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XIV

PROCEEDINGS

14th International Symposium
on Vulcanospeleology

Undara Volcanic National Park
Queensland, Australia

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14th INTERNATIONAL SYMPOSIUM ON VULCANOSPELEOLOGY

UNDARA VOLCANIC NATIONAL PARK, QUEENSLAND, AUSTRALIA
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Edited by
Gregory J. Middleton

Proceedings of the 14th International Symposium on Vulcanospeleology
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14th International Symposium on Vulcanospeleology,

UNDARA EXPERIENCE, NORTH QUEENSLAND, AUGUST 2010

The participants: Back Row, left to right:

Nicholas White, Greg Middleton, Árni Stefánsson, Caba Olah, Stephan Kempe, Jan-Paul Van der Pas, Harry Marinakis, Gerry Collins, Greg Tunnock, Peter Whitehead, Philip Holberton, John Brush, Tony Culberg, Martin Mills, Arthur Clarke.

Front Row, left to right:

Kenneth Ingham, Diana Northup, Gunnhildur Stefansdóttir, George Szentes, Julia James, Anne Atkinson, Mick Godwin, Siobhan Carter, Pat Culberg, Marj Coggan, Susan White, Kirsty Mills.

Absent: Lana Little, Nick Smith

Photo by Kenneth Ingham, 14 August 2010

Preface

The 14th International Symposium on Vulcanospeleology was held at Undara Volcanic National Park in far North Queensland, Australia, 12-17 August 2010, following a Pre-Symposium Excursion to the Western Volcanic province of Victoria, about 3000 kilometres to the south. The Symposium was supported the Australian Speleological Federation, Australasian Cave & Karst Management Association and the Queensland Parks & Wildlife Service. There were 30 participants, 11 of whom were from outside Australia, and a total of 19 presentations were delivered (two of them on behalf of authors unable to attend).

These Proceedings have been produced as PDF files on a DVD, to minimise costs and resource use. Of course individual papers or the whole volume can be printed if desired. A separate PDF file of each paper (except abstracts) has also been provided. The Proceedings are also provided in EPUB format, for anyone wanting to read them on an e-Reader (but the transfer to this format is much inferior to PDF; figures have been transferred to the end of most papers and table formats have been changed).

Thanks to the cooperation of all presenters, the DVD also contains the PowerPoint files used by the various authors to present their papers. These should not be used or re-presented without full acknowledgement of authorship and source.

The Symposium and Excursion could not have taken place without the active participation and cooperation of a number of people. At the risk of omitting someone, I would like to acknowledge the following:

• Cathie Plowman (who was unable to attend) for arranging design of the logo and production of the symposium bags and polo shirts.

• Ken Grimes (also unable to attend the symposium proper) for planning and organising the highly successful excursion to Western Victoria, with assistance from Susan & Nicholas White and others.

• Rauleigh Webb, of ACKMA, for setting up and maintaining our website.

• Julia James for preparing the abstracts, planning and running the scientific program.

• Tony Culberg for taking charge of the finances.

• Assistance in various forms was also given by Doug Irvine and Les Pearson of Chillagoe Caving Club, Lana Little and Nick Smith of the Queensland Parks & Wildlife Service and John Brush.

• Greatly contributing to the success of the event were Mayor Tom Gilmore of Tablelands Regional Council who opened the symposium, Gerry and Bram Collins and the staff of the Undara Experience who looked after us at Undara, Joe Lockyer of Bedrock Village, Mount Surprise, who arranged and led our excursion to The Wall, Tallaroo Hot Springs and Copperfield Gorge.

Special mention is due to Anne Atkinson and Mick Godwin, two people whose contributions to the study, documentation and promotion of the Undara Caves have been outstanding. Both Anne and Mick, despite not being in good health, made a special effort to participate in the symposium and in so doing contributed significantly to its success. All participants wish them speedy recoveries.

Finally, my thanks to all authors of presentations who have made their papers available for inclusion in these proceedings – the on-going legacy of the 14th International Symposium.

Greg Middleton

Convenor and Editor

Sandy Bay, Tasmania, December 2010

The Regional Context of the McBride Basalt Province and the Formation of the Undara Lava Flows, Tubes, Rises and Depressions

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Abstract

The McBride Basalt Province covers approximately 5500 km² and is one of 11 discontinuous regions of Cenozoic volcanic rocks in north Queensland. These provinces are the northernmost part of a chain of volcanics that extend down the entire eastern coast of Australia, from the Torres Strait to southern Tasmania. These volcanics can be subdivided into central volcano provinces, lava field provinces and lesser leucitite provinces. The central volcano and leucitite provinces contain some felsic volcanics and form hotspot trails, whereas the lava field provinces are entirely mafic and do not have a well defined age-latitude relationship. All of the north Queensland provinces are of the lava field type and are centred around the Great Divide, suggesting a genetic relationship between the divide and the volcanic provinces.

164 eruption centres have been identified within the McBride Basalt Province. The majority of flows are less than 3 Ma, with the youngest volcano (Kinrara) being less than 50,000 y. Remnants of older flows of around 8 Ma occur in the southwest. A hiatus in eruptions is evident from 8 Ma to 3 Ma.

Lavas from the 190,000 year old Undara volcano, cover about 1550 km². Undara crater is nearly circular with a diameter of around 330 m and is about 60 m deep. It forms the highest point of the McBride Basalt Province, at 1020 m a.s.l., although its low rim rises only 20 m above the surrounding lava field. Unusually for the McBride Province, the Undara vent does not have associated pyroclastic material.

The longest of the Undara flows is some 160 km, with an average gradient of just 0.3°. Thermal insulation provided by the solidification of the crust above the actively flowing lava is required to produce flows of such length. In the distal regions, the confinement of the initial flows within pre-existing drainage channels also assists the development of such long flows. Lava tube caves occur up to 30 km from Undara crater, where the gradient is > 0.6°. Up to five successive flow units, demarcated by pahoehoe surfaces, can be seen in the walls of some caves. The caves developed by erosion through the lower units. Entrance to the caves is by steep collapse structures.

Lava inflation features, such as lava-rise ridges and lava-rise pits, are common in the Undara flows. A particularly long lava-rise ridge, known as "The Wall", extends for some 40 km. It is up to 20 high, and around 200 m wide. Formation was due to the inflation of a flow in a confined channel. Where a section of a flow solidifies, it is not underlain by actively flowing lava, so can not inflate. Where the surrounding region may undergo inflation, a depression is left at the level of the pre-inflation surface. Such lava inflation pits have more gently sloping sides than lava tube collapses and may contain pahoehoe floors that continue up their flanks. A series of lava-rise pits occur in close alignment to the main lava tube lines at Undara. In places, lava tubes head towards a depression, then are deflected around the solidified obstruction.

Introduction

The Undara lava field is the most extensive of the basalt flows of the McBride Basalt Province in north Queensland, which forms part of the East Australian Volcanic Zone. The Undara basalts are well known for the impressive lava tube caves, but are also notable for the length of the flows and for the lava inflation structures that have developed on the flows.

This paper seeks to place the Undara lava field into its regional context, by providing an overview of the Eastern Australia Volcanic Zone and the McBride Basalt Province. The nature of the Undara basalt flows and their physical features are also reviewed. Although some of the surface details at Undara have been lost through weathering and erosion, similar structures occur in younger and better-preserved basalt flows, such as the Toomba basalt flow, in the Nulla Basalt Province, approximately 190 km to the south, and in Hawaii, where they can be observed during their formation.

The Eastern Australia Volcanic Zone

The east Australian passive margin is characterised by Cainozoic volcanic provinces, which occur from Torres Strait to Tasmania (Fig. 1). These volcanics can be subdivided into central volcano provinces, leucitite provinces and lava field provinces (Wellman & McDougall 1974).
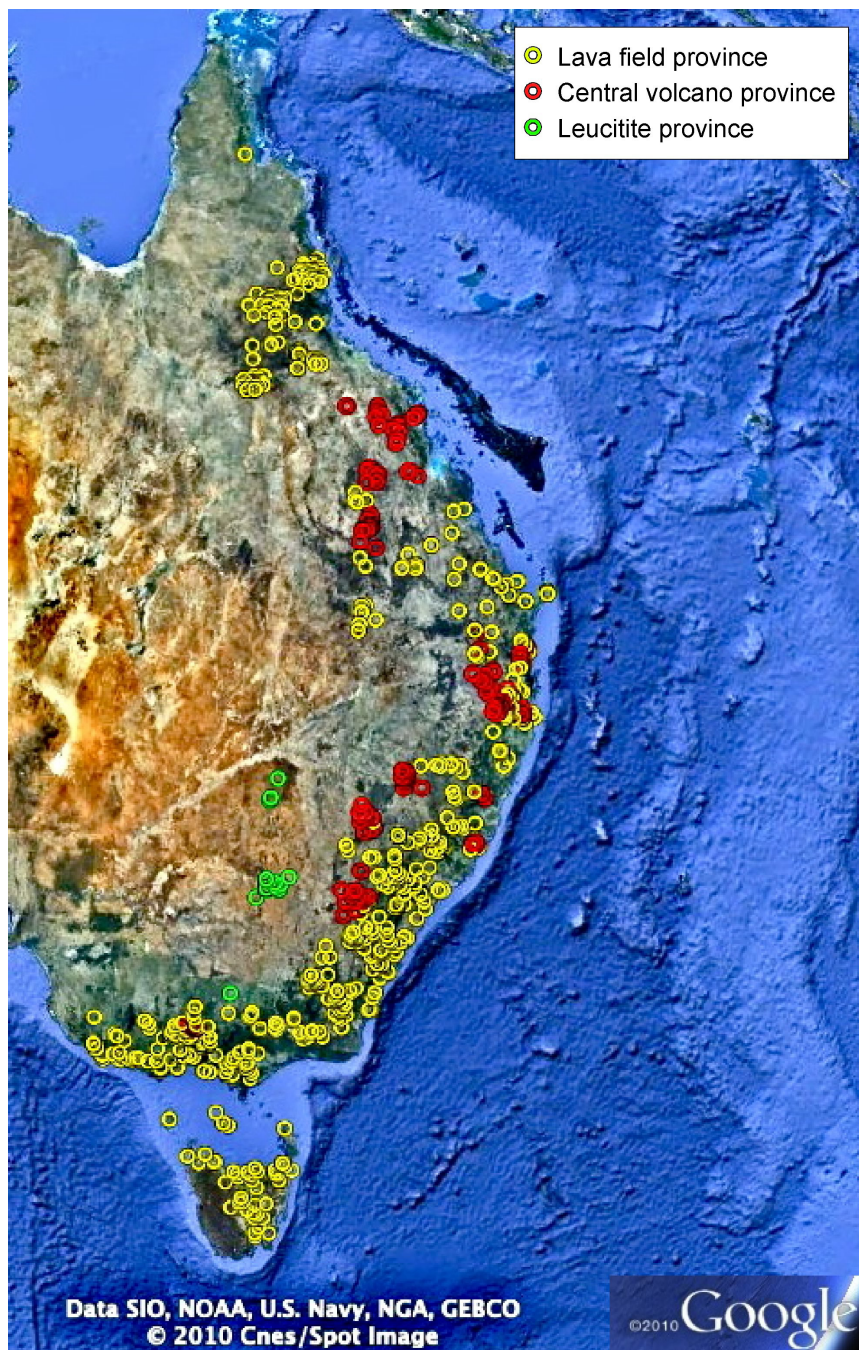
Fig. 1. Locations of Cainozoic volcanic rocks dated by K-Ar, compiled by (Gibson 2007) plotted on Google Earth. The trails of the Tasmantid seamounts can be seen to the east.

The central volcano and leucitite provinces form a hotspot trail with a well-defined age-latitude relationship (Wellman & McDougall 1974; Duncan & McDougall 1989). The oldest of the central volcano provinces is the Hillsborough Province in central Queensland, with an average age of 33.2 Ma (Duncan & McDougall 1989). Ages decrease with latitude, with the youngest felsic volcanism being the Macdon-Trentham Province of Victoria with an age of 6 – 7 Ma (Price et al. 2003). The oldest felsic samples from the Hillsborough and Macedon-Trentham Provinces are 34.1 ± 0.8 Ma (McDougall & Slessar 1972) and 8.3 ± 0.1 Ma (Gibson 2007) respectively. There is a distance of 1865 km between these two locations, giving an overall migration rate of 72.3 ± 2.5 mm/yr. Wellman & McDougall (1974) and Duncan & McDougall (1989) used the mean age of analysed samples for each province to derive average migration rates of 66 ± 5 mm/yr and 65 ± 3 mm/yr respectively. The predicted latitude for the present location of the hotspot, derived from the oldest felsic age in each province, is 40.6°S (Fig. 2a), which is close to the 40.8°S calculated by (Wellman & McDougall 1974) using the mean ages. Using the oldest sample for each province may provide a better indication of the relative location of the hotspot over time and avoids possible sampling bias, whereby the numbers of samples of a particular age may give an undue weighting in the calculation of the mean. Furthermore, although Wellman & McDougall (1974) claim that a southward younging can be observed within certain provinces, such as Peak Range, Nandewar and Warrumbungle, the data compiled by Gibson (2007) show a step-wise age-latitude plot, with each province having a much more restricted latitude range than that predicted by the continuous movement of the lithosphere over a stationary hotspot (Fig. 2b). This implies that magma from the sub-lithospheric hotspot source migrates into the lithosphere and is carried along with the lithosphere until the connection with the hotspot plume is broken and the next province commences at a higher latitude.

The central volcano provinces are predominantly basaltic, but include felsic lava flows or intrusions. The provinces are centred around a central vent or cluster of vents. The leucitite provinces contain mafic, high-K minor intrusives. They are petrologically and spatially distinct, being restricted to three aligned provinces in central N.S.W. and northern Victoria. The lava field provinces are exclusively basaltic. They contain abundant vents that are dispersed throughout the province, with widespread lava flows. Flows are generally relatively thin, but valley-filling flows can produce basalts in excess of 100 m thick. All of the north Queensland provinces are of the lava field type and are centred around the Great Divide.
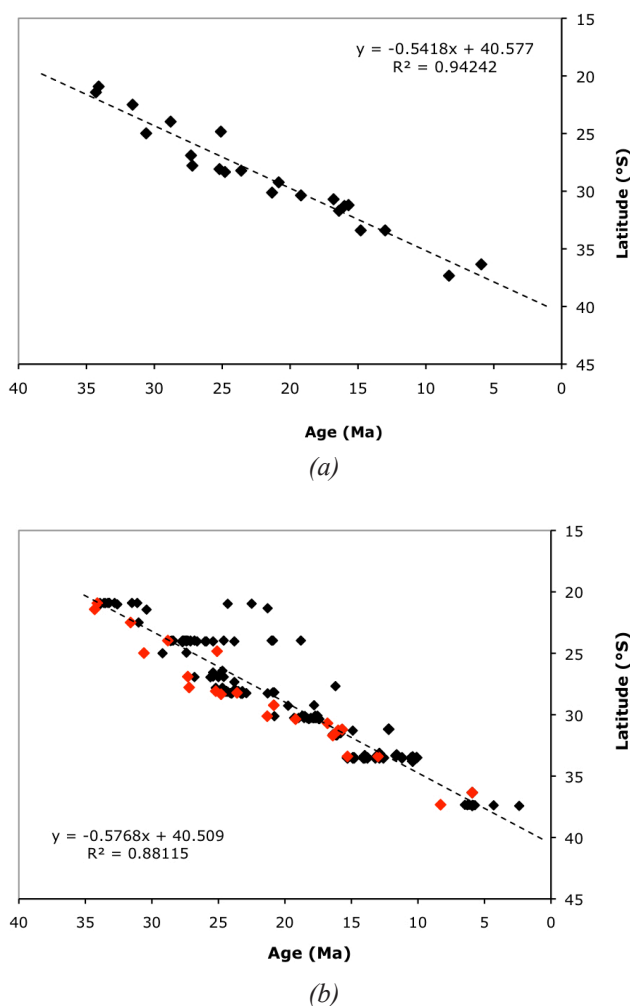
(a)

(b)

Fig. 2. Age:latitude relationship for the central volcano and leucitite provinces. (a) Oldest sample from each province. (b) All dated samples, showing the step-wise relationship between provinces. Red points are the oldest samples for each province.

The trend of the apparent hotspot locations agrees with the northward migration of the Australian plate. A postulated trend (Fig. 3a) from the oldest (Hillsborough) to youngest (Macedon-Trentham) central volcanic provinces, passes through the leucitite province in central New South Wales and is close to the current movement of the Australian plate, as determined by Global Positioning System measurements (Jet Propulsion Laboratory 2010). Such a trend, however, does not align with the trend of the Tasmantid seamounts to the east, which have a near north-south alignment (Fig. 1). A similar, north-south trend (Fig. 3b) of the central volcanic provinces would align the N.S.W. leucitite volcanics with the co-magmatic Cosgrove leucitite in north-central Victoria (Birch 1978), but leaves the Macedon-Trentham Province considerably to the west of the central volcanics trend. The divergence of the current movement of the Australian plate, as determined by GPS measurements, from the long-term trend, may be due to recent rotation of the Australian

plate. A more easterly movement is thought to have started approximately 6 million years ago, due to the interaction of the Ontong Java Plateau with the Australia plate, which still continues today (Wessel & Kroenke 2000). Fig. 3c gives possible trends for an initial northerly migration of the Australian plate, with a more recent easterly movement.

In contrast to the central volcano provinces, the lava field provinces show little apparent correlation of age to their latitude. A plot of all Cainozoic K-Ar ages for eastern Australia (Gibson 2007) is shown in Fig. 4.

The McBride Basalt Province

The McBride Province is one of nine lava field provinces in north Queensland. The provinces are closely aligned to the Great Divide, which may suggest a relationship between volcanism and uplift. Wyatt & Webb (1970), however, noted that basalts in the Chudleigh, Sturgeon and Nulla Provinces, to the south of the McBride Province, flowed away from the divide down preexisting drainages. The divide must therefore have occupied its present position prior to the development of these provinces. But some post-eruption uplift is also evidenced by the rejuvenation of drainages at rates that are much greater than that of the regional denudation (Wyatt & Webb 1970).

The McBride Province covers approximately 5500 km² and contains some 164 eruption centres (Griffin 1977). It forms a topographical dome, with flows generally radiating away from the central area (Fig. 5). The highest point is Undara crater, which is located on the Great Divide, at an elevation of 1020 m above sea level (a.s.l.). The periphery of the main body of flows has an elevation of 500 – 600 m a.s.l., with the most distal flows having elevations of around 400 m a.s.l. Although it is possible that the total thickness of basalt is up to 500 m, basalts adjacent to granitic inliers, 17 km west of Undara crater, have a surface elevation of around 650 m a.s.l., so it appears that the province is located on a preexisting regional dome, similar to that on which the Chudleigh, Sturgeon and Nulla Provinces are centred. There is a relatively constant slope of the basalts from the 700 m elevation to Undara crater, however, suggesting that the basalt pile may well be over 300 m thick.

The oldest flows in the McBride Province have K-Ar dates of 8.0 Ma (Griffin & McDougall 1975, recalculated to IUGS constants by Gibson 2007). The bulk of the eruptions, however, have occurred within the last 2.7 Ma. There have been spasmodic, but essentially continuous eruptions since that time, with the youngest centre being Kinrara, 22 km southeast of Undara crater. Kinrara has a K-Ar age of 52 ka (Griffin & McDougall 1975), but this age
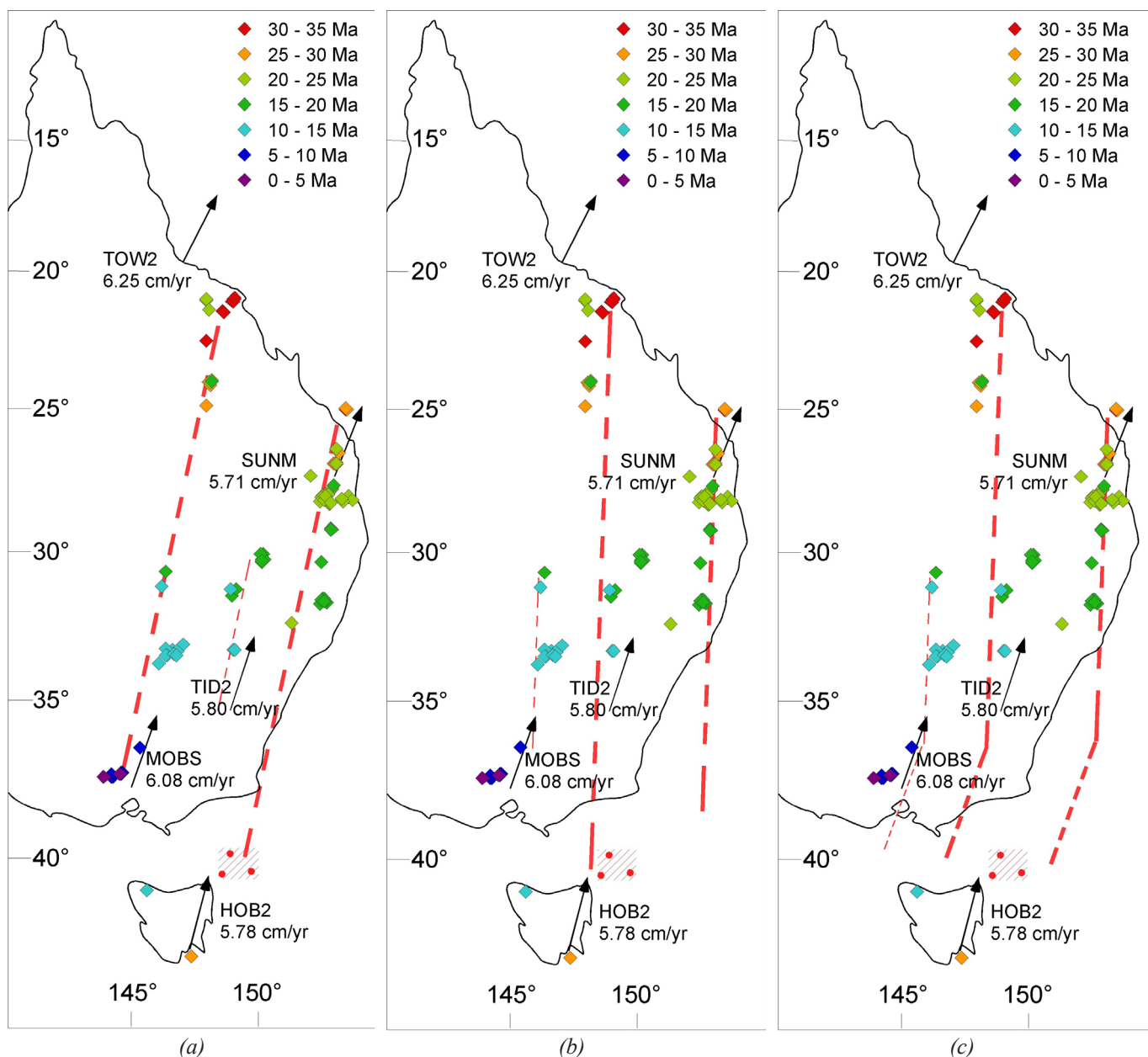
Fig. 3. Postulated trends in the Australian plate, from central volcano and leucitite province ages. (a) Trend defined from linking the oldest and youngest central volcano provinces. (b) Northward trend, similar to that of the Tasmantid seamount chain (Fig. 1). (c) Northward trend, followed by an easterly rotation 6 million years ago. Dots and hashed region off northeast Tasmania is a zone of recent earthquakes (Wellman 1989). Maps are drawn to a transverse Mercator projection, to preserve directions as straight lines. Arrows show the direction of movement of the Australian plate (Jet Propulsion Laboratory 2010).

may be regarded as a maximum age. The degree of preservation of the Kinrara basalts is similar to that of the Toomba flow, in the Nulla province, which is only 18 ka (Stephenson *et al.* 1978). The McBride Province has a similar age range to the Chudleigh, Sturgeon and Nulla provinces to the south and to the Atherton province to the north. As intermittent volcanism has been occurring for at least the last 5 million years, it is probable that eruptions will continue into the future, although volcanism appears to be waning (Whitehead *et al.* 2007).

Undara Basalts

The Undara lava flows cover an area of 1510 km²

(Stephenson *et al.* 1998). K-Ar dates taken from Undara crater and from "The Wall", 54 km to the northwest, have identical ages of 0.20 Ma (Griffin & McDougall 1975, recalculated to IUGS constants by Gibson 2007). Most of the lavas flowed to the west and north, with one flow to the east. Lava tubes developed in the flows to the west, northwest and north. Caves exist up to 30 km from the crater, where the gradient is greater than 0.7°. Numerous structures formed by lava inflation occur, including a prominent lava rise ridge known as "The Wall" (Atkinson *et al.* 1975), which starts 60 km down flow from Undara crater and extends for another 40 km.
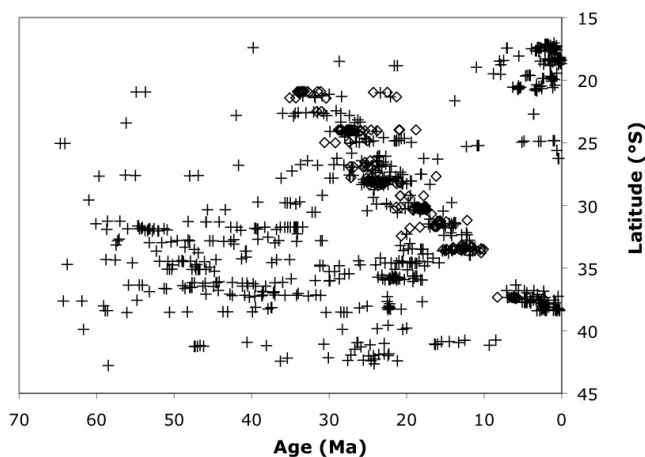
Fig. 4. Age:latitude relationship for Cainozoic igneous rocks of eastern Australia. Samples from central volcano and leucitie provinces are shown as diamonds, all others as crosses.

Undara crater lies close to the centre of the McBride Province and marks the highest elevation of the province. The crater has a low rim about 330 m in diameter that rises about 20 m above the surrounding land. The crater is about 60 m deep and drops steeply to a floor about 190 m across. This low cone is the only source that has been identified for the extensive Undara lava fields.

Undara crater is unusual in that it occurs at the top of a regional dome rather than being the summit of a discernible volcano. Although any lava pile from a single vent may essentially be equated to forming a shield volcano, the gradients radiating out to 5 km from Undara crater range from only 0.7° to 1.4°, which is considerably less than those of typical shield volcanoes. Mauna Loa, for example, has slopes ranging from around 7°- 9° and Skjaldbreiour ("broad shield" in Icelandic) has slopes of around 6°-7°. The existence of such a small cone perched on top of several hundred metres of basalt, suggests that the present Undara crater is simply the last manifestation of the vent that produced the Undara lava field.

Flows from Undara extend up to 160 km from the vent. The north Queensland basalt provinces contain many flows of considerable length, with twenty flows being known to extend for over 50 km (Stephenson 2005). These lengths were achieved despite a low regional gradient of 0.2°- 0.4° for the distal portions of many of the flows. The lavas were not unusual with regards to their composition, eruption temperature or viscosity (Stephenson *et al.* 1998). Notably, however, modelled temperatures suggest that there was very little cooling of the lavas down the length of the flows and there is little change in the basalt texture from the proximal to
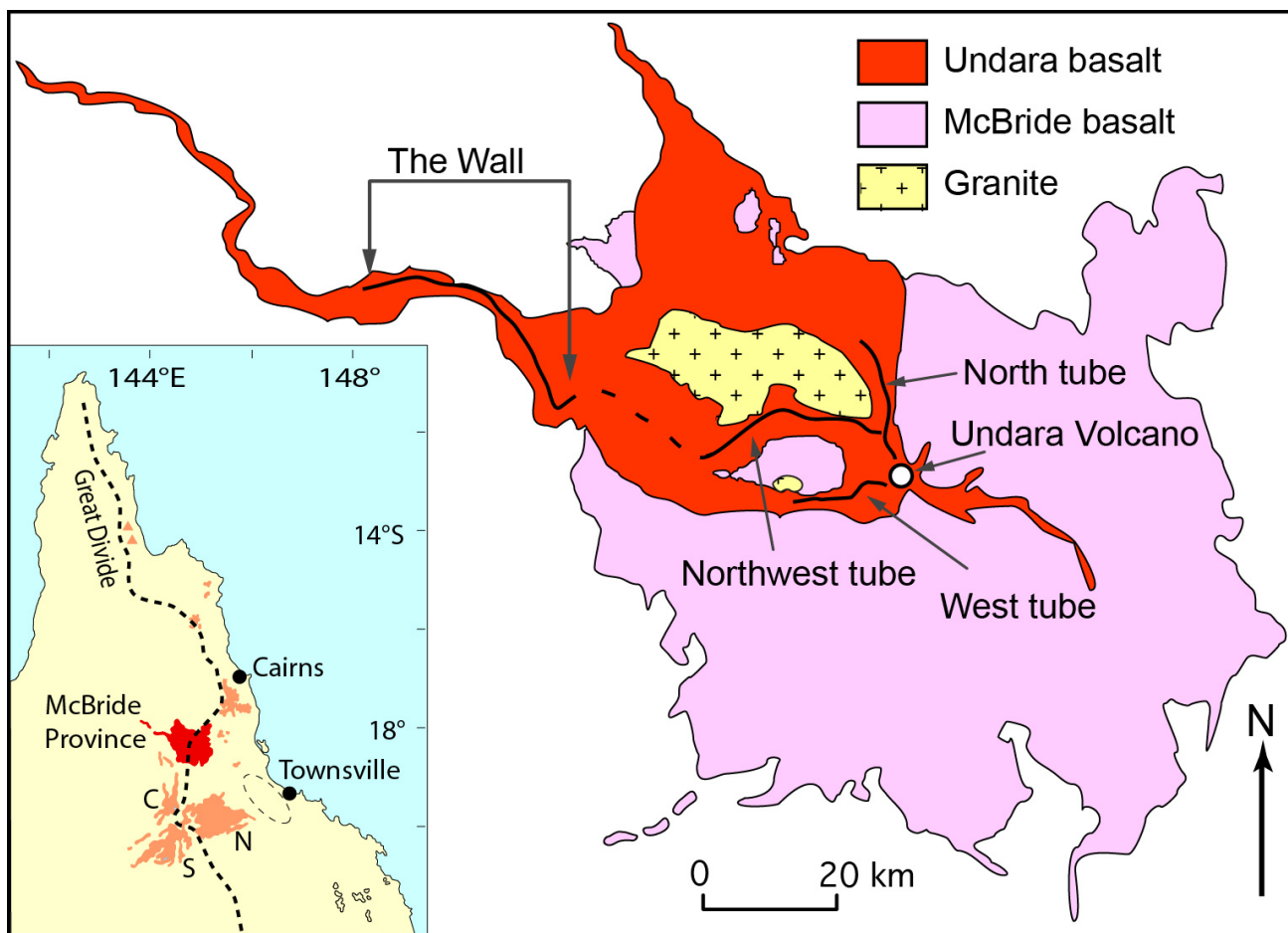
Fig. 5. Outline of the McBride Basalt Province, showing the extent of the Undara basalts and major lava tube lines. Inset: Basalt provinces of north Queensland. C – Chudleigh, N – Nulla, S – Sturgeon.

distal flows. Several factors are believed to have aided the development of the long flows, including—

- the continuity of the eruption
- the existence of drainage channels that were dry or contained low water levels
- the flow of lava along insulated conduit systems
- repeated breakouts from static flow fronts to sustain flow advance (Stephenson *et al.* 1998)

Lava Tubes

The term "lava tube" is commonly used in everyday language, with the "Thurston Lava Tube" of Hawaii being a well-known example. In the geological and speleological literature, however, the term has been used for a variety of features (Halliday 2008). Here, the term "lava tube" is restricted to a locally channelised flow of lava that flowed sub-surface, creating an approximately cylindrical structure. The formation of an open space, by either the down-cutting or partial drainage of the flowing lava, is termed a "lava tube cave". It is proposed that any other type of cavity within solidified lava flows be termed "lava caves". All other sub-surface passages of lava that lead to the incremental lengthening of lava flows, are here termed "lava conduits".

The concentration of lava into a lava tube can lead to the thermal erosion of the underlying rock. Observations of flowing lava tubes in Hawaii showed the lowering of the tubes by an estimated 15 m over a nine month period (Swanson 1973). Pinkerton *et al.* (1990) calculated erosion rates of between 6 cm/day and 22 cm/day for the 1984 Mauna Loa eruption, based on the thermal properties of the basalts, the channel dimensions and discharge and viscosity data. Direct measurements of the depth of an active lava tube by were undertaken by Kauahikaua *et al.* (1998) over a two month period, where an average erosion rate of 10 cm/day was obtained, after which the rate of erosion lowered substantially. The surface of the stream receded to 5.2 m below the surface, with the depth of the lava stream being measured as 0.7 m when it was close enough to the surface for measurements to be taken. The velocity of the lava was measured at around 2.5 m/s. The surface gradient was 2.7° in the upstream direction and 3.4° downstream.

Over 60 lava tube caves and arches have been discovered in the Undara lava field (Atkinson & Atkinson 1995). The caves are preserved within Undara Volcanic National Park but only a few caves along the northwest tube line are open to the public. These caves may be viewed on guided tours, run by commercial tour operators that have been certified by the Queensland Parks and Wildlife Service. No caves are freely accessible to the public.

The northwest tube line extends for 30 km from Undara crater. Lava tube caves are generally large structures, averaging around 14 m wide and up to

Fig. 6. View of "The Wall", in the Undara lava field.
Photo taken from approximately 18° 5.1'S, 144° 4.9'E, looking to the north.

19.5 m high. The longest is Bayliss Cave, which runs for 1.3 km (Atkinson & Atkinson 1995). The caves display features that are typical of formation from thermal erosion by the lava, including benches and flow lines, although wall linings frequently conceal these features. In "The Archway", a series of 5 flow sub-units can be seen in the 14 m high walls, defined by vesicular, pahoehoe surfaces. The lava lines, benches and sub-units seen in the cave walls are consistent with their derivation from the thermal erosion of a confined lava tube. The gradient along the northwest tube line averages 0.7°, which is greater than the 0.5 ° required to allow drainage (Hatheway & Herring 1970).

The tube line closely follows a line of surface depressions, which continue beyond the last known cave. No access to the caves can be obtained from the depressions, which appear to be derived from a separate flow. Caves are accessed by narrower and steeper depressions, formed by cave collapses.

Lava Inflation structures

Lava inflation occurs when pressure from the liquid lava produces a swelling of the solidified crust (Walker 1991). They are thus distinguished from pressure ridges where lateral compression forms a buckling of the crust. Lava inflation structures can occur as point form structures (tumuli), as plateaux (lava rises), or as long, narrow ridges (lava rise ridges). Regions of lava flows that fail to inflate and hence indicate the original level of the flow prior to inflation, are termed lava rise pits. Observation of the Kalapana flow in Hawaii showed a flow 150 m across, that was initially less than 0.5 m thick, became inflated to greater than 10 m thick over 22 days (Kauahikaua et al. 1998).

"The Wall" at Undara is interpreted as a lava rise ridge (Fig. 6). It is 40 km long but generally less than 200 m wide. The Wall is breached in several places, but is effectively continuous. It rises up to 20 m above the surrounding lava field to the south, but has lower relief on the northern edge, where a later flow has apparently banked up against it (Stephenson & Whitehead 1996). The gradient over the length of the Wall is less than 0.09°.

The Wall is believed to have formed by lava being confined to a stream bed and that subsequently underwent inflation. Similar structures are found in the Toomba flow of the Nulla province to the south (Whitehead & Stephenson 1998). The Toomba flow is only 13 ka (Stephenson et al. 1978) and features such as inflation clefts and banded and striated surfaces that characterize inflation structures, are still well preserved on the lava rise ridges (Fig. 7). Such features are not apparent in The Wall, although the remnants of a lava inflation cleft may be preserved near the termination of The Wall (illustrated in Atkinson & Atkinson

(a)

(b)

Fig. 7. (a) Lava inflation cleft on the edge of a lava rise ridge in the Toomba basalt field. (b) Banding within the lava inflation cleft, caused by incremental opening of the cleft. Scale bar is 1 m.

1995, pp. 50-51). The Wall has been suggested as an analogue to basaltic ridges that can be seen on the moon (Atkinson 1992). As lunar flows could not have been confined to fluvial channels, the lunar ridges may be pressure ridges, rather than lava inflation ridges.

In several places on the Wall there are roughly circular depressions, up to 100 m across. Similar depressions occur in many places within the Undara basalt flows. Notably, aligned depressions occur close to the north and northwest lava tube lines. Possible interpretations of these depressions are as collapsed lava ponds or collapsed tubes (Atkinson *et al.* 1975), shattered rock rings (Kauahikaua *et al.* 1998) or as lava rise pits (Stephenson *et al.* 1998).

