region (USFWS 2008b). These are appropriate for laboratory scientific

staff going into the field but speleologists and cavers need to study them closely before undertaking caving in bat caves, mines or tunnels. There are many ways to cut down on clothes and equipment to reduce the risk of transporting infected material to a new site. The protocols request that all cave visitors in the affected region follow a decontamination procedure for all clothing, boots and equipment before departure and prior to going to another cave area. This needs careful thinking about because equipment includes helmets, lighting, ropes, harness and other hardware. In the case of scientists, as well as the above it includes all materials such as notebooks, pens and pencils, measuring instruments such as probes or thermometers, sampling materials such as specimen containers and bags. For any of these visitors it would also include cameras. This is a very daunting task to comply with, particularly as individuals are very jealous about their personal caving gear and its treatment. Except for underwater cameras, cameras are not designed for liquid disinfection protocols, however, 70% alcohol (or 70% isopropanol) swabbing would be both effective and should not be deleterious to modern cameras. It is not too much to dispose of pencils and paper after some form of permanent record keeping (photography). Deliberately taken samples or pathological specimens should only be taken where there are good laboratory protocols for handling infectious or genetic materials. Should multiple visits be contemplated to caves in affected areas some much more stringent protocols should be considered such as disposable outer clothing, treating helmet and light as disposable by using cheap LED headlights and construction helmets but this approach might preclude vertical cave visiting. There should also be a cleanup interval between successive visits and consideration should be given to using a different vehicle to each new site. None of this avoidance of cross-contamination between caves is intuitive but it is vital that cavers and researchers are not the medium of spread.

Even though fungi and their spores are difficult to inactivate it is generally considered that chlorine based disinfectants are the most satisfactory. The most effective are bleach or hypochlorite solutions. These act by disrupting nucleic acids but they also inactivate proteins by cross-linkages. The quaternary ammonium compounds are effective at disrupting bacteria and fungal hyphae but are less effective with the tough cell wall structures of spores and thus should not be used for cleaning soiled caving clothing, etc. Oxidizing agents such as hydrogen peroxide are also effective and have a place when used on metal surfaces but need probably too much care and technical knowledge for effective use by cavers.

For the laboratory worker, there are other ways of disinfecting such as autoclaving. The use of aldehyde treatments such as formaldehyde gas or solution or glutaraldehyde surface treatments have their place but only where there is a standardized protocol in the laboratory that recognizes the hazardous nature of the compounds. Some of the chlorine dioxide oxidizing agents such as Virkon S or Oxy-Sept 333 might be preferable in these situations if they can be shown to inactivate fungal spores. Germicidal ultraviolet treatment of surfaces is also effective but UV will not work on shadowed or covered areas.

In general, trips should be carefully planned so that gear taken into the cave is kept to a minimum. After coming out of the cave, boots and clothing should be cleaned of excess mud. All contaminated clothing and boots should be placed in sealed plastic bags for later decontamination. Other materials should also be transported in plastic bags before cleaning and swabbing to decontaminate them. The clothing and boots should be soaked in 1:10 bleach solution for at least 10 minutes before washing and drying, For nylon ropes, slings and harnesses mild detergent washing will certainly reduce the spore load. CMC Rescue Equipment suggest short bleach treatment is acceptable for ropes and webbing but this may cause slight discoloration (CMC Rescue). Such treatment is not acceptable to many cavers. Metal hardware needs scrubbing brush treatment in mild detergent but also 70% alcohol swabbing or hydrogen peroxide treatment would inactivate fungal spores without affecting the metal surfaces. Helmets and lights present another problem. They are made of a variety of materials that should be cleaned by scrubbing but then swabbed as above with either the alcohol or peroxide solutions followed by drying.

4. Caving and Access Controls

People resent controls on their liberties. Policy implementation requires effective communication methods to achieve desired outcomes. Now that the northeast States of the USA have restrictions on cave access (USFWS 2009) it is pertinent to pose questions such as:

- What level of control on caving activities do we expect if bat populations are at risk?
- Should this expectation of caving control be any different if an endangered species is at risk?
- How effective should the caving controls imposed by officialdom be adhered to given the constrained budgets of Federal and State agencies?

The organized speleological community accepts that some caves are gated or need permits for access. It is fortunate that many of the caves and mines in the northeast States of the USA that are hibernation caves are protected and gated.

