OVERVIEW OF KARTCHNER CAVERNS, ARIZONA

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In this paper, the sequence of events for Kartchner Caverns and surrounding region are correlated and traced from the Mississippian Period to the present. Pre-cave events include the deposition of the Escabrosa Limestone during the Mississippian Period and block faulting and hydrothermal activity in the Miocene Epoch. The cave passages formed in the shallow phreatic zone ~ 200 Ka. Vadose events in the cave include the inwashing of pebble gravels and a maximum deposition of travertine during the Sangamon interglacial. Backflooding by undersaturated water caused bevelling of the limestone and travertine. Recent events include the habitation of the cave by vertebrates and invertebrates, and the discovery and development of the cave by humans.

This paper provides an overview of events affecting Kartchner Caverns. An outline of this sequence of events, integrated with respect to regional events, has been compiled from the literature and from the results of this Symposium (Table 1).

Kartchner Caverns is located in the Whetstone Mountains, ~13 km south of Benson, Arizona, USA, just west of Arizona State Highway 90. The cave is developed in a downdropped block of Mississippian Escabrosa Limestone. The cave is over 3 km long, and is developed primarily along one level at an elevation of ~1410 m (4625 ft). The cave contains spacious rooms, one as long as 100 m. Kartchner Caverns is Arizona's 25th and newest State Park and is due to open in November 1999.

PRE-CAVE EVENTS

Mississippian Escabrosa Limestone deposition began around 320 Ma (million years ago). These limestone units are currently exposed in the cave walls and ceiling (Jagnow 1999). The permeability of these units has influenced later groundwater movement and cave development.

The next major pre-cave event happened during the Miocene Epoch (13-5 Ma). Basin and Range tectonics created a graben and horst topography in Arizona where disconnected mountain ranges and valleys, such as the Whetstone Mountains and San Pedro Valley, became the predominant features. During this time the Escabrosa Limestone was faulted, and the block of limestone in which Kartchner Caverns was later developed was progressively downdropped against Precambrian alaskite granite (Jagnow 1999). Hydrothermal solutions ascended along fault zones which became filled with illite clay, quartz, and hematite. Temperatures of these hydrothermal solutions ranged from about 125-170°C as evidenced by fluid inclusion temperatures of the quartz. During this time the processes of cooling and thermal-mixing corrosion (Bögli 1980) may have dissolved some karstic cavities along the fault zones.

After the main Basin and Range thermal events, solutions cooled and deposited calcite as vein and spar material within the host limestone and along faults. Carbon-oxygen isotope values for two analyses of vein calcite are: $\delta^{13}C$ = -0.3‰, +0.6‰ and $\delta^{18}O$ = -12.4‰, -10.5‰, respectively. Calcite depositional temperatures based on these oxygen isotopes range from 30-40°C. Movement along these faults disaggregated or pulverized some of the vein calcite and the older vein quartz.

SHALLOW-PHREATIC EVENTS

Main cave passageways of Kartchner began to form during the Late Pleistocene Epoch. This time correlates with maximum filling of the San Pedro Valley with the fluvial and lacustrine St. David Formation, the upper unit of which is <730 Ka (thousand years ago) (Johnson *et al.* 1975). Cave passages in Kartchner are essentially horizontal and cut across bedding even where bedding dips at high angles. This indicates strong water-table control on cavern dissolution. The water table must have been stable at one level for a long period of time, and it must have been aggressive in order for it to cut across bedrock, impermeable fault gouge, and quartz veins alike. Cave dissolution began around 200 Ka or somewhat earlier. This age is known from dating the cave travertine: the oldest age of any dated speleothem in the cave is ~194 Ka (Ford & Hill 1999). This time may correlate with water table development in the St. David Formation. It is not known if the St. David Formation ever extended as high as the cave, but if it did, it could have provided the regional water table necessary for cave dissolution at the 1408-1411 m (4620-4630 ft) level.