The depressions are regarded as being analogous to the lava rise pits of the Toomba lava field (Stephenson & Whitehead 1996). At Toomba, the depressions are commonly 20 m deep and 50 m to 100 m long, with pahoehoe preserved on the floor and the steeply sloping sides (Fig. 8). Most of the depressions contain tapering cavities within the walls, commonly close to the level of the floor. These cavities are large, sub-horizontal lava clefts and contain sagging lava wedges with banded and striated surfaces (Fig. 9). These features are diagnostic of lava inflation (Walker 2009). No evidence of lava tube entrances were found in any of the depressions.

Similarly, at Undara, no cave entrances are to be found from the depressions. Where the depressions lie over the line of a lava tube cave, no collapse is apparent in the cave beneath, which may have indicated a collapse feature (Stephenson & Whitehead 1996). Rather, the depressions appear to act as a constraint to the tubes, which bifurcate around the depressions. This is consistent with there being a region that acted as a barrier to the flow of lava. Where lava tubes were formed, the tubes deviated around the obstruction. Where broad lava conduits led to the inflation of the surface, the solidified section of the flow failed to inflate, leading to the development of lava inflation pits.

Lava inflation versus thermal erosion

Lava inflation structures may occur throughout lava fields, both close to the volcano, where gradients are generally steepest, and in the distal portions, which generally contain the lowest gradients. Lava tube caves, however, are restricted to regions of higher gradient, above the 0.5° required for tube drainage (Hatheway & Herring 1970). There is a fundamental dichotomy between the processes required to form lava inflation and thermal erosion. For inflationary structures to form, lava conduits must underlie the entire structure that is undergoing inflation. The lava conduit must be filled, leading to hydrostatic pressure which forces the surface of the lava flow to rise above its original level. Any breakage of the surface would lead to a squeeze-up of lava from below. Intuitively, the formation of lava inflation structures would require the lava to be advancing relatively slowly. Conversely,

Fig. 8. Lava inflation pit in the Toomba basalt flow.

for thermal erosion to occur, the lava must be channelled along a confined stream and be freely flowing. Lowering of the lava stream leads to an unsupported roof, which can lead to the formation of skylights by roof collapse.

At Undara, although the aligned depressions, which are here interpreted as lava inflation pits, and the lava tube caves are in close proximity, the contrasting methods of formation mean that they must have been formed from different flows. In the more distal regions, where The Wall occurs, gradients are too low for the formation of lava tube caves. The depressions in The Wall are here interpreted as lava inflation pits, by comparison with similar features in the younger and better-preserved Toomba flow, rather than collapse features.

(a)
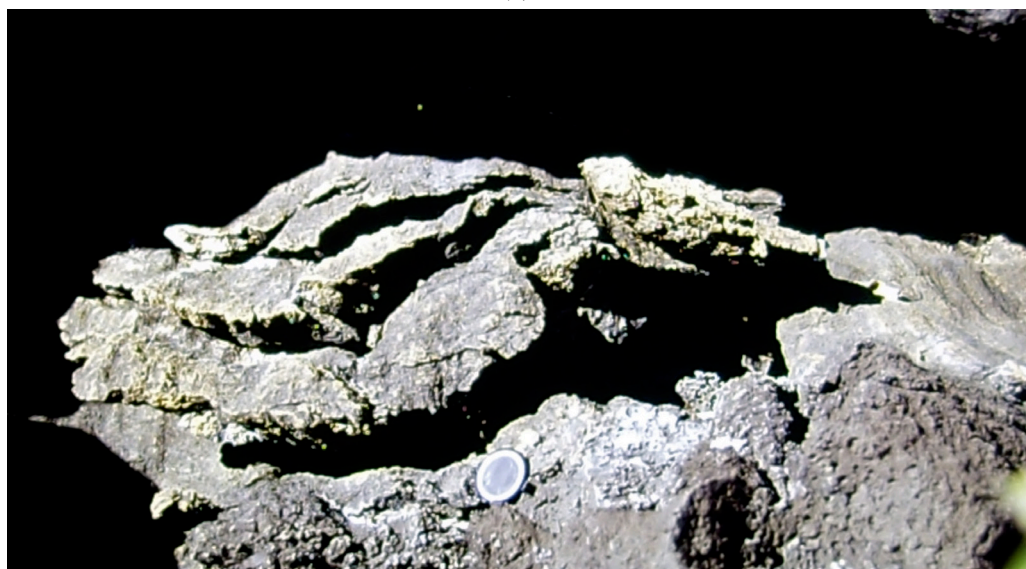
(b)

Fig. 9. Lava wedges, Toomba. (a) Vertical lava wedge in a lava inflation cleft, formed by horizontal movement as the cleft opened. (b) Horizontal lava wedges at the base of a lava inflation pit, indicating vertical movement as the sides of the pit inflated.

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Undara Volcano, North Queensland, Australia and its Lava Field – Lava Caves, Depressions and The Wall – a Possible Lunar Analogue

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Abstract

The Undara Lava Tube System, North Queensland, Australia, is remarkable not only for its geology, but also for unique flora and vertebrate and invertebrate fauna. This paper considers some aspects of its geology and provides details, in particular, of aspects relevant to discussion of the aligned depressions which mark the location of tubes from the Undara Crater to Barkers Pond.

More than 60 caves and arches have now been discovered in the system. Most caves are less than 200 metres long but the system includes Australia's longest lava tube, over 1,350 metres. More than six kilometres of tubes have been surveyed and the first profile ever to depict a source volcano in addition to representative caves and arches is presented.

190,000 years ago, the Undara volcano erupted 23 cubic kilometres of basaltic lava at temperatures ranging from 1,170° Celsius to 1,220° Celsius, covering an area of 1,150 square kilometres. With an average gradient of only 0.3°, one of the flows extended more than 160 kilometres to become the world's longest 'recent' flow from a single volcano. This great length is attributed to very high effusion rates, favourable topography, and lava tube efficiency.

The lava tube system extends more than 110 kilometres and includes caves, arches, and an almost level ridge that is 35 kilometres long and is known as "The Wall." The Wall is considered the best Earth volcanic feature analogous to the smaller basaltic ridges on the Moon.

Adjacent to, or aligned with, the caves and arches there are oval and elongate depressions. Most of these depressions are much wider than the caves and arches and appear to have formed contemporaneously by the draining of lava ponds. Darker green "rain forest" type vegetation within the wider depressions contrasts sharply with that of the surrounding eucalypt woodland and is indicative of former greater areal extent of rain forests, now confined to coastal and near-coastal areas.

Comparison of features of the Undara tubes with those of currently active and Recent Period tubes elsewhere in the world, indicates that the tubes of the Undara System were formed by the draining of roofed lava channels, whose locations were determined by palaeotopography.

Introduction

In photographs of the lunar surface, the shape of channels (Fig. 1) suggests fluvial origin. This hypothesis, however, had to be dismissed in the absence of atmosphere. A number of papers appeared suggesting that the sinuous rills on the Moon could be collapsed lava tubes (Kuiper et al. 1966; Oberbeck et al. 1969; Greeley 1970 and 1971a; Cruikshank and Wood 1972). These papers stimulated the study of lava tubes on Earth. Further impetus to this study came with the discovery 20 years ago that some of the first lunar rock samples were very similar, megascopically (Figs 4 and 5) and microscopically, to terrestrial basalts with only minor geochemical differences (MacKenzie et al. 1982).

As an analogue to the smaller basaltic ridges of the Moon (Fig. 2), the length and shape of The Wall (Fig. 3) of the Undara Lava Tube System is considered Earth's best volcanic feature (Greeley, pers. comm. 1972 and 1991).

The first International Symposium on Vulcano-speleology and its Extra-Terrestrial Implications was convened in 1972 and, at the request of the chairman, Dr. Halliday, the first paper on the Undara Lava Tube
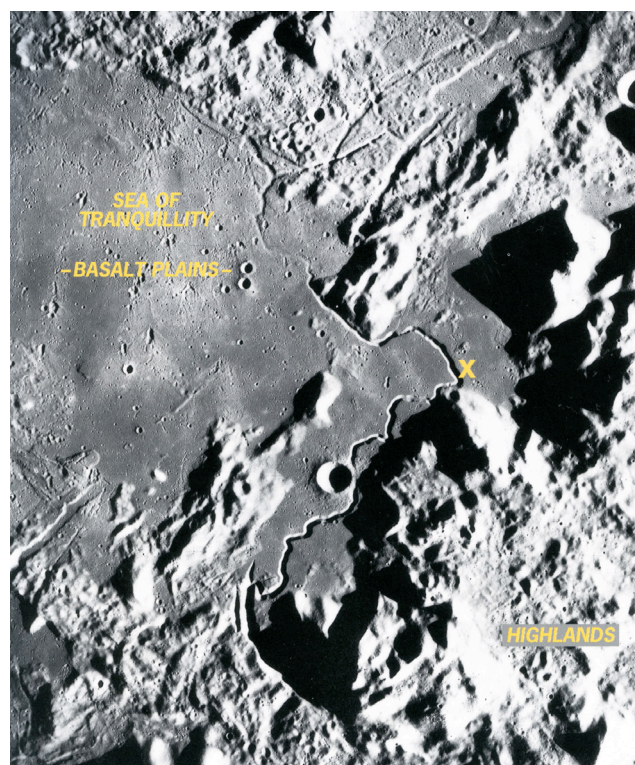

Fig. 1. View of the Moon, showing a meandering channel, 115 km long, which may represent a collapsed lava tube in a basaltic area. Apollo 15 landing site indicated by cross. (photo: Astronaut A.M. Worden, by courtesy NASA.)
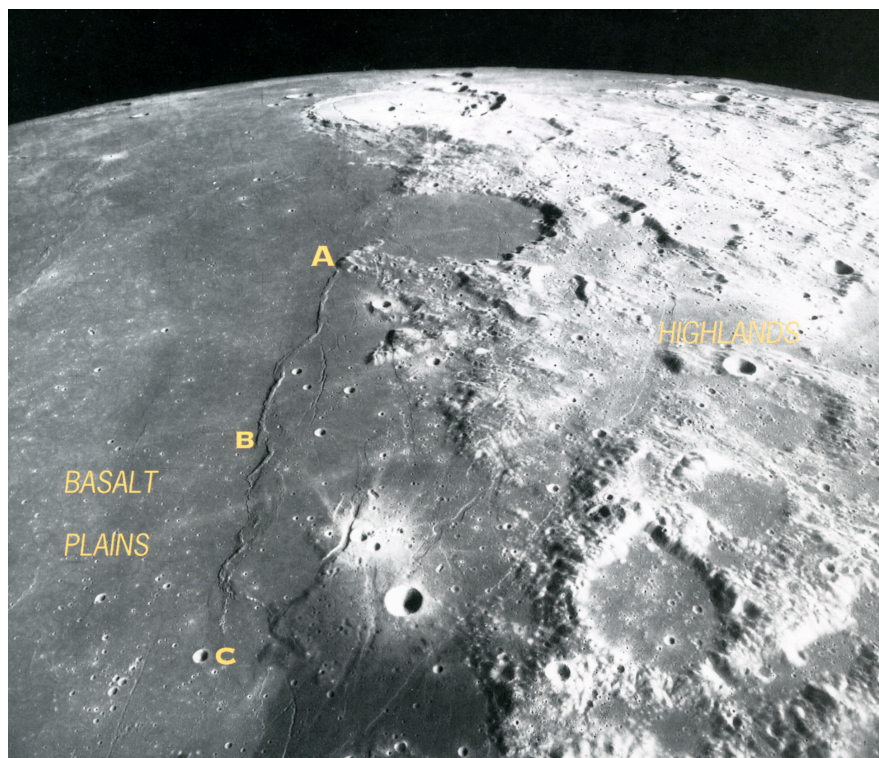
Fig. 2a. *Area of the Moon showing Highlands and Basalt Plains (darker areas) where A-B-C indicates a ridge. The numerous 'pock' marks in the basalt plains are impact craters, not volcanic craters.*
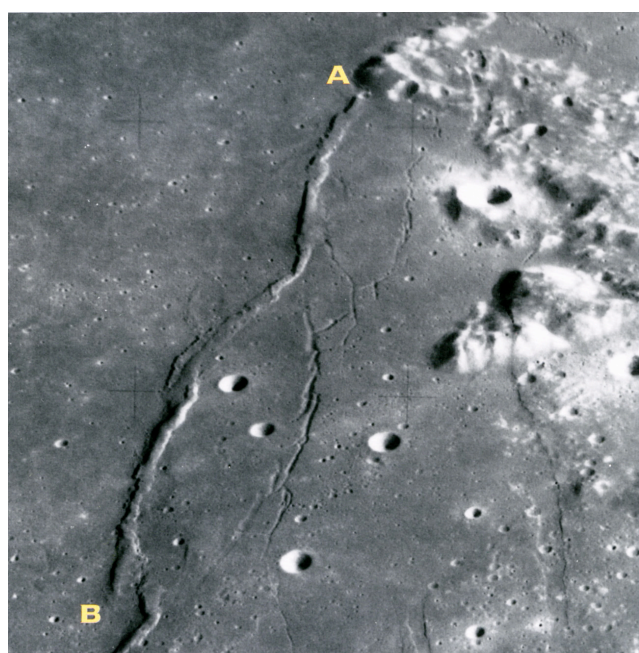
Fig. 2b. *Detail of section A-B of the basaltic ridge marked A-B-C in photograph above.*
(photos: courtesy of NASA, Frame No. AS17-0939)

System was presented - six pages, including figures, map (Appendix 2) and references. NASA's astro-geologist Ron Greeley attended this symposium. The author requested he view the geological map of the Undara area and photos she had taken of the lava ridge known as "The Wall" near Mount Surprise, seeing it as a possible Earth analogue to a lunar ridge depicted in the National Geographic. Greeley and his colleagues had searched air photos of Earth's major basaltic areas

and had found no Earth feature to compare with The Wall. He insisted the author bring the map and photos to NASA, in California. She returned to Australia with two requests from that meeting:

• To profile the Undara Crater and representative caves in the flow that led to The Wall;

• To make a study of The Wall.

Many of Undara's surface and lava tube features, have been photographed and described previously (Atkinson *et al.* 1976; Atkinson 1985–95; Atkinson and Atkinson 2001). However, for those not familiar with these features, this paper provides photographs, figures and descriptions of many and in particular, those relevant to discussion of the aligned depressions that mark the location of lava tubes between Undara Crater and Barkers Pond.

Location and Geological Setting of the Undara Lava Tube System

Cainozoic volcanism in eastern Australia extended more than 4,000 kilometres (Fig. 6, Stephenson, Griffin and Sutherland 1980). In north Queensland, within 200 kilometres of the east coast, there are five major provinces (Fig. 7).

The Undara Lava Tubes are found within lava flows from the Undara Volcano (Fig. 9) which is located approximately 200 kilometres southwest of Cairns in North Queensland, Australia. This volcano is situated near the centre of the McBride Province (Fig. 7) which covers approximately 5,000 square kilometres (White 1962), and topographically forms a broad dome. There are over 160 vents in the province (Griffin 1976), the majority of which are in the central region.

The Undara Volcano (Fig. 8) rises to 1,020 metres above sea level (ASL) and is the highest point in the McBride Province. Its impressive crater (Figs 8, 9, 10) is 340 metres across and 48 metres deep with inner slopes of up to 40°. The rim rises only 20 metres above the surrounding lava field. Outward slopes from the rim vary from 30° to 5° on the northwest side where the major outflows occurred.

The crater walls are mainly covered by angular blocks (up to several metres across) of highly vesicular to massive lava. Several indistinct terraces inside the

Fig. 3. Vertical aerial photograph of the western end of the Wall Section of the Undara Lava Tube System. This low basalt ridge is 35 km long and may be analogous to the sinuous ridges on the Moon. (photo: Dept. of National Mapping)

Fig. 4. Basalt from the Moon. Despite its age of ~4,000 million yrs, this specimen could be mistaken for a fragment of newly erupted terrerstrial lava. Its surface is not weathered because the Moon has no atmosphere. The numerous holes, or vesicles, formed when dissolved gasses expanded as pressure decreased during magma's ascent to the Moon's surface. When the lava cooled and solidified the bubbles were trapped within it.
(photo: courtesy of NASA.)

Fig. 5. Undara basalt. These blocks, on the inner slope of Undara crater, have many gas holes, or vesicles, giving them some resemblance to the lunar basalt pictured at left. Zones of vesicular basalt are very comon in basaltic lava flows on Earth, especially at the tops of flows. (Pocket knife for scale is 10 cm.) (photo: Tom Atkinson)

Undara lava flows cover 1,550 square kilometres in the McBride Province and are basaltic in composition. Appendix 1 gives chemical analyses of six basalt specimens from the Undara flow.

One flow to the north is, in part, rough spinose a'a basalt but most of the Undara lava field is of the smooth pahoehoe type. Present understanding, based on records of historic flows and observation of current flows, is that volumetric flow rate controls whether the flow will be of pahoehoe or a'a type basalt - the historic lava flows in Hawaii are pahoehoe if they formed at a lower flow rate, which allowed time for de-gassing (Rowland and Walker 1990).

crater may mark former levels of a lava lake. Part of the crater floor is covered with a fine red soil containing small fragments of scoriaceous material and a small area of the floor is smooth pahoehoe basalt. The volcano erupted 190,000 years ago (Griffin and MacDougall 1975).

In the McBride Province, only one volcano, Kinrara, is younger than the Undara Volcano (White 1962). The

Fig. 6. Cainozoic basalt outcrops of eastern and southeastern Australia occur within 400 km of the coast and extend for over 4,000 km. (after Stephenson et al. 1980)

Fig. 7. The main provinces of Cainozoic basalt outcropping in northeastern Australia. The area within the rectangle is shown enlarged in Fig. 8.

It is in pahoehoe flows that the long lava tubes of the world have formed and can currently be observed forming on the Island of Hawaii (Greeley 1971b, 1972, 1978; Peterson & Holcomb 1989; Peterson & Swanson 1974; Rowland & Walker 1990). The feeding rivers of pahoehoe can be extremely complicated. Flow patterns frequently consist of an internal network of interconnecting conduits which sometimes attain considerable vertical and horizontal complexity (Wood 1976). However, almost all the tubes of the Undara System are simple in plan and appear to be single-level. (To date the only multi-(three)-level tube

discovered in the McBride Province is on the flank of the source volcano of an adjacent flow of slightly greater age).

Lava flowed in all directions from the Undara Crater, but the main flow was to the northwest (Fig. 8). The flow to the north was approximately 90 kilometres long and entered the Lynd River. The voluminous northwest flow, however, followed precursors of Junction Creek, Elizabeth Creek and the Einasleigh River (Fig. 8) for more than 160 kilometres to become the longest single-volcano lava flow in the world (in relatively recent times). For lava to travel from Undara Crater to the termination of The Wall, Walker (pers. comm. 1972) believed would have taken no more than a matter of weeks, owing to increasing viscosity is the flow cooled. Later, in view of the insulation property of basalt, he believed that it would have taken considerably longer – perhaps a number of years (Walker 1973).

Jim Kauahikaua (pers. comm. 2010) advised that flows in lava tubes from Kilauea Volcano on the island of Hawaii have already been recorded for 28
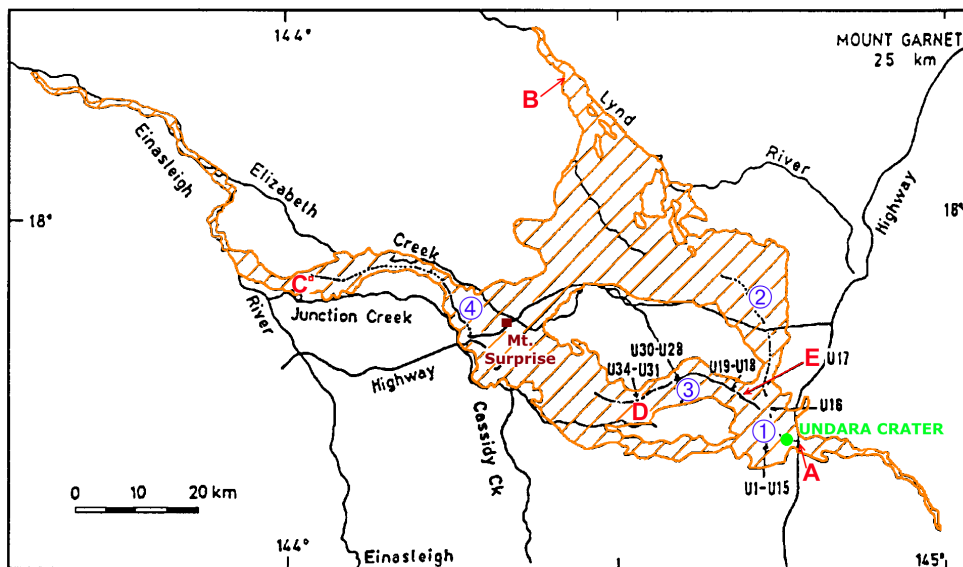
Fig. 8. The Undara lava field (orange outline). Circuled numbers denote sections of the lava tube system referred to in the text; other numbers refer to cave entrances. Letters A to E denote locations of basalt specimens chemically analysed (see Appendix 1)

Fig. 9. Aerial oblique view of Undara Crater, 340 m across, looking west. The tube system commences in the line of depressions that runs away from the Crater towards the right. (photo: Tom Atkinson)

Fig. 10. Undara Crater viewed from the north rim,. early morning (Winter 1973). (photo: Anne Atkinson)

years and are still active. This is the longest period of continuous volcanic activity in recorded history.

The Undara lavas were erupted at temperatures ranging from 1,175° Celsius to 1,220° Celsius (Roeder and Emslie 1970, cited in Atkinson et al. 1976). They do not appear to have unusual viscosities (Shaw 1972; Bottinga and Weill 1972; cited in Atkinson et al. 1976) which accords with the conclusions of Walker (1973), that very long lava flows reflect continued high effusion rate. Stephenson and Griffin (1976) reached a similar conclusion in a study of eight long basaltic flows in Queensland.

General thickness of the Undara lava field is estimated from 5 metres near the edges to up to 20 metres or more in the thickest parts. Along The Wall, west of Mt Surprise, the flow could be up to 40 metres thick but this is probably restricted to the width of The Wall. Exploratory drilling on the north side of The Wall showed basalt depth of 25 metres. If an average thickness of 15 metres is estimated for the whole flow, the total volume of lava erupted from the Undara Volcano is approximately 23 cubic kilometres.

Where rock is exposed near the axis of the flow, polygonal mega-jointing (Spry 1962), which formed as the lava cooled and contracted, of up to 1.75 metres is evident throughout the 90 kilometres from the crater to the termination of The Wall.

The constant range in size of jointing over a distance of 90 km seems to indicate an homogeneous flow. There may be similar jointing beyond the termination of The Wall, but this area has not yet been investigated.

The lava tube system from the Undara Crater has been divided into the following five sections (Fig. 8) in order to describe the locations of the caves and arches:

Crater Section – extending north from Undara Crater for four kilometres; average slope 1°.

West Section – west from the crater, extending approximately 15 kilometres; average slope 0.75°.

North Section – continuing north from the Crater Section at least a further 8 kilometres, possibly 28 kilometres, average slope 0.5°.

Yaramulla Section – extending west-northwest from the northern end of the Crater Section for over 35 kilometres; average slope 0.7°.

Wall Section – approximately 35 kilometres; an almost continuous narrow ridge, known locally as The Wall; average slope 0.09°.

The distribution of caves within the lava flow is as follows: The Crater, the West, and the Yaramulla sections contain both caves and arches. In the North Section no caves had been found, but a line of collapse depressions suggested the presence of a lava tube. In 1989, systematic search in the North Section led to the discovery of three caves. The author believes that The Wall Section contains a major lava tube with a very thick roof but to date no access to such tube has been discovered.

Investigations of the Undara Lava Tube System

The Undara Lava Tubes had attracted the attention of three geologists prior to the investigations described in this paper. When discussing the distribution of volcanic centres in the McBride Province, Twidale (1956) noted two lineaments; he incorrectly interpreted the aligned collapses (Figs 11 and 12) as " ... a clear arcuate fissure ... with a centre of eruption at its southeast end". Best (1960) and White (1962) subsequently recognized the lava tube system. Without opportunity for detailed

Fig. 11. Aerial oblique view of wide collapse depressions aligned with and/or adjacent to the Yaramulla Section of the Undara Lava Tube System. (photo: H.J.L. Lamont, JCUNQ)

investigation, they interpreted the pattern of collapse features (Figs 11 and 12) as a collapsed lava tube, with north and west branches.

The first speleologists to visit the area were from the University of Queensland Speleological Society. They explored and mapped Barkers Cave (Shannon, 1969).

In 1972 the author's studies were commenced. It was proposed:

(1) To measure and map representative caves in order to establish whether there were any relationships between shape, size, and distance from the source volcano. This was undertaken at three locations, namely: in proximity to the crater, at a maximum distance from it, and at an intermediate location;

(2) To seek evidence of the mode of formation of the Undara Lava Tube System.

(3) To investigate the geomorphology of The Wall. At the same time, and subsequent to this investigation, the speleologists were continuing exploration of the caves. Grimes (1973) published a compilation of the results of earlier studies of Undara Lava Tubes. In the Australian Speleological Federation Karst Index, Matthews (1985) recorded the cave names, numbers, and brief descriptions.

The Chillagoe Caving Club also continued exploration of the lava tubes. In 1988, members discovered the Wind Tunnel and Inner Dome Cave and in 1989 they investigated areas within six kilometres west of the Crater and discovered ten caves. In addition, a number of expeditions from the Explorers Club have examined the lava tubes and researchers, sponsored by the Explorers Club, consider that the invertebrate community in Bayliss Cave makes it one of the world's most biologically significant caves (Howarth 1988).

In 1989, 100 volunteers (in groups of 20) from London-based Operation Raleigh camped on site for three months to investigate areas not explored by the author. Under the guidance of QNPWS officer Mick Godwin, they surveyed collapse depressions in the Undara Crater National Park and in 10 kilometres upflow from Bayliss Cave, an area never previously studied. They discovered and surveyed 23 new caves. Their systematic search in the North Section resulted in the first discovery of caves in this section, viz. Dingbat, Hot Hole and Wishing Well Caves, about 21 kilometres north of the Crater. Their assistance in collection of specimens and data of flora and fauna led to valuable additions to the records of the Undara lava field (Godwin 1993).
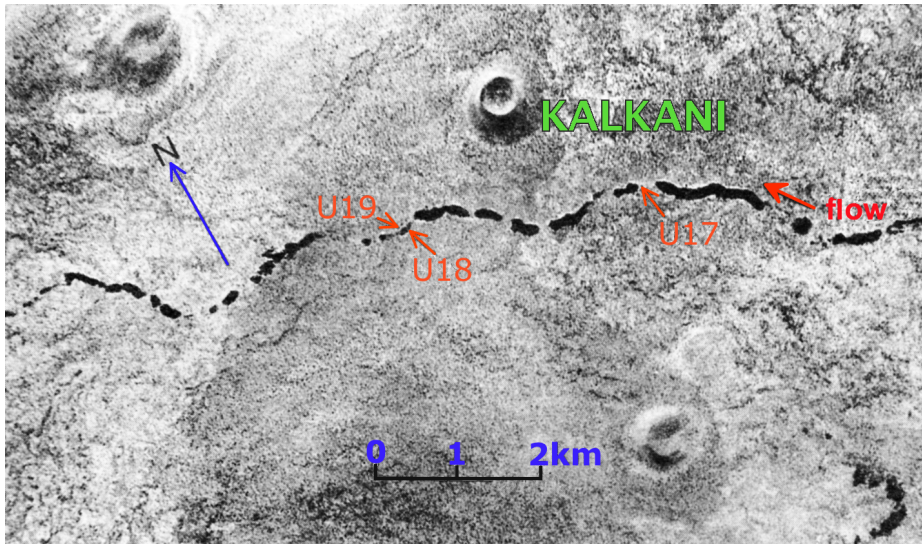
Fig. 12. Vertical aerial view of wide collapse depressions aligned with and/or adjacent to the Yaramulla Section of the Undara Lava Tube system. (photo: Dept. of National Mapping, Australia).

Methods

The Undara Lava Tube System can be clearly located on aerial photographs (Figs 11 and 12). It stands out because many of its collapse depressions support rain forest type vegetation which contrasts sharply with the open forest of the surrounding country. Some of the caves, for example Road Cave (Fig. 13) and Barkers Cave (Fig. 14). have been known for more than 100 years. The majority of caves, however, were located by systematic exploration of collapse depressions by the author and assistants between 1972 and 1974, members of the Chillagoe Caving Club 1985 to 1988, and Operation Raleigh volunteers in 1989.

Initially each cave entrance was marked with a 10cm square painted on a conspicuous block at the base of each entrance collapse. These squares were used as the datum for cave surveys. A surface datum was painted to correspond as closely as possible with the cave datum in order to ascertain roof thickness. Steel posts on the surface corresponded with cave survey stations.

Caves and collapse depressions were surveyed using steel tape, prismatic compass, and Abney level. The same instruments were used to connect underground and surface datum points and to measure the lengths and inclinations of entrance collapses.

To provide data for longitudinal and transverse cave profiles, cave heights were measured with strong helium-filled balloons, a method recommended by R. Greeley. A narrow ribbon was marked, rolled onto a fishing reel and attached to the balloon. Helium was found to be the best gas for this purpose. On one occasion cheaper "balloon gas" was supplied by an agent trying to be helpful and reduce our costs. It proved to be quite unsatisfactory .

The results of the surveys were presented (Atkinson *et al.* 1976) as plans with some transverse profiles (Fig. 15) and, as requested by NASA in 1972, as a longitudinal profile through the source crater and representative caves (Fig. 16) – the world's first such profile ever to include the crater of origin.

Caves and Arches

The results of the cave exploration and mapping are shown in Table 1. Sixty-one arches and caves have now been discovered in the Undara Lava Tube System and a total length of over 6 km of lava tube caves has been surveyed. The largest passage yet measured is in Barkers Cave where passage width reaches 18.9 m and height 13.5 m.

Fig. 13. Road Cave, north wall. Lava level lines extend from floor to roof of this cave. They are among the most distinctive yet discovered in the system and are more easily studied than at other locations as they are in daylight at the eastern entrance. There is an imprint of ropy lava above the entrance. (photo: H.J.L. Lamont)

Fig. 14. Barkers Cave, 50 m from its entrance. Note the gutter on the left and, on the distant wall, near-horizontal ridges evident almost to the roof. these represent periods when the lava river remained at a cons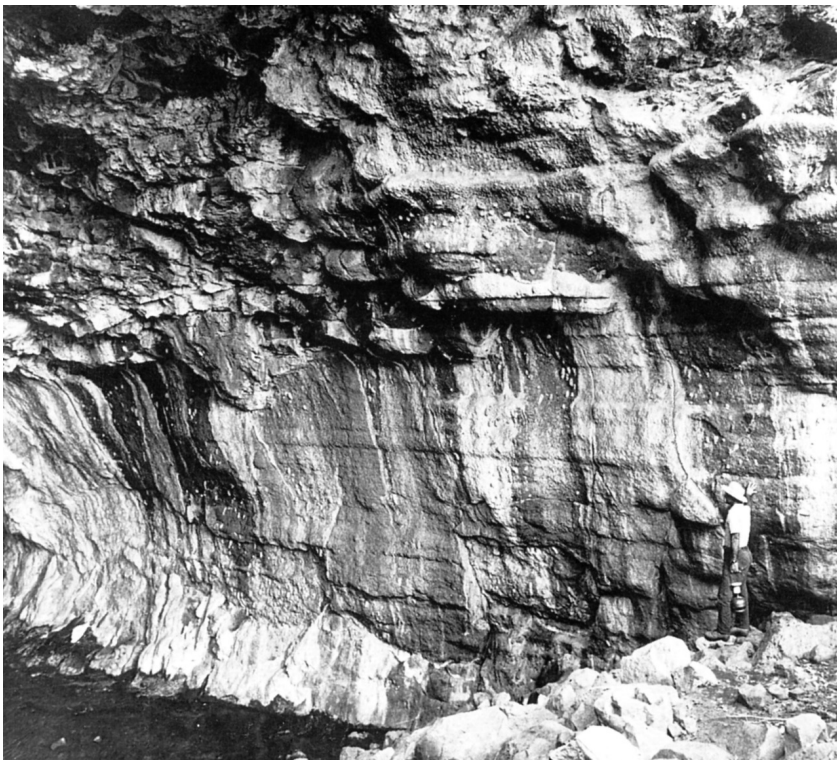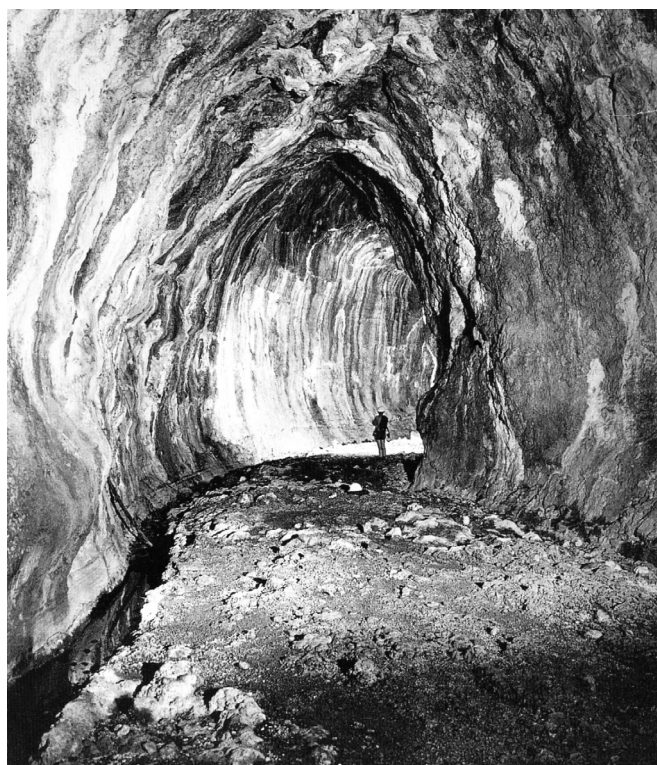tant level. The cave is 13.5 m high at this point, the greatest height measured to date in the Undara Lava tube system. (photo: H.J.L. Lamont, JCUNQ)

Table 1: Undara Lava Tube System – Cave Dimensions Revised and updated (Atkinson 1990b)

ASF * Number	Cave	Length	Max. Width	Max. Height	Survey by
U1	Hanson	40	12	3	**
U2 U3e	Dunmall Arch	-	6	2	**
U4	Taylor	108	16.3	10.8	**
U5	St. Pauls	30	-	-	**
U6	Sarah	10.7	0.9	1.4#	**
U7	Peter	13.8	9.9	3.8	**
U8	Ollier	49.4	10.4	3	**
U9 U10e	Harbour Bridge	35	14.3	5	**
U11 U12e	Greeley	103	12.4	3.8	**
U13	Frances	14#	6	3	**
U14	Opera House	30	10	7.5	**
U15	Peterson	102	17.1	3.7	**
U16	Stevens	70.4	8.8	3	**
U17	Pinwill	150	21	8.9	**
U18	Traves	67	14	10.6	**
U19 U20	Atkinson	101.2	28	7.8	**
U21	Stephenson	156#	>25#	> 10#	PD
U22	Arch	10.5#	28#	9#	PD
U23	Ewamin	162#	21#	> 8#	PD
U24	Picnic I (down)	420	22	15	PD
U25	Picnic II (NE)	45	12	> 14#	PD

ASF * Number	Cave	Length	Max. Width	Max. Height	Survey by
U26	Dave I (up)	50	10#	8#	PD
U27	Dave II (down)	27	-	-	PD
U28 U29e	Road	220	21.2	9.4	**
U30	Bayliss	> 950	18.9	11.5	**
	ext'n (1988)	> 400			PM, DR
U31	Darcy	99	16.3	6.3	**
U32 U33e	Matthew	40	7#	3#	**
U34	Barkers	560+	19.8	13.5	CS
U35	Raleigh I	23	15.8	7.3	OR
U36	Raleigh II	29.8	17	8.5	OR
U37	Lost World	74.2	13.5	5.7	OR
U38	Tween	24	11.5	6.5	OR
U39	Eptesicus	42	22#	6.1#	OR
U41	Inner Dome	68	22	7.5	OR
U42	Wind Tunnel	293	32	8#	OR
U43	Short Little Arch	15.8	5#	2#	OR
U44	Mikoshi	46.6	14#	11#	OR
U45	Misplaced Arch	22	22#	11#	OR
U46	Nasty	127	15	8#	MG
U47	Fortune	52.9	4.4#	2.5#	OR
U48	Temple of Doom	49.5	6#	4.5#	OR
U49	Fun	33.2	9.8	1.25	OR
U50	Ding Bat	60.4	17.1	7#	OR
U51	Hot Hole	171.9	13.5	3.5	OR
U52	Wishing Well	104	13	3.3	MG
U53	Moth	9.2	4	1.8	OR
U54	Sunset	> 30	5.2#	2.2#	OR
U55	Wallabys Hideaway	38.5	9	4#	OR
U56	Expedition I	30#	12	5#	DR
U57	Expedition II	28	20	4#	DR
U58	arch (unnamed)	8.5	10	2.2#	OR
U59	Tom Tom	34	9.5	2.5	OR
U60	arch (unnamed)	16	13	2.5#	OR
U61	Komori	> 85	9	3#	OR
U62	Speaking Tube	25.2	7.7	3.2	OR
U63	Flat Ceiling	80	15#	3#	DR
U64	Branch	10	10#	2#	DR
U65	San	25	10#	2#	DR
U66	Graham	22	3#	3#	FS
U67	Upper Secret	150#	-	-	FS
U68	Lower Secret	70#	-	-	FS
	Total	**6,324.7**			

* *Australian Karst Index* (Matthews 1985)
\# Estimate only
** V. and A. Atkinson and assistants
Abbreviations: CS = C. Shannon, DI = D. Irvin, DR = D. Ray, FS = F. Stone, OR = Operation Raleigh, PD = P. Dwyer, PM = P. Mainsbridge.
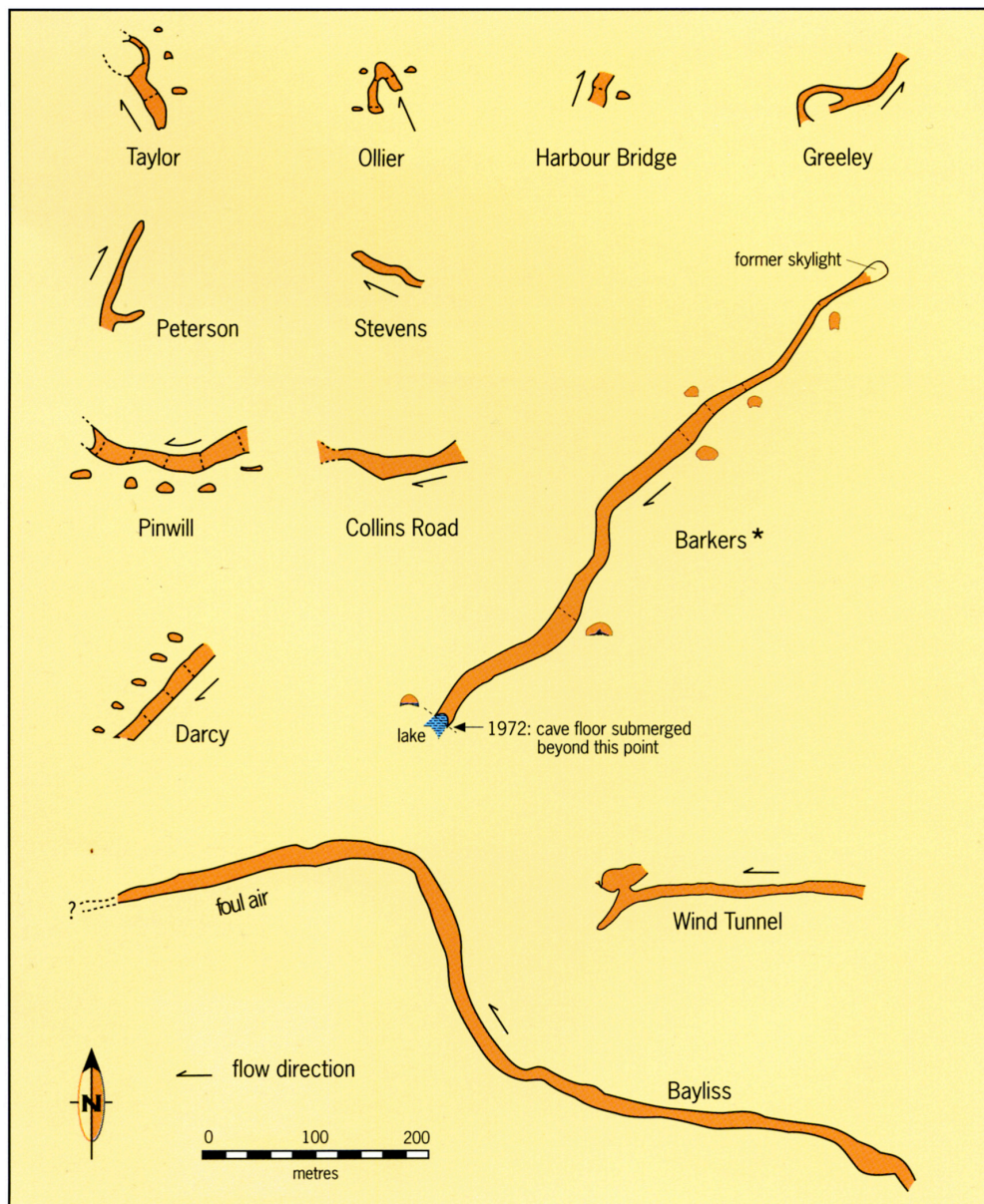
< Fig. 15. Maps of selected caves with some cross-sections.