The NE Cave Conservancy, NY Department of Wildlife Conservation and the US Fish and Wildlife Service immediately the seriousness of WNS became apparent applied movement and access controls (USDWS 2008a). They also implemented publicly available explanations of their actions. This was coupled with trying to obtain records of all cave visits to assist with research knowledge of the WNS. Once again these strictures may be acceptable to the organized speleological groups and researchers but quite different communication methods are needed with recreational cavers not part of the NSS. Signage at each entrance of all bat habitat caves at any time of year would be very difficult to implement.

Evidence that human activity was assisting the spread of WNS has now led to the USFWS issuing a Cave Advisory to stop caving activity in all states where WNS has been found and restrictions in neighboring areas as well as for cave scientific activities (USFWS 2009).

Exercising successful human access control to all caves, mines and tunnels will be difficult. The multiple ownership of the many caves across the northeast States is another complexity with which the caving and wildlife community needs to contend if the spread and magnitude of the disease in bats of the northeast States is to be controlled. The syndrome is associated with an infectious agent that does not respect boundaries between private land, public land or reserved land. Even if there was a total ban on entry into caves, mines and tunnels that bats frequented it may be that bat transmission would continue to occur but human cave access controls are warranted to help reduce the spread of the syndrome.

5. Discussion

WNS is spreading accompanied by such high mortality rates that regional extinctions may occur. There has been a recently recommended suspension of caving and associated activities in the all the northeast region of the United States because of evidence that spread has been assisted by human activity (USFWS 2009). This moratorium on caving needs a sophisticated communication program if it is to be successful.

This syndrome is now into its third year since being recognized. The initial responses of State and Federal wildlife biologists and the speleological community represented by NSS members and the North East Cave Conservancy were very quick to sound the alarm, to put in place movement and entry controls together with appropriate contamination and disinfection advice (USFWS 2008a). It is at this stage now we know the implications of continued spread of WNS that we need to pose the questions of whether the provisions of the Endangered Species Act 1973 are sufficient and whether agencies charged with protection of endangered and threatened species have the resources and budgets necessary to ensure that their responsibilities can be discharged satisfactorily. I do notice there have been few changes to the Endangered Species Act 1973 in the last 10 years. Is this because of politics or are US citizens happy with the provisions of the Endangered Species Act? Has WNS shown up shortcomings in Government and Agency responses and might inadequate funding of these agencies lead to regional extinctions?

Cavers and speleologists are always pleading a special case for bats. Is this valid? Certainly in relation to cave dwelling bats the actual caves are "critical habitat" for both the common species of bat and those listed as endangered. Do our caving activities harm bat populations? Do we have good constraints on the conduct of recreational caving? The NSS has been at the forefront of advocating responsible caving with both policies and activities promoting responsible caving. In Australia, the Australian Speleological Federation has both a Code of Ethics (ASFa) and a Minimal Impact Caving Code (ASFb). Is the caving community ready for much reduced cave access due to the continued spread of WNS? Codes are only useful amongst the indoctrinated caving fraternity and cannot reach people going caving outside the organized caving groups. This poses real problems for exercising a moratorium on caving on both public and private cave and mine owners. The moratorium will need high profile advertising as well as careful communication with private owners of caves and mines used by bats. Public land managers of caves will also need the resources to effectively communicate and manage cave access in their lands. Have cavers, speleologists and the bat fraternity been lobbying their politicians for more support for the money to communicate with the public as well as for bat research funding, for better on-ground monitoring and planning to reduce the likelihood of spread of the WNS and of regional bat extinctions?

Parallels have been drawn between WNS and colony collapse disorder in bees, but the only parallel I can see is that they may be associated with impaired immune function.

Regarding the chytrid fungal disease of frogs, there are many similarities between WNS and the frog disease although the frog fungus is spread by water borne routes and this may prove a more effective mechanism of spread. Both these fungal diseases were new to science as pathological fungal diseases when they were discovered. *Histoplasma capsulatum* is a fungus that grows in animal droppings and exposed humans get histoplasmosis which is a lung infection. Cavers exposed to bat guano may become infected with the fungus. Humans need to guard against exposure but because of the ubiquitous nature of the fungus, control of it has never been contemplated. In a similar way, cavers may get exposed to bat rabies in aerosols when in bat caves. Infections have been few in number and we now have vaccination protocols that are effective for bat workers and cavers who wish to protect themselves. Bat rabies infections do not appear to threaten the survival of bat populations as does the fungus infection associated with WNS. It is fortunate that bats in the USA are valued for insects they eat but elsewhere in the world they do not enjoy such values and are in fact feared because of their association with diseases or myths. Several newer virus diseases have emerged from bat populations and these have affected domestic animals and led to fatal human cases in Australia and Malaysia but as with rabies these do not appear to threaten the bats populations survival as does WNS. It is rare for a lethal syndrome such as WNS to occur in a wildlife population and it certainly needs a concerted research program to understand it.