A variety of domes, solution pockets, channels, and anastomoses exist in the Kartchner Caverns ceiling. These features also indicate that cave dissolution occurred at or near the water table in the shallow-phreatic zone. Ceiling solution pockets are interpreted to form primarily by the process of mixture-corrosion (Bögli 1980). However, gravitational convection may also play a secondary role (Ford & Williams 1989). Where vadose water descending along a joint or fracture encounters and mixes with water at the water table, a renewed aggressiveness occurs so that dissolution takes place up and into the joint. Convection of water then enlarges these voids to form ceiling pockets or domes along the joints.

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Table 1. Sequence of events in Kartchner Caverns correlated with that of the surrounding region. Regional geologic events are taken mainly from Linsay *et al.* (1990).

Time Interval	Events
	Pre-Cave Events
Mississippian (~320 Ma)	Deposition of the Escabrosa Limestone.
Miocene (~15-5 Ma)	Basin and Range faulting and uplift. Time of heating, influx of hydrothermal solutions along fault zones; solutions enriched in Si, Fe and other metals. Illite clay from underlying Piñal Schist fills fault zones. Quartz veins form at T=125-170°C within fault zones. Minor paleokarst development along fault zones. 'Birdsnest' quartz needles grow from hot solutions into illite-rectorite clay matrix in paleokarst cavities. San Pedro Valley forms by block faulting; Escabrosa Limestone segments are let down against Precambrian alaskite granite.
Pliocene-Pleistocene (~5-1 Ma)	Wet and cool period; perennial streams and marshes; fluvial and lacustrine sediment of the St. David Formation fills San Pedro Valley. Subsequent progradation of coarse-grained alluvial fans. Calcite precipitates as vein material within limestone and along faults at T=30-40°C. Renewed faulting pulverizes some of the calcite and quartz.
Late Pleistocene (<730 Ka)	Time of maximum valley filling. Upper part of St. David Formation <730 Ka.
	Shallow-Phreatic Events
~200 Ka	Water table stable (in St. David Formation?) at about 1410 m (4625 ft) elevation. Cave passages dissolve at or near the water table. Fault clay gouge residue from fault zones settles to the cave floor and forms blocky clay unit. Cave becomes air-filled and travertine starts to grow.
	Vadose Events
Illinoian glacial (170-120 Ka)	Granite wash unit deposits on erosional surface of St. David Formation. Granite wash debris washed into cave. First pebble-gravel (pg1) influx at ~130 Ka.
Sangamon interglacial (120-70 Ka)	Downcutting of valley fill; development of Whetstone Terrace across San Pedro Valley. Time of warm, humid, more-forested climate. Major amount of speleothem growth. Second pebble-gravel (pg2) influx at ~100 Ka. Aggressive flood water enters from downcutting Guindani Wash and creates bevels. Alteration of illite clay to nontronite under high pH, low Eh conditions. Sloth bones wash into the cave ~85 Ka.
Wisconsin glacial (70-10 Ka)	San Pedro River cuts down through Whetsone Terrace. A Pleistocene lake exists in San Pedro Valley from 30-10 Ka. Travertine growth declines. Bats inhabit the cave by 50 - 40 Ka.
Holocene (10 Ka to present)	Downcutting of San Pedro River to present level. Wetter climate replaced by arid desert climate. Travertine growth continues to decline. Earthquake activity causes minor speleothem damage. Flood water still backs up into lower sections of the cave. Discovery and development by humans.

Since no deep-phreatic pits or other bathyphreatic features are known in the area of Kartchner Caverns (Lange 1999), the phreatic regime of cave development was probably entirely shallow rather than deep. Phreatic scallops in the cave measure 0.3-0.6 m in length, corresponding to a water velocity of ~1.2 cm/s (Curl 1974). Joints, rather than faults, have controlled the position of cave passages in Kartchner Caverns. This is typical of caves in general (Ford & Williams 1989).