(Diagrams from Atkinson & Atkinson 1995, derived from those in Atkinson et. al. 1976)

v Fig. 16. Longitudinal profiles of selected caves down-flow from the Undara Crater. Floor symbols: sediment (.....), ropy lava (/////).
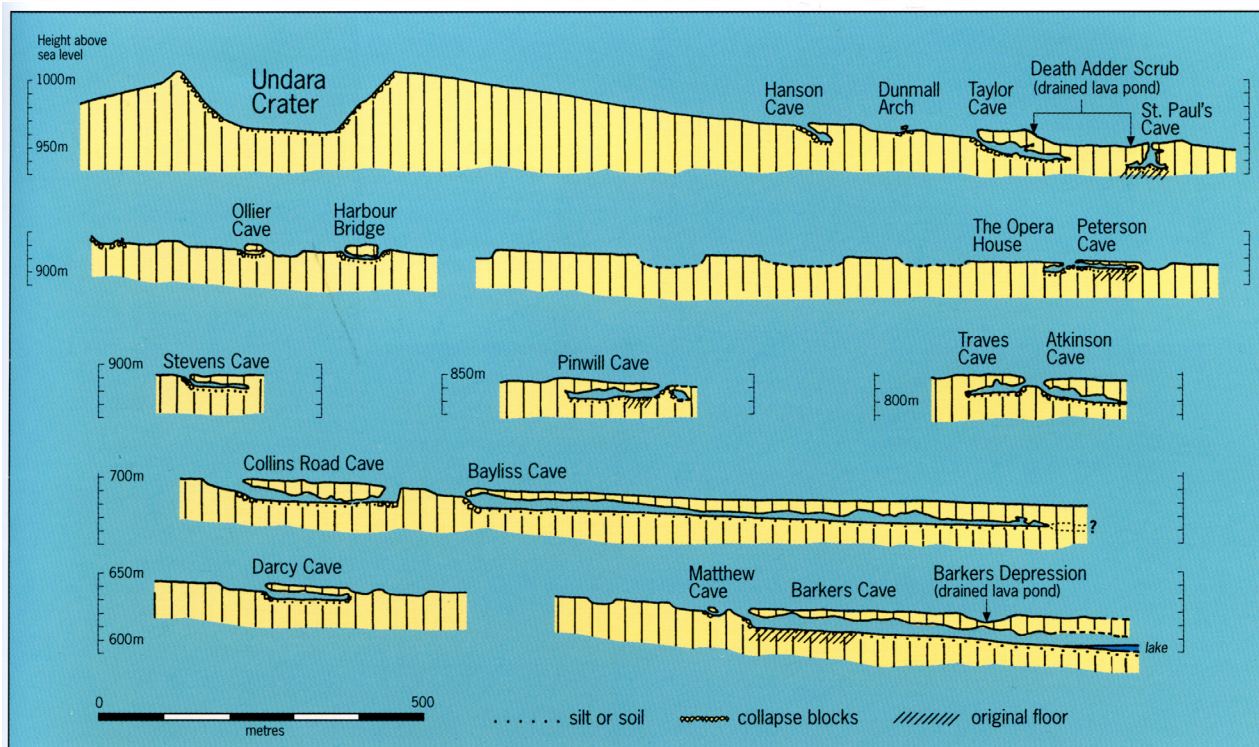
Features of the Caves and Arches

Although the Undara Lava Tubes were formed about 190,000 years ago (Griffin and McDougall 1975) they have retained many original features. These features show minimal alteration due to their protection from weathering.

Even where floors have been covered with later sediment, sufficient features remain to provide evidence of the mode of formation of the Undara Lava Tubes. Original dark grey to black interiors are yellow, brown or buff due to a thin coating of secondary minerals. In some roofs, white or light coloured bands of secondary minerals up to 10 centimetres wide outline polygonal jointing.

*Fig. 17a. An area of floor in Pinwill Cave shows development of ropy structure, characteristic of pahoehoe (trewacle-like) lava flows. This structure sometimes forms when molten lava under still-plastic crust continues to move, causing the crust to twist into forms that resemble ropes. (photo: M. Williams, TCKRG)*

Fig. 15 shows the plans of representative caves. Most of the cave passages are elongate in the direction of the lava flow. Fig. 16 shows longitudinal profiles through representative caves in the Crater Section and Yaramulla Section of the System. These profiles illustrate the variation in shape, size and roof thickness of the caves.

The largest cave passages are found in the Yaramulla Section and they are mostly simple tubes. The only lava tube cave in this area to show complex development is Wind Tunnel and Inner Dome Complex but the development is on one level and is characteristic of the tendency of lava rivers to braid.

Lava Tube Floors

Floors of the caves, when not covered by sediment or water, represent the final flow of lava in the tube. With the exceptions of areas of rough, spinose a'a basalt (Macdonald 1967) on the floor of Pinwill Cave, Yaramulla Section, and Wishing Well Cave, North Section, the exposed floors show features typical of pahoehoe type basalt flow.

At the entrance to Barkers Cave (Fig. 14) the floor is arched, with a single rope structure running down-flow. Beyond this, the floor has distinct marginal gutters up to one metre deep. Fine lava level lines on the outer walls of the gutters correspond, but are absent on the inner walls, which show some evidence of formation as levees. The raised central portion of the cave is therefore interpreted as a final channel flow in this cave.

Good examples of ropy lava are visible in Pinwill
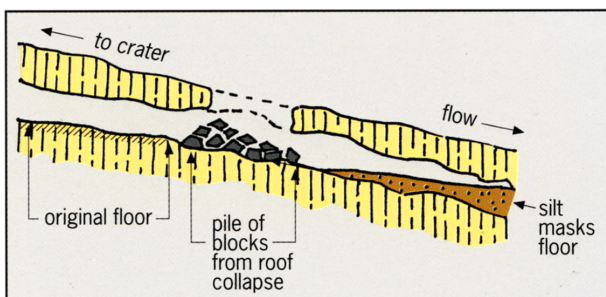
Fig. 17b. Why so little original cave floor is exposed in the Undara caves – less than 200 m of over 6 km surveyed. Most cave entrances are at the end nearer the crater which has allowed silt to wash in and mask floors. It is imperative that what remains visible is protected.

Cave (Fig. 17a) and the South Chapel of St. Pauls. In a central position near the entrance to Barkers Cave, crust fragments, approximately eight centimetres thick, have been rafted at varying oblique angles (Fig. 18) in a manner similar to ice slabs on a frozen river. In Peterson Cave there is a small floor surface where lava drops from roof re-melt appear to have pitted the floor, as rain drops pit a muddy surface.

Prolonged flow at constant level is evidenced by the "pavements" in Taylor Cave (Fig. 19). Where rate of flow is less against a convex bank, lava consolidates in a manner similar to the deposition of alluvium on convex banks of rivers.

Walls and Roofs

There is a lava lining on the walls and roof of most caves. Typically the lining is a single layer of up to 20 centimetres, but in places may approach one metre in thickness. At various locations the tube lining has fallen off the wall to expose the host lava behind it.
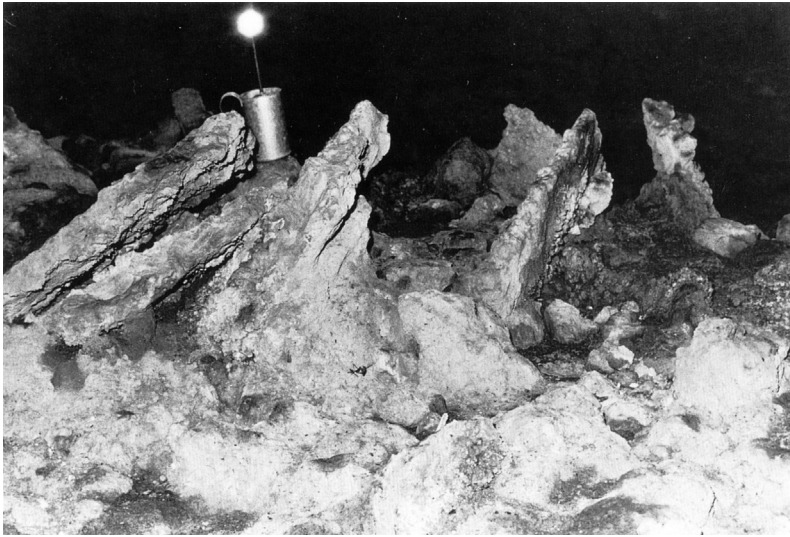
Fig. 18. "Rafted" blocks of the crust of the final flow in Barkers Cave have jammed at various angles. (photo: Vernon Atkinson)

Fig. 19. The prominent "pavements" (marked 1 and 2) in Taylor Cave are evidence of an extended period of constant rate of flow. Solidification has been greatest at the apex of convexity, as in a fluvial river. There is a cylindrical opening (3) in the roof above the figure. The location of this openinmg suggests that some lava ponded in the death adder depression (in alignment to the north) drained back into the tube through this conduit. (photo: H.J.L. Lamont)

The lining is sometimes multi-layered. The best example of this is in Pinwill Cave where 15 layers, 2 to 4 centimetres thick are revealed at one location (Fig. 20). At the entrance to the same cave, a thin slab of lining called The Table has become dislodged and now rests in a near horizontal position (Fig. 22).

On most walls and roofs are some areas of very low vesicularity and showing drip and dribble structures resembling cake icing (Fig. 23). At the entrance to Barkers and Picnic Caves these drips are deflected. In historic tubes such surfaces have been seen forming by remelting and, because of their lustre are appropriately termed "glaze," but in the Undara tubes the remelt surfaces have weathered to a dull or earthy lustre.

In places there are lavicicles (lava stalactites), commonly two centimetres to three centimetres and occasionally up to eight centimetres long, suspended from the roof, inclined walls, and in wall cavities (Fig. 25). Lava stalagmites are rare, as are lava columns. No "straw" stalactites have been found - no doubt because of their extreme fragility.

In most caves, lava level lines and ledges on the walls represent fluctuating lava levels. The highest levels are usually evident close to the roof, as seen in Taylor, Road (Fig. 13), Arch, Ewamin, Picnic I, Picnic II and Barkers Cave (Fig. 14). The lava level lines usually slope down-tube at low angles, probably reflecting the original tube slope.

Termination of the Lava Tubes

The caves generally terminate down-flow with collapses, or with a gentle downward curve of the ceiling to a silt floor. Barkers Cave ends in a lake, the cave ceiling steadily declining to water level. Several caves have down-flow entrances and have little or no silt on their floors. Pinwill Cave (Fig. 27), The Opera House (Fig. 28), Picnic and Wishing Well Caves terminate with walls.

Human Use of the Undara Lava Tubes

There is little evidence that the Undara lava tubes were used in prehistoric times.

Fig. 20. Multi-layered lining. Up to fifteen layers are exposed at this location in Pinwill Cave. (photo: Vernon Atkinson)

10cm

Fig. 21. Specimen from the entrance to Barkers Cave. When closely examined the apparent single lining (right edge) proved to consist of several distinct, annealed layers, indicating deposition of successive linings on still molten surfaces.
Note the elongation of the vesicles and the difference in their alignment; as would be expected, they are predominantly horizontal in the host rock but vertical in the lining. Specimen collected and presented to JCUNQ by Tom Atkinson. (diagram: P.J. Stephenson, JCU)

Local Aborigines believe that their people would have avoided such places. No drawings or evidence of fires have been found in the caves, though some artifacts were found at one cave entrance.

Depressions in the Undara Lava Field and their relationship to Lava tube caves

There are two distinct types of depression for convenience here named Narrow Depressions and Green Depressions.

1. Narrow Depressions

The narrow depressions, 30-50 metres wide, commonly give entry to lava tube caves. They contain vegetation little different from the surrounding open forest and as a result, they are difficult to detect in aerial photography. They occur between some of the aligned green depressions. They are assumed to represent collapses of tube roofs.

2. Green Depressions

Green depressions, with rainforest type vegetation, and distinctive in aerial photography, occur in two areas:

a) In a clear alignment from Undara Crater to Barkers Pond (Fig. 11)

The aligned Green depressions vary in width from 50 to 100 metres and in shape from oval to elongate in the direction of the lava flow. To date no cave entrances have been found in them. Most have elevated rims and slopes are commonly covered with erratic shaped blocks of varying sizes.
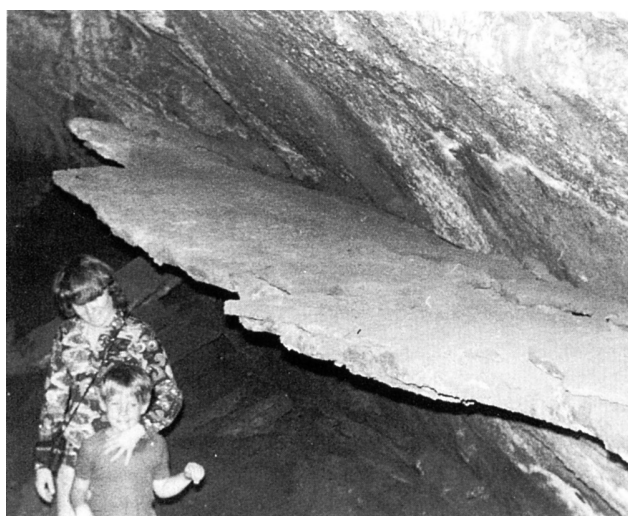
Fig. 22. "The Table" – a thin sheet of lining near the entrance to Pinwill Cave shows a degree of plastic deformation. (photo: Vernon Atkinson)

Fig. 23. Vertical lava dribbles in Barkers Cave. (photo: M. Williams, TCKRG)

Fig. 24. Deflection from vertical is evidence of the speed and heat of the final flow in the tube at this point in Road Cave. This may indicate that there was an opening in the roof of the chanel while the lava was flowing, or that the meeting of lava and groundwater caused a phreatic explosion nearby. (photo: M. Williams, TCKRG)

Fig. 25. Lavacicles up to 6 cm long in Bayliss Cave. (photo: Vernon Atkinson)

b) Green Depressions, non-aligned

In the area west of Barkers Pond the lava, no longer restricted by the granitic topography, spread to become a sheet flow. The depressions are irregular in shape, size and location. To date no cave entrances have been found in them. These depressions are wider than the tube and erratic in shape and location (Fig. 29). These features suggest that they may represent lava rise pits (Walker 1991), left by the collapse of lava rises formed by inflation of areas of semi-solid crust of a sheet flow.

Formation of the Aligned Green Depressions

Peterson, Scientist-in-Charge USGS's Hawaii Volcano Observatory 1970-75, viewed photographs and a map of the Undara area with Atkinson in 1972 and considered that the aligned Green Depressions of the Undara Lava Flow probably originated in the following manner: Peterson (pers. comm. 1975) and others of the US Geological Survey's Hawaii Observatory had observed that lava becomes ponded in specific areas, particularly where the slope is small. Once formed, the ponds tend to perpetuate themselves during the life of the flow, even when the flow front has advanced further. These ponds crust over and the molten lava beneath the crust is interconnected with lava tubes that had been developing in the flow both upstream and downstream from the pond. The crusted surfaces of these ponds have been observed to subside as the flow dwindles and the ponded lava drains back into the tube (Peterson pers. comm. 1975) (Fig 19). Peterson suggested mapping two of the aligned green depressions and the adjacent lava tubes. He was very pleased indeed to see the maps (Fig. 31).

Fig. 26. Boating party on the terminal lake, Barkers Cave (photo: R. Dutton)

Fig. 27. "The wave" – termination of Pinwill Cave which has a downflow entrance. (photo: Mick Williams, TCKRG)

collapse is now known as a lava rise pit (Walker 1991).

While this mechanism may be applicable to some of the depressions in the Undara lava field, the author doubts it can explain all the features of the aligned wider depressions between Undara Crater and Barkers Pond. In that area Peterson's observation of lava ponding in alignment with and adjacent to active flows in Hawaii seems to offer a more feasible mechanism.

There is a depression 60 metres in north of the entrance to Taylor Cave. This long depression lies directly in line with the entrance section of the cave. The cave was found not to terminate in a collapsed beneath the depression, as was expected, but close to the edge of the depression. The cave branches and two branches roughly follow the outer margins of the depression. Each branch closes to an inaccessible tunnel and near its termination the east branch divides again. The lava level lines in the east branch are nearly horizontal and proceed along both sides of the cave and across the wide pillar at the end (Fig. 30).

After discussion with Jim Kauahikaua (pers. comm. 2010) and intensive studies (Kauahikaua *et al.* 1998, Stephenson et al. 1998, Whitehead & Stephenson 1998, Orr 2010) an entirely different mechanism for the formation of the wide depressions in the Undara flow has been proposed. This mechanism involved lava rises (Walker 1991) that have formed above active lava tubes in sheet flows, then collapsed back into the sheet flow. That is possibly when the lava flowed on into the Einasleigh River then into the palaeochannel of Junction and Elizabeth Creeks. The flow may have filled the creek and formed levées. This type of

The relationship of the Taylor Cave passages to the depression suggests the collapse interfered with the still-functioning tube. When the lava pond drained and its crust collapsed the tube bifurcated around the collapse, but was being constricted and eventually dammed. Subsequently the dammed lava inside the tube drained through minor outlets. A cylindrical vent in the roof of Taylor Cave (Fig. 19) is interpreted as a location where some of the lava that pondered above the main tube drained back into it. A minor lava fall, approximately a metre high, emerges from under the

floor of the west terminal branch of the cave and is interpreted as another point of "drain back".

There is much interesting work to be done at Undara for many years to come, and many questions still to be answered – perhaps some questions will never be answered.

Barkers Pond

The oval depression 220 metres West of Barkers Cave entrance, known as Barkers Pond, is approximately 100 metres long and 60 metres wide. Fig. 31 shows how Barkers Cave changes its course seeming to deviate around the depression, Barkers Pond, 220 metres west of the Cave entrance. There is a small cavity in the cave roof under the

Fig. 28. Termination of The Opera House (note wings). Entrance is down flow. (photo: H.J.L. Lamont, JCUNQ)

Fig. 29. Irregular shaped depressions which resulted from the draining of areas where lava had ponded during the period of active flow. (photo: Tom Atkinson)
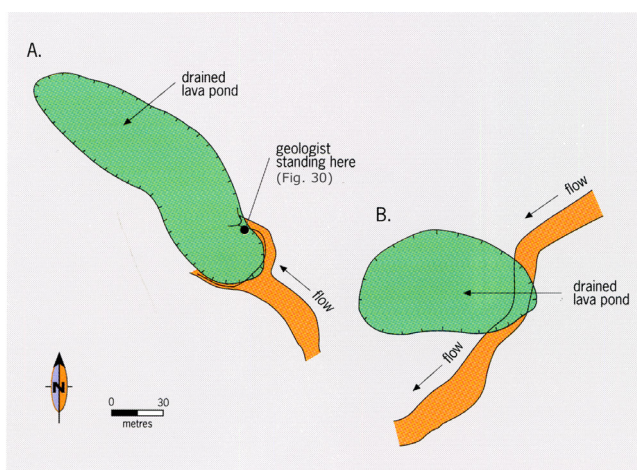
Fig. 31. Relationship between surface depressions and caves. (A) Taylor Cave, (B) Barkers Cave. (from Atkinson & Atkinson 1995)

eastern end of the depression. It seems that the lava, which had ponded in the depression, may have drained back into a flowing tube forcing it to alter its course. Near the top of the inner western margin of Barkers Pond is an area of very finely vesicular blocks – which may be termed a mosaic (Fig. 32). Close examination of these blocks indicates they were once adjacent – distinctive, fine cracks can be traced from each block to an adjacent block. This is interpreted as indicating they were once the degassed surface of former pond crustal blocks.

Though in quite a different situation, the 1898 photo of the lava lake retained by its own levée in Halemaumau Crater within Kilauea Caldera (Fig. 33) shows features which the author sees as comparable with those of Barkers Pond before it drained.

Formation of Barkers Pond

With such a volume of lava contained in a low, cone shaped pond (with the apex at the bottom) irrespective of the rate of drainage, the rate of lowering of the Pond surface would have increased as drainage proceeded. This would seem to explain why the only 'mosaic' of crustal blocks is near the top of the inner west wall of the Pond.

As drainage progressed crustal blocks would have become broken and deposited in what Stephenson and Whitehead (1996) in their Chapman Conference Excursion Guide, termed "a frustrating complex of blocks, some ropy… chaotic in their distribution". They consider the chaotic distribution probably represents "mass-movement down the slope of the lava rise pit" (Walker 1991). Could these observations not equally indicate their origin as segments of pond

Fig. 30. Termination of Taylor Cave (east branch) as two closing tunnels behind geologist T.J. Griffin. Note the prominent horizontal lava level lines and ledges on walls and central column. (photo: H.J.L. Lamont)

< Fig. 32. Detail of inner wall of Barkers Depression to show a small "mosaic" of distinctive blocks of former pond crust. (photo: Sarah Collins)

Fig. 33. Halemaumau Crater within Kilauea Crater, Haewaii, 1895. The lava lake is held in a ring-shaped levée built up by spattering and repeated overflows, such as those visible in the picture. (photo: R.J. Baker Collection, Bishop Museum, Honolulu, Hawaii)

crustal blocks? If they had examined the blocks more closely they may have found some, as depicted in Fig. 34 with the gradation of vesicularity from a smooth, apparently non-vesicular surface to an opposite surface with quite large vesicles. Search for similar blocks lower on the pond walls and near the base of the Pond showed many blocks with gradation in vesicularity.

Fig. 34. Lava blocks in Barkers Pond, showing gradation in vesicularity from apparently none to quite large on the opposite surface. (photo: Anne Atkinson)

From the lowest area of the Pond voices are audible immediately below in the tube – a point assumed to be the place where lava drained back from the pond into the tube. At this point in the tube there is no indication of roof collapse, as stated by Stephenson & Whitehead (1996). The author's 1972 map of Barkers Cave (Fig. A2-1) shows two heaps of what she termed rock fall. These are some distance upflow and downflow from the location which she assumes to be the cave end of the drainage from Barkers Pond. From this point in the cave voices can be heard from the lowest point in Barkers Pond above. With more sophisticated modern instruments, mapping may prove that the 1972 map has some minor errors.

The Wall

The Wall (Figs 3, 35 and 36) consists of a very long, narrow ridge that rises up to 20 metres above the general level of the flow and can be traced for 35 kilometres. The upper surface of the ridge is relatively flat and varies in width from 70 metres to 300 metres. Its down-flow slope averages only 1.72 metres per kilometre with occasional undulations. The side slopes of the ridge are up to 29°. There are several depressions within five kilometres of the termination of The Wall. One of these depressions may represent a collapsed lava pond which drained into the tube below. Edmonds Lake, a narrower axial oval depression has been interpreted as a collapsed segment of the tube.

The tongue of lava surmounted by The Wall flowed down a precursor of Junction and Elizabeth Creeks. Functional water bores in the vicinity of The Wall confirm that the narrow ridge is localized above a former stream bed.

Formation of The Wall

Stephenson and Whitehead (1996) and Jim Kauahikaua (pers. comm. 2010) see The Wall as a lava rise ridge (Walker 1991). The author, however, believes this formation may have involved a different mechanism.

In July 1974 she observed (Appendix 3, Figs. A3.1, A3.2 & A3.3) lava flowing in, crustal blocks forming on, and moving on a channel built in three days by lava fountains on the floor of Kilauea Caldera. The steep channel walls appeared to have been built by levées. This allowed the mechanism depicted in Atkinson & Atkinson (1995) and Fig. 37, to be proposed as a possible mode of formation of The Wall and some of the features near its termination.

Mode of Formation of the Undara Lava Tube System

Lava rivers and associated tube systems are the main distributors of the lava during a pahoehoe lava eruption. Evidence of how the Undara lava tube system

Fig. 35. Oblique aerial view of western end of 'The Wall' from the south. Note polygonal basalt columns flanking central collapsed area at the termination. (photo: Jon Edmonds).

Fig. 36. Termination of 'The Wall' viewed from the north. Arrows point to the columnar blocks on the horizon. (photo: Tom Atkinson)

and the caves in it may have formed has been preserved for 190,000 years. This, together with observations of caves forming in active and recent lava flows in Hawaii (Jaggar 1947, cited in Wood 1976; Wentworth and Macdonald 1953; Greeley 1971b, 1972a and 1987; Macdonald and Abbott 1970; Cruikshank and Wood 1972; Peterson and Swanson 1974; Peterson and Holcomb 1989), and Iceland (Kjartansson 1949, cited in Wood
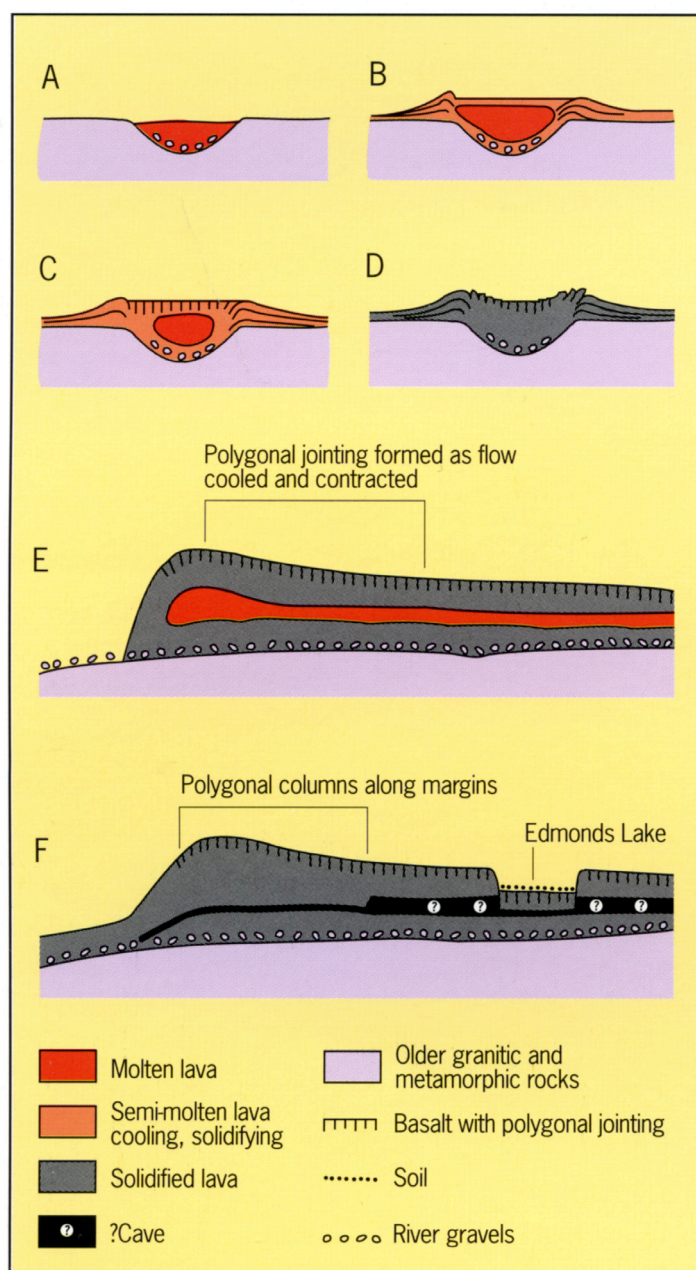
Transverse sections

A. Lava flowing in a valley …

B. … built up levées along its main channel.

C. Lava hardened against the valley walls, at the base and top of the flow and in the levées but the central tube allowed lava to flow on. As the top of the flow cooled, it contracted and polygonal joints formed. The resulting columns show remarkable similarity in cross-section measurements throughout the length of the flow. When the end of the flow hardened, the lava was dammed behind it.

D. A surge of lava broke through the lava dam, allowing still molten lava to escape. The channel roof sagged, leaving the prominent marginal polygonal columns.

Longitudinal profiles

E. (corresponding to C. above) The roof of the elevated channel cooled and polygonal joints formed. Further pressure of lava caused slight elevation at the termination.

F. Renewed activity from the vent broke the terminal dam and allowed the lava to flow on to the Einasleigh River. With the final withdrawal of supporting lava, a central oval section near the termination collapsed to form Edmonds Lake.

Fig. 37. Possible mode of formation of 'The Wall', particularly its western termination. (from Atkinson & Atkinson 1995)

1976), has resulted in the following discussion of the mode of formation of the Undara Lava Tube System (Fig. 38).

A river of pahoehoe lava, confined in a valley, quickly crusts over and develops a roof. The flow also begins to solidify against the valley walls and floor (Fig. 38-A). The roofing occurs in several different ways including growth of semi-solid surface crusts by cooling, crusts floating down the channel jamming and accumulating at obstructions, and the growth of levees from the channel sides through repeated overflows, splashing and splattering. Examination of the roofs in the Undara lava tubes indicates that most of the roofing took place by the growth of semi-solid surface crusts.

As solidification of the roof, walls, and base continue, the flow becomes concentrated within a cylinder (Fig. 38-B). If the eruption ceases at this time, and the tube drains completely, its cross section is circular.

When the supply of lava diminishes during an eruption, it no longer fills the whole tube. Volcanic gases escaping from the flow into this cavity may ignite producing temperatures considerably higher than that of the molten lava. This may cause some remelting of the roof with drips of lava forming lavicicles (Fig. 38-C) which are commonly vertical. Deflection is rare and is thought to be caused by a current of very hot air. In the Undara Lava Tube caves deflection has been noted near the entrance to Picnic I and Barkers caves.

Effusion rates fluctuate during an eruption but whenever a constant rate is maintained, near-horizontal ledges of lava solidify on the tube walls–lava level lines. Further diminution of the flow lowers the level in the tube and finally the flow congeals to form the floor (Fig. 38-D).

Many or most of the lava tubes in a flow will remain filled with lava and caves form only if the tube drains or partially drains. Examination of recent lavas in Hawaii and Iceland has shown that many entrances form during eruption. Other entrances are opened by roof collapse, weathering processes, or excavation by man.

Once the initial Undara Lava Tube System formed there was subsequent thickening of tube roofs by later surface flows (as seen in Road Cave, Fig 13, and Peterson Cave, Fig. 39). Some of these flow units passed over ropy surfaces and now bear ropy imprints on their lower surfaces. A good example of this is found just inside the entrance of Road Cave. The low incidence of ropy surfaces and imprints at Undara support the observation by Macdonald and Abbott (1970) that ropy structure is often evident only over a small proportion of any flow. Fig. 40 shows the thickness of various lava tube cave roofs: (a) Taylor, (b) Harbour Bridge, (c) Peterson, (d) Pinwill, (e) Road, (f) Barker.