6. Conclusions

As with any new or emerging disease there are many more field observations than hard research facts. It is imperative that research funding be increased and that the research be focused in ways that provide information with which to better manage our caves and the bats that use them.

There should be no complacency about the spread of this syndrome even if it is shown that the fungus is responsible and bat to bat transmission and spread is confirmed. If this fungus is so devastating in New England then it will be just as devastating in the rest of the northern United States and Canada where there is a true hibernation period. It might be the fungus can also affect over-wintering bats at higher ambient temperatures (12-16°C) than in the present affected sites. This makes it imperative that cave visitors be they researchers or cavers do not spread the fungus due to poor or inadequate adherence to the disinfection protocols either between caves on a trip but more importantly between different caving areas, states or regions or at worse continents.

The disinfection protocols for rope, webbing, hardware, lights, helmets and cameras could well have some more comprehensive research done to provide protocols that cavers can easily practice. It might be that the use of one of the chlorine dioxide or similar products could be recommended and give better disinfection as well as better acceptance by cavers. However, if the rescue professionals accept a disinfection protocol for ropes and harnesses with bleach treatment then cavers need to decide between foregoing caving or instituting such disinfection protocols.

The NSS Conservation Policy addresses the values of caves and why they are precious and need protection of all their values. In Australia, the Australian Speleological Federation has found that deliberately having a Code of Ethics (ASFa) and a Minimal Impact Caving Code (ASFb) has improved caver relations with managers, has improved caving practice and the Codes have been adopted by managers as requirements for use by recreational cavers. It is important that the conservation reasons behind these Codes are not hidden but that they are accessible to new generations of cavers. In these Codes, there are clauses covering not unduly disturbing bats and certainly not over-wintering populations. There is also a clause requiring cavers to disinfect clothing and gear between caves and caving areas. This clause probably needs expansion in the light of the WNS experience. These Policies and Codes of NSS or ASF are directed at cavers who join the organized caving fraternity but other methods are needed to reach the inquisitive first time cavers who head for a cave without mentoring from experienced cavers.

The WNS brings reality to your front door. It may cause local or widespread extinctions. Is there enough being done to understand it and control its spread, if this is possible? Is the community being well served by its legislators and backed up by budgetary support and visionary managers? If not what should be done?

7. Acknowledgements

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A COMPARATIVE CAVE CLIMATE STUDY IN SOUTHEASTERN ARIZONA -- PARTNERSHIPS IN CAVE MANAGEMENT AND CLIMATE CHANGE MODELING

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Abstract

Kartchner Caverns State Park showcases portions of a beautiful and live cavern complex that is located in southeastern Arizona. The caverns host a total of 7.08 kilometers of known and accessible passageways, of which only 1.6 kilometers have been developed for public viewing. The first public touring of one of the cavern's major rooms commenced on November 12, 1999. Two years later, Arizona State Parks (ASP) opened a second room for viewing and public education. Up to 750 people can tour these rooms in one day.

Pre-development cave studies predicted that when the cave opened as a show cave, temperatures would rise as a consequence of development. Predicted rises in cave temperatures have been further compounded by a decrease in annual total precipitation across the region. To establish adequate baselines for sound cave management, eighteen HOBO temperature data loggers were placed at various locations throughout the caverns. These stations were established in combination with other environmental monitoring stations that were set up prior to and since the opening. Four of these stations are located within the so-called "Back Section". This area of the caverns contains numerous passageways and rooms that remain undeveloped, and are visited only 1 or 2 times per year for research purposes.

Arizona has been experiencing severe drought conditions throughout the last seven years. Consequently, the area has been receiving significantly less than the average yearly rainfall that marked a previous wetter climate cycle that took place during the cavern's discovery and development. To answer the question of how much of the rise in cave temperature within the major show rooms is linked to visitation and management practices, or to the effects of the current regional drought, ASP has partnered with the U.S. Forest Service (USFS) to do a comparative study of cave climate data in other caves across southeastern Arizona. In addition to the Kartchner data set, temperature and relative humidity are collected at three USFS caves. These caves are comparable in size and elevation to Kartchner's Back Section area. One USFS station lies within the Whetstone Mountains, 16 kilometers west of the park. The others are located 64 kilometers to the south in the Huachuca Mountains, and 112 kilometers to the east in the Chiricahua Mountains. The USFS data set is combined with Kartchner's Back Section data to establish a regional baseline trend. Such data are helping cave managers distinguish changes associated with regional and cyclic climate changes, and those imparted by show cave operations and visitation levels. The first year of USFS data shows stable conditions that match with the data from the Back Section. Temperature and humidity data has not changed much since predevelopment. Because elevated and fluctuating temperatures characterize the tour route at Kartchner Caverns, research into ways to mitigate heat production and moisture loss continue to be major elements of our cave management. As additional data is collected each year, we hope to determine exactly how much change is related to natural climate variations versus that associated with show cave operations.