VADOSE EVENTS

Even later (<200 Ka), after the main episode of cave development at or near the water table, aggressive solutions continued to dissolve the host limestone as indicated by the many corrosion notches and bevels in the cave. Corrosion notches are indentations in bedrock walls formed by seasonal flooding, where the incoming water has not equilibriated with limestone and is still aggressive with respect to it. Corrosion bevels are an extension of notches, where a flat roof is created by aggressive back-up flood water, regardless of geologic structure (Ford & Williams 1989). Corrosion bevels in Kartchner Caverns are well developed in many areas of the cave, and they occur both in limestone (Graf 1999, Fig. 4) and travertine (Ford & Hill 1999, Fig. 3). Leveling data on more than 80 different corrosion bevels in Kartchner show that these features occur at many elevations. Hence, the bevels most likely correspond to a number of flood events, where water became ponded at different levels between impermeable fault 'locks' during the cave's vadose history (Graf 1999).

Vadose scalloping can be found on travertine and bedrock in some parts of the cave. The size and asymmetry of these scallops record the direction and velocity of past intermittent vadose stream flow. Also, vadose downcutting of sediment and the presence of black, manganese-coated stream clasts in downcut channels is further evidence of vadose flow in Kartchner Caverns (Hill 1999b).

Sometime after the cave became air filled, it was inhabited by bats and also visited by other animals. Sloth bones found in the cave have been uranium-series dated at ~85 Ka (J. Mead & C. Johnson, pers. com., 1999), and bat bones (from *Myotis velifer*, the same species that resides in the cave today) have been dated at ~50-45 Ka (Buecher & Sidner 1999). Fossil insects (mites) have been isolated from travertine dated at ~100-90 Ka (Davis 1999), and insects have continued to populate the cave until the present time (Welbourn 1999).

Travertine decoration in Kartchner also occurred under air-filled vadose conditions (Hill 1999a). This travertine has been dated from almost 200 Ka to ~40 Ka, and records a major amount of deposition during the warm, humid climate of the Sangamon interglacial (Ford & Hill 1999). A higher percentage of trees and sagebrush existed on the surface during the period ~176 – 78 Ka, as determined by pollen analysis of cave travertine (Davis 1999). A number of speleothems are still growing in Kartchner Caverns today, even under the arid desert surface conditions, and this 'live' travertine accounts for the exceptional beauty of the cave.

The most recent events in the history of Kartchner Caverns were the discovery and exploration of the cave by cavers Tufts and Tenen (1999), and the development of Kartchner Caverns into an Arizona State Park. Of special conservation significance is the study by Buecher (1999) on the microclimate of the cave. The parameters of air temperature, soil temperature, relative humidity, airflow, and carbon-dioxide and radon levels in the cave were all monitored so that the original pristine conditions of the cave could be known and maintained in the future.

CONCLUSIONS

This paper is a synthesis of information that relates to the history of events for Kartchner Caverns. In summary, these events are:

(1) Pre-cave events. Deposition of the Escabrosa Limestone took place in the Mississippian Period, and Basin and Range block faulting and hydrothermal activity occurred in the Miocene Epoch. Minor paleokarst development along faults may have also developed during the Miocene. The clay mineral, illite, in the faults was changed to rectorite by hydrothermal solutions, and quartz needles grew into the rectorite within paleokarst cavities.

(2) Shallow-phreatic events. Dissolution of Kartchner Caverns in the shallow-phreatic zone took place at about 200 Ka or somewhat earlier. Autochthonous residue from the dissolution of the Escabrosa Limestone formed a blocky clay unit on the floor in parts of the cave.

(3) Vadose events. Pebble gravels were washed into the cave from the surface and overlie the blocky clay unit. Illite-rectorite clay was reconstituted to nontronite under high pH, low Eh back-water flood conditions, and back-up flood water also bevelled limestone and cave travertine. Maximum speleothem growth took place during the Sangamon interglacial when the climate was more humid and the surface more forested than it is today. Invertebrate and vertebrate animals inhabited the cave soon after it became air filled. Finally, the cave was discovered by humans and developed as Arizona's newest State Park.

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