Subsequent flows, as well as thickening the tube roofs, may form additional lava tubes. If these connect with existing caves, a complex cave system will develop. In the Undara Lava Field there is such development in the Crater Section and in the vicinity of the Wind Tunnel.
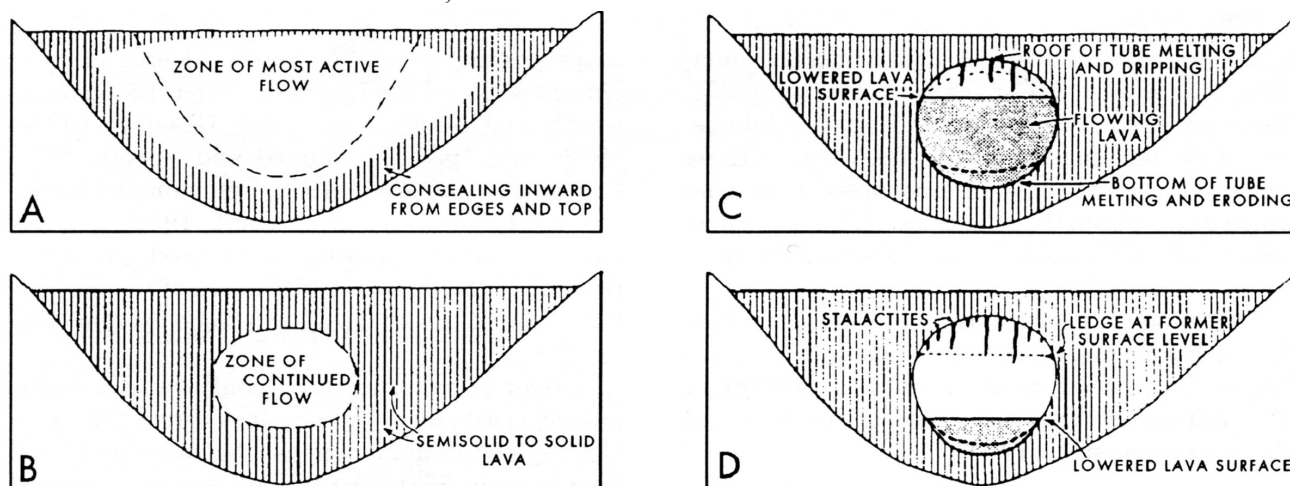
Fig. 38.   Stages observed in the development of the lava tubes in Hawaii (after Macdonld and Abbott 1972). Examination of evidence in the Undara Lava Tubes indicates that this explanation is directly applicable.

a.   The lava flow, confined in a valley, develops a thin crust, by one or more processes and starts to solidify inwards from the edges, the centre continuing to flow.

b.   The active movement of liquid becomes restricted to a more or less cylindrical, pipe-like zone near the axis.

c.   The supply of lava diminishes and the liquid no longer fills the pipe, burning gases above the liquid heat the roof of the pipe and cause it to melt and drip.

d.   Further diminution of supply lowers the level of the surface of the liquid which finally congeals to form the floor of the tube.
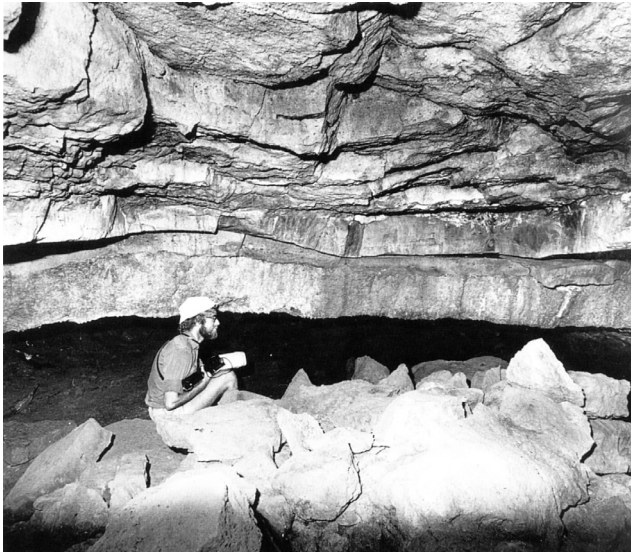
Fig. 39.   Roof structure inside Peterson Cave (east branch). The prominent arched flow unit just above the observer's head has a ropy surface. Higher ropy surfaces also occur. (photo: H.J.L. Lamont)
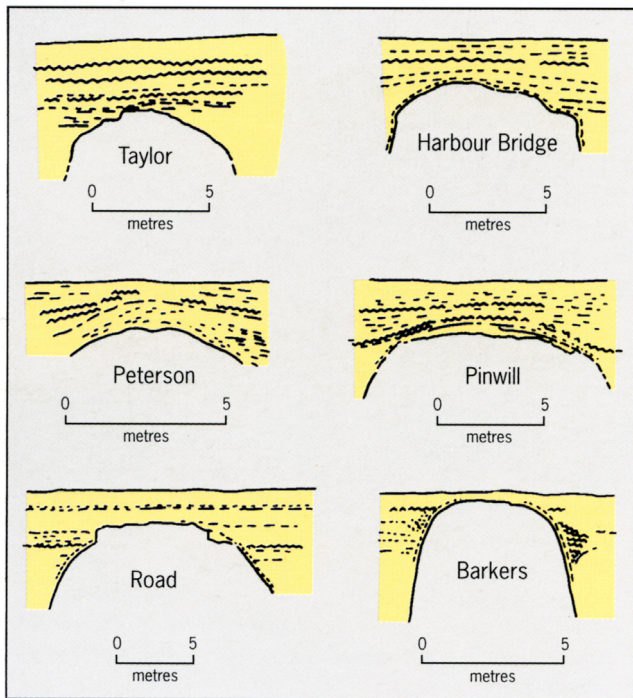
Fig. 40.   Cave entrance structures showing thickening of roofs by successive surface flow units. Wavy lines indicate recognisable flow unit surfaces. Other near-horizontal lines are major vesicle zones. (diagram: P.J. Stephenson)

Beyond the Yaramulla Section, the continuation of the lava tube system is The Wall. That it is 20 metres above the associated lava field with a minimal gradient, suggests that it represents an elevated channel flow whose "toe" solidified initially where The Wall now terminates. This caused a temporary blockage which allowed the channel to roof over to form a major lava tube. The large polygonal jointing (Figs 35 and 36) is taken to evidence considerable roof thickness. A surge of lava through the tube broke down the toe of the flow and continued a further 70 kilometres. Slumping

of the tube roof at the termination left a colonnade of roughly columnar blocks (Fig. 36). It would be of great interest to confirm the structure of this unusual feature by geophysical investigation or drilling near the centre of the ridge.

Conclusion

Favourable palaeotopography, continued effusion and an efficient lava tube system, allowed one flow from the Undara Volcano to extend 160 kilometres to become the longest recent single-volcano flow in the world. This flow contains the longest lava cave in Australia – Bayliss Cave, with more than 1300 metres. Within the caves and arches of the lava tube system, protection from weathering has allowed the preservation of many features similar to those in active and recent lava flows. From such features it can be concluded that the lava tube system and the caves in it formed in a manner similar to those that have been observed forming during historic eruptions of pahoehoe lava in Hawaii and Iceland.

Acknowledgements

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APPENDIX 1

UNDARA LAVA TUBE SYSTEM LAVAS – MAJOR ELEMENT CHEMICAL ANALYSES

(from Atkinson, Griffin and Stephenson 1976, Table 1)

Specimen	1.	2.	3.	4.	5.	6.
SiO_2	48.85	48.80	48.20	49.30	49.50	51.6
TiO_2	1.82	1.71	1.75	1.70	1.67	2.20
Al_2O_3	15.23	15.12	15.80	15.40	15.90	16.6
FeO_3	2.52	2.94	4.46	11.00	10.53	8.17
FeO	7.46	7.94	6.38	trace	0.06	0.66
MnO	0.16	0.17	0.17	0.15	0.15	0.13
MgO	8.55	8.88	7.85	8.10	7.10	2.80
CaO	9.16	9.73	8.02	8.02	8.39	5.50
Na_2O	3.90	3.34	3.57	4.20	3.87	5.30
K_2O	1.75	1.20	1.71	1.77	1.53	3.25
H_2O+	0.35	n.d.	n.d.	n.d.	n.d.	n.d.
H_2O-	0.17	*	*	*	*	*
P_2O_5	0.64	0.34	0.72	0.50	0.34	0.87
CO_2	0.13	n.d.	n.d.	n.d.	n.d.	n.d.
Total	**100.69**	**100.17**	**98.63**	**100.14**	**99.04**	**97.08**
Location (Fig. 8)	A	B	C	D1	D2	E

*These analyses on samples dried at 110°C

n.d. = not determined

Specimen locations (A to E) are shown on Fig. 8. C is the western end of The Wall;
    D1 is host rock, Barkers Cave entrance; D2 is lining at Barkers Cave entrance;
    E is host rock lava drip, Pinwill Cave.

Analytical techniques used for specimens:

1. XRF; Na, flame photometric; Fe[2], by titration - by T.J. Griffin
2 - 6. Atomic absorption (HF - Boric acid digestion; P, spectrophotometric; Fe[2], by
    titration - by P.J. Stephenson and T.J. Griffin.

THE AUTHOR'S FIRST MAP AND TRANSVERSE SECTIONS, BARKERS CAVE, UNDARA
(modified for Atkinson & Atkinson 1995)
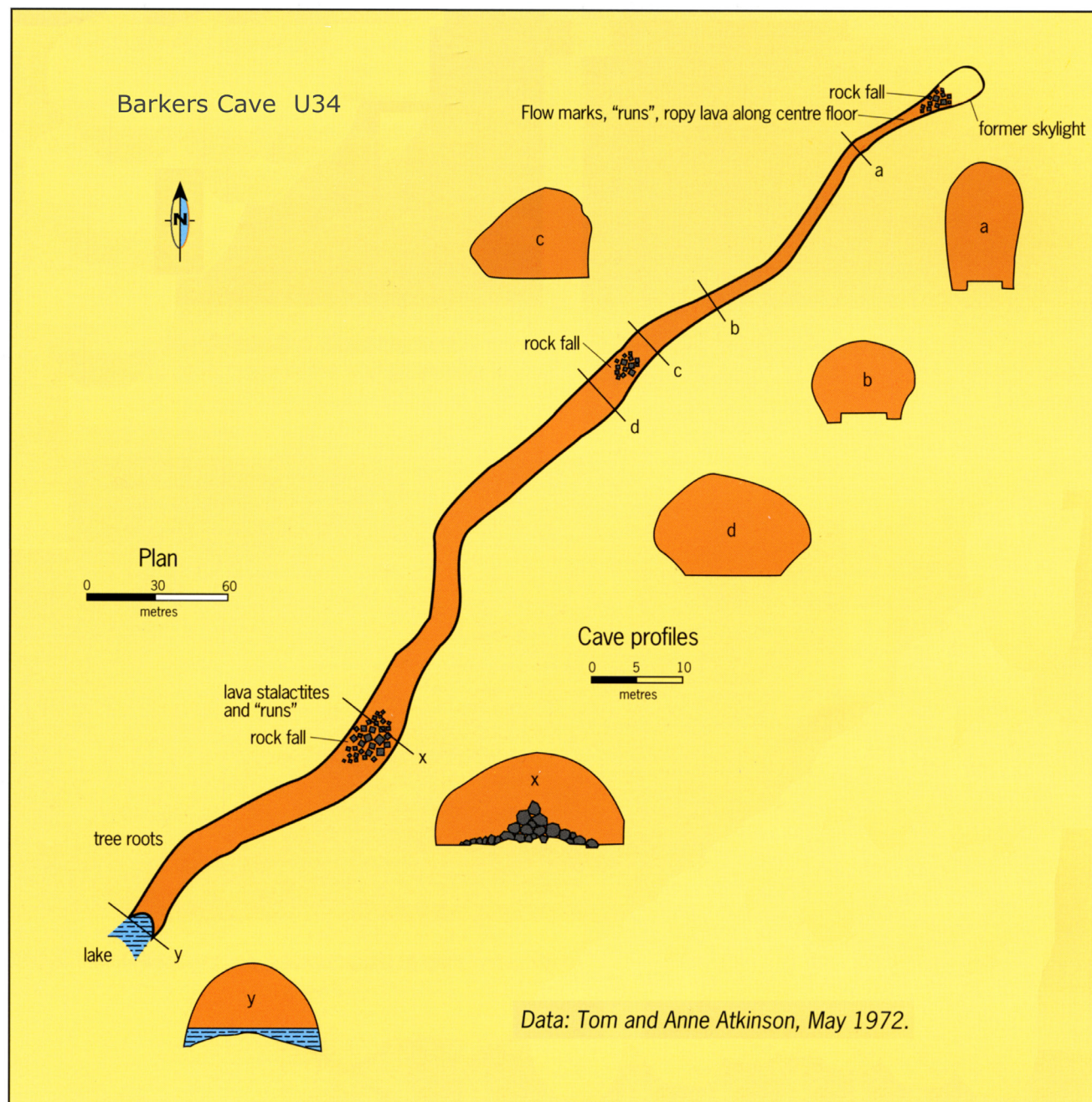
Fig. A2-1. Map of Barkers Cave (survey data by Tom and Anne Atkinson, 1972)
(first published in Stevens & Atkinson 1975).
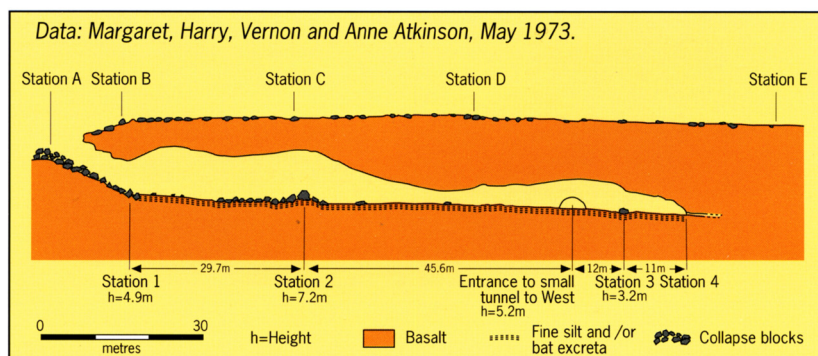
Fig. A2-2. First longitudinal profile, Undara Lava Tube
System: Atkinson Cave.

APPENDIX 3 – **HAWAII**

Under the guidance of Dr Donald Peterson, Scientist-in-Charge (1970-75), USGS Hawaii Volcanoes Observatory, and later with Christina Heliker, a senior field geologist, the author had the extraordinary good fortune to see:

- 1972: waves of lava flowing into a lava lake, summit Mauna Ulu;

- 19 July 1974: spectacular lava fountains, Kilauea caldera floor, (Fig. A3-1);

- 20 July 1974: minor flows from final fountaining built their own levées; crustal blocks forming and moving on cooling surface. The side of channel was near vertical (Figs. A3-2, A3-3);

- 21 July 1974: eruption nearly over (Fig. A3-4);

- Patches of ropy lava forming in the semi-solid crust on the gentle slope near sea level (Fig. A3-5);

- 1991: lava flowing in a lava tube (Figs. A3-6, A3-7).

- 1991:

- An earlier lava flow

- Vernon Atkinson standing on very new Pahoehoe lava watching "toes" bud and ropy lava form.
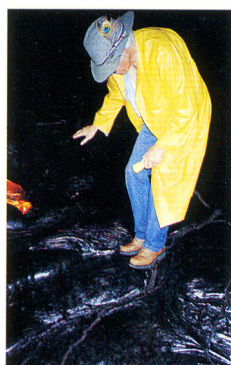
Though she will never claim to be an authority on any matters vulcanological, these incredible sights and sounds had a profound influence on the author.

Discussions by letter and in person with members of USGS Hawaii Volcano Observatory staff, Dr Donald Peterson, Scientist-in-Charge 1970-75, Christina Heliker, a senior field geologist, Jim Kauahikaua, present Scientist-in-Charge, and others were invaluable. Their knowledge and the opportunity to observe the above phenomena have greatly influenced the author's opinion re likely mode of formation of many surface and lava tube features in the areas selected for field work in 1972 of the 190,000 year old Undara lava field.

Hawaii – Suggested additional reading

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APPENDIX 4

CHEMICAL COMPOSITION OF LAVAS

Composition of lava influences its viscosity. Similarity of composition of Undara lava (Griffin 1977) and average Hawaiian lava is noted in the table below. For interest, average composition of lava from Mt. St. Helens 1980 explosive eruption is also given.

	Undara*	Hawaiian Islands[#]	Mount St. Helens (1980)
Silicon SiO_2	48.9	48.4	63.5
Titanium TiO_2	1.8	2.8	0.6
Aluminium Al_2O_3	15.2	13.2	17.6
Iron FeO	10.5	11.2	4.2
Magnesium MgO	8.6	9.7	2.0
Calcium CaO	9.7	10.3	5.2
Sodium Na_2O	3.9	2.4	4.6
Potassium K_2O	1.8	0.6	1.3
Other Oxides	-	1.4	1.0

Table of average chemical composition *of lavas expressed as weight percent oxides from the Hawaiian Islands, Mt. St. Helens, U.S.A., explosive eruption (1980) and one analysis from an Undara flow.*

\#   Average of 53 analyses of olivine basalts.
*   Host rock, Barkers Cave entrance; analysis: T.J. Griffin.

Undara Volcanic National Park Management

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Abstract

Undara Volcanic National Park protects an outstanding volcanic landscape in the north-western part of the McBride lava province and is situated approximately 200 km south west of Cairns in north Queensland. The national park was dedicated to represent the outstanding volcanic formations of this region. Access to most of the park's significant volcanic tubes and caves is by the means of guided tours only. The National Park Geology is the focus of both protection and presentation in the park; management aims to protect Its outstanding volcanic features and present representative features to visitors with minimal impact on their natural and cultural values. The park is classified as having very significant presentation values.

The Ranger in Charge of this iconic park will present a brief history of this internationally significant well-preserved lava tube system. The presentation will then focus on the challenges faced in managing the risks involved with these environments. Over 30 000 visitors arrive annually from both domestic and international origins, wanting to experience this natural geological wonder.

Arch Cave, Undara Volcanic National Park
[Department of Environment & Resource Management, Queensland]

Bayliss Lava Tube and the Discovery of a Rich Cave Fauna in Tropical Australia

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Abstract

Australia, including the tropical north, is currently recognized as having one of the world's richest underground faunas. Until fairly recently, it was widely believed that cave adapted species (troglobites) did not exist in the tropics. Lava tubes were also considered to be devoid of troglobites, and the Australian continent was thought to have relatively few cave adapted species due to its aridity. Leleup in the Galapagos in 1968, Howarth in Hawai'i in 1971, and subsequent researchers discovered numerous troglobites in lava tubes on volcanic islands in the tropical Pacific. Based on his work in Hawai'i, Howarth developed a bioclimatic model including the "tropical winter" effect to explain the restriction of troglobites to deep cave zones and small subsurface voids (mesocaverns) with constant high humidity. Brother Nicholas Sullivan, with the Sydney Speleological Society and the Chillagoe Caving Club, began to survey the biology of the Chillagoe limestone caves and in 1984 invited Francis Howarth and Fred Stone to join the 1984 to 1986 expeditions with support from The Explorers Club. During the 1984 expedition, they learned of Anne Atkinson's detailed studies of a number of lava tubes in the McBride Volcanic Province at Undara and in 1985, guided by Douglas Irvin of the Chillagoe Caving Club, they went to investigate. With enthusiastic support of the Pinwill family, who held the grazing lease, they were able to enter many of the lava tubes at Undara and on the neighbouring cattle stations managed by the Collins brothers. Bayliss lava tube had an ideal conformation to foster a stable, humid deep cave climate, with a restricted entrance, a sealed back end, and barriers to air circulation plus abundant food supplies from bat guano and tree roots. Two dozen previously unknown cave adapted species were discovered. An additional feature was a high level of carbon dioxide in the deep cave where troglobites were the most abundant. This combination of high humidity and carbon dioxide makes Bayliss lava tube a "window" into the much broader mesocavernous zone. Other lava tubes in the McBride Province with similar conditions were found to have several additional troglobitic species. These discoveries complemented the work on tropical volcanic islands by showing that tropical continental lava tubes were also rich in troglobitic species. Comparisons between the old Chillagoe limestone caves and relatively young (190,000 year old) lava tubes confirmed the bioclimatic model. Subsequent work across Australia by Humphreys, Clarke, Eberhard and numerous others has resulted in discovery of subterranean "hot spots" in other geologic formations in which caves and/or mesocaverns occur. Where these formations lack caves, well bores and mining test bores are being sampled with bait traps. Other Australian volcanic areas, such as Black Braes, show high potential for cave species, and where lava tubes are lacking well bore sampling could reveal their mesocavernous fauna.

No tropical troglobites

Until fairly recently, it was widely believed that cave adapted species (troglobites) did not exist in the tropics. For one hundred years or more, according to conventional wisdom, no truly cave adapted species had been found in the tropics, except for some aquatic species (Vandel 1965). The dominant evolutionary theory was based on allopatric speciation, the necessity for a complete physical barrier to gene flow between populations in order for separate species to evolve (Mayr 1963). Biospeleologists developed the Glacial Relict Theory of troglobite evolution, hypothesizing that continental glaciation could have caused widespread populations of epigean troglophiles to become extinct, allowing the isolated cave dwelling populations (in areas marginal to the glaciers) to undergo reorganization of the genome and evolve specialized adaptations to deep cave existence (Barr 1968, 1973).

The glacial relict theory has two important components; first, the lack of troglobites in tropical areas (and their presence in temperate zone areas) and second, the necessity that there be a lack of epigean (troglophilic) sibling species that could explain the isolation of cave populations and their subsequent evolution of obligate cave species.

Since the apparent lack of tropical troglobites was based on lack of evidence, the possibility existed that tropical caves had not been sufficiently searched for obligate cavernicoles. However, the discovery of tropical troglobites does not falsify the relictual speciation hypothesis, since other major climate changes or geological processes might cause the epigean populations to become extinct. Therefore, it is necessary to find both tropical troglobites and their epigean relatives, and to determine their close evolutionary relationship as sympatric or parapatric species.

In the 1960s, my colleague Francis (Frank) Howarth and I worked in Southeast Asia with International Voluntary Service, and in our free time we began searching for troglobitic species in caves of Thailand and Laos. We were successful in finding several candidate troglobite species, but without the evidence of epigean sister species. It was also difficult to find systematists with experience in Southeast Asia for many of the taxa.

In 1971, Howarth, then a Ph.D. student in Entomology at the University of Hawai'i, was working as site manager for the International Biological Program at the Hawaii Volcanoes National Park. On his time off, he was exploring a lava tube in Bird Park and he discovered a blind planthopper on a tree root (Howarth 1972).

This led to his employment as an Entomologist at Bishop Museum (where he currently has an endowed chair), grants, and intensive searches in lava tubes throughout the Hawaiian Islands. In the next few years, he discovered many more cave adapted species, and new species are still being discovered at the present time. These include cave water striders, no-eyed "big-eyed" hunting spiders, cave moths and cave crickets (Howarth 1973, 1981)

In 1986 planthopper specialists Dr. Manfred Asche and Dr. Hannelore Hoch visited Bishop Museum to study the planthopper collection, and Hannelore became entranced by the blind cave planthoppers. They joined the research, and have discovered numerous species in caves and lava tubes around the world (Hoch 1999; Hoch & Asche 1993).

Frank Howarth's discovery of the troglobitic planthoppers, followed by over 75 other troglobitic species from Hawaiian lava tubes, falsified the "No Tropical Troglobite" hypothesis. However, it has taken much longer to do the detailed research that will determine whether epigean sibling species exist, and how closely they are related to the cave species, work that is still ongoing, currently assisted by the development of new genomic approaches to DNA analysis (Wessel 2008; Taiti & Howarth 1997; Rivera *et al.* 2002).

Soon, troglobites were reported from other tropical and subtropical areas, including Jamaica, Galapagos (Leleup in 1968), Canary Islands, Congo, Thailand and Central America (Peck & Finston 1993).

Howarth developed the bioclimatic model to explain the distribution (and difficulty of finding) tropical troglobites. This model showed that troglomorphic species are restricted to habitats at or near saturated humidity. In humid temperate climates, cave adapted species move into deep cracks in the winter to escape

the drying effect of cold air entering the caves (Barr, 1973). The "Tropical Winter Effect" occurs on a diurnal basis, with cool, desiccating surface air flowing into caves every night, limiting the suitable troglobite habitat to cave areas where the entrance effect is minimal or absent. Certain cave morphology, including goose-neck passages, upward sloping passages, dead-end passages, rooms accessed from low crawl passages, and areas far from entrances reduces the winter effect and allows water vapour to accumulate (Howarth 1980, 1983a, b, 1988a).

According to Howarth's model, caves have five zones: the Entrance Zone and Twilight Zone are strongly influenced by surface air and temperature. The Transition Zone is influenced by surface air, and experiences the "Tropical Winter Effect". The Deep Cave Zone is not affected by surface air, and has constant high humidity, close to saturation. The fifth zone is the Stagnant Air Zone. This zone does not have air circulation, and carbon dioxide can increase. Troglobitic species cannot survive in the Entrance, Twilight and Transition zones, so to find them it is necessary to find the high humidity and low air flow zones of the Deep Cave and Stagnant Air zones (Fig. 1).

Lava flows are porous and contain numerous small lava tubes and mesocaverns. These small spaces tend to have restricted air flow and high humidity. Cave species live in the mesocaverns and move into the larger lava tubes when conditions permit (deep cave zones) (Fig. 2).

Many biospeleologists did not agree that the "Glacial Relict Theory" had been falsified: Oceanic Pacific islands were thought to have "special conditions" that permitted cave species to evolve (Culver 1982; Holsinger 1988; Holsinger & Culver 1988). However, Peck & Finston (1993) supported Howarth's model by citing many cases of sibling cave and surface species in tropical Pacific Islands.

Tropical Australia was considered to have very few cave adapted arthropods due to its aridity following a series of continental drying events (Hamilton-Smith 1967). Brother Nicholas Sullivan, based on earlier cave surveys by the Sydney Speleological Society and the Chillagoe Caving Club, in 1982 began to survey the biology of the Chillagoe limestone caves and in 1984 invited Frank Howarth and Fred Stone to join the 1984 to 1988/9 expeditions with support from The Explorers Club (Sullivan 1976, 1983a, 1983b, 1984, 1989) (Fig. 3).

Chillagoe tower karst in northern Queensland is an ideal tropical continental area to compare with the Hawaiian Islands. It has numerous isolated karst
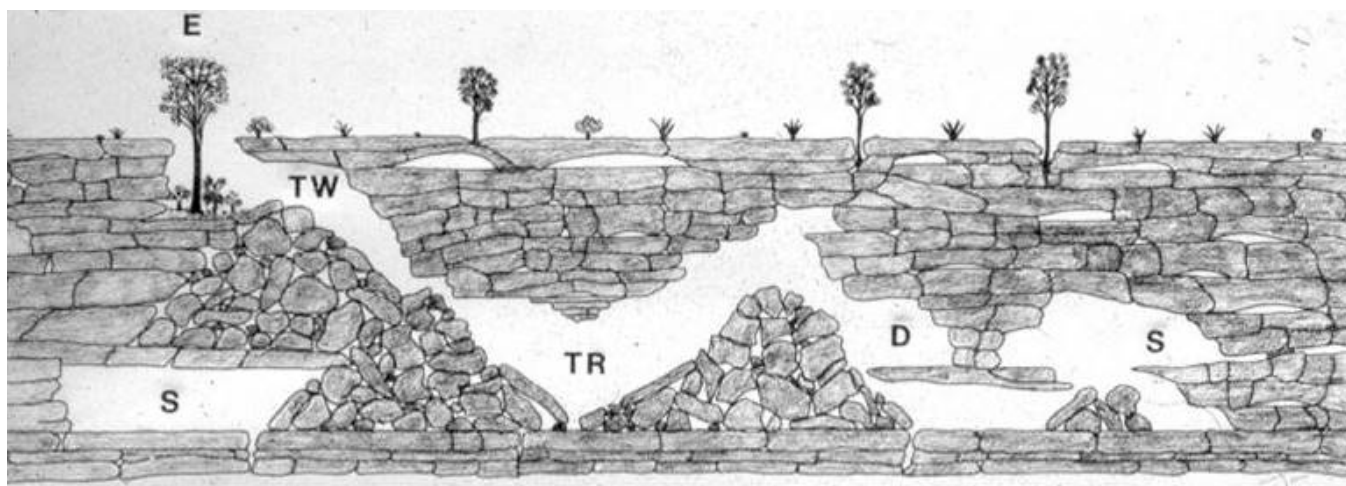
Fig. 1. Cave Zones [after F. Howarth]. E: Entrance Zone; TW: Twilight Zone; TR: Transition Zone; D: Deep Cave Zone; S: Stagnant Air Zone.

Fig. 2. Mesocaverns in lava flow (photo: F. Howarth)

towers spread over 200 kilometres, similar to an island archipelago. There are abundant caves with tree roots, including *Ficus* and *Brachychiton*, that send their roots deep into caves to reach water. Chillagoe has both large and small caves, in which humid areas are present and where troglobites could occur. Planthoppers and cockroaches are two groups in which cave adapted forms have been discovered in Chillagoe caves (Hoch & Asche 1988; Howarth 1988b; Stone 1988; Stone *et al.* 2005, Sullivan 1988; Slaney 1996).

During the 1984 expedition, we learned of Anne Atkinson's detailed studies of a number of lava tubes in the McBride Volcanic Province at Undara, and in 1985, guided by Douglas Irvin of the Chillagoe Caving Club, and with the support of Brother Nick and the Explorers Club, went to investigate (Atkinson, Griffin & Stephenson 1976) (Fig. 4).

With enthusiastic support from the Pinwill family, who held the grazing lease for Yaramulla Station, we were able to enter many of the lava tubes at Undara and on the neighbouring cattle stations of Spring Creek and Rosella Plains, managed by the Collins brothers (Fig. 5).

We investigated Barkers Cave because it has a lake at its far end. It has a large entrance and a large passage throughout, but because of the large, open entrance, the deep cave environment does not occur. Many of the Undara caves are fairly short and are open at both ends, such as the Wind Tunnel. These tubes have mostly Entrance, Twilight and Transition zones, but no Deep Cave zone.

Fig. 3. Explorers Club Expedition 1989: Frank Howarth, Stefan Eberhard, Hannelore Hoch, Manfred Asche, Bro. Nicholas Sullivan, Don Matts, Fred Stone, Grace Matts, Terry Matts & friend. (Photo Eileen Carol)

Fig. 4. Undara lava flow [from aerial photo].

Fig. 5. Manfred Asche, Frank Howarth, Hannelore Hoch, Lauren, Sonia, Michael, Troy & Don Pinwill & friends, 1989

We finally entered Bayliss Cave. A low entrance crawl opened into the top of a breakdown slope into a large passage. The cave felt humid, and water was condensing on the ceiling just inside the entrance. Bayliss has a restricted entrance and it is sealed at its lower end, so there is minimal air circulation. At about 350 metres, there is a low ceiling that traps water vapour, which is less dense than air. The downward sloping cave and a rock barrier at about 650 metres ('The Wall') trap carbon dioxide, which is denser than air. The cave has bat roosting areas, and the carbon dioxide is most likely generated by decomposition of the bat guano, which also consumes oxygen (Figs 6, 7, 8, 9).

The cave was appreciably more humid beyond the Duckunder, and roots become more abundant (probably *Ficus* or *Brachychiton*, although they haven't been positively identified). The cave floor has accumulated a thick layer of soil, and the roots grow through it. Besides providing moisture to the roots, the bat guano is a rich source of nutrients. The roots, in turn, provide a food source for the cave troglobite community. Passing the Duckunder is like Alice going down the rabbit hole—the far side has creatures that are very strange indeed. We found about 24 troglobites, all previously unknown, making it one of the most diverse cave communities in the world (Howarth & Stone 1990) (Fig. 10).

A list of the species found in Bayliss Cave is appended. Included are three species of troglobitic millipedes, a troglobitic Scutigeromorph
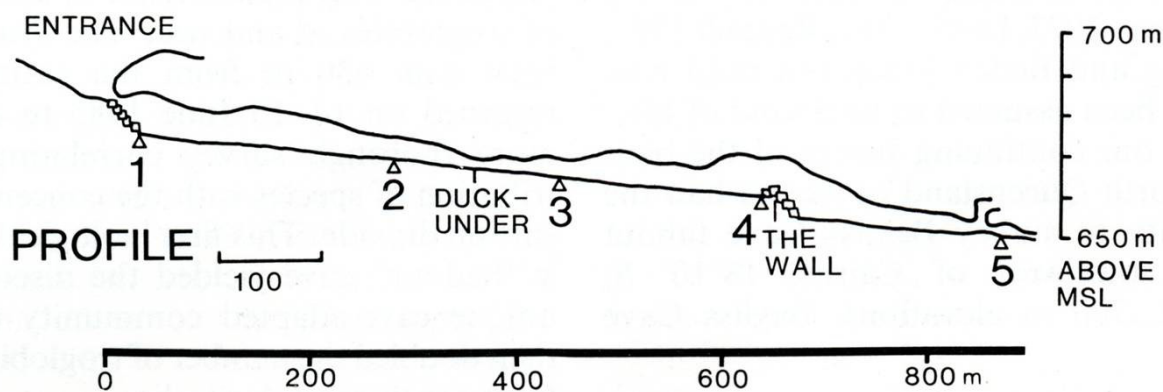
Fig. 6. Bayliss Cave profile (after Howarth & Stone 1990)

Fig. 7. Base of entrance breakdown, Bayliss Cave.
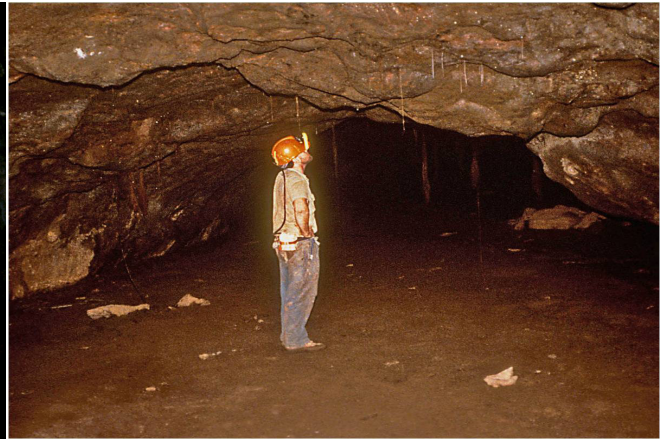
Fig. 8. S. Robson at Duckunder, Bayliss Cave
(photo: F. Howarth).

Fig. 9. F. Howarth and S. Robson on The Wall,
Bayliss Cave (photo: S. Robson).

Fig. 10. S. Robson beyond the Duckunder, Bayliss Cave
(photo: F. Howarth).

centipede that walks slowly, doesn't react to light but is sensitive to touch, and *Pirates*, a troglobitic predatory bug common in the deep cave zone. The highly troglomorphic Bayliss planthopper, *Solonaima baylissa,* completely eyeless, and a surface species, *Solonaima pholetor,* are good candidates as sibling species (Hoch & Asche 1988; Hoch & Howarth 1989a, b) (Figs 11, 12, 13, 14, 15).

Paratemnopteryx stonei is a partially troglomorphic cockroach that occurs in entrance, twilight and transition zones, as well in deep zones, of caves at Chillagoe and Undara. It occurs in the outer section of Bayliss Cave. An eyeless troglobitic species, *Neotemnopteryx baylissensis* Slaney 2000, occurs from the Duckunder into the deep cave and stagnant air zones. A small-eyed cave species, *N. undarensis* Slaney 2000, occurs in other lava tubes in the Undara area. Slaney believed that the cave species were relicts from continental drying, based on their distribution and DNA evidence (Roth 1990; Slaney 1996, 2000, 2001; Stone 1988) (Figs 16, 17).

A highly troglomorphic cockroach in the family Nocticolidae, genus *Nocticola,* occurs on The Wall and in the deep and stagnant air zones. I am currently preparing a description of this species. *Nocticola*

australiensis from Royal Arch Cave and Donna Cave in Chillagoe is less cave adapted than the Bayliss species, and occurs in twilight and transition zones as well as in the deep cave zone. These two species are potentially sibling species, but further work on their DNA is necessary to determine how closely they are related (Stone 1988) (Figs 18, 19).

On 14 and 15 June 1985, we did a complete inventory of populations and species in Bayliss at five locations (base of the entrance slope, just before the Duckunder, the top of the Wall, the bottom of the Wall, and just before the tight crawl that was considered the end of the cave), and measured the temperature, relative humidity, carbon dioxide and oxygen (Fig. 20).

The temperature increased from about 23°C at the base of the entrance breakdown to just over 26° at the inner end. Humidity was over 94% below the entrance and increased to 98-100% from the Duckunder (although humidity measurements above 90% are not very accurate). Oxygen was between 19 and 21% (ambient) from the entrance to the Duckunder, and then dropped rapidly to 15% at the inner end. Carbon dioxide was less than 0.5% below the entrance, increased to 0.5% at the Duckunder, then increased to 2.5% at the top of The Wall, 4.5% at the bottom of The Wall, and 6% at the inner end (Howarth & Stone 1990) (Fig. 21).

Fig. 11. Bayliss Cave millipedes (photo: F. Howarth)

Fig. 12. Bayliss Scutigeromorph centipede
(photo: F. Howarth)

Fig. 13. Bayliss Pirates troglobitic assassin bug
(photo: F. Howarth)

Fig. 14. Bayliss planthopper, Solonaima baylissa
(photo: Hubert Reimer)

Fig. 15. Surface planthopper, Solonaima pholetor
(photo: Hubert Reimer)

Fig. 16. Troglophilic cockroach, Paratemnopteryx stonei

Fig. 17. Bayliss troglobitic cockroach, Neotemnopteryx
baylissensis *(photo: G. Thompson, Queensland Museum)*

Fig. 18. Bayliss troglobitic Nocticolidae cockroach
(photo: F. Stone)

Fig. 19. Nocticola australiensis *from Chillagoe*
(photo: D. Ward)

Fig. 21. Plots of Bayliss Cave temperature,
relative humidity, oxygen and carbon dioxide
(after Howarth & Stone 1990)

Fig. 20. Frank Howarth recording data.
(photo: Eileen Carol)
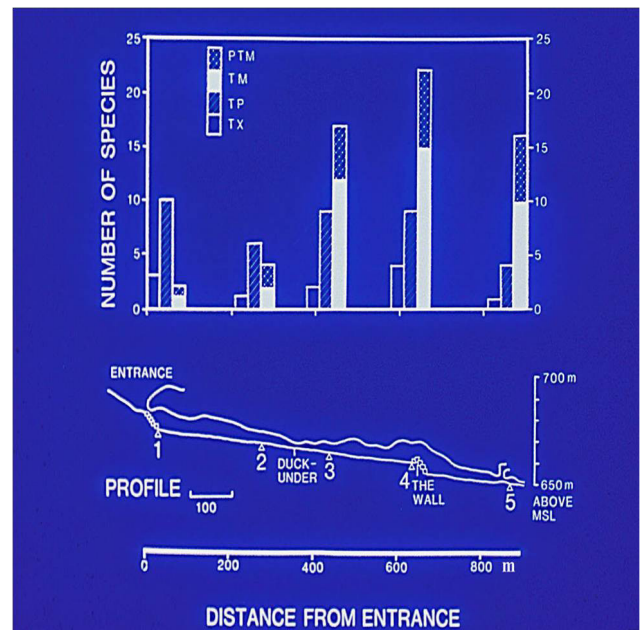
Fig. 22. Distribution of species through Bayliss Cave
(after Howarth & Stone 1990)

The six trogloxenic species (which spend part of their lives in caves and part outside, generally going out to feed) were found throughout the cave. The 16 troglophilic species (which can live both in caves and out of caves) tended to be more abundant before the Duckunder, although some of them were also in the deep cave and stagnant air zones. The 24 troglobitic species (obligate cave dwellers, partially troglomorphic and troglomorphic) had their highest populations in the deep cave and stagnant air zones (Figs 22, 23).