CAVE CONSERVANCY MANAGEMENT

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Cave conservancies are specialized land trusts that manage caves or karst features as their primary mission. They are usually non-profit organizations, and their management methodologies are diverse. The number of cave conservancies in the United States grew from one in 1968 to 25 in 2009. Conservancies have become the primary means by which appropriate caves and karst areas are managed by cavers. Resources have come from many hundreds of volunteers who have applied their diverse skills as cave managers, fund-raisers and speleologists. Their cave management control methods take different forms, including enlightened management by the owner, informal management arrangements, leases and various types of contracts, conservation easements, and fee simple ownership. Cave conservancies manage more than 185 properties, with over 3186 hectares of karst. These managed lands have more than 409 caves and more than 571 km of cave passage.

The conservancy movement's success can be attributed to various factors. Competence and success are norms within the organized caving community, and these values inspire other cavers to greater effort. Each subsequent managing group has built upon the accomplishments of the previous leaders. Applying a consistent management model typifies the conservancies that are continuing to grow. Conservation and access are the duel driving forces that provide the motivation cave conservancies use for building volunteer commitment and fundraising success. Although there are a few exceptions, cave conservancies rely on volunteers almost exclusively to manage and operate. Relatively high living standards in the United States since World War II, along with sufficient leisure time, have allowed enough interested cavers to have the resources necessary to build these organizations.

The cave conservancies were ranked according to several cave ownership factors and then grouped into nine levels that show the extent of the conservancy's success in acquiring caves. The most important factors contributing to cave acquisition success are listed in an approximate order of importance: (1) have cave acquisition as a primary mission; (2) operate where there are many caves; (3) have a management structure that is independent of outside control; (4) have an effective risk management plan; (5) have strong leadership capable of developing the organization, overcoming distractions, and staying on mission; (6) have effective resource gathering systems; and (7) be either owners, to acquire the most caves, or servers and do it well. These seven factors are correlated with cave acquisition success, and conservancies that can utilize these factors will acquire more caves than those that do not.

1. Cave Conservancy - Definition and Scope

Cave conservancies are specialized land trusts that manage caves or karst features as their primary mission. They are usually non-profit organizations, and their management methodologies are diverse. Conservancies that manage karst with few caves are usually and appropriately called karst conservancies. These are included in this study, although the focus of the research is cave management. When land trusts own caves, but cave management is not part of their mission, then these land trusts are not considered cave conservancies and they are not part of this study. The number of cave conservancies in the United States grew from one in 1968 to about 25 in 2009. Conservancies have become the primary means by which significant caves and karst areas are managed, other than those caves managed by governmental agencies. Cave conservancies in the United States now manage more than 185 properties, with over 3186 hectares of karst and at least 409 caves, with more than 571 kilometers of cave passage. Abbreviations are used exclusively in this paper to identify the 25 conservancies. Their names are listed in column 3 in Table 1.

2. Goals and Motivation

Cavers have experienced access problems from owners concerned about liability or owners who have the perception that people entering the caves are undesirable visitors

engaged in a high risk activity. Land development is another reason caves have been closed to cavers. The dual driving forces of cave access and conservation, both intellectual and emotional, drive the cave conservancy movement and account for much of its success. The environmental philosophy has provided the intellectual rationalization to justify the importance of cave conservation and protection by conservancies. Mineral formations are especially vulnerable to both intentional and unintentional damage, and once damaged, they usually remain so forever. Cave biota face the same threats and risks, as cave life has often evolved in isolated cave environments, with small populations that are vulnerable to extinction. The emphasis placed on either access or conservation varies according to the circumstances of each conservancy. Access threats can be a powerful incentive to a dedicated caver perceiving a favorite cave will be closed. Cave conservation has almost universal appeal and is the basis of marketing and tax exempt status. Educational interests also support the movement, as supporters envision the cave resource as a tool with which to educate for science and conservation. Once a conservancy is established, it may also rely more on the social dynamics of group cohesiveness to build an organization and achieve its goals. Many long-time and older cavers feel an obligation to protect the resources and to contribute to the activity in which they have been involved for much of their lives. Physical limitations from aging may change the nature of their participation to more managing and conserving than caving. Many cavers have also come to understand that good stewardship extends to protecting the land above the caves, as well as the cave passage below.

3. Volunteerism

Americans have served extensively as volunteers in all types of organizations throughout the history of the republic, so it is no surprise that cave conservancies rely on volunteers almost exclusively to manage and operate. With the exception of religious activities, no other society has a comparable amount of volunteer activity and the number and diversity of non-profit organizations as does the USA. The form taken by cave conservancies in the USA and the level of success is comparable to voluntarism in other types of non-profit organizations.

4. Funding

People who give their time to an organization as volunteer workers are making a "cash in kind" donation; this is the primary source of wealth for many cave conservancies, and often it is conservancy members who have been the major cash contributors as well. Several examples are BCCS, IKC, NSS, and SCCI, which are notable for their success in both these areas. Dues, donations, major gifts, small fundraising events, and fees for services are the most widely used means of fundraising. This is in addition to the extensive volunteer time that all cave conservancies receive in significant amounts. CCV is unique among cave conservancies in that it uses gaming as an effective fundraising tool. Establishing a gaming infrastructure is capital and labor intensive and accompanied by assorted risks. This form of funding is not likely to be used by other conservancies.

5. Cave Management Control Type

The following is the sequence of control levels that are used to classify the type of legal relationship the conservancy has with a cave property. The six methods identify in increasing order of strength the control the conservancy has in managing a cave property. SICLEO system: enlightened Self management by owner, Informal management arrangement, general Contract, Lease, Conservation Easement, and Own. Many conservancies use several of these methods. The Table 1 lists the primary method used by each conservancy.

6. Management Structure

All cave conservancies have some form of board management. They fall into four types. The most common is a board that is independent and self-perpetuating. The second is a board that has members appointed by another organization such as an NSS Grotto. Two conservancies have this structure: PCC and NJCC. This structure seems to present the most difficulty for effective management. The conservancies with boards appointed by other organizations as a group manage the fewest caves and have the least resources. The third board type has a strong paid executive. Conservancies are mostly volunteer organizations. Only two conservancies have paid staff. The president of TCC is an employee, and CCV has several paid fundraisers. The fourth type is an organization controlled by one person or a small group. This type will have a nominal board.

7. Nominal and Incidental Cave Conservancies

Some cave conservancies are not cave and land managers, but rather organizations with cave related missions such as public education, grant making, and cave conservation. While these functions are worthwhile and are often needed, they are not the focus of this study, which evaluated functions that relate to cave management and control. This type of conservancy is included in this study for comparison purposes. Some very significant land trusts are not included in this study. The Nature Conservancy, which owns many caves as an incidental part of its mission, is the most significant example of this type. Governmental agencies which own many of the most significant caves are also not

Group Factor Criteria 1	Name of Conservancy 2	Name Abbr 3	Prop 4	Hectares 5	Caves 6	Km 7	Primary Own 8
10 - Own at least: 25p, 100km, 400 ha	Southeastern Cave Conservancy	SCCI	27	492	63	121	Yes
9 - Own at least: 5 p, 25 km, 50 ha	National Speleological Society	NSS	13	74	18	64	Yes
	Butler Cave Conservation Society	BCCS	5	61	9	65	Yes
	Indiana Karst Conservancy	IKC	9	57	12	29	Yes
8 - Own at least: 4 p, 15 km, 10 ha	West Virginia Cave Conservancy	WVCC	7	12	8	68	Yes
	Cave Conservancy of Hawaii	CCH	4	19	2	40	Yes
7 - Own at least: 3 p, 10 km, 8 ha	Mid-Atlantic Karst Conservancy	MAKC	7	1768	39	14	No
	Texas Cave Management Assoc	TCMA	10	147	22	11	Yes
6 - Own or lease at least: 2 p, 5 km, 4 ha	Texas Cave Conservancy	TCC	66	89	171	8	No
	Cave Conservancy of the Virginias	CCV	2	69	5	46	Yes
	Appalachian Cave Conservancy	ACC	7	4	9	29	No
	Springfield Plateau Grotto	SPG	7	9	18	8.2	No
	Northeastern Cave Conservancy	NCC	5	10	9	5.1	Yes
5 - Own or lease at least: 1 p, 4 km, 1.2 ha	Carroll Cave Conservancy	CCC	1	1.2	1	19	Yes
	American Cave Conservation Association	ACCA	1	1.6	1	16	No
	Karst Conservancy of Illinois	KCI	1	1.4	1	9.7	Yes
4 - Own or lease at least: 1 p, 0.5 km, 0.1 ha	Michigan Karst Conservancy	MKC	3	238	5	0.8	Yes
	Rockcastle Karst Conservancy	RKC	1	123	1	1.2	Yes
	Missouri Caves & Karst Conservancy	MCKC	5	2	6	.5	No
	Western Cave Conservancy	WCC	2	6	2	1.2	Yes
3 - Own or lease at least: 1 cave	Bubble Cave LLC	BCL	2	3.6	4	.2	Yes
	Sinnett-Thorn Cave Conservancy	STCC	1	0	1	.8	No
	New Jersey Cave Conservancy	NJCC	1	0	2	.5	No
Total	Total		187	3187	409	558	
2 - Has no caves or land	Pennsylvania Cave Conservancy	PCC	0	0	0	0	No
	Canadian Cave Conservancy	CaCC	0	0	0	0	No
1 - Failed cave conservancies or transferred conservancy function to other organization	Black Hills Cave Conservancy	BHCC	0	0	0	0	No
	Bluegrass Karst Conservancy	BKC	0	0	0	0	No
	Ellis Cave Conservancy	ECC	0	0	0	0	No
	Greater Cincinnati Grotto - the conservancy function was given to RKC	GCG	0	0	0	0	No