Undara Lava Tubes, Bayliss and other lava tubes studied in 1985 and 1986, were important in establishing that Australia could support rich subterranean communities where the deep cave and mesocavernous conditions occurred. This confirmed that Hawaiʻi and other tropical oceanic islands are not "special cases", but that the same bioclimatic controls
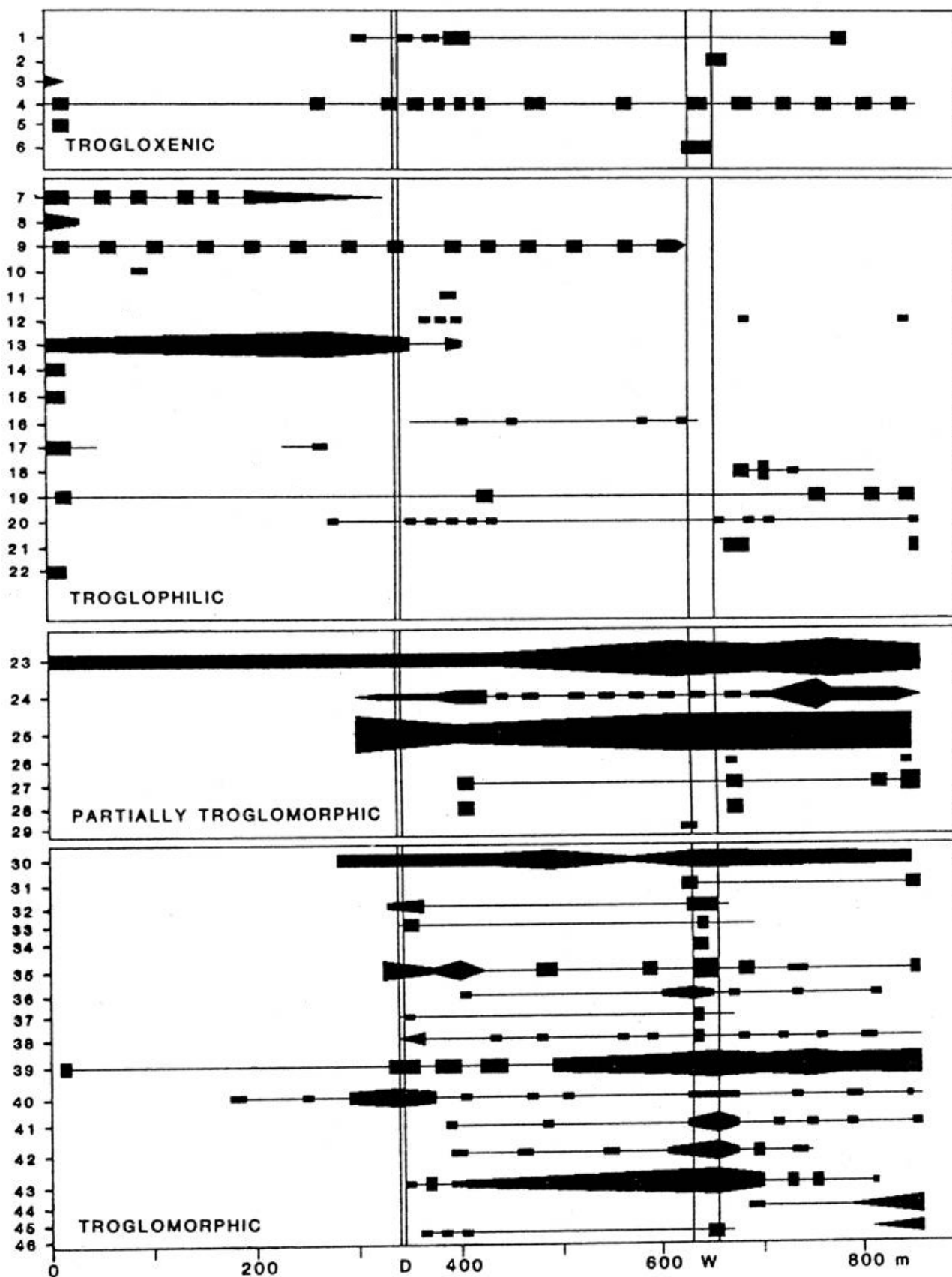
Fig. 23. Species distribution through Bayliss Cave (after Howarth & Stone 1990)

are present in both continental and island caves, and that troglobitic communities exist wherever the conditions support them.

In 1986, while Frank and the Explorers Club expedition went back to Undara to continue with the study there (Fig. 24), I joined Louis Deharveng and Anne Bedos for a trip to Thailand. Deharveng had recorded several high CO_2 caves in his previous Thai expeditions, but hadn't spent a lot of time looking for cave species in them. We visited limestone caves in northwest Thailand, and in most of the high CO_2 (and high humidity) caves, I discovered new species of highly cave adapted Nocticolidae cockroaches. This gave further confirmation to the presence of troglobites in tropical caves with the right deep cave conditions (Deharveng & Bedos 1986).

Fig. 24. 1989 expedition members Manfred Asche, Frank Howarth, Terry Matts, Douglas Irvin and Hannelore Hoch.

However, climatic shift and relictual speciation due to continental drying is an alternative hypothesis. It is possible that both processes (relictual or allopatric speciation and para- or sympatric speciation) may be represented (Humphreys 1991, 1999; Slaney, 2001).

Further work depends on getting the species identified, described and compared using both traditional morphology and current DNA analysis. This involves seeking the expertise of specialists and provision of grant money to pay for their work.

The work of Bill Humphreys at Western Australian Museum and biospeleologists including Arthur Clarke, Stefan Eberhard, and members of many caving clubs have established that a rich diversity of subterranean life occurs wherever there is a porous substrate and a food source (Humphreys 1993a, b, c, 1994, 1995, 1999).

Credits

Appendix: Species from Bayliss Cave
   (Howarth & Stone, 1990)
Trogloxenic
1. Thysanura: Atelurinae: undet. sp. 1
2. Isoptera: undet. Sp. 1
3. Lepidoptera: Noctuidae: *Sericea spectans* Guerin
4. Hymenoptera: Formicidae: *Paratrechina* sp.1
5. Hymenoptera: Formicidae: *Paratrechina longicornis*
6. Hymenoptera: Formicidae: *Platythyrea* sp. 1

Troglophilic
7. Aranae: Sparrasidae: *Heteropoda* sp. 1
8. Aranae: Pholcidae: *Spermophora* sp. 1
9. Aranae: Nesticidae: *Nesticella* sp. 2
10. Scolopendrida: *Scolopendra* undet. Sp. 1
11. Geophilida: undet. Sp. 1
12. Symphyla: undet. Sp. 1
13. Blattodea: Blattellidae: *Paratemnopteryx stonei* Roth (1990)
14. Hemiptera Auchenorrhyncha: Cixiidae: *Undarana rosella* Hoch & Howarth (1989a)
15. Hemiptera Auchenorrhyncha: Cixiidae: *Oliarus* sp. 1
16. Hemiptera Auchenorrhyncha: Coccoidea: undet. Sp. 1
17. Coleoptera: Scarabacidae: undet. Sp. 1
18. Coleoptera: Ptiliidae: undet. Sp. 1
19. Lepidoptera: Gelechiidae: undet. Sp. 1
20. Lepidoptera: Noctuidae: *Schrankia* sp. 1
21. Diptera: Psychodidae: Phlebotominae: undet. Sp. 1
22. Diptera: Phoridae: undet. Sp. 1

Troglobitic (partially troglomorphic)

23. Isopoda: Oniscomorpha: undet. Sp. 1
24. Isopoda: Oniscomorpha: undet. Sp. 2
25. Diplopoda: Polydesmida: undet. Sp. 1
26. Collembola: undet. Sp. 1
27. Diplura: undet. Sp. 1
28. Thysanura: Nicoletidae: *Nicoletia*? Sp. 1
29. Hemiptera: Heteroptera: Reduviidae: *Pirates* sp. 1

Troglobitic (strongly troglomorphic)

30. Aranae: Pholcidae: *Spermophora* sp. 2
31. Aranae: Nesticidae: *Nesticella* sp. 1
32. Aranae: Miturgidae: new genus & species
33. Aranae: Zodariidae: *Storena* sp. 1
34. Aranae: Linyphiidae? Undet. Blind sp. 1
35. Diplopoda: Polyxenida: undet. Blind sp. 1
36. Diplopoda: Polydesmida: undet. Blind sp. 2
37. Diplopoda: Cambalida: undet. Blind sp. 1
38. Scutigerida: undet. Blind sp. 1
39. Collembola: Entomobryidae: *Pseudosinella* sp. 1
40. Blattodea: Blattellidae: *Neotemnopteryx baylissensis* Slaney (2000)
41. Blattodea: Nocticolidae: *Nocticola* sp. 1
42. Hemiptera: Heteroptera: Reduviidae: *Micropolytoxus cavicolus* Malipatil & Howarth (1990)
43. Hemiptera Auchenorrhyncha: Cixiidae: *Solonaima baylissa Hoch & Howarth (1989b)*
44. Coleoptera: Pselaphidae: undet. Blind sp. 1
45. Coleoptera: Staphylinidae: undet. Blind sp. 1
46. Coleoptera: Curculionidae: Rhytirhininae: n. gen. and sp. 1

Additional species from lava tubes in the McBride Province (Howarth 1988b):

• Onychophora: peripatus: 210 and Long Shot Caves (Troglobitic?)
• Arachnida: Schizomida: Barkers Cave (cave adapted?)
• Phalangidae: Long Shot Cave (troglobitic?)
• Blattodea: *Nocticola* sp. 2: Long Shot Cave (troglobitic)
• Blattodea: Blattellidae: *Neotemnopteryx undarensis* Slaney (2000). Undara lava tubes (troglobitic?)
• Hemiptera: Heteroptera; Reduviidae (Emesinae): *Ploiaria* species 1 Long Shot Cave (troglobitic)
• Hemiptera: Heteroptera; Reduviidae (Emesinae): *Ploiaria* species 2 Long Shot and 210 Caves (troglobitic)
• Hemiptera Auchenorrhyncha: Cixiidae: *Undarana collina* 210 Cave, Collins Cave
• Coleoptera: Curculionidae, Rhytirhininae: sp. 2 Taylor Cave

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An Overview of Invertebrate Fauna Collections from the Undara Lava Tube System

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Abstract

In the summer of 1988/1989, the author visited the Undara Lava Tube System, undertaking a study of invertebrate fauna, collecting species from the arid surface and humid subterranean environments. The visit immediately followed the 17th ASF Conference (Tropicon) at Lake Tinaroo, near Cairns, where the significance of the hypogean biodiversity at Undara had been highlighted. The author's subsequent fauna collection at Chillagoe and Undara was undertaken under the auspices of a permit from the Queensland Parks and Wildlife Service.

Serious biological collecting at Undara commenced under the patronage of Brother Nicholas Sullivan from the Explorers Club, New York; he introduced two Hawaiian cave biologists: Fred Stone and Frank Howarth. All three visited and collected from Undara for the first time in 1985, together with local cavers including Doug Irwin. In the following years, they were joined by other expedition biologists, such as the German planthopper specialists Hannelore Hoch and Manfred Asche. Later studies were also carried out on Operation Raleigh by their biologist Michael Godwin and in 1995 and 1997 during the fieldwork conducted by David Slaney working on his PhD dissertation. Unfortunately, there is scant mention of the cave fauna in the September 1999 Management Plan for the Undara Volcanic National Park.

Although a condition of the author's permit required all collected specimens to be lodged in the Queensland Museum (QM), cave fauna from Undara has also been deposited in the Australian Museum (AM) in Sydney and the Australian National Insect Collection (ANIC) in Canberra. Some specimens are being worked on in Germany and USA, where, for example, specimens from QM have been loaned to the Bernice Pauahi Bishop Museum of Honolulu in Hawaii. However, some of the Undara collections have still not been determined for various reasons, including issues related to museum policy and resources, insufficient numbers of a particular species, the immaturity of individual specimens or the absence of an adult male usually required as the holotype for the description of a new species. There is no doubt that the lava tube caves at Undara are amongst the world's most biologically significant and many troglobitic species are recorded. Amongst the best known cavernicolous species from Undara are the troglobitic spiders studied by Mike Gray and Rob Raven, plus the reduviid bugs, planthoppers and cockroaches.

Introduction

The Undara Lava Tube system is located about 270 km southwest of Cairns, approximately 18°15' south of the equator in the tropical zone of Australia. Covered by savannah grassland, the Undara cave system forms part of the broad area of vine forest depressions and lava tubes that comprise the McBride Volcanic Province in Far-North Queensland. Invertebrate fauna has been recorded from five areas of number-tagged lava tube caves in the McBride Province: Kinrara (K) Murronga (M), Racecourse (RC), Silent Hill (SH) and Undara (U) (Slaney 2000; Bannink in prep.). Two former Undara caves have been re-allocated: Kenny Cave (formerly U-40, is now part of Silent Hill (SH-1) and U-72 is one of the Racecourse Lava Caves (Bannink in prep.).

The more focussed research of lava cave fauna and ecosystems at Undara did not commence until the mid-1980s. The initial impetus for this hypogean research stemmed from the knowledge that invertebrates had colonised the geologically young lava tubes of Hawaii and were already evolving as tropical zone cave-adapted species (Howarth 1987, 1988; Stone 1988; Sullivan 1988). The search for, and determination of, cave-limited obligates and "non-relictual" troglobites proved to be a major direction for the first significant study in 1985-86, particularly following the discovery of "bad air" or foul air caves such as Bayliss Cave, which subsequently revealed a remarkable diversity of species (Howarth 1987, 1988; Howarth and Stone 1990). In part coincidental, the second wave of major study and collection at Undara followed immediately after the ASF "Tropicon" Conference held at Lake Tinaroo near Atherton, in late December 1988.

Fig. 1. Looking towards the back end of Pinwill Cave main chamber, showing the tree roots which provide a habitat, source of food and moisture for many tropical cave species such as beetles, bugs, cockroaches, isopods, planthoppers and spiders. (photo: Arthur Clarke, 13 August 2010)

Unfortunately, very few of the lava tube cavernicoles collected from Undara have been taxonomically determined to species level. There are only five groups of described cave-dwelling invertebrates: a troglobitic spider and reduviid bug, three species of cave-limited planthoppers, a troglophilic fly and five cockroaches with two species variants. Two of the cockroach species from Undara are also found in caves at Chillagoe. Among the undescribed species there are three species of a highly troglomorphic cockroach: *Nocticola* sp. (Blattaria: Nocticolidae) known from Bayliss Cave and other lava tube sites (Stone 1988; Howarth & Stone 1990).

The published description of new species is usually accompanied by collection details (collection date, collector's name, specimen maturity and sex, etc) for all included specimens. Much of this data or information is contained on collection labels that accompany specimens, sitting inside the vials that form part of a curated museum repository or privately housed collection. This data is particularly important to provide some background to the origin of a specimen, for description of any new species holotype (usually a male) or paratypes and to record detail of the type locality (original or first collection site) where the holotype and possibly some of the paratypes were collected. The following sections provide a chronological history of cave fauna studies at Undara. However, without access to collectors' original records, museum collections and their databases, this present paper is purely based on the published

records of the very few Undara cave invertebrates that have been described to species level by taxonomists such as Mike Gray, Hannelore Hoch, Mallik Malipatil, Rob Raven, Louis Roth and David Slaney.

The earliest collection records for Undara

The first speleological exploration of the Undara lava tubes was primarily undertaken by Brisbane-based members of the University of Queensland Speleological Society, evidenced by early survey maps of The Arch, Barkers, Daves, Ewamin, Picnic and Stephensons Caves etc by Dwyer in 1968, plus Hanson and Taylor caves by Ken Grimes in 1977 (Grimes 1977; Godwin 1993). Dwyer was also involved with studies of lava tube dwelling populations of bats at Undara during the early 1970s (Godwin 1993).

One of the first records of invertebrate species from Undara are two spiders from Barkers Cave, recorded by Gray (1973) as *Heteropoda* sp. (then as Family Sparassidae) and *Spermophora* sp. nov. B (Pholcidae: Pholcinae). Related as a *"Daddy Long Legs spider"* (Gray, unpublished), this pholcid was one of the first recorded troglobites in Australia (Gray 1973). Although unclear who observed or collected these spiders, it is probable that most of the early collections were lodged with the Australian Museum in Sydney or

*Fig. 2. Photomicroscopy image of **Paratemnopteryx stonei** "Race C" variant (Roth 1990) together with a blind isopod (see Fig. 16), both collected from Barkers Cave by Arthur Clarke, 6 January 1989.*

ANIC in Canberra. Although Sullivan (1988) reports that Bayliss, Nasty and Pinwill Caves had been biologically studied during three speleo expeditions in the early 1980s, at present, in the absence of museum, collectors' or speleo-biology specimen records there is little supporting evidence. The next recorded biological study at Undara was undertaken by Doug Irvin on the weekend of 11-12 July 1984, when he collected three cockroaches from Pinwill Cave and Barkers Cave (Godwin 1993). These specimens were subsequently determined as variants (Race C) of *Paratemnopteryx stonei* (Fig. 2), a species originally described and predominantly known from Royal Arch Cave at Chillagoe (Roth 1990).

The first systematic collections at Undara during the mid to late 1980s

The more serious or intensive cave biology studies at Undara commenced under the patronage of Brother Nicholas Sullivan's Explorers Club expeditions, run in conjunction with members of the Sydney Speleological Society and Chillagoe Caving Club. During the 1984 and 1985 speleo expeditions to Chillagoe, Sullivan was accompanied by Hawaiian entomologists: Frank Howarth and Fred Stone (Matts 1987; Howarth 1988). In 1985, Howarth and Stone learnt about Anne Atkinson's studies of the basalt lava tubes at Undara, south of Mt. Garnet (Stone pers. comm.[1]; Stone 2010).

Initially guided by Douglas Irvin of the Chillagoe Caving Club in late May 1985 (Stone 2010), Howarth and Stone were also accompanied by Mariam Anderson, Kevin Ridgeway and Tom Robinson (Stone pers. comm.). With enthusiastic support of the Pinwill family who held a grazing lease on Yaramulla Station, Howarth and Stone were able to enter Pinwill Cave (Fig. 1), plus Taylor Cave, Barkers Cave and Bayliss Cave. Their first recorded collection was made by Frank Howarth in Pinwill Cave on 18

May 1985; he took a male and nymph of the new cockroach subsequently described as *Paratemnopteryx stonei variant* C (Roth 1990) (see Fig. 2). Two days later, Howarth, Stone and Irvin collected another 32 specimens (21 males, 4 females and 7 nymphs) and an ootheca (egg case) of this same cockroach, all from Pinwill Cave (Roth 1990).

Together with Dan and Jerry Collins, the team inspected Collins No. 1 Cave and Collins No. 2 Cave on Spring Creek Station (and possibly also Two Ten Tunnel). Over a period of eight days (from 19 to 27 May) Howarth, Irvin and Stone collected a total of 17 adults and three juveniles of a new troglobitic planthopper species *(Undarana collina)* from the neighbouring Collins caves (Hoch & Howarth 1989a). On 21 May, Howarth, Stone and Irvin collected six females of the "C" variant of *P. stonei* from Barkers Cave (Roth 1990). Two days later, in the same cave, they collected four males of the *P. stonei* "C" variant (Roth 1990) and a juvenile schizomid both from near the far reaches of Barkers (Harvey 2001); a possible troglobite, it is probably a new species of the genus *Notozomus* (Schizomida: Hubbardiidae), formerly F. Schizomidae.

Fig. 3. **Solonaima baylissa** (Hemiptera: Fulgoroidea: Cixiidae) collected from Bayliss Cave by Arthur Clarke, 6 January 1989.

Bayliss Cave on Rosella Plains Station became very much the focus of attention, in part due to its unusual lava tube structure with a confined entrance, sloping but undulating floor with a duck-under and wall-like ridge near the lower end. Both these latter-mentioned features appeared to assist the pooling and concentration of trapped carbon dioxide (CO_2) gas emanating from a bat roost and the guano deposits. Combined with the abnormally high gas levels – up

to 200 times the ambient atmospheric level (Howarth & Stone 1990) – there was the near constant high humidity. During May and June 1985, Howarth and Stone began a systematic collection of cave fauna from selected sites in Bayliss Cave in conjunction with a meteorological study to record CO_2 gas levels, temperature and humidity (Howarth & Stone 1990). The strategically positioned fauna collection sites in Bayliss Cave directly correlated to their series of pre-determined observation points. The recordings were conducted in two phases, firstly from 21 to 23 May 1985, then three weeks later on 14-15 June, when Joan Bresnan joined them (Howarth & Stone 1990; Stone pers. comm).

Fig. 4. Latero-ventral view of the blind cockroach (Neotemnopteryx baylissensis) *from Bayliss Cave collected 6 January 1989 by Arthur Clarke.*

On 21 May 1985, Howard, Stone and Irvin collected eight cockroaches (5 males, 2 females and a nymph) in Bayliss Cave; the specimens were subsequently determined by Roth (1990) to be another variant ("Race B") of *Paratemnopteryx stonei*. The following day Irvin collected another female of this "B" variant and Stone found a male plus an egg sac (Roth 1990). On this same day (22 May), Irvin and Howarth collected the first specimens of a blind planthopper, a male and a juvenile located amongst tree roots 700 m into Bayliss in the deep dark zone. This particular male planthopper specimen was later used as the holotype in description of *Solonaima baylissa* (Hoch & Howarth 1989b). On 23 May 23, Howarth, Irvin and Stone collected two more males and a female of the *P. stonei* B variant, plus the first two specimens (a female

and nymph) of a blind cockroach (Roth 1990). Initially described by Roth simply as *Paratemnopteryx* sp. 4, this blind species was subsequently re-described as *Neotemnopteryx baylissensis,* following the discovery of four additional specimens in Bayliss and a female in Kenny Cave (Slaney 2000). During this same three day period (21-23 May), Howarth, Stone and Irvin collected two males of a cave-adapted reduviid hemipteran in Bayliss Cave; both specimens were subsequently used as the holotype male and a paratype male for description of this bug as *Micropolytoxus cavicolus* (Malipatil & Howarth 1990) (see Fig. 5).

Three weeks later, Howarth and Stone, in company with Joan Bresnan, conducted further studies in Bayliss Cave during which time the bulk of their arthropod fauna collection was taken. Although there is a record of Irvin collecting the *P. stonei* B variant in Bayliss Cave with Howarth and Stone on 14 June 1985 (Roth 1990), this is probably not correct, based on the recent information given to the writer (Stone pers. comm.) and the lack of corroborating evidence from other sources, e.g., (Hoch & Howarth 1989a; Raven *et al.* 2001). It would appear that Irvin was not at Undara during this period. So it seems more likely that Howarth, Stone and Bresnan collected the *P. stonei* B variant in Bayliss on 14 June, along with the first specimens of a troglophilic planthopper: *Undarana rosella* (Hoch & Howarth 1989a). On

Fig. 5. With reduced eyes, this setose hemipteran bug from Bayliss Cave, described by Malipatil and Howarth (1990) is considered to be a troglobitic (cave-adapted) species (Howarth and Stone 1990).

this same day in the same cave, Howarth, Irvin and Bresnan collected the first specimen (a male) of the blind spider *Amauropelma undarra* (Ctenidae) from Bayliss Cave (Raven *et al.* 2001). A female specimen of this eyeless spider is shown in Fig. 6. By way of example of how the classification of species is an ever-changing taxonomic process, when initially examined by Gray (unpublished), this blind spider from Bayliss was listed as a new genus and species of Family Miturgidae: Machadoniinae; then a year or so later Gray (1989) recorded the spider as *Janusia* sp. (F. Ctenidae). On the following day Howarth, Irvin and Bresnan collected two females of this blind ctenid spider in Bayliss (Raven *et al.* 2001) plus an egg sac of the *P. stonei* B variant cockroach (Roth 1990). Finally, on this same day (15 June 1985), three specimens (a male, female and egg sac) of the *P. stonei* C variant cockroach were found in Barkers Cave (Roth 1990) along with the only female paratype of the reduviid bug *Micropolytoxus cavicolus* (Malipatil & Howarth 1990) – shown in Fig. 5.

*Fig. 6. Head of blind ctenid female spider (**Amauropelma undarra**) showing lack of eye spots or lenses. Collected by A. Clarke from Bayliss Cave, 6 January, 1989; it is an unregistered specimen in QM.*

In May and June 1986, while Stone was in Thailand, Frank Howarth was joined by Manfred Asche, Hannelore Hoch, Doug Irvin, Simon Robson and others studying the fauna of lava tube caves on Spring Creek Station and Rosella Plains Station (Stone pers. comm.). A summary of the 1986 expedition to Chillagoe and Undara is provided by Grace Matts who states that *"...Howarth had made 27 visits to 18 different* [presumably lava] *caves, collecting both environmental and biological data. Nearly 1000 specimens of invertebrates are now being processed and identified"* and in regard to the Undara cave biology, *"...Howarth and Irvin collected between 10 and 15 new troglobitic invertebrates in Long Shot and 210 Cave (lava tubes)..."* (Matts 1987). Amongst the recorded troglobites, Matts reports a *"blind thread-legged bug and a new Nocticola* [cockroach]*"*; among the reported troglophiles are *"a blue Peripatus...*

(and)...a population of singing crickets in the deep cave zone" (Matts 1987). In May 1986, five more of the new planthopper *U. rosella* were collected from Bayliss Cave (Hoch & Howarth 1989a). Additional adult and juvenile specimens of *S. baylissa* were collected from Long Shot Cave and Nasty Cave in late May (Hoch & Howarth 1989b). During the last four days of May, Howarth and Irvin collected two females of the blind ctenid spider *Amauropelma undarra* in Bayliss Cave (Raven *et al.* 2001) and on 31 May they found another male of the reduviid bug *Micropolytoxus cavicolus* (Malipatil & Howarth 1990), shown in Fig. 5. In mid-June 1986, a male and female of the same *A. undarra* spider were collected from Bayliss Cave by Howarth, Irvin and Robson (Raven *et al.* 2001).

Fig. 7. Head and forelimbs of an undescribed thread-legged bug collected from Wind Tunnel by Arthur Clarke, 7 Jan. 1989 (Hemiptera: Reduviidae: Emesinae). Similar to the troglobitic species in Figs 5 and 14, the red colour around the eyes suggests that the eyes are non-functional. (photo: Arthur Clarke)

Summarising the cave biology expeditions to Chillagoe and Undara, Howarth (1988) recorded that *"...about 5000 specimens of cavernicolous arthropods have been collected from the caves in the study area. These represent hundreds of species, many new to science."* Aside from the few voucher specimens deposited at the Queensland Museum, the balance (i.e., vast majority) of the collection was deposited in the Bishop Museum in Honolulu. Some specimens were also distributed to collaborating taxonomists (Howarth 1988). In discussion of results of their Undara studies, Howarth (1987; 1988) states that over 40 troglobitic species are known from two lava tube systems within the McBride Formation and that over one half (24 species) are found in Bayliss Cave and three-quarters of these occur within the delimited stagnant (high CO_2) air zone. A total of 52 species are recorded for Bayliss Cave; the troglobites, defined as *"obligate cave-dwelling species"*, are recorded in

an Appendix, together with more troglobitic species from other lava tubes (Howarth 1988). This list was subsequently refined in Howarth and Stone (1990, p. 212) recording only the Bayliss Cave species.

In June 1987, Asche and Hoch returned to Undara with Doug Irvin, collecting more planthoppers from Bayliss Cave, including four males of *U. rosella* plus 17 males and three females of *S. baylissa* (Hoch & Howarth 1989a; 1989b).

Following the 17th ASF Conference ("Tropicon") held in late December 1988 at Lake Tinaroo, when the Undara lava tubes and their biology were highlighted (Atkinson 1988; Hoch & Asche 1988; Howarth 1988; Stone 1988), the year 1989 proved to be the commencement of another significant period for cave fauna collections at Undara. During the latter part of the first week of January 1989, together with Mick Williams from the Snowy Mountains Speleological Society, the writer commenced a collection of species from Undara at the behest of Anne Atkinson and members of the Chillagoe Caving Club, under permit from the Queensland Parks & Wildlife Service.

Barkers Cave and Bayliss Cave were inspected, sampled and photographed by Clarke and Williams on 6 January 1989. The collected specimens from Barkers Cave include a number of adult and juvenile cockroaches, presumably the *Paratemnopteryx stonei* (Race C) variant; a hemipteran reduviid bug: *Coranus* sp., undetermined ants (Formicidae: Dolichoderinae) and weevil beetles (Coleoptera: Curculionidae), some *Omorgus* sp. hide beetles belonging to a cave-like sounding family (Superfamily Scarabaeoidea: F. Trogidae) and several large and very setose (hairy) normal-eyed huntsman spiders: *Heteropoda* sp. (F. Sparassidae, formerly Heteropodidae). The Bayliss specimens included several prominently troglobitic species such as the blind cockroach *(Neotemnopteryx baylissensis),* a depigmented centipede with reduced eyes, several blind isopods, a sightless silverfish (Thysanura), the cave-adapted hemipteran bug *Micropolytoxus cavicolus* (Reduviidae) with non-functional eyes, a tiny blind mite, the blind cave spider *Amauropelma undarra* (Ctenidae) and several specimens of the seemingly cave-adapted long-legged spiders assigned as undetermined species of Pholcidae. The following day we were in Wind

Fig. 8. Blind cheliferid pseudoscorpion (Protochelifer, near P. cavernarum) with long but powerful pedipalps, collected from Wind Tunnel by Arthur Clarke on 7 January 1989; now (unregistered) in QM.

Tunnel (U-42), where a blind pseudoscorpion was discovered; the collected specimen of *Protochelifer* sp., near *P. cavernarum* (Cheliferidae) is shown in Fig. 8. Also seen grazing on a small mound of bat guano were some cockroaches and several undetermined beetles (carabids and staphylinids), plus *Pterohelaeus* sp. (Tenebrionidae), *Omorgus* sp. (Trogidae) and an undetermined dermestid beetle. Some depigmented ants were tentatively determined as species of *Paratrechina* (Formicidae: Formicinae) and the hemipteran bug (shown in Fig. 5) is likely to be a new unknown species of the reduviid sub-family Emesiinae.

Barkers Cave was revisited during the evening on 7 January to photograph the emergence of bats (Fig. 9) and the pythons at the cave entrance and to sample epigean (surface) species found in the forest litter near (just outside/inside) the cave entrance. The collected entrance species include several beetles: *Australobolbus* sp. (Scarabaeoidea: Bolboceratidae), two tenebrionids: *Pterohelaeus* and *Ommatophorus* sp. and an undetermined scarab (Scarabaeoidea: Scarabaeidae: Melonthinae); a cicada *Illyria burkei* (Hemiptera: Cicadidae); a hemipteran bug *Diplonychus* (Hemiptera: Belostomatidae), a termite: *Mastotermes darwiniensi* (Isoptera: Mastotermitidae); *Polistes* sp. wasps (Vespidae); *Anochetus* sp. ants (Ponicerinae); and undetermined tabanid horse flies. Collected species from within Barkers Cave included cockroaches, isopods, millipedes, dolichoderid ants and a chrysomelid beetle (Chrysomelidae: Galerucinae). The few species collected from Pinwill

Fig. 9. *Emergence of bats from Barkers Cave, just after dusk on the evening of 7 January 1989. This photograph by Arthur Clarke was used as the front dust cover photo of Atkinson & Atkinson (1995).*

Fig. 10. *Huddling together for warmth, with minimal hair covering and still unopened eyes, these juvenile bats were photographed by Arthur Clarke on 7 Jan. 1989, at the edge of a maternity site on the wall above the lake in Barkers Cave; a former lake level is just discernable near the bat's left ear.*

Cave on 8 January include some undetermined but spinose and setose cave-adapted spiders, pholcid spiders, guanophile mites, an unknown reduviid bug, tineid moths, histerid beetles, an undetermined Psocoptera and a range of undetermined ants.

Following the departure of Clarke and Williams, another group of ASF Conference attendees (all cave biologists) arrived at Undara to accompany Fred Stone and Frank Howarth, including Irvin, Hoch and Asche, plus Stefan Eberhard from Tasmania. Present from 10 to 12 January 1989, the group inspected and sampled a number of lava tubes including Bayliss Cave, Nasty Cave, Darcy Cave and Barkers Cave (Stone pers. comm.).

Later that same year, from September to November 1989, the London-based Operation Raleigh venturers came to Undara and commenced a determined programme of cave exploration, surveying and mapping. Lead by Brian Furniss, the activities of the Raleigh group were supervised by Mick Godwin from the Qld. National Parks & Wildlife Service; he also performed most of the cave biology work. Godwin was the only person actively engaged with invertebrate collections during the time of Operation Raleigh when over 30 new lava tubes were discovered, in addition to the mapping of over 30 known lava tubes, making a total of about 65 lava tubes (Stone pers. comm.). On 13 October 1989, Mick Godwin collected the very first

specimens of *Neotemnopteryx undarensis* (Blattaria: Blattellidae) from Undara in Hot Hole (U-51), then ten days later (24 October), Lana Little collected the first specimens of *N. undarensis* from U-52 (Wishing Well Cave) (Slaney 2000). During the time of Operation Raleigh and over the next four years, Mick Godwin compiled all the relevant data for Undara, culminating in a large 360 page report including Appendix listing the known and recorded vertebrates and invertebrates from caves and surface sites (Godwin 1993).

Towards the end of December 1989, Fred Stone was at Undara again in the company of Tanya Stone, Troy Pinwill, Don Pinwill and others (including Lauren, Sonia and Michael) (Stone pers. comm.). Amongst the many caves visited and sampled were: Archways, Picnic Cave, Road Cave, Bayliss Cave, Kenny Cave, Pinwill Cave, (Don Pinwill's) Secret Caves, where a blind cockroach was discovered in U-67 (CCC map no. 409 in Godwin 1993), Wind Tunnel, Travis Cave, Johnson Cave, Hanson Cave, Taylor Cave, Michaels Cave, Grahams Cave, Barkers Cave and Nasty Cave.

Further collections in the 1990s

The January 1990 Explorers Club expedition was once again lead by Brother Nicholas Sullivan and partially sponsored by Dick Smith and the Australian Geographic Society (Dyce & Wellings 1991). An unusual discovery was the first record of phlebotomine sandflies at Undara with 40 specimens (20 males and 20 females) of *Idiophlebotomus wellingsae* (Psychodidae: Phlebotominae) collected in Pinwill Cave, with the aid of a light trap (Dyce & Wellings 1991). Also known from three caves at Chillagoe (Haunted Cave No. 2, Donna Cave and Tea Tree Cave), these sandflies are generally found in association with bat guano.

On 10 April 1990, Mick Godwin collected *Neotemnopteryx baylissensis* from Kenny Cave and then on 14 April he located additional specimens (a female and two juveniles) of *Neotemnopteryx undarensis* in Wishing Well Cave (Slaney 2000). On 19 November 1993, Philip Weinstein collected a single female and two oothecae (egg cases) of *Neotemnopteryx baylissensis* from Bayliss Cave. In mid-September 1994, Godwin and Barnes collected *Neotemnopteryx undarensis* from Stephens Cave (U-16) (Slaney 2000). On 3 February 1995, a blind male cockroach was collected from Bayliss Cave by David Blair; this specimen ultimately became the holotype for description of *Neotemnopteryx baylissensis*.