Column Headings

1 - Criteria for ranking of conservancy - Own or lease: p = number of cave properties, km = kilometers of cave passage,
ha = number of hectares of karst land managed

2 - Conservancy name

3 - Conservancy abbreviation

4 - Number of properties owned, leased, or managed

5 - Number of acres owned, leased, or managed

6 - Number of caves owned, leased, or managed

7 - Miles of cave passage owned, leased, or managed
8 - Is cave or land ownership the primary means, more than half, of management or control?

Group Factor criteria 1	Abbr 3	Founding Date 9	Primary mission 10	Acq import 11	Ind Org 12	Branch 13	Service Area 14	Main area 15
10 - Own at least: 25p, 100km, 400 ha	SCCI	1991	Yes	Yes	Yes	O/C	States	TAG +
9 - Own at least: 5 p, 25 km, 50 ha	NSS	1939/1967	No	Yes	Yes	O/C	Nation	USA
	BCCS	1968	Yes	Yes	Yes	O/M	Region	The cove VA
	IKC	1985	Yes	Yes	Yes	O/C	State	S. IN
8 - Own at least: 4 p, 15 km, 10 ha	WVCC	1997	Yes	Yes	Yes	O/C	State	WV+
	CCH	2002	Yes	Yes	Yes	O/C	State	HI
7 - Own at least: 3 p, 10 km, 8 ha	MAKC	1997	Yes	Yes	Yes	O/P	States	PA+
	TCMA	1985	Yes	No	Yes	O/P	State	Texas
6 - Own or lease at least: 2 p, 5 km, 4 ha	TCC	1994	No	Yes	Yes	S/P,DC	State	Texas
	CCV	1980	No	No	Yes	O/M	States	VA WV
	ACC	1977	Yes	Yes	Yes	S/P	Region	SW VA+
	SPG	2006	No	Yes	Yes	S/C	Region	SW MO
	NCC	1978	Yes	Yes	Yes	O/C	States	NY+
5 - Own or lease at least: 1 p, 4 km, 1.2 ha	CCC	1998	Yes	No	Yes	O/M	1 cave	1 cave
	ACCA	1978/1986	No	No	Yes	S/P, SG	Nation	USA
	KCI	1998	No	Yes	Yes	O/P	State	IL
4 - Own or lease at least: 1 p, 0.5 km, 0.1 ha	MKC	1983	No	Yes	Yes	O/P	State	MI
	RKC	2004	No	No	Yes	O/P	1 cave	1 cave
	MCKC	1995	No	Yes	Yes	O/C	State	MO
	WCC	2002	No	Yes	Yes	O/C	States	CA +
3 - Own or lease at least: 1 cave	BCL	1999	No	No	Yes	O/C	State	WV
	STCC	?	No	No	No	S/P	1 cave	1 cave
	NJCC	1984	No	No	No	S/SG	State	NJ +
Total								
2 - Has no caves or land	PCC	1984	No	No	No	S/P	States	PA +
	CaCC	1986	No	No	Yes	S/P	Nation	Canada
1 - Failed cave conservancies or transferred conservancy function to other organization	BHCC	2002 est.	?	?	?	?	Region	SD
	BKC	2003	?	?	Yes	?	Region	KY
	ECC	1985	No	?	?	?	1 cave	1 cave
	GCG	1989/	No	?	No	S/P	1 cave	1 cave