From April 1994 to July 1995, a large collection of *Paratemnopteryx stonei* cockroaches was amassed by David Slaney and Philip Weinstein, removed from caves at Undara and Chillagoe (Slaney & Weinstein 1997). Slaney and Weinstein were assisted by David Blair, Doug Irvin, Fred Stone, Erich Volschenk, Deborah Ward and others (Stone pers. comm.). A total of 164 adult specimens were selected from a much larger collection of *P. stonei* cockroaches, taken from seven caves, with over half of these (89 adults) taken from two caves at Undara: Barkers Cave (16 males and 25 females) and Bayliss Cave (21 males and 27 females) (Slaney & Weinstein 1997). The adults were subsequently examined and dissected by Slaney and Weinstein to ascertain the geographical variation in different troglomorphic adaptations between cave populations, e.g., eye width, eye length and tarsus (foot) length. In late July 1995, Messrs. Irvin, Slaney and Stone, plus Debbie Ward collected other cave-dwelling invertebrates from Nasty Cave and Pinwill Cave (Stone pers. comm.).

*Fig. 11. Scavenging **Paratemnopteryx stonei** (Race C variant) cockroaches on the bat guano strewn walls of Barkers Cave. (photo: Arthur Clarke 7 January 1989)*

During 1995-96 five additional *Paratemnopteryx* cockroaches were collected from caves (Slaney & Blair 2000) and together with the previously sampled specimens were subjected to Scanning Electron Microscope examination to conduct further morphometric analyses. In this second round of studies, the respective populations of *P. howarthi* and *P. stonei* from caves at Undara and Chillagoe were examined to determine the variation and differences in mouthpart structures and antennae. The cockroach collections

were primarily used to compare the differences in *P. stonei* morphology between Bayliss and Barkers and the morphological variations between the Undara and Chillagoe populations of *P. howarthi* (Bland *et al.* 1998a; 1998b). Several variations in the cave dwelling populations of *P. stonei* had previously been noted by Louis Roth who defined the Bayliss Cave population as "Race B" and Barkers Cave as "Race C" (Roth 1990). On 5 February 1996, David Slaney and Erich Volschenk collected male and female cockroaches and their oothecae (egg cases) from Wishing Well Cave (U-52), including the specimen which became the male holotype for the description of *Neotemnopteryx undarensis* (Slaney 2000). On 8 February 1996, a male spider collected from Bayliss Cave by Erich Volschenk and David Slaney subsequently became the holotype for description of *Amauropelma undarra* Raven and Gray (Ctenidae) (Raven *et al.* 2001).

In the following year (1997), Stone was at Undara once more, this time for a shorter period from 22 to 24 March (Stone pers. comm). Accompanied by Dave Rowe and Merv Shaw, they collected species from Bayliss Cave, Barkers Cave, Nasty Cave and Pinwill Cave (see Fig. 12). Collection records indicate that on 23 March 1997, Stone took another female and two juveniles of *Neotemnopteryx baylissensis* from Bayliss Cave (Slaney 2000). Three months later, Stone was back again, and on 17-18 June, he was accompanied by Irvin inspecting cave fauna habitats and collecting troglobitic "nockies" *(Nocticola* cockroaches) in Long Shot Cave on Spring Creek Station, in preparation for a proposed description of this new nocticolid species.

In the most recent times, surveys of the Undara lava tube fauna have been conducted in conjunction with vertebrate studies under the auspices of the Einasleigh Fauna Survey (Mick Godwin pers. comm. 11 Aug. 2010). This fauna survey has been run sporadically by several people, the most recent being Keith McDonald

from the Environment Protection Agency in Atherton. Most of the Undara invertebrate specimens have been housed with the Mick Godwin Collection (MGC) at QPWS in Cairns, whereas the vertebrate specimens were generally sent to the Queensland Museum in the first instance or QPWS.

A summary of the known troglobitic species

Although the exact number of cave-dwelling species at Undara will probably never be known, present estimates indicate that among the species showing some degree of troglomorphic (cave adaptation) characters, there are a number of troglobitic obligates (Howarth 1987), most of which are locally endemic. There is an observed correlation between the evolution of troglomorphic characters or troglobitic diversity and the harsh or tenuous living habitats of subterranean bio-space (Clarke 2006). A correlation of troglobitic diversity due to "bad air" (high CO_2 levels) and constant high humidity in Bayliss Cave was noted during the studies by Frank Howarth and Fred Stone in 1985 and 1986 (Howarth 1987; 1988; Howarth and Stone 1990).

Together with recent updates from Stone, plus the work of Mick Godwin and others e.g., Pearson (2010), the report by Howarth and Stone (1990) has been used by the Queensland Parks and Wildlife Service to produce a management plan for the Undara Volcanic National Park (QPWS 2000). Although relatively scant in cave fauna detail, the management plan includes the following statement: *"…Within the lava tubes are found distinct communities of troglobitic species, many of which are undescribed and/or endemic to these systems. This includes isopods of the Superfamily Oniscoidea, spiders of Family Pholcidae (*Spermophora *sp. nov. B), Family Zodariidae, Family Nesticidae and a sightless hunting spider of unknown affinity, two species of Polydesmida, centipedes (Chilopoda: Scutigeromorpha), silverfish (Thysanura), cockroaches (Family Blattellidae), two species of assassin bugs (Family Reduviidae) and a number of beetles (Family Staphylinidae) (Gray 1989; Howarth 1988)…"* (QPWS, 2000).

Amongst the many undescribed troglobites from Undara there are the numerous centipedes (e.g., Fig. 13), millipedes and spiders (Fig. 20), plus pseudoscorpions (Fig. 8), schizomids, isopods (Fig. 14), springtails, curculionid weevils, thysanura (silverfish or bristletails)

Fig. 12. Hemipteran reduviid bug, in Pinwill Cave (photo: Arthur Clarke, 13 August 2010)

Fig. 13. *Photomicroscopy image taken by Arthur Clarke, showing head and forelimbs of an undescribed blind centipede collected from Bayliss Cave on 6 January 1989. The sharply pointed, highly sclerotinised and modified spines, suggest this is likely to be another troglobitic species.*

Fig. 14. *Undescribed blind isopods, such as this specimen collected from Bayliss Cave on 6 January 1989, are known from several other lava tube caves at Undara.*

and cockroaches (see below). There are a number of other likely troglobites including carabid and staphylinid beetles, thread-legged emesine reduviids and dolichoderine or formicine ants (Formicidae). The known described species fall into four groups: cockroaches, reduviid bugs, spiders and planthoppers.

(a) Cockroaches (Dictyoptera: Blattaria: Blattellidae & Nocticolidae)

The described troglobitic species are the blind *Neotemnopteryx baylissensis* (Blattellidae) from Bayliss Cave and Kenny Cave (Slaney 2000) plus *Neotemnopteryx undarensis* (Blattellidae) from Stephens Cave, Hot Hole and Wishing Well Cave (Slaney 2000). *N. baylissensis* was formerly described as *Paratemnopteryx* sp. 4 in Roth (1990). Three troglophilic blattellid species are known: *Paratemnopteryx stonei* (Race B) variant from

Bayliss Cave (Roth 1990; Slaney & Blair 2000), *Paratemnopteryx stonei* (Race C) variant in Barkers Cave and Pinwill Cave (Roth 1990) and U-42(?) and *Paratemnopteryx howarthi* from Nasty Cave (Bland *et al.* 1998a; 1998b). There is at least one, and possibly more, highly troglomorphic nocticolid cockroach species. Likely to be species of *Nocticola* (Nocticolidae) they are known from Bayliss Cave (Fig. 15), Long Shot Cave, Pinwill Cave (Fig. 16) and Upper Secret Cave (Stone 1988; Howarth & Stone 1990; Godwin 1993; Clarke 2010).

Fig. 15. *Photomicroscopy image of the translucent body of a blind **Nocticola** (Nocticolidae) cockroach collected from Bayliss Cave on 6 January 1989; **Nocticola** are referred to as "nockies" by Fred Stone.*

Fig. 16. *Possibly a nocticolid, this fast moving and apparently blind and quite setose cockroach was photographed by Arthur Clarke, as it was carrying its egg sacs and scurrying across the floor of Pinwill Cave, on 13 August 2010.*

(b) Reduviid bugs (Hemiptera: Heteroptera: Reduviidae: Saicinae)

Micropolytoxus cavicolus (Reduviidae) from Bayliss Cave (Malipatil & Howarth 1990).

(c) Spiders (Araneae: Ctenidae, Heteropodidae, Nesticidae, Pholcidae & Zodariidae)

Initially recorded as *Janusia* sp. (Ctenidae) by Gray (1989), this blind troglobitic ctenid has been described

as *Amauropelma undarra* (Ctenidae) from Bayliss Cave (Raven & Gray 2001) (see Fig. 6). Additional troglobitic, but still undescribed, spiders from Bayliss include: *Nesticella* sp. 1 (Nesticidae), plus *Storena* sp. (Zodariidae) (Gray unpublished; 1989; Howarth and Stone 1990; Bannink 2010). Possibly adapted, but nevertheless troglophilic, spiders include *Heteropoda* sp. (Family Heteropodidae), *Nesticella* sp. 2 (Nesticidae) and *Spermophora* sp. nov. B (Pholcidae) (Gray 1973; 1989).

Fig. 17. Photomicroscopy image depicting the head of a new undescribed spider from Pinwill Cave. The eyes (without pigment) would appear to be non-functional and with the dense matt of sensory hairs (looking like a paint brush) at the front of its head and the antenna-like spines, it is likely to be a troglobitic species.
(photo: Arthur Clarke)

(d) Planthoppers (Hemiptera: Fulgoroidea: Cixiidae: Cixiinae)

Two troglobitic obligates: *Undarana collina* (Hemiptera: Fulgoroidea: Cixiidae: Cixiinae: Brixiini) from Collins No. 1 and Collins No. 2 Cave and *Solonaima baylissa* (Hemiptera: Fulgoroidea: Cixiidae: Cixiinae: Brixiini) from Bayliss Cave, Long Shot Cave and Nasty Cave (Hoch & Howarth 1989a; 1989b). A troglophilic cixiid: *Undarana rosella* is recorded from Bayliss Cave (Hoch & Howarth 1989a) and Pinwill Cave (Wessel *et al.* 2007).

Surface collections in and around the lava tube entrances

Aside from the surface collections by Godwin and Clarke and any recent endeavours under the auspices of the Einasleigh Fauna Survey, the Queensland Naturalists Club ran a series of investigations searching for scarab dung beetles at Undara in the summer of 2002-2003. The two caves selected for pitfall trapping were The Arch and Wind Tunnel (Monteith 2003). A

total of 33 species of this superfamily Scarabaeoidea were recorded, principally *Amphistomus squalidus,* five different species of the genus Onthophagus (including a new species of the pexatus-group), plus two species of genus *Coptodactyla,* though *C. gabricollis* appears more restricted to the enclaves of granite (Monteith 2003).

Fig. 18. Marauding scarab dung beetles near bat carcass and dung on dirt floor of Barkers Cave; note the dried skeletal remains of bats.
(photo: Arthur Clarke, 7 January 1989)

Locating the collected Undara specimens and getting determinations

As a general rule, collected biological specimens are deposited with an institution or organisation in the region, State or Country where collected. There are exceptions, especially, for example, when there is no local or regional expertise or means to have biological specimens registered (or accessioned) in a recognised institution, then adequately curated in appropriately sealed or stoppered glass containers with the correct preserving liquid and accompanying collection labels. If being deposited in an institution or museum, it is assumed that the lodged specimens will acquire some degree of taxonomic determination at least to Family level or genus and if new species, they will eventually be described. In some instances, where for example the collectors are taxonomists or invertebrate specialists based in a recognised museum or institution, such as Asche, Hoch, Howarth, Malipatil, Slaney and Stone, the bulk of their collection can be taken interstate or overseas, providing that at least one of each collected species is deposited as a voucher specimen in a central location, e.g., a capital city museum in the State or Country of collection. Alternately, specimens can be accessioned to a museum and then sent off on "loan" to taxonomists or specialists.

Under the auspices of the Queensland Parks and Wildlife Service (QPWS) permit requirements, Arthur Clarke's collected Undara specimens were lodged with the Queensland Museum and have remained

there ever since, unregistered and in the different sections, e.g., Entomology, Arachnids, Molluscs, etc. Following some updated determinations from their retired entomologist, Geoff Monteith, the insect component of Clarke's collection has been forwarded to the Tasmanian Museum in Hobart, where Clarke is currently engaged as a volunteer. The rest of Clarke's collection, including several undescribed troglobites, remains with the Queensland Museum, still not registered and without determinations. Aside from issues related to specimen damage during collection or inadequate curating, specimens from collections may not be determined for various reasons, including issues related to museum policy and resources, insufficient numbers of a particular species, the immaturity of individual specimens or the absence of an adult male (usually required as the holotype for the description of a new species).

*Fig. 19. A scavenging cockroach amidst tree roots on the floor of Pinwill Cave.
(photo: Arthur Clarke, 13 August 2010.*

Major repositories for the Undara invertebrate fauna collections

Most of the invertebrate species taken from Undara have been lodged in museums within Australia, e.g., Australian Museum in Sydney or the Queensland Museum in Brisbane and overseas in the Bernice P. Bishop Museum in Honolulu or the Museum of Natural History at Humboldt University in Berlin. Listed alphabetically by acronym, the following are the major known repositories for the cave and surface specimens from Undara:

ACC (Arthur Clarke collection): insects held at Tasmanian Museum & Art Gallery, Hobart with the arachnids, millipedes, centipedes, and snails, etc still held at Queensland Museum;

AHC (Asche and Hoch Collection): Museum für Naturkunde (Museum of Natural History) at Humboldt University in Berlin, Germany, e.g., planthoppers;

ANIC (Australian National Insect Collection), CSIRO, Canberra, ACT: e.g. *Neotemnopteryx* cockroaches. Despite the name, this institution is also home to numerous non-insect specimens;

AUSMUS (Australian Museum) Sydney, NSW, e.g., cave spiders;

BDUH (Biology Department, University of Hawai'i) in Hilo, Hawaii, USA, e.g., cockroaches;

BMNH (British Museum of Natural History), London, e.g., *Solonaima* planthoppers;

BPBM (Bernice Pauahi Bishop Museum) Entomology section, Honolulu, Hawai'i, USA, e.g., the Bayliss Cave collection of troglobites and other species;

FSC (Fred Stone collection), Kurtistown, near Hilo, Hawai'i, USA, e.g., *Nocticola* cockroaches;

MCZH (Museum of Comparative Zoology Harvard University), Cambridge, Massachusetts, USA, e.g., *Paratemnopteryx* cockroaches (Roth 1990);

MGC (Mick Godwin collection) at the Dept. of Environment & Heritage, Cairns, Qld: e.g. *Neotemnopteryx* cockroaches;

NTMAG (Northern Territory Museum & Art Gallery) in Darwin, e.g., *Micropolytoxus* reduviid bugs;

QM (Queensland Museum) in Brisbane, e.g., spiders, insects, gastropods, centipedes, etc.

Where to from here? Expanding our Undara collection knowledge

In order to expand the knowledge of the collected Undara cave fauna, there is a need to access museum collections, their card indexes or electronic databases to check their lists of registrations or accessions, or in the case of unregistered material, to inspect their lodgements.

Following are some questions that could be asked of museums, their collection managers or specialist curators:

Where are the specimens now (institutional lodgement; private collection)?

Do you have any knowledge of, or record of, invertebrate fauna specimens from Undara in your collections?

Is there a record of when the specimens from Undara were collected (year/ month/ day, etc) and when they were lodged in your institution?

Is there any indication whether these were collections undertaken by invertebrate specialists or cave biologists, or were they just incidental collections by cavers or visitors at the time of lava tube exploration or surface transects?

Who were the collectors (name of collector/s or taxonomist/s)?

How was the collection performed, i.e. under what auspices (expedition; private visit; specific research project; post-grad degree project)?

Do your records show what sort of species were collected and from what habitats (surface epigean terrestrial; subterranean hypogean terrestrial/ aquatic)?

Are we able to ascertain the precise whereabouts or collection sites for these specimens at Undara (surface site locations; named or un-named caves or lava tubes)?

What types of species were collected?

When were the specimens determined and/ or described (and who is the species authority)?

*Fig. 20. Long-legged spider, possibly a pholcid, manipulating egg sac bundle along its silken web strands amidst tree roots in Pinwill Cave.
(photo: Arthur Clarke, 13 August 2010)*

Addendum: Recorded invertebrates from the Undara region

Four major lists of invertebrate species from Undara are known to this writer. Firstly, the published list of fauna from Barkers, Bayliss, Collins, Long Shot, Nasty, Road, Taylor and Two-Ten caves, recorded as Appendix 1 in Howarth (1988) and then the Bayliss Cave collection alone in Howarth and Stone (1990: p. 212). In this latter paper, the authors list 46 species collected at specific sites on 14-15 June 1985. The species are listed according to their subterranean ecological status as trogloxenes (6 species), troglophiles (16), partially troglomorphic troglobites (7) and strongly troglomorphic troglobites (17) (Howarth and Stone 1990). Almost half of these have been determined to genus level with six to species level. There is a minor error in the original 1990 list where the two partially troglomorphic terrestrial isopods, correctly listed in Howarth (1988) as Oniscoidea, are listed in Howarth

and Stone as undetermined species 1 and 2 of "Isopoda: Oniscomorpha". In fact, the term "Oniscomorpha" refers to a different group of animals known as pill millipedes which have a close resemblance to certain isopods, particularly the so-called pill bugs of the family Armadillidiidae. It is possible that there was some confusion in the compilation of this 1990 list, because some of these pill bug isopods are recorded from caves at Chillagoe (Howarth 1988).

Howarth (1988) also lists a number of invertebrates from additional lava tube sites at Undara; most of these are considered to be troglobitic (Tb) species:

Aquatic Amphipoda: Road Cave (Tb);

Arachnida: Araneae: Pholcidae: *Spermophora* sp. B from Collins Cave (Tb);

Arachnida: Araneae: Zodariidae: Nasty Cave;

Arachnida: Phalangida *"Daddy Long Legs"* (i.e., opiliones harvestmen): Long Shot Cave (Tb?);

Arachnida: Schizomida: Schizomidae (schizomids): Barkers Cave (Tb?);

Chilopoda: scutigeromorpha (centipede): Barkers and Nasty caves (possibly Tb?);

Coleoptera: Curculionidae: Rhytirhininae (blind weevil): Taylor Cave (Tb);

Dictyoptera: Blattaria: Nocticolidae: *Nocticola* cockroaches: Long Shot and Nasty caves (Tb);

Diplopoda: Cambalida: (millipede): Nasty Cave (Tb);

Hemiptera: Reduviidae: Emesinae (thread-legged bugs): Long Shot and Two-Ten caves (Tb);

Homoptera: Cixiidae: Cixiinae (planthoppers): Collins, Long Shot, Nasty and Two-Ten caves (cave-adapted & Tb?);

Isopoda: Oniscoidea (terrestrial isopods): unspecified Undara lava tubes (cave-adapted?);

Onychophora (peripatus): Long Shot and Two-Ten caves (possibly Tb?).

Unfortunately, the higher order taxonomy for some species in Howarth (1988) and Howarth and Stone (1990) is not correct, possibly because their taxonomy and distribution was not accurately known at the time. For example, species of Family Schizomidae are only recorded in Mexico and North America and the reference to "cambaliform millipedes" (Howarth 1988) or the blind "Cambalida" millipede (Howarth and Stone 1990) is not applicable here in Australia. It should be noted that while *"Cambalida"* is the genus name for a spider (Family Corinnidae) known only from West Africa, there is a "Cambalida" group of millipedes that include cave dwelling and cave adapted species, but these are predominantly recorded from North America and Hawai'i. To confuse the issue further, there is at least one Australian species

belonging to the millipede family Cambalidae (Order Spirostreptida) recorded from near Scone in NSW (Mesibov 2002). Although Godwin possibly intended to include these millipedes in a similar manner, perhaps by Order name, being listed as *"Cambalida* sp." (Godwin 1993) this could be misread as a genus name.

The third list of invertebrate species was compiled by Mick Godwin, forming part (pp. 350-354) of Appendix 11 ("Fauna") of his 1993 compilation. Recording his species according to the relevant "MGC" (Mick Godwin Collection) number, this list also includes a number of epigean (surface) species such as gastropod snails collected from *"under bark of ironbark trees"* (Godwin 1993). Although about 70 different cave-dwelling species are recorded, including most of those recorded by Howarth and Stone (1990), the lack of taxonomic resolution as a "black hole" in biospeleology is noted by Godwin (1993) with many species simply listed, for example as "Isopod sp. 1" to "sp. 6".

A list of the species collected by the author in January 1989 is included as Appendix.

All photographs in this paper are © Arthur Clarke 2010.

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APPENDIX:
Invertebrate species collected in January 1989 by Arthur Clarke from selected caves and surface sites near cave entrances in the Undara lava tube system.

Number	Collection site	Date	Higher order classification	Genus species (if known)	home
189/110	Barkers Cave (U-34)	06-Jan-1989	Arachnida: Araneae: Sparassidae (?)	undetermined spider, possibly Tb	QM
189/111	Barkers Cave (U-34)	06-Jan-1989	Arachnida: Araneae: Sparassidae (?)	undetermined spider, possibly Tb	QM
189/112	Barkers Cave (U-34)	06-Jan-1989	Arachnida: Araneae: Sparassidae (?)	undetermined spider, possibly Tb	QM
189/113	Barkers Cave (U-34)	06-Jan-1989	Arachnida: Araneae: Pholcidae (?)	undet. pholcid spider	QM
189/114	Barkers Cave (U-34)	06-Jan-1989	Blattaria: Blattellidae: Blattellinae	*Paratemnopteryx stonei* (Race C)	TMAG
189/115	Barkers Cave (U-34)	06-Jan-1989	Blattaria: Blattellidae: Blattellinae	*Paratemnopteryx stonei* (Race C)	TMAG
189/116	Barkers Cave (U-34)	06-Jan-1989	Blattaria: Blattellidae	undetermined cockroach	TMAG
189/117	Barkers Cave (U-34)	06-Jan-1989	Crustacea: Isopoda: Oniscoidea	undet. blind oniscoid isopod	TMAG
189/118	Barkers Cave (U-34)	06-Jan-1989	Crustacea: Isopoda: Oniscoidea	undet. oniscoid isopod (tiny eyes)	TMAG
189/119	Barkers Cave (U-34)	06-Jan-1989	Hemiptera: Reduviidae: Harpactorinae	*Coranus* sp.	TMAG
189/120	Barkers Cave (U-34)	06-Jan-1989	Hymenoptera	undetermined ant	QM
189/121	Barkers Cave (U-34)	06-Jan-1989	Formicidae: Dolichoderinae	undetermined ant	TMAG
189/122	Barkers Cave (U-34)	06-Jan-1989	Formicidae: Dolichoderinae	undetermined ant	TMAG
189/123	Barkers Cave (U-34)	06-Jan-1989	Coleoptera: Curculionidae	undetermined weevil	TMAG
189/124	Barkers Cave (U-34)	06-Jan-1989	Coleoptera: Trogidae	*Omorgus* sp.	TMAG
189/125	Bayliss Cave (U-30)	06-Jan-1989	Blattaria: Blattellidae: Blattellinae	*Neotemnopteryx baylissensis*	TMAG
189/126	Bayliss Cave (U-30)	06-Jan-1989	Blattaria: Blattellidae: Blattellinae	*Neotemnopteryx baylissensis*	QM
189/127	Bayliss Cave (U-30)	06-Jan-1989	Chilopoda: Scutigeromorpha (?)	undertermined centipede	QM
189/128	Bayliss Cave (U-30)	06-Jan-1989	Chilopoda: Scutigeromorpha (?)	undertermined centipede	QM
189/129	Bayliss Cave (U-30)	06-Jan-1989	Arachnida: Ctenidae	*Amauropelma undarra*	QM
189/130	Bayliss Cave (U-30)	06-Jan-1989	Crustacea: Isopoda: Oniscoidea	undet. blind oniscoid isopod	TMAG
189/131	Bayliss Cave (U-30)	06-Jan-1989	Thysanura: Nicolectidae (?)	?*Nicoletia* sp. (blind)	TMAG
189/132A	Bayliss Cave (U-30)	06-Jan-1989	Lepidotera: Geometridae	undetermined larva	TMAG
189/132B	Bayliss Cave (U-30)	06-Jan-1989	Diplopoda: Polydesmidae	undet. polydesmid millipedes	TMAG
189/133	Bayliss Cave (U-30)	06-Jan-1989	Hemiptera: Reduviidae: Saicinae	*Micropolytoxus cavicolus*	TMAG
189/134	Bayliss Cave (U-30)	06-Jan-1989	Hymenoptera: Formicidae: Ponicerinae	*Amblyopone* sp	TMAG
189/135	Bayliss Cave (U-30)	06-Jan-1989	Diplopoda: unknown	undetermined millipede	QM
189/136	Bayliss Cave (U-30)	06-Jan-1989	Arachnida: Acarina	undetermined blind mite	QM
189/137	Bayliss Cave (U-30)	06-Jan-1989	Arachnida: Araneae: Nesticidae (?)	?*Nesticella* sp.	QM
189/138	Bayliss Cave (U-30)	06-Jan-1989	Arachnida: Araneae: Pholcidae (?)	undet. pholcid spider	QM
189/139	Bayliss Cave (U-30)	06-Jan-1989	Arachnida: Araneae: Pholcidae	undet. pholcid spider	QM
189/140	Bayliss Cave (U-30)	06-Jan-1989	Arachnida: Araneae: Pholcidae	undet. pholcid spider	QM
189/142	Wind Tunnel (U-42)	07-Jan-1989	Pseudoscorpionida: Chelifreridae	*Protochelifer cavernarum* (?)	QM
189/143	Wind Tunnel (U-42)	07-Jan-1989	Blattaria: Blattellidae: Blattellinae	*Paratemnopteryx stonei* (Race C)	QM
189/144	Wind Tunnel (U-42)	07-Jan-1989	Coleoptera: Carabidae	undetermined carabid beetle	QM
189/145	Wind Tunnel (U-42)	07-Jan-1989	Hymenoptera: Formicidae: Formicinae	*Paratrechina* sp.	TMAG
189/146	Wind Tunnel (U-42)	07-Jan-1989	Arachnida: Araneae: Family unknown	undet. spider, possibly Tb	QM
189/147	Wind Tunnel (U-42)	07-Jan-1989	Arachnida: Araneae: Family unknown	undet. spider, possibly Tb	QM
189/148	Wind Tunnel (U-42)	07-Jan-1989	Arachnida: Araneae: Pholcidae (?)	undet. pholcid spider	QM
189/149	Wind Tunnel (U-42)	07-Jan-1989	Hemiptera: Reduviidae: Emesinae	undet. reduviid bug	TMAG
189/150	Wind Tunnel (U-42)	07-Jan-1989	Coleoptera: Trogidae	*Omorgus* sp.	TMAG
189/151	Wind Tunnel (U-42)	07-Jan-1989	Coleoptera: Dermestidae	undet. dermestid beetle	TMAG
189/152	Wind Tunnel (U-42)	07-Jan-1989	Coleoptera: Tenebrionidae	*Pterohelaeus* sp.	TMAG
189/153	Wind Tunnel (U-42)	07-Jan-1989	Coleoptera: Tenebrionidae	*Pterohelaeus* sp.	TMAG
189/154	epigean, outside U-34	07-Jan-1989	Coleoptera: Tenebrionidae	*Pterohelaeus* sp.	TMAG
189/155	epigean, outside U-34	07-Jan-1989	Coleoptera: Bolboceratidae	*Australobolbus* sp.	TMAG
189/156	epigean, outside U-34	07-Jan-1989	Hemiptera: Belostomatidae	*Diplonychus* sp.	TMAG
189/157	epigean, outside U-34	07-Jan-1989	Scarabaeidae: Melolonthinae	undet. scarab beetle	TMAG
189/158	epigean, outside U-34	07-Jan-1989	Coleoptera: Tenebrionidae	*Ommatophorus* sp.	TMAG

Number	Collection site	Date	Higher order classification	Genus species (if known)	home
189/159	epigean, outside U-34	07-Jan-1989	Isoptera: Mastotermitidae	*Mastotermes darwiniensis*	TMAG
189/160	epigean, outside U-34	07-Jan-1989	Diptera: Tabanidae	undetermined horse fly	TMAG
189/161	epigean, outside U-34	07-Jan-1989	Diptera: Tabanidae	undetermined horse fly	TMAG
189/162	epigean, outside U-34	07-Jan-1989	Hemiptera: Cicadidae	*Illyria burkei*	TMAG
189/163	epigean, outside U-34	07-Jan-1989	Hymenoptera: Vespidae	*Polistes* sp.	TMAG
189/164	epigean, outside U-34	07-Jan-1989	Arachnida: Araneae: Family unknown	undetermined spider,	QM
189/165	epigean, outside U-34	07-Jan-1989	Hymenoptera: Formicidae: Ponicerinae	*Anochetus* sp.	TMAG
189/166	epigean, outside U-34	07-Jan-1989	Hymenoptera: Formicidae	undetermined ant	TMAG
189/167	Barkers Cave (U-34)	07-Jan-1989	Blattaria: Blattellidae: Blattellinae	*Paratemnopteryx stonei* (Race C))	TMAG
189/168	Barkers Cave (U-34)	07-Jan-1989	Crustacea: Isopoda: Oniscoidea	undet. oniscoid isopod (tiny eyes)	TMAG
189/169	Barkers Cave (U-34)	07-Jan-1989	Diplopoda: unknown	undetermined millipede	QM
189/170	Barkers Cave (U-34)	07-Jan-1989	Arachnida: Acarina	undet. microscopic blind mites	QM
189/171	Barkers Cave (U-34)	07-Jan-1989	Collembola: Entonmobryidae	undetermined springtail	QM
189/172	Barkers Cave (U-34)	07-Jan-1989	Coleoptera: Scarabaeidae	undetermined scarab beetle	QM
189/173	Barkers Cave (U-34)	07-Jan-1989	Coleoptera: Carabidae	undetermined carabid beetle	QM
189/174	Barkers Cave (U-34)	07-Jan-1989	Lepidotera: Pyralidae	*Pyralis* sp., near *P. manihoialis*	QM
189/175	Barkers Cave (U-34)	07-Jan-1989	Chrysomelidae: Galerucinae	undet. chrysomelid beetle	TMAG
189/176	Barkers Cave (U-34)	07-Jan-1989	Coleoptera: Tenebrionidae (?)	undet. tenebrionid (?) larva	TMAG
189/177	Barkers Cave (U-34)	07-Jan-1989	Oligochaeta	undetermined earthworms	TMAG
189/178	Barkers Cave (U-34)	07-Jan-1989	Blattaria: Blattellidae	oothecae of cockroach	TMAG
189/179	Barkers Cave (U-34)	07-Jan-1989	Formicidae: Dolichoderinae	*Iridomyrmex* sp.	TMAG
189/180	Barkers Cave (U-34)	07-Jan-1989	Arachnida: Araneae: Nesticidae (?)	undet. spider, same(?) as 189/137	QM
189/181	Barkers Cave (U-34)	07-Jan-1989	Arachnida: Araneae: Family unknown	undetermined spider, possibly Tb	QM
189/182	Barkers Cave (U-34)	07-Jan-1989	Arachnida: Araneae: Nesticidae (?)	undet. spider, same(?) as 189/137	QM
189/183	Barkers Cave (U-34)	07-Jan-1989	Arachnida: Araneae: Family unknown	undet. spider egg sacs	QM
189/184	epigean, outside U-17	07-Jan-1989	Coleoptera: Scarabaeidae: Aclopinae	*Phaenognatha* sp.	QM
189/185	epigean, outside U-17	07-Jan-1989	Hymenoptera: Formicidae: Formicinae	*Polyrhachis* sp.	TMAG
189/186	epigean, outside U-17	07-Jan-1989	Hymenoptera: Formicidae: Ponerinae	*Rhytidoponera* sp.	TMAG
189/187	epigean, outside U-17	07-Jan-1989	Hymenoptera: Formicidae: Formicinae	undetermined ant	TMAG
189/188	epigean, outside U-17	07-Jan-1989	Hymenoptera: Formicidae: Ponerinae	*Rhytidoponera* sp.	TMAG
189/189	epigean, outside U-17	07-Jan-1989	Hymenoptera: Formicidae: Ponerinae	*Platythyrea* sp.	QM ?
189/190	epigean, outside U-17	07-Jan-1989	Hymenoptera: Formicidae	undetermined ant	TMAG
189/191	epigean, outside U-17	07-Jan-1989	Formicidae: Dolichoderinae	*Iridomyrmex* sp.	TMAG
189/192	epigean, outside U-17	07-Jan-1989	Hymenoptera: Formicidae: Formicinae	*Camponotus maculatus* group	TMAG
189/193	epigean, outside U-17	07-Jan-1989	Formicidae: Pseudomyrmecinae (?)	undet. ant, poss. *Tetraponera* sp.	TMAG
189/194	epigean, outside U-17	07-Jan-1989	Formicidae: Proceratiinae	*Proceratium* sp.	TMAG
189/195	epigean, outside U-17	07-Jan-1989	Hymenoptera: Formicidae	undetermined ant	TMAG
189/196	epigean, outside U-17	07-Jan-1989	Hymenoptera: Formicidae	undetermined ant	TMAG
189/197	epigean, outside U-17	07-Jan-1989	Diptera: Chironomidae	undetermined chironomid	TMAG
189/198	epigean, outside U-17	07-Jan-1989	SOIL SAMPLE	DISCARDED	
189/199	Pinwill Cave (U-17)	08-Jan-1989	Arachnida: Araneae: Nesticidae (?)	undet. spider, same(?) as 189/137	QM
189/200	Pinwill Cave (U-17)	08-Jan-1989	Arachnida: Araneae: Nesticidae (?)	undet. spider, same(?) as 189/137	QM
189/201	Pinwill Cave (U-17)	08-01-1989	Arachnida: Araneae: Pholcidae	undetermined spider	QM
189/202	Pinwill Cave (U-17)	08-01-1989	Arachnida: Acarina	undet. blind guano mites	QM
189/203	Pinwill Cave (U-17)	08-01-1989	Arachnida: Acarina	microscopic eggs of undet. mite	QM
189/204	Pinwill Cave (U-17)	08-01-1989	Blattaria: Blattellidae: Blattellinae	*Paratemnopteryx stonei* (Race C)	TMAG
189/205	Pinwill Cave (U-17)	08-01-1989	lepidoptera: Tineidae	undet. moths from tree roots	TMAG
189/206	Pinwill Cave (U-17)	08-01-1989	Dpitera: Family unknown	undetermined fly larva	TMAG
189/207	Pinwill Cave (U-17)	08-01-1989	Dpitera: Family unknown	undetermined fly larva	TMAG

Number	Collection site	Date	Higher order classification	Genus species (if known)	home
189/208	Pinwill Cave (U-17)	08-01-1989	Coleoptera: Carabidae	undet. carabid beetle	QM
189/209	Pinwill Cave (U-17)	08-01-1989	Coleoptera: Histeridae	undet. histerid beetle	TMAG
189/210	Pinwill Cave (U-17)	08-01-1989	Crustacea: Isopoda: Oniscoidea	undet. blind oniscoid isopod	QM ?
189/211	Pinwill Cave (U-17)	08-01-1989	Hymenoptera: Formicidae: Ponerinae	?*Hypoponera* sp.	TMAG
189/212	Pinwill Cave (U-17)	08-01-1989	Hymenoptera: Formicidae: Formicinae	*Prolasius* sp.	TMAG
189/213	Pinwill Cave (U-17)	08-01-1989	Psocoptera	undetermined psocopteran	TMAG
189/214	Pinwill Cave (U-17)	08-01-1989	Coleoptera: Histeridae	undet. histerid beetle	TMAG
189/215	hut on Yaramulla Stn.	08-Jan-1989	Hymenoptera: Formicidae: Formicinae	*Camponotus maculatus* group	TMAG
189/216	hut on Yaramulla Stn.	08-Jan-1989	Chilopoda	undetermined centipede	QM ?
189/217	hut on Yaramulla Stn.	08-Jan-1989	Arachnida: Araneae: Psechridae	undetermined spider	QM
189/218	hut on Yaramulla Stn.	08-Jan-1989	Coleoptera: Buprestidae	*Merimna atrata*	TMAG
189/219	hut on Yaramulla Stn.	08-Jan-1989	Diptera: Tabanidae	undetermined horse fly	TMAG
189/220A	hut on Yaramulla Stn.	08-Jan-1989	Diptera: Family unknown	undetrermined fly	QM ?
189/220B	hut on Yaramulla Stn.	08-Jan-1989	Diptera: Family unknown	undetrermined fly	QM ?
189/221	hut on Yaramulla Stn.	08-Jan-1989	Arachnida: Acarina	undetermined mite	QM
189/222	Inner Dome (U-41)	07-Jan-1989	Diplopoda: unknown	undetermined millipede	QM ?

Fig. 21. Mick Williams (who accompanied the writer to Undara in January 1989), outside one of the property gates on the road formerly used to access the Undara lava tubes.

Air Quality Measurements in the Undara Lava Tubes

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Abstract

Air quality data for Undara lava tubes is limited with the only gases that have been measured there being carbon dioxide (CO_2), oxygen (O_2) and radon. In Bayliss Cave the CO_2 levels were found to be high and its possible sources, concentrations, distribution and movement both spatially and temporally are discussed. For Bayliss Cave a management strategy for cave visits is in place and is controlled by CO_2 and O_2 measurements. The allowable concentrations of these gases before visitors are permitted to enter Bayliss Cave are presented. The use of oxygen masks, CO_2 scrubbers and SCUBA by lava tube explorers are commented on. Radon measurements made in Wind Tunnel, Barkers, Arch and Road Caves were taken as part of a Worksafe supported study of the occupational exposure to radon in Australian tourist caves, an Australia-wide study. Two important conclusions were reached from the Worksafe study: that the radon flux in the Undara lava tubes shown to tourists and the radiation exposure to the Undara guides from radon is low.

Introduction

The Undara Lava Tubes are located in McBride Volcanic Province in Queensland, Australia. The Undara area is at ~760 m. asl and 18º S. with hot wet summers and warm dry winters. The wet summer is known as the "Green" season; during this period the lava tubes can flood. Major parameters can be measured to define air quality; they are temperature, humidity, carbon dioxide (CO_2), oxygen (O_2), particulates (notably dust and spores), pollutant gases and trace gases, for example, ammonia in bat caves and radon. Portable apparatus for air quality measurements are available to volcano speleologists but are often expensive and need regular calibration for reliable results. Hence, complete air quality analyses are rarely performed and this has been the case at Undara with only relative humidity, temperature, CO_2, O_2 and radon being published. High levels of CO_2 are encountered in both lava tubes and caves in other rocks world-wide and it is often the only gas measured although measurement of O_2 at the same time is becoming more common.

Bayliss Cave – carbon dioxide

Bayliss Cave is 1.3 km long with passages up to 12 m in height and 25 m wide. There is a rock fall forming a constriction at 620 m known as The Wall. Beyond The Wall, roots of surface vegetation hang from the roof. The tree roots house a diverse-specialized fauna (Howarth and Stone 1990). Bayliss Cave is used for nursing and roosting by bats. The dangerously high levels of CO_2 in Bayliss Cave were first recorded by the Chillagoe Caving Club (Atkinson and Atkinson 1995). The air made foul by the high CO_2 was limiting their exploration of the cave beyond the constriction caused by rock fall at The Wall. They measured levels of up to 6% still further into the cave. In order to continue exploration of the cave the cavers used O_2 masks and CO_2 scrubbers. Stone (2010) records air

quality data for Bayliss Cave; his data is presented in Table 1 and graphically in Figs 1 and 2.

Site	% volume/ volume CO_2	% volume/ volume O_2
Surface	0.04	21
Entrance	0.2	20.8
Point 2 (225 m)	0.5	20.5
The Duckunder		
Point 3	0.75	20.25
The Wall	3.0	18
Point 5 (650 m)	6.0	15

Table 1. Values of CO_2 % volume/volume with distance into the cave.

The measurements confirm the earlier observations and results of the Chillagoe cavers that the CO_2 concentrations increased with distance from the cave entrance and that they were accompanied by a reduction in O_2 concentrations. This is to be expected as Bayliss Cave has only one known entrance and hence is a barometric breather with airflow controlled by climatic air pressure change and to a lesser extent diurnal air pressure change.

The graph (Fig. 1) shows the relative humidity in Bayliss Cave rapidly increases to close to 100 %. Relative humidity is difficult to measure and experimental errors are known to be large. This pattern is typical for a poorly ventilated cave in the tropics. Even during the dry season in August 2010 the relative humidity in the Undara lava tubes was high with the walls being covered with condensation droplets. The temperature follows the same pattern as relative humidity, increasing with distance into the cave. The temperature close to the entrance may vary with season and may be either below or above temperatures deep in the lava tube.
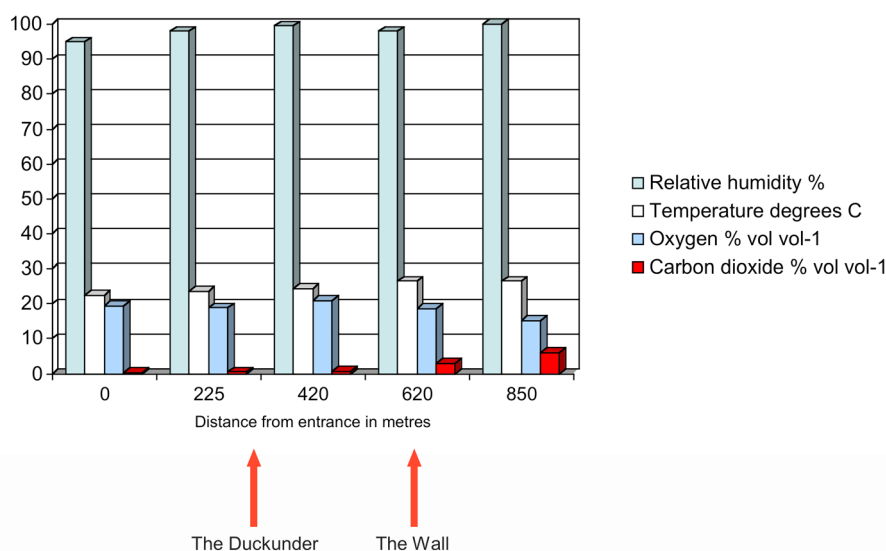
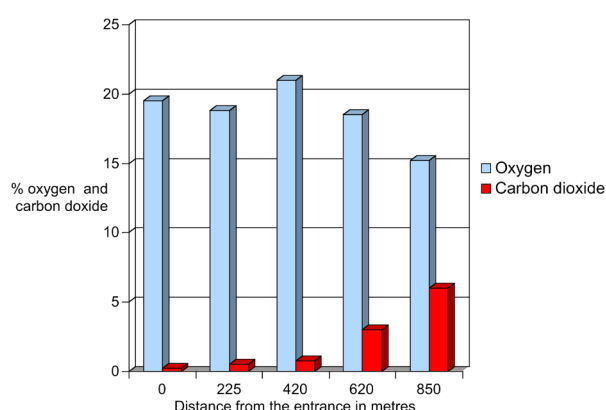*Fig. 1. Air quality measurements for Bayliss Cave, as recorded in Stone (2010).*

Characterized by presence of gases associated with low oxygen levels – e.g. H_2S and CH_4. Examples of limestone caves containing Type III atmospheres are given in James (1995), Table 1.

All three types are expected to be found in lava tubes.

Experimental results for air quality represented in a Gibbs Triangle can further be used to identify types of CO_2 enriched air (Halbert 1982).
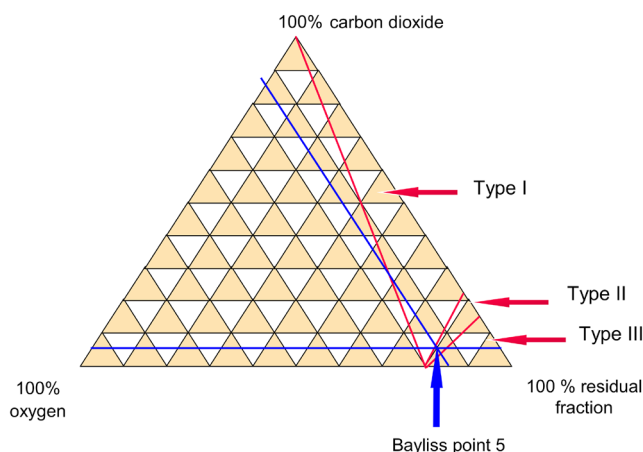

Fig. 2. CO_2 and O_2 measurements from Fig. 1.

Fig. 3. Types of CO_2 as defined by a Gibbs Triangle for dry air (after Halbert 1982).

The graph in Fig. 2 is expanded to show the relationship between O_2 and CO_2 more clearly. The oxygen levels decrease to first approximation with an increase in CO_2. If the figures are taken for the point 5 and the ideal gas equation is assumed; for 1 molecule of CO_2 generated one molecule O_2 is consumed. This relationship allows the source/s of CO_2 to be identified and characterizes the type of CO_2 enrichment.

James (1977) postulated that there are three distinct types of CO_2 enrichment in cave air. The identification of types of CO_2 sources has been reduced to two and incorrectly attributed in Halliday (2009). The accepted distinct types of CO_2 enrichment and their sources are:

Type I   Addition of CO_2; dilution of O_2 and the residual fraction: examples are CO_2 evolution from cave waters and speleothems, anaerobic CO_2 production by microbes and volcanic emissions.

Type II   Replacement of O_2 by CO_2: respiration and combustion.

Type III O_2 depleted significantly more than in Type II

Using the Gibbs Triangle and plotting the results at Bayliss Cave point 5 from Table 1, the blue lines at 6% CO_2 and 15% O_2 intersect in the area designated as Type II enrichment. That is, the replacement of O_2 by CO_2. Thus, the possible CO_2 sources are the respiration of tree roots and cave fauna – notably the bats and microbes in Bayliss Cave. The conditions in the lava tube are perfect for continuous microbial CO_2 production, that is warm, wet and with a nutrient supply brought into the lava tube by floods and bats. CO_2 generated by the respiration of microbes and roots in the surface soils and descending through cracks into the lava tube is unlikely as such low concentrations of CO_2 do not separate out of the lava tube air by gravity (Badino 2005). However, in some circumstances – notably if there is a direct connection with the surface – CO_2 enriched air can be dragged into the tube from the surface soil as the lava tube ventilates.

Type I CO_2 enrichment will be present in some of the Undara lava tubes as some contain calcium carbonate deposits. However, calcium carbonate deposits are not present in the high CO_2 areas of Bayliss Cave. Bayliss

Cave is in a relict lava flow in which volcanic activity that formed it stopped many tens of thousands of years ago. Thus, Type I CO_2 enrichment is not expected from volcanic emissions. Type III CO_2 enrichment is also unlikely because the catchments of the lava tubes are protected from pollution as they are in a national park.

The conclusion that the CO_2 enrichment is Type II from respiration can be further confirmed by the carbon stable isotopes analyses. Such analysis is not able to identify which of the specific respiration sources is dominant in Bayliss Cave.

In conclusion, the modest experimental studies carried out in Bayliss Cave have defined:

- the extent of CO_2 enrichment in the lava tube
- the type of cave air produced and its possible sources
- the distribution of CO_2 in the cave system.

The diurnal and seasonal movement of CO_2 enriched air has not been established for Bayliss Cave. To comment on this would require further research as in tropical lava tubes the gas may not move in the manner established for temperate limestone caves (James 1977).

Once the type of CO_2 enrichment has been established, a management strategy for cave visits can be put in place and entry can be made subject to CO_2 and O_2 measurements. The aim of management strategies should be to increase the comfort, protect the health and ensure the safety of visitors and employees without damaging the cave or its ecosystems. The concentrations of these gases that need to be reached before visitors should be excluded from these caves are open to debate. In the modern work place, health and safety regulations must be evoked and a definition of the lava tube as a work place is required and the period that can spent in the Type II CO_2 enriched air. In New South Wales it is recommended that visitors and guides must/should not be exposed to cave air that fails to meet statutory conditions for mines (CO_2 > 1.25% and O_2 < 19%). The expected time in air with these characteristics for a miner is a shift of 8 hours. It is not desirable that tourists or guides should develop symptoms or signs of hypercarpnapia in caves where significant exercise is required. Halliday (2009) discuses in detail the health and safety requirements pertinent to the lava tubes in the United States.

The Queensland National Parks Service permit for Bayliss Cave requires that CO_2 concentrations be less than 0.5% and O_2 more than 19.5% for entry to the cave to be permitted. Bayliss Cave is a wild cave and access is now only granted for scientific purposes. During the exploration of the cave by Chillagoe Caving Club members used oxygen masks and CO_2

scrubbers to enter the areas of high CO_2 and reached 1.3 km into the cave. With the present knowledge of the composition of the lava tube air, they should have been using SCUBA equipment and breathing and expelling fresh air. For the lava tube explorer who encounters CO_2 enriched air, essential reading is James *et al.* 1975. Alan Rogers, one of the authors, is a medical respiratory physiologist and in that paper the authors detail the synergistic physiological effects encountered in Type II CO_2 enriched air.

Undara Lava Tubes - Radon

A 12-month study of radon commenced in March 1994 (Solomon *et al.* 1996). At Undara, radon monitors were placed in 4 lava tubes: in Arch Cave, 2 sites in Road Cave, 4 sites in Wind Tunnel and 14 sites in Bakers Cave.

At each site a pair of passive integrating radon monitors based on CR-39 detectors was used to measure both 3-monthly seasonal and 12 monthly annual radon levels.

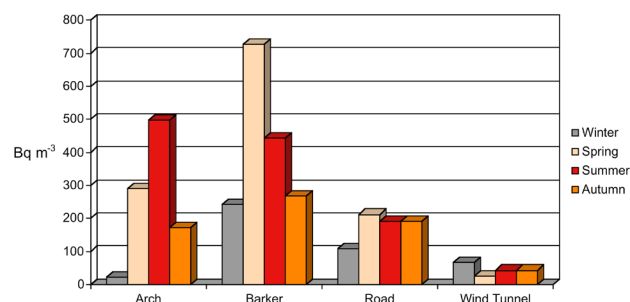*Fig. 4. Seasonal radon levels in Undara lava tubes.*

The results do not show any consistent trends from lava tube to lava tube with season, indicating that the lava tubes are ventilating differently with season. A year-long meteorological study of the individual lava tubes in association with air quality measurements is much needed.
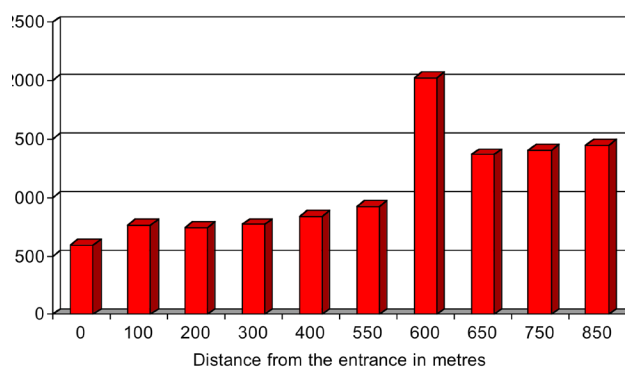
Fig. 5. Annual radon levels in Barkers Cave with distance from the entrance.
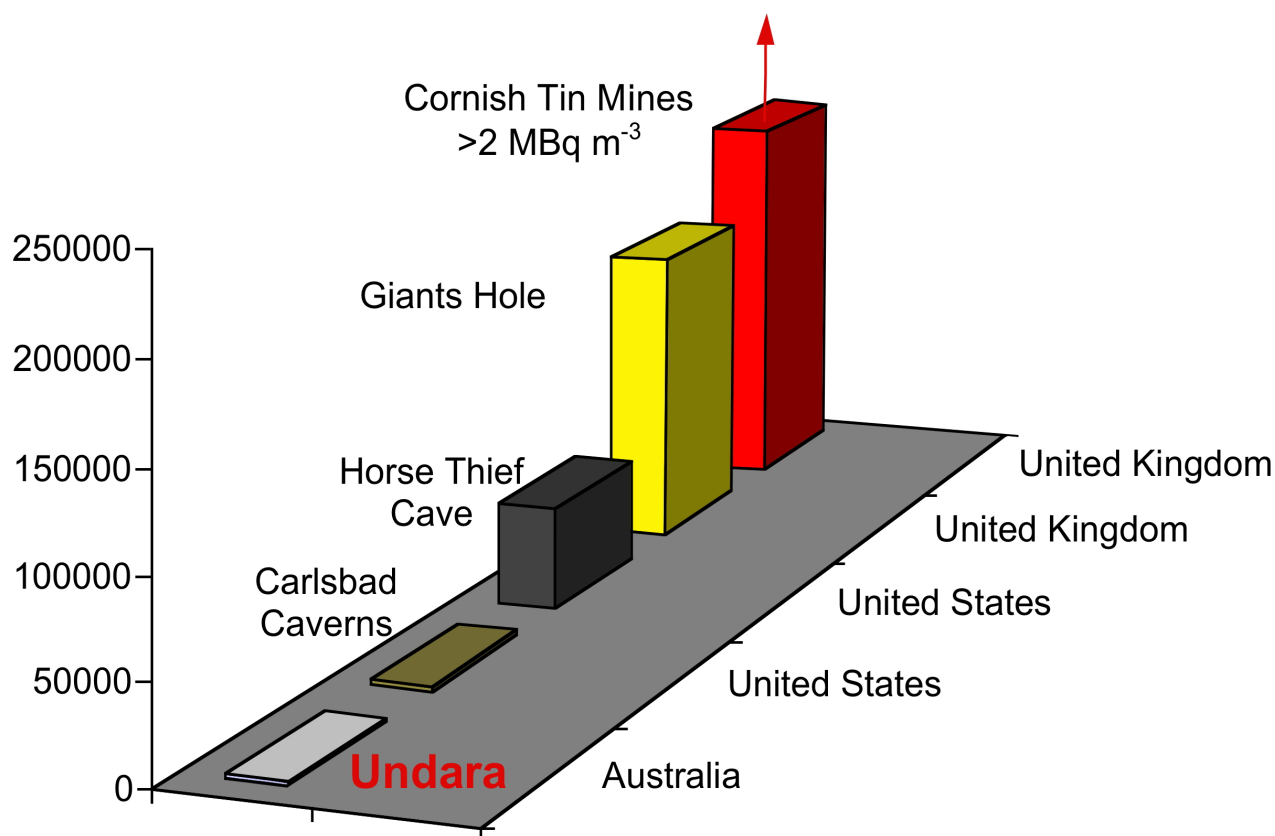
Fig. 6. Comparison of highest radon levels measured in world caves and mines, with those at Undara.

Radon shows the same trend as CO_2 in that its concentrations increase deeper into the lava tube.

The Undara radon flux is exceptionally low when compared with some limestone caves and considerably lower than those encountered in some mines. Work records for six guides were supplied by the Undara management and allowed yearly radiation doses for each guide from taking cave tours to be calculated. The annual radiation dose received by the Undara Guides in 1994 as a consequence of taking cave tours was less than 0.5 mSv per year and thus not considered to be an occupational hazard.

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Novel Bacterial Diversity in Lava Tubes in the Azores, New Mexico and Hawai'i

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Abstract

Lava tubes in the Azores, New Mexico, and Hawai'i host extensive, colorful microbial mats. We conducted a culture-independent study of white and yellow colored mats in these three locations to test the hypothesis that these differently colored mats will differ in species composition.

We also wished to begin to elucidate the environmental controls on microbial diversity in the subsurface. White and yellow microbial mats were collected from lava tubes from the Azorean island of Terceira (temperate), El Malpais National Monument (ELMA, NM) (semi-arid), and the Big Island of Hawai'i (semi-arid to tropical). Scanning electron microscopy of mat samples showed similarities among the mat microorganisms in these three locations. To assess the species composition of the bacterial mats, we extracted DNA from samples collected aseptically and preserved in sucrose lysis buffer. The 16S rRNA gene was amplified, purified, and sequenced in order to determine the diversity within these caves. PCA analysis conducted in UniFrac showed that geographical location was the major contributor to differences in community structure between the Azorean and Hawaiian samples. Fifteen phyla were found across the samples, with notable differences in the number of clones retrieved from phyla at any given location. More *Actinobacteria* clones were retrieved from Hawaiian communities, while more *Alphaproteobacteria* clones were found in Azorean communities. The *Actinobacteria* exhibited considerable novel diversity, with several distinct novel clades.

Considerably less diversity was found in the ELMA clone libraries. Closest relatives suggest that heterotrophy and nitrogen cycling may be among the metabolic capabilities of members of these communities. These culture-independent studies are revealing a novel and diverse community of bacteria within these microbial mats.

Pressure Ridges Caves:
a Comparison between the Jordanian Caves of the Quis/Makais Volcanic Field and the Hawaiian Mauna Loa Eclipse Cave

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Abstract

Apart from pyroducts (lava tunnels, lava tubes) that actively conduct lava subterraneously, there are many other types of lava caves that can reach appreciable sizes. In the Cenozoic (Oligocene-Quaternary) alkali-basalt fields, the "Harrats", in Jordan we have surveyed 10 caves that lack any signs of laterally flowing lava. They all belong to the lava field of the combined Qais/Makais volcanoes. The field covers an area 28 km long and 6 to 10 km wide. It forms only a small fraction of entire Harrat. The field also contains two pyroducts, Al-Jolous Cave (113 m long) and Hashemite University Cave (231 m long), illustrating that the lavas are duct-transported pahoehoe flows. The age of the flow field is several hundred thousand years. Nevertheless it belongs to the younger flow fields in the Harrat since it has not developed an appreciable wadi network.

The caves form two groups, one to the north of the two volcanoes at an altitude at around 900 m and one to the south of the volcanoes at an altitude of around 780 m. Most of the caves are oriented perpendicularly to the flow direction and are associated with low ridges at the surface. All of the caves are very wide and low. The longest is Al-Ameed: a 120 m long cavity combining two very low and wide vaults connected by a wide and low passage. Due to the loess cover of the Harrat, these caves are all filled with an unknown depth of sediment, so that we cannot see the rock floor of them.

Caves that lack evidence of lateral lava flow are known also from Hawaii, but are so far poorly documented. Eclipse Cave occurs in a young lava flow of the Mauna Loa W-Rift. This cave turns out to be a combination of a pressure ridge cave and a small pyroduct. The pressure ridge hall is aligned perpendicular to the direction of flow. It is 70 m long and up to 2.5 m high, forming a rather regular vault. At the surface a low ridge exists above the hall. The surface pahoehoe slaps forming it, are tilted suggesting yield to a lateral pressure.

Our observations suggest that "pressure ridge caves" formed by the buckling up of one or a few inflationary lava sheets due to lateral pressure when half-solidified surface sheets yield to the shoving of the hotter lava below by doming upward, perpendicular to the direction of pressure. The caves are however, not bound to pronounced tumuli but can occur under low, lateral or dome-like rises. In case of the Jordanian caves it appears as if the lava of the Qais and Makais Volcanoes had properties sustaining the formation of the pressure ridge caves that are not matched by the properties of the other lava fields composing the Harrat.

Introduction

Apart from pyroducts (lava tunnels, lava tubes; for term "pyroduct" see Kempe, 2002, 2009 and Lockwood, 2010) that actively conduct lava subterraneously, there are many other types of lava caves that can reach appreciable sizes. In the Cenozoic (Oligocene-Quaternary) alkali-basalt fields, the "Harrats", in Jordan (Fig. 1) we have surveyed 10 caves (Table 1) that lack any signs of laterally flowing lava. They all belong to one lava field, i.e. that of the combined Quis/Makais volcanoes at 32° 17.105'N/36° 35.992'E (Fig. 2). The lava is an alkali basalt and the flow field covers an area of 200 km², 28 km long and 6 to 10 km wide with a slope of ca. 0.8° and a flow direction of 212° (Fig. 3). The field also contains two pyroducts, Al-Jolous Cave (113 m long) and Hashemite University Cave (231 m long), illustrating that the lavas are duct-transported pahoehoe flows. The lava field forms only a small fraction of Jordanian Harrat of about 11,400 km² but contains 12 of the 22 known caves (as of 2009; Kempe *et al.,* 2009). The age of the flow field is according to sample 47 of Tarawneh et al. (2000) about 500 ka. It therefore belongs to the younger flow fields in the Harrat, just as the Al-Fahda flow field further to the east, and it has not yet developed an appreciable wadi network. Instead the surface of the flow field appears to be "mottled". This pattern arises from the fact that the entire Harrat is covered by 1 to 2 m of loess that is washed into the depressions between the flow ridges,
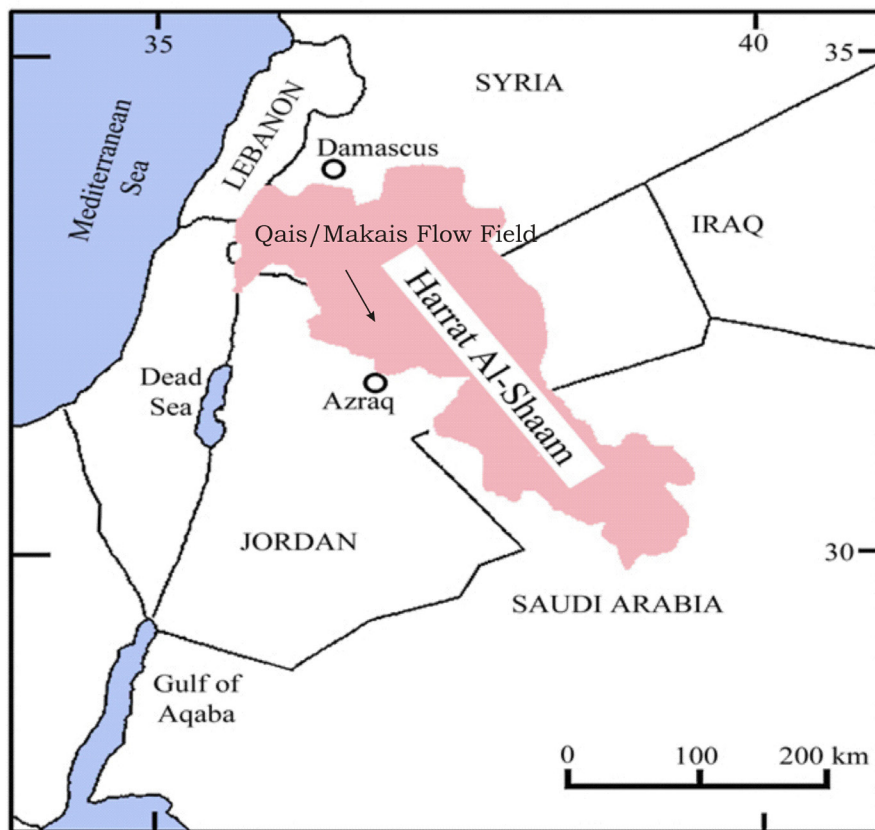
Fig. 1. Map showing extent of the Harrat in Syria, Jordan and Saudi Arabia.

thin. Other cavities are found below rather steep oval tumuli of debated origin. Overall these caves "were formed by drainage of sub-crustal injection and lava breakout" (Halliday, 2009). The first cave that, in our opinion, can be directly compared to the Jordanian caves is Eclipse Cave. It was incidentally discovered by one of us (SK) when parking the car along the highway to observe the total solar eclipse on 11th July, 1991. In March 2010 we (SK and IB) surveyed Eclipse Cave. It occurs in tholeiitic basalt lavas at 19°3.944'N/155°42.135'W that erupted from the Mauna Loa SW-Rift (Fig. 4). The flow is, compared to the Jordanian lavas, very young, but one of the older in this section of the Mauna Loa SW-Rift. ^{14}C sample W4232 collected at 19°05'41"/155°42'09", i.e. 3.2 km above our site, yielded an age of 780±70 aBP (Rubin *et al.,* 1987.)

Fig. 2. Panorama view of the tephra ring of the Quis Volcano to the north. Tephra is quarried from the western side the volcano.

thereby forming small irregular playas. Erosion has also removed the typical ropy surface features of pahoehoe. Similarly, the typical glazing of the lava cave walls has long been lost due to weathering and ceiling and walls show irregular pockets interpreted to be caused by weathering.

Caves that lack evidence of lateral lava flow are known also from Hawaii, but are so far only poorly documented. About 250 caves have been reported in the Kilauea caldera 1919 Postal Rift flow that are of varying genesis and that cannot be classified as pyroducts (Halliday, 2009). Many of them are low residual cavities along the perimeters of lava rises, wide and low bulges that collapsed after the lava that filled them drained. Lava drainage features are seen in some of them. The roofs of these caves are generally

Pressure Ridge Caves of the Quis/Makais Volcanoes

The pressure ridge caves of the Quis/Makais Volcanoes form two groups (Fig. 3), one to the north of the two volcanoes at an altitude at around 900 m (No. 4, 6, 7, 8; Table 1) and one to the south of the volcanoes (No. 1, 2, 3, 5, 9 and 10) at an altitude of around 780 m. However, this distribution may only represent our current knowledge, since we have not had the time to research the entire lava field for additional caves. Most of the caves are oriented perpendicularly to the flow direction (Table 1) and are associated with low ridges at the surface. All of the caves are very wide and low. They are elongated and can have several
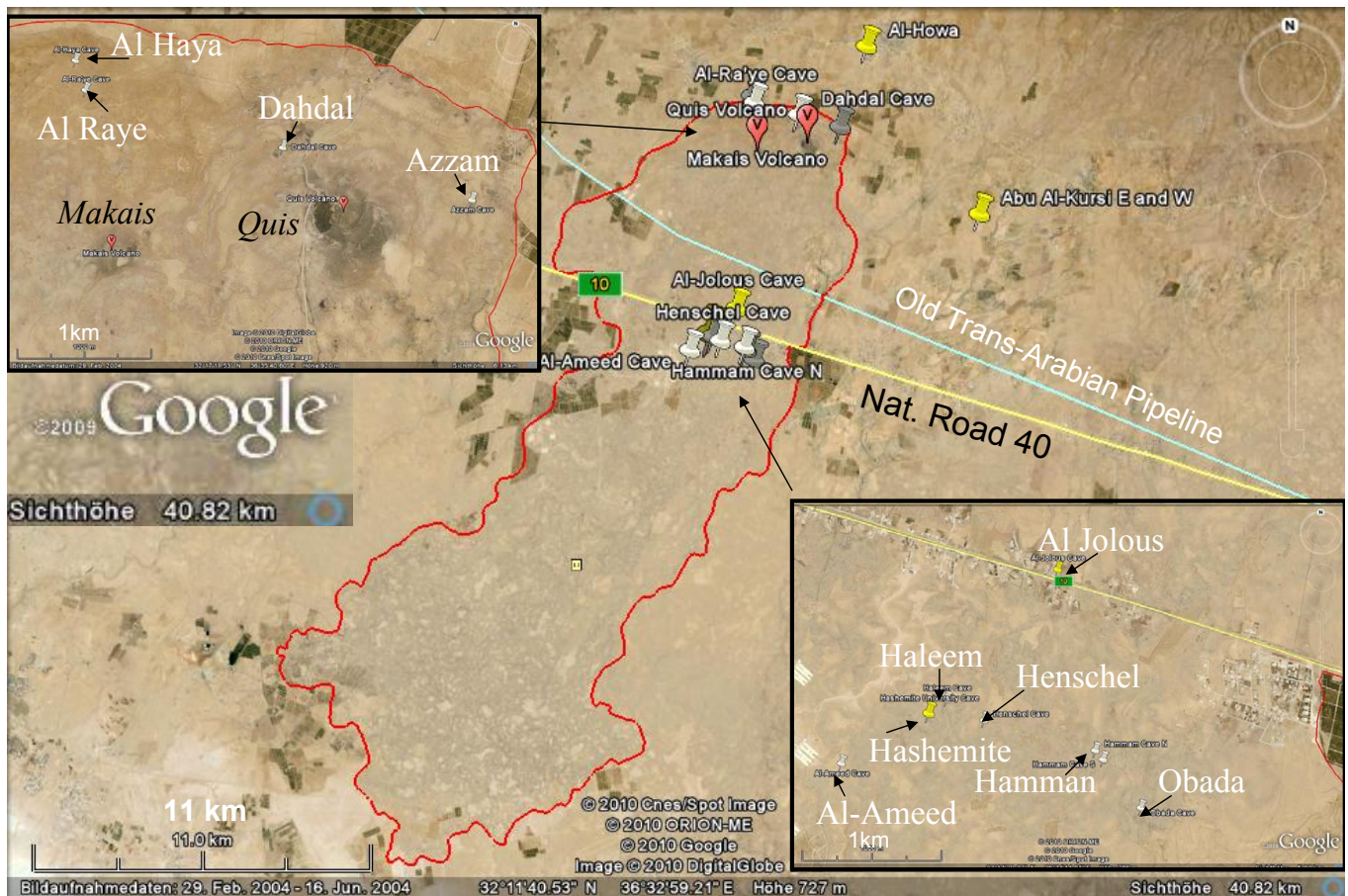
Fig. 3. Situation of the Quis/Makais Lavafield (Google Earth Picture). Insets show close-ups of northern area (upper left) and central area (lower right) with caves. Yellow pins mark pyroducts (including two systems to the NE in older lavas: Al-Howa and Abu Al-Kursi); white pins mark pressure ridge caves.

branches, petering out at their ends. Due to the loess cover of the Harrat, these caves are all filled with an unknown depth of sediment, so that we cannot see the rock floor in any of them. Most have been used by hyenas as dens and left plenty of bones and coprolites (Kempe *et al.,* 2006).

Table 1: basic data of "pressure ridge caves" investigated in this project.