Column Headings
9 - Organization founding date and cave conservancy function start date, if different
10 - Is cave ownership or acquisition the primary mission of the organization?
11 - Is acquisition of additional caves an important part of the organization's mission?
12 - Is the organization an independent organization not controlled by another organization or group of organizations?
13 - The 1st letter codes are O = Primarily Owner or S =Service provider to owner. The 2nd letter codes are the Beneficiaries,
C = Cavers, M = Members, P = the Public, DC = Developer or Corporation, and SG = a State or Government agency.
14 - The type of service area
15 - The main area of cave ownership or management. + sign = Conservancy has additional service areas.

included in the study.

8. Cave Acquisition Success Factors

The conservancy movement's success can be attributed to various factors. Competence and success are norms within the organized caving community, and these values inspire other cavers to greater effort. Each subsequent managing group has built upon the accomplishments of the previous leaders. Relatively high living standards in the United States since World War II, along with sufficient leisure time, have allowed enough interested cavers to have the resources necessary to build these organizations. All active conservancies have had some degree of success in meeting their goals. The significance of these varied accomplishments has often been quite important; however, this study only evaluated success of cave acquisition by any means that achieved operational control of caves. Public trust is necessary for the long-term survival of the organization, and most conservancies have done some work in establishing credibility among some components of the public. A potential follow-up study could evaluate karst management by conservancies. Long-term success of cave acquisition methods is more difficult to measure. For example, one may conclude that fee simple ownership represents a more effective long-term solution than leasing or other means of cave management control. There is insufficient long-term data to make a valid comparison. Present information indicates that many leased cave agreements continue for many years and that some convert to ownership. Ownership is usually very capital intensive. More time is needed to make conclusions on the relative effectiveness of different cave management control methods.

9. Methodology

We found seven factors related to cave acquisition success by cave conservancies. The twenty-five known cave conservancies were ranked according to their success in acquiring significant caves and cave properties in quantity.

The size of the managed property and length of the cave passage were used for practical reasons as proxies for cave and land significance, since no adequate information on the geologic, biologic, and aesthetic value of caves and land is available in a comparative format. The number of properties owned or leased is an indicator of cave acquisition commitment and effectiveness. These three criteria (property size, number of properties, and cave length) were used to create ten groups of increasingly stringent qualifications with group ten having the highest standards. Each of the twenty-five conservancies was placed in the highest group for which it met all three standards. A weighting system of these three criteria was used to rank each conservancy within its group. The researchers examined the practices, websites, and some publications and reports of each conservancy in addition to interviewing selected leaders. This study did not evaluate other valid accomplishment areas such as public education, grant making, or karst management that involved few or no caves.

10. Conclusions

The seven most important factors contributing to cave acquisition success are listed in an approximate order of importance. Please refer to Table 1 for data on each item.

1. Mission

All of the cave conservancies that own or manage significant caves either have cave ownership as a primary mission or have cave acquisition by various means as an important component of its mission. All of the conservancies in the four most effective groups, seven through ten, have one or both mission types. All conservancies with more than ten miles of cave passage have cave acquisition as their primary mission, except for two national organizations and CCV, which acquired a large cave under special circumstances. Organizations with missions that are clear and consistent have more properties than those that have experienced mission creep or flip between different or opposing missions.

Conservancies have a continuum of different cave access models. Their acquisitions range from caves that are completely open to visitation, to very restrictive and closed access caves, depending of the circumstances and philosophy of each conservancy leadership. The explorers, the preserver, the conservers, the scientists, the recreationalists, and the managers have specific interests. The mission emphasis of each conservancy varies significantly depending on the degree to which the leadership adheres to the interests of one or more of these groups. The explorer philosophy predominates in some conservancies that have made exceptional efforts to find, explore, map, and control new caves. They often have acquired caves that were never popular or were newly discovered. Recreational and project cavers dominate conservancies that have concentrated on acquiring popular recreational caves, usually for the purpose of maintaining open access. Conservation emphasis often predominates in conservancies that have restricted access.