Jordan	Name of Cave	Length	Depth	Direction	Altitude
1	Al-Ameed Cave	208	4.0	SW-NE	777 m
2	Hammam Cave N	123.4	4.5	NW-SE	780 m
3	Obada Cave	107.6	3.5	NW-SE	766 m
4	Al-Haya Cave	81.3	4.2	NW-SE	902 m
5	Haleem Cave	70.7	4.7	NW-SE	791 m
6	Azzam Cave	44.1	4.2	NNW-SSE	902 m
7	Al-Ra'ye Cave	42	3.5	NW-SE	900 m
8	Dahdal Cave	28.9	0.0	SW-NE	920 m
9	Henschel Cave	21	2.5	W-E	788 m
10	Hammam Cave S	12.4	2.4	NW-SE	780 m
	Total:	739.4			
Hawaii	Eclipse Cave total	140.6	3.8		
	Eclipse Cave pressure ridge section	70	3.8	NW-SE	636 m

The longest cave is Al-Ameed (Fig. 5). It consists of a 120 m long low cavity. Only two stations have ceiling height above 1 m. The cave is a combination of a 20 m wide vault in the north with a 15 m wide one in the south connected by a wide and low (0.6 m) passage. The northern vault collapsed centrally forming the current entrance. At the entrance the 2 m thick roof consists of five inflationary sheets between 30 and 45 cm thick. These layers are relatively thin, indicating that the lava was still very hot when the roof was emplaced at this location. This in turn is the consequence of the duct-fed pahoehoe that even 8 km below its source was still fluid enough to form thin sheets. It appears that in the northern vault, a sort of column existed since at St. 15, possibly an analogue to the column in Eclipse Cave (see below). The direction of Al-Ameed is more or less in direction of the flow (which is in contrast to most of the other caves in the flow field) and the surface ridge above the northern section is striking at an angle to the strike of the cave.
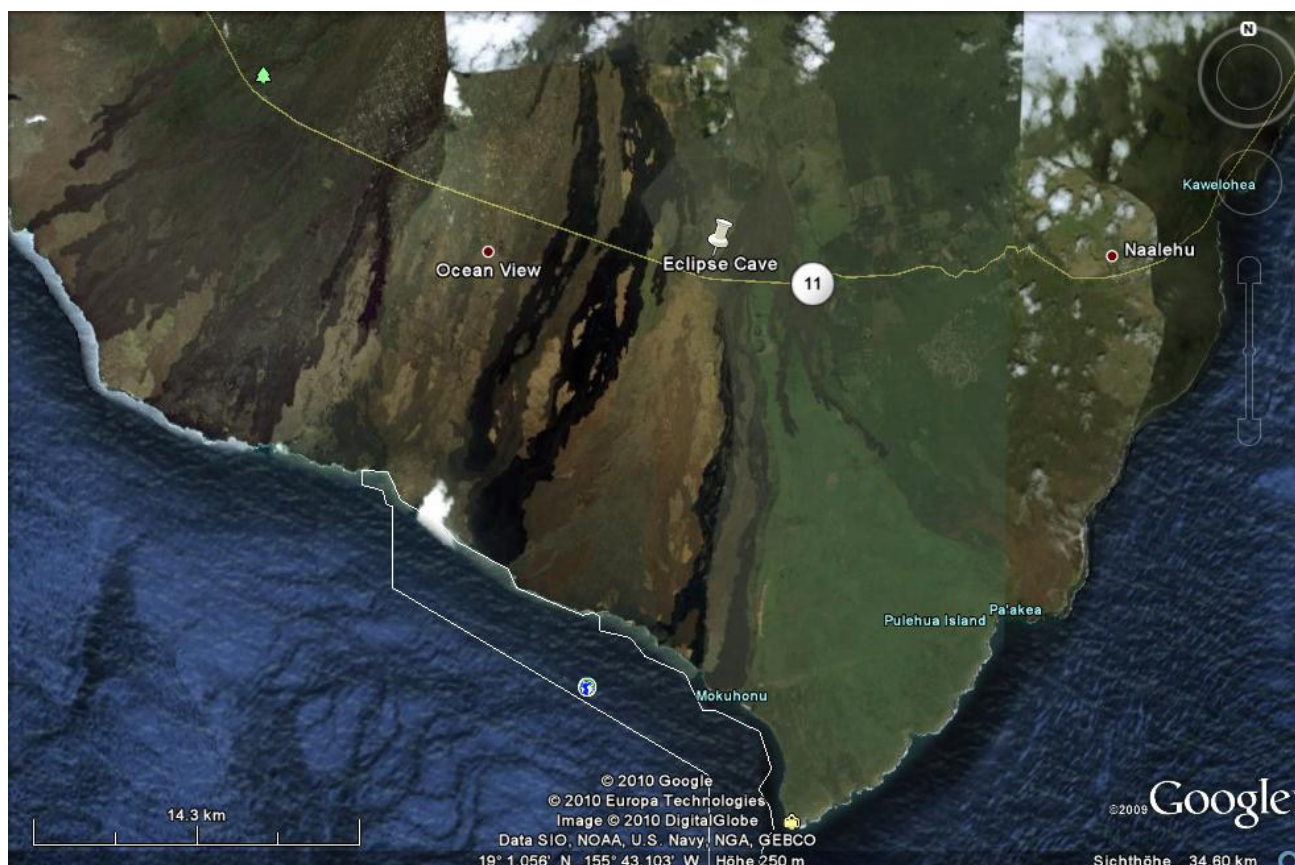
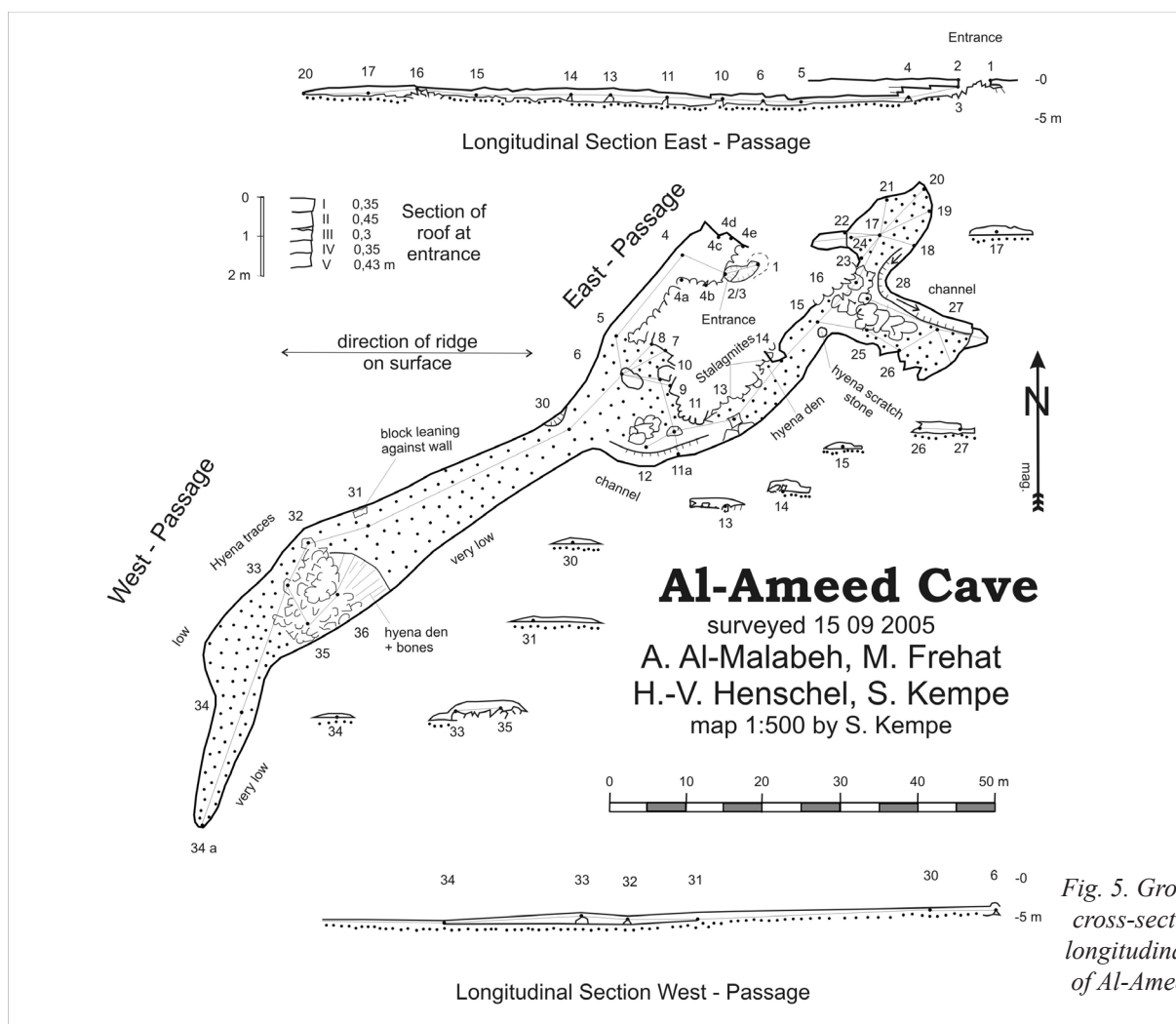Fig. 4. Location of Eclipse Cave, Mauna Loa, Hawaii (Google Earth Picture).

Fig. 5. Ground plan, cross-sections and longitudinal section of Al-Ameed Cave.
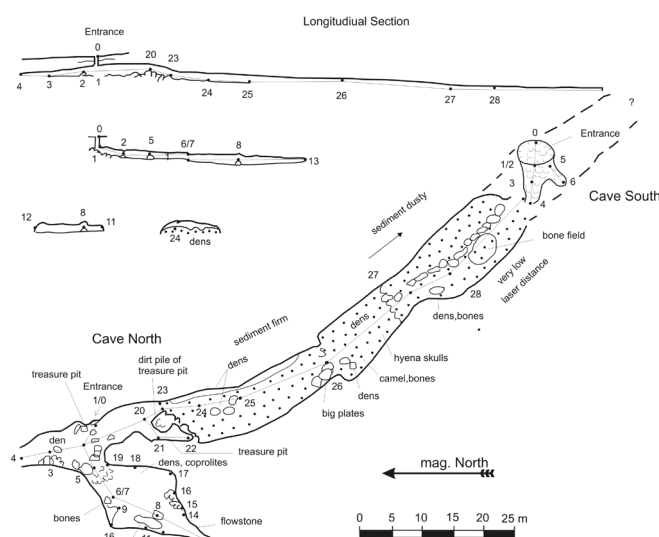
Fig. 6. *Ground plan, cross-sections and longitudinal section of Hammam Cave.*

The next longest cave is Hammam Cave North that, looking at the ground plan, might be mistaken for a pyroduct (Fig. 6). However, nowhere is there any sign of flowing lava and the branch to the SW, a room that has standing height in contrast to the rest of the cave that only allows crawling, with its circular is typical for the pressure ridge cave morphology. The main branch (Fig. 7), that leads southeast toward another entrance (Hammam Cave South) is low throughout. The roof height is again in the order of 2 m.

Obada Cave has three fingers, all ending very low (Fig. 8). The view into the main chamber (Fig. 9) reveals
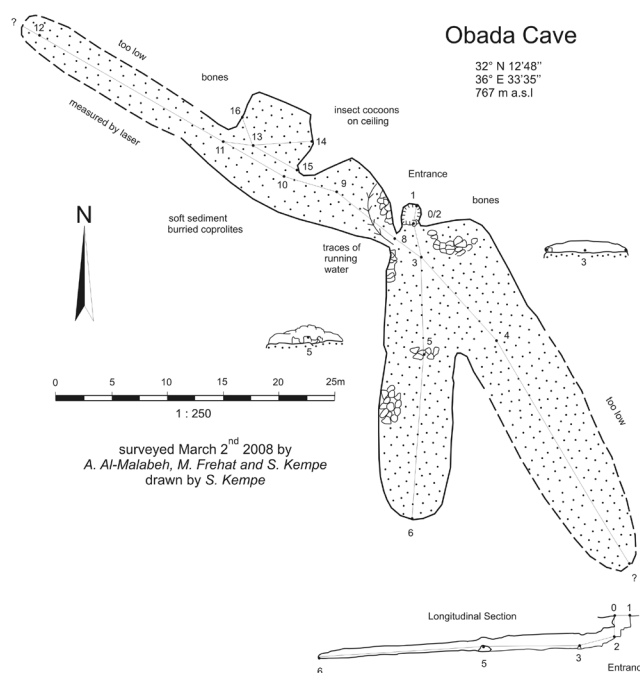
Fig. 8. *Ground plan, cross-sections and longitudinal section of Obada Cave.*

a very low, wide vault. The southern end of Haleem Cave is also a 20 m wide hall, nowhere high enough to stand (Figs. 10, 11). The cave has two openings, one that can be entered and a slot, not wide enough for adult humans to squeeze through. The cave follows a surface flow ridge (Fig. 12). Henschel Cave consists essentially of only one large low and circular room (Fig. 13). Its entrance is so small and has only recently been enlarged, that it has never been entered by hyenas; rather it contains a number of bird bones.

The largest cave in the northern group is Azzam Cave (Fig. 14), the one we explored first in Jordan. It is well known locally and its entrance has been artificially enlarged and stabilized because it is used as a sheep pen from time to time. The entrance is surrounded by a wall, also serving the modern herders. The sediment dug from the entrance pit was deposited nearby; it contains pot shards from various times. There is no distinct surface ridge above the cave (Fig. 15). This may indicate that the

Fig. 7. *View to south-east into main passage of Hammam Cave.*

Fig. 9. Panorama view into Obada Cave.

Haleem Cave
surveyed 21.2.2009
*S. Kempe, H.-V. Henschel
B. Müller-Neuhof
A. Al-Malabeh, A. Kalifeh*
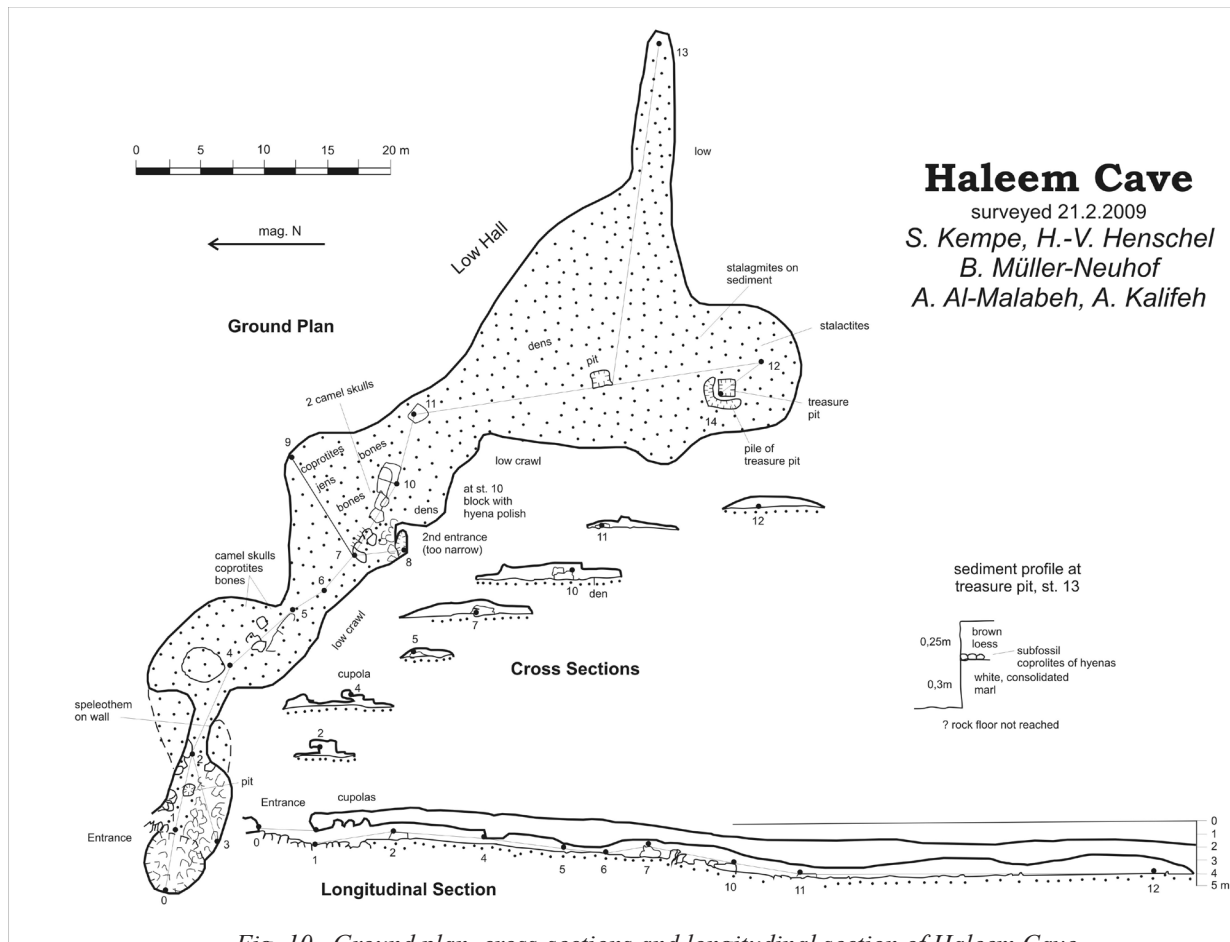
Fig. 10. Ground plan, cross-sections and longitudinal section of Haleem Cave.

Fig. 11. View east into the low and wide hall at the southern end of Haleem Cave.

original flow that contains the cave was later covered by other surface flows from the nearby volcano. Due to the weathering such features cannot be differentiated any more.

Eclipse Cave, Mauna Loa Hawaii

Eclipse Cave actually consists of a combination of a pressure ridge cave and a small pyroduct (Fig. 16). The pressure ridge hall is aligned perpendicular to the direction of flow. It is 70 m long and up to 2.5 m high, forming a rather regular vault up to 18 m wide (Fig. 17). The hall has a flat lava floor lacking any signs of lateral flow. Contraction cracks are as deep as 1.8 m, showing that the floor must have solidified from a very deep layer of fluid lava. To the west we discovered

Fig. 12. View south-east along the surface ridge above Haleem Cave.

that the cave also features a small pyroduct originated in a niche below the northern rim of the entrance puka (sinkhole) (Fig. 16). There lava upwelled from below, possibly an overflow from the actual mean pyroduct underneath. The lava then flowed downhill into a 2-3 m wide but very low tunnel (Fig. 18) that we could follow for about 20 m but did not survey. This conduit showed all the features associated with lateral flow of lava. The floor of the pressure ridge on the other hand is flat and does not show any flow lobes or any measureable slope. At the surface a low ridge exists above the hall (Fig. 19). The surface pahoehoe slaps forming it are tilted suggesting yield to a lateral pressure.

Conclusions

All these observations suggest that "pressure ridge caves" formed by the buckling up of one or a few inflationary lava sheets due to lateral pressure when half-solidified surface sheets yield to the shoving of the hotter lava below by doming upward, perpendicular to the direction of pressure. The caves are, however, not underneath pronounced tumuli but can occur under low, longitudinal or dome-like rises. Most interesting is the column in Eclipse Cave. It is not a lava stalagmite created by lava invading a crack from above. Around its foot it is surrounded by welded rough aʻa-like apron. The only explanation for this unique feature we can suggest is that it was created during the process of upward doming of the roof. When the roof started to

Henschel Cave
surveyed 26.02.09
S. Kempe, H.-V. Henschel
A. Al-Malabeh, A. Kalifeh
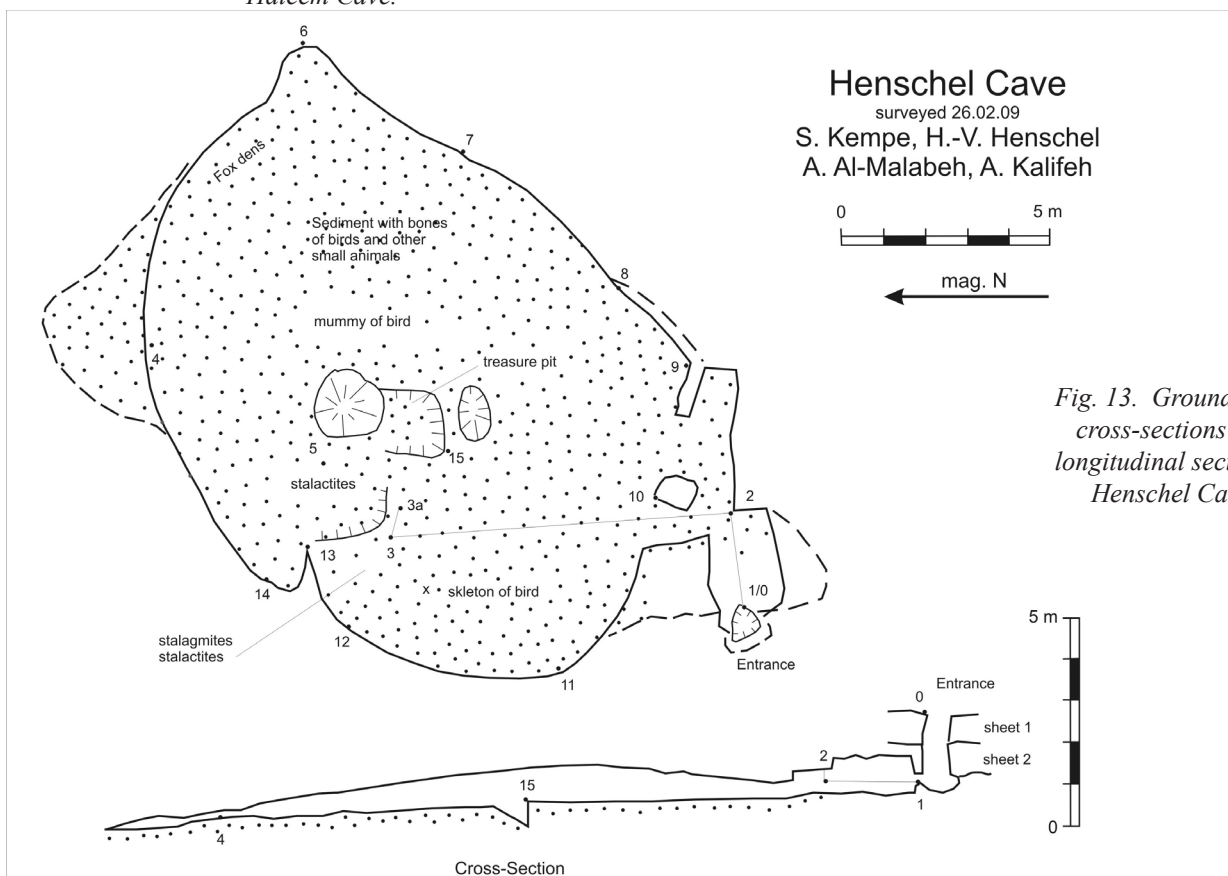
Fig. 13. Ground plan, cross-sections and longitudinal section of Henschel Cave.
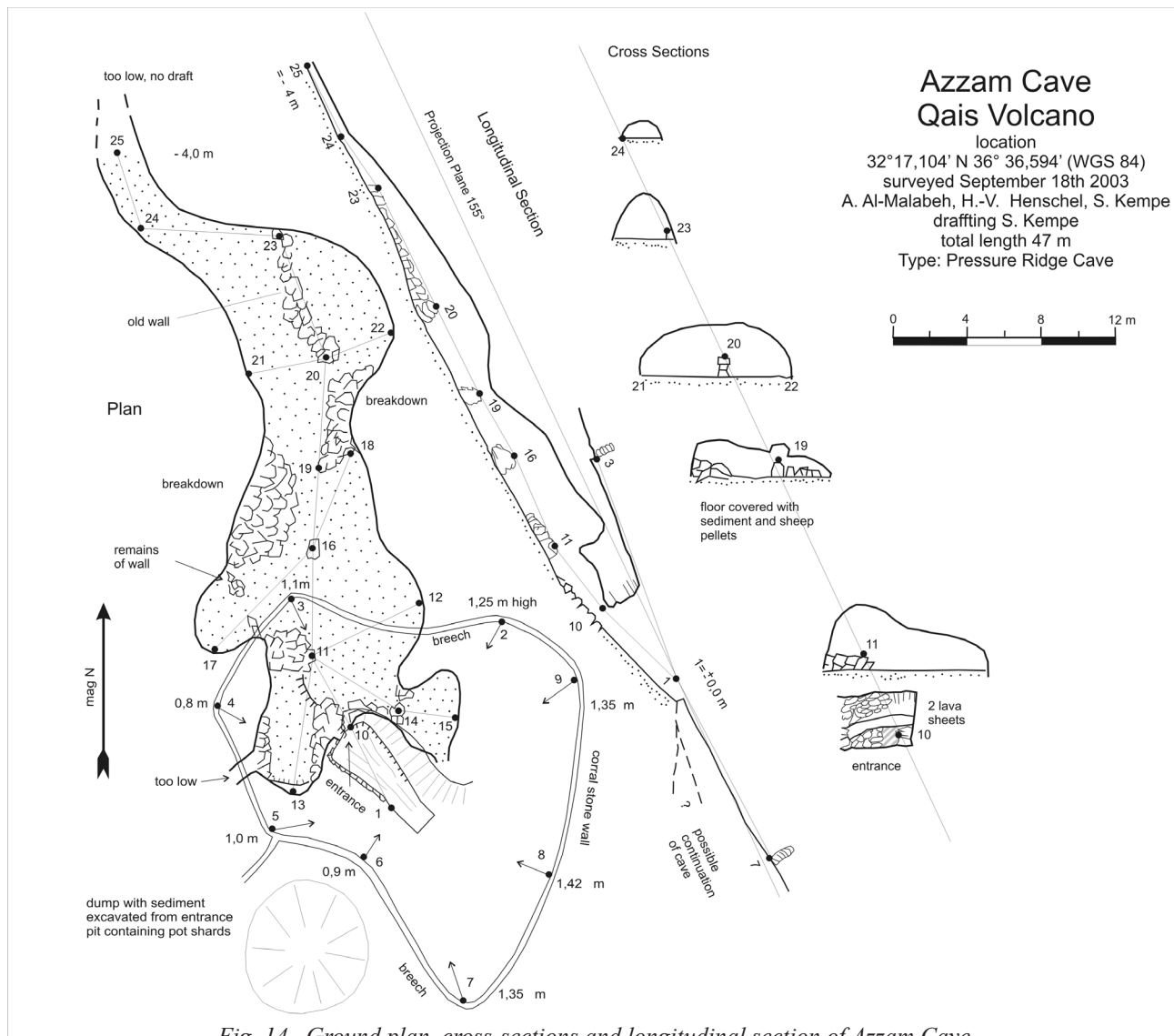
Fig. 14. Ground plan, cross-sections and longitudinal section of Azzam Cave.

Azzam Cave
Qais Volcano
location
32°17,104' N 36° 36,594' (WGS 84)
surveyed September 18th 2003
A. Al-Malabeh, H.-V. Henschel, S. Kempe
draffting S. Kempe
total length 47 m
Type: Pressure Ridge Cave

Cross Sections

Plan

Longitudinal Section

Projection Plane 155°

mag N

too low, no draft

old wall

breakdown

breakdown

remains of wall

1,1 m

1,25 m high

breech

1,35 m

1,35 m

1,42 m

corral stone wall

possible continuation of cave

too low

entrance

dump with sediment excavated from entrance pit containing pot shards

floor covered with sediment and sheep pellets

2 lava sheets

entrance

Fig. 15. View across the entrance of Azzam Cave towards the eastern flank of the Quis Volcano tephra ring.
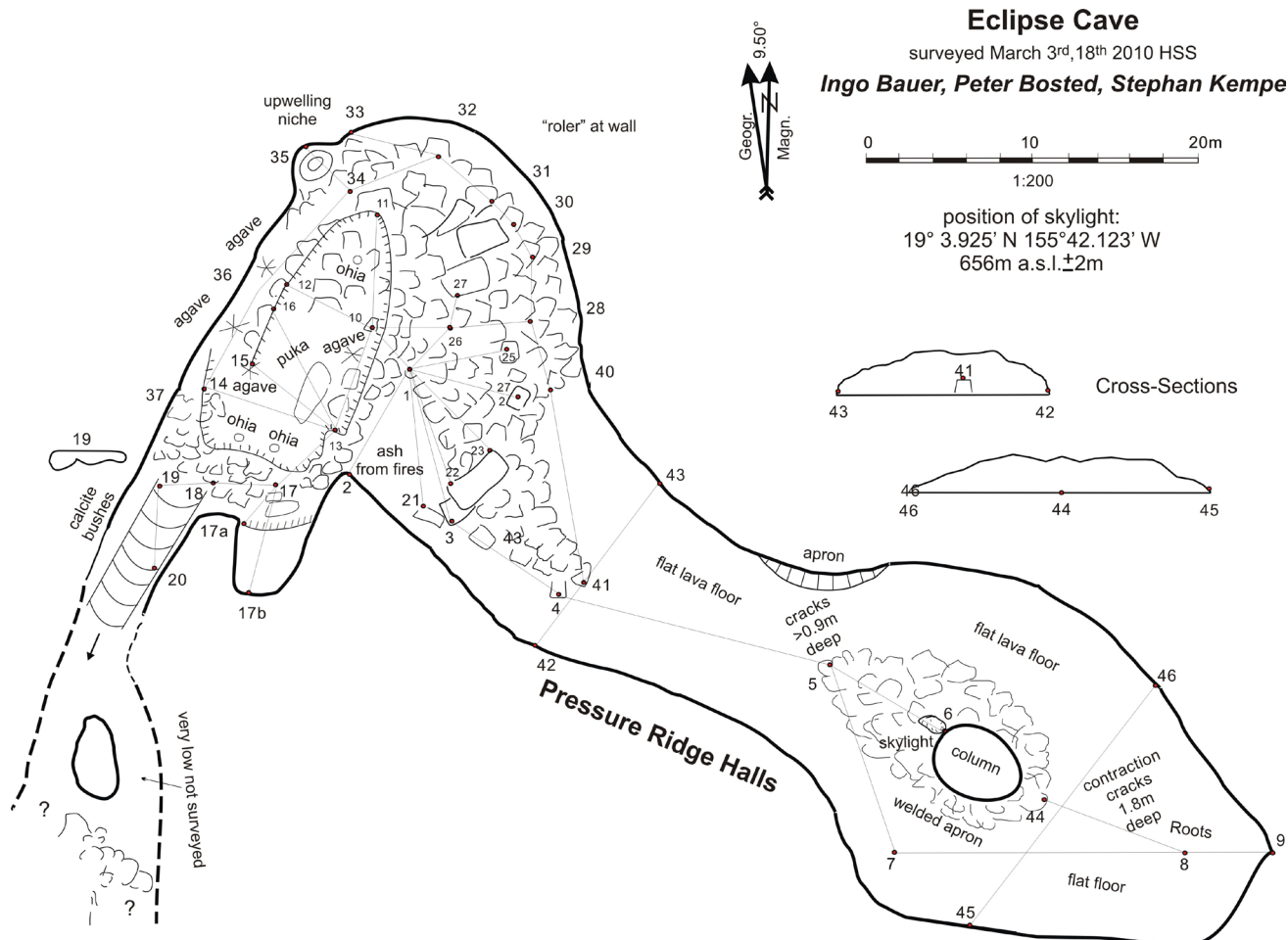
Fig. 16a,b *Ground plan, cross-sections and longitudinal section of Eclipse Cave, Mauna Loa, Hawaii.*
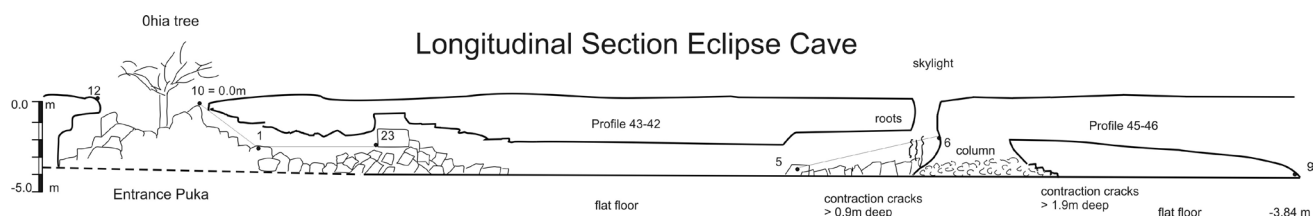
Fig. 17. *Panorama view of the "column" to the west from the end of the pressure ridge section of Eclipse Cave. That the floor appears higher on the right side is an artefact of the construction of the panorama.*

separate from the later floor, it could at first have stuck to the floor at this place. Then, as the roof moved up, the ceiling at this spot pulled lava up from the still molten floor chewing gum-like, peeling the original surface sideward to form the aʻa-like apron.

In case of the Jordanian caves it appears as if the lava

Fig. 18. *Panorama view into the downhill side of the small and low pyroduct to the western side of the Eclipse Cave.*

Fig. 19. *Panorama view of the ridge from the north below which the pressure hall section of Eclipse Cave is situated. The trees to the right mark the "puka", i.e. the entrance to the cave. The trees to the left have their roots in the cave, as seen on figure 17. The plates that form the roof of the cave have been tilted upward (center). Person (I.B.) for scale on the far left.*

of the Quis and Makais Volcanoes had properties sustaining the formation of the pressure ridge caves that are not matched by the properties of the other lava fields composing the Harrat. What these properties are in detail and how they compare to that of the Elipse Cave Flow remains to be studied. It could be that during the cooling of lava a certain "viscosity window" exists that allows doming upward of a ca. 1-2 m thick surface layer separating it from the hotter layers below without breaking it.

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Inflationary versus Crusted-over Roofs of Pyroducts (Lava Tunnels)

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Abstract

Many types of lava caves exist. Of these longitudinal conduits that serve for long-distance, underground, post-eruptional transport of (with a few exceptions) basaltic lavas are the largest and most common. They represent the mechanisms building low-slope (often <2°) shield volcanoes. Originally described from Iceland, these caves were observed actively forming in Hawai'i and in 1844 were named "pyroducts" (a term taking precedence over the later - post 1940 - term "lava tube" that may incorrectly imply that lava can flow upward like in plumbing tubes). However, formation of pyroducts is still a subject of debate in textbooks.

During recent decades, interest in these transport ducts increased also because of the discovery of long volcanic flows on the Moon, Venus, Mars and Io. The longest surveyed uninterrupted pyroduct is Kazumura Cave (65.5 km) (Hawai'i, Kilauea Volcano) and the longest duct-supported flow on Earth is the 160 km long Undara flow, site of our symposium. The Hawaiian Speleological Survey has explored and surveyed many other caves on Hawai'i and elsewhere that allow us to study the formation and evolution of these "pyroducts" from the inside.

Apparently several modes exist: In the "inflationary" mode lava flows grow at their distal tips where hot lava quickly covers the ground in thin sheets. The next advance will lift this sheet up ("inflation") before forming the next distal surface sheet. The process can be repeated many times, forming a primary roof with several sheets, separated by sheer interfaces (only the first or top sheet displays ropy pāhoehoe surfaces). Another mode is the "crusting over of channels" that appears to have two cases: closure by slab jam and closure by lateral shelf growth.

In the first case shoals, blocks, lavaballs and secondary clasts of already solidified lava form a "log jam" on the surface of a channelized lava flow. This jam is highly porous and not very stable. But since it floats on the channel, it is injected by molten lava from below that form characteristic, upward directed "squeeze balls". In this way the roof is gaining mass and stability. The high porosity allows air to circulate through the forming roof. It can not only oxidize the lava slabs, turning them reddish, but also freeze-out layers of lining originating from the top of the hot lava in the channel. These layers often show thin lamination and can grow to a thickness of 10 cm or more, also stabilizing the roof. It is conceivable that the roof may break up several times, forming larger agglomerations. Once it is established, it can also be reinforced by later overbank events depositing layers of pāhoehoe on top of the roof. Often this secondary reinforcement is the only stable element in the roof structure while the slab-jam caves-in once the lava below has receded, depriving the roof of its buoyancy.

Closure by lateral shelf accretion, on the other hand, apparently needs a rather calm and steady lava flow and is therefore most probably operating in the formation of secondary roofs inside the downcutting pyroduct and not so much in the formation of primary roofs.

Our investigation shows that, apparently, most of the long Kilauea ducts, including Kazumura, Keala, Ainahou, Keauhou Trail and others, as well as several of the Hualālai Caves, such as Huehue, are of the inflationary type, while the Mauna Loa Kipuka Kaohina Cave System is of the slab-jam type.

Examples of roof sections of some of these caves will be given, illustrating the importance of studying roof structure at pukas and at sites of breakdown in the cave.

1. The problem

Many types of lava caves exist. Of these, longitudinal conduits that serve for long-distance, underground, post-eruptional transport of (with a few exceptions) basaltic lavas, are the largest and most common. They represent the mechanisms building low-slope (often <2°) shield volcanoes. Originally described from Iceland (e.g., Kempe, 2008), these caves were observed actively forming in Hawai'i and in 1844 (Coan 1844) were named "pyroducts" (a term taking precedence over the later - post 1940 - term "lava tube" that may incorrectly imply that lava can flow upward like in plumbing tubes) (for history of term pyroduct see Kempe 2002; Lockwood & Hazlett 2010). However, the importance and formation of pyroducts is still of debate in geological and volcanological textbooks that turn out to be extremely imprecise - if they mention pyroducts at all:

- Gordon Macdonald & Agatin Abbot (1970) state: *"The feeding rivers of pahoehoe flows quickly crust over and develop more or less continuous roofs, and thenceforth the lava stream flows within a tunnel of its own making."* (p. 26).

- Ronald Greeley (1987) writes: *"The term 'lava tube' may be defined as the conduit beneath the surface of solidified lava through which molten lava flows. 'Lava channels' however contain non-roofed rivers of lava that frequently develop surface crusts. Many (if not most) lava tubes develop from the roofing of channels. ... the distinction between channels and tubes is made in regard to the roof crust. So long as the crust remains mobile and free-floating on the active flow the structure is regarded as a channel section in which the crust is continuous across the active flow and fixed to the immobile parts of the flow are considered lava tubes. Thus even if the roof collapses when the flow drains the feature is considered to be a lava tube..."* (p. 1590).

- Robert and Barbara Decker (1991) state: *"Beneath the hardened surface of a pahoehoe flow, hot lava still flows rapidly in tunnels that supply the advancing front. These lava tubes form a complex network that transports molten rock from the vent to flow front over ... several km. ... Small lava tubes feeding individual lobes apparently coalesce as the multiple flow lobes pile up and form lava tunnels as much as 10 m in diameter and many km long."* (p. 80).

- Peter Francis (1993) summarized *"Lava tunnels form when the surface of a flow crusts over, while hot lava continues to flow beneath. If the rate of flow is sufficiently fast the flow may erode its way thermally into underlying lava, producing ... distinctive, figure-8-shaped profiles. When the lava supply is cut off, the lava filling the tube drains away ..., leaving behind an empty conduit."* (p. 149).

- Jacque-Marie Bardintzeff (1999) writes: *"An den Rändern des Lavastromes, die schneller als die Strommitte erstarren, bilden sich manchmal richtige „Dämme", die die Lava kanalisieren. Wenn dann auch das Dach des Lavastromes erstarrt, fließt die Lava durch einen Tunnel... . Später kann sie unter ihrer festen Kruste heraus fließen und einen weithin offenen Lavatunnel hinterlassen, ... der mehrere km Länge erreichen kann."* (p. 77). ("At the fringes of the lava flow, that solidify faster than the center of the flow, real dams can sometimes form that channelize the lava. If then also the roof of the lava flow congeals, the lava flows through a tunnel … Later it can flow out from underneath its solid crust leaving a wide open lava tunnel, … that can reach several kilometres in length". Translation by author.)

- Paul Spudis in the *Encyclopedia of Volcanoes* (2000) defines lava tubes as: *"A lava channel that is partly or completely roofed over to enclose the lava stream may form a cave after the flow has cooled."* (p. 697).

- This long-standing theme of "crusting-over of channels" as the origin of pyroducts is still dominant in Jack Lockwood's (Lockwood & Hazlett 2010) chapter, albeit followed by the inflation mode of information: *"On steeper slopes ... pāhoehoe flows are ... fed by well-defined channels... these channels will commonly crust over to form pyroducts. The formation of pyroduct roofs involves two processes: a) narrowing of the channel rims by freezing of lava levees along channel walls, and b) the accretion of plates of crust that are skimmed off channel surfaces .... Once a pyroduct roof segment is established that roof forms a blockage for crustal fragments moving downstream and the roofed-over area will rapidly propagate upstream as more crustal fragments plate onto the pyroduct entrance. Pyroduct roofs are also thickened by new lava that may flow onto them .... Where pāhoehoe flows reach more gentle terrain channel development mostly ceases and is much less important a mode of pyroduct development. Most lava instead is supplied by high pressure inputs beneath inflating crusts (Hon et al. 1994). Such flowage tends to be concentrated along the most efficient pathways which evolve into persistently active pyroducts as eruption continues. ..."* (pp. 140-141).

These statements are derived from watching active lava flows, but they entirely lack the evidence gained from studying lava caves internally.

2. Pyroduct roofs

During the last decades, interest in volcanic surface placement increased also because of the discovery of long volcanic flows on Moon, Venus, Mars and Io. The longest surveyed uninterrupted pyroduct