2. Location

The conservancy's area of operation must have sufficient caves with perceived significance to justify the effort to acquire caves. Conservancies in Michigan, New Jersey, and the Northeast, for example, are constrained in

cave acquisition by a more limited supply compared to conservancies in Hawaii, Tennessee, Texas, Virginia, and West Virginia. The "Factors" table shows that groups 5 through 10 have more than 99 percent of the managed cave passage, and all of the conservancies but two are in cave rich areas. The WCC is limited in cave acquisition, as most of the significant caves in the western United States area are government owned. Conservancies in groups 6 and above function as cave conservancies and may have a karst conservancy function. Groups 3, 4, and 5 are mostly karst conservancies or one cave conservancy. Both location and mission may be a significant factor in the organization's emphasis as a cave or karst conservancy.

3. Management Structure

All of the conservancies in the groups 4 through 10 are independent organizations. Three of the five conservancies in group 2 and 3 are dependent organizations. For example, in dependent organizations, most of the board members are appointed by other organizations. This arrangement prevents the development of a strong organization agenda with the leadership to implement it. Leadership is dependent on the whims of other groups. Dependent organization structure appears to be very strongly correlated with limited cave acquisition.

4. Risk Management

Irrational fear of lawsuits and other calamities will prevent conservancies from pursuing cave acquisition. Cave acquisition will be effectively stopped if people who have an expectation that cave acquisition must have zero risk before it can be done become influential in the organizational leadership. The most effective conservancies have realistic and cost effective risk management plans, including plans to reduce negligence in the management of their properties. Some additional methods include liability insurance and liability waivers. A few conservancies are self-insured. They have also worked to mitigate members' irrational fears.

5. Leadership

Successful conservancies recognize the need for situational flexibility. They have usually not selected leaders with dogmatic ideologies or stubborn adherence to ideas that were not productive in their situation. Mission consistency, developing leadership, and a membership base are important factors for any organization to achieve. Organizations must develop and replenish their leadership base and have effective decision making processes. There is a positive correlation with the number of people involved in the leadership and the number of caves managed. All of the failed conservancies were weak in the leadership area.

6. Resource Gathering

Various fundraising methods, property gifts, barter, and volunteer labor have all been used by successful cave acquiring conservancies. All of the conservancies in groups 4 through10 have been effective in at least one area of resource gathering. Only one conservancy in group 3, BCL, has been effective in resource gathering. At this time only one conservancy generated most of its assets from unrelated sources. No evaluation was done on unrelated funding.

7. Owners, Servers, Customers, and Beneficiaries

In addition to the legal qualifications for tax exempt status, conservancies provide services to varied beneficiaries. In addition to future generations who benefit from protected caves, the main beneficiaries of the conservancies' efforts may vary. Historically, cavers have worked with cave owners as an effective strategy in meeting their various cave related goals.

This approach has evolved into the "servers" branch of conservancies. This branch has taken the idea of working with cave owners to its logical conclusion and provides cave management services to the cave owners. There are three sub-branches depending on the type of owner served. The "private cave owners" sub-branch, manages caves for land owners who appreciate this usually free service offered to them. In return, the conservancy gains cave access and can protect the cave. The "government" sub-branch, assist government agencies with publicly owned caves. The "developers" sub-branch servers assist companies and civic groups to manage caves in developments which have set aside land required as part of the land development. Cave management and consultant services may be provided to the developers.

The cave "owners" branch is composed of conservancies that have become the cave owners through fee simple land acquisition. The "owners" branch is split into sub-branches. One sub-branch, "cavers," serves cavers in general, in addition to the general public in some cases. They make their properties accessible to most people, with a few special exceptions of caves requiring special protection for conservation. The "owners" model, best typified by the SCCI, allows almost anyone to have access to its caves.

The other sub-branch of "owners," the "members," has fairly strict control of its caves. Their management plans tend to make their caves open for members and restrictive to others. The "members" is best typified by the BCCS, which restricts access to members and their guests for most

of its caves. It has regular expeditions during which other cavers and people with limited caving skills are allowed to enter appropriate caves. The "owners" branch has acquired more caves than the "servers"; however, in recent years the "servers" have been increasing their rate of cave acquisition.

A potential eighth factor, age, appears to be somewhat related to cave acquisition; however, the correlation is low. All of the oldest conservancies that started conservancy work before 1980 have done well and are in groups six and above; however, several conservancies founded in the 1980s are the least successful in acquiring caves. The most successful cave acquirer, SCCI, was not founded until 1991.

These seven factors are correlated with cave acquisition success, and we think the conservancies that consider these factors in their organization's management will acquire more caves than those that do not. It is recognized that correlation does not necessarily mean causation, so judgment is needed to evaluate decisions regarding cave acquisition in each situation. Additional information is available at the NSS Cave Conservancy Committee website, www.caves.org/committee/ccc.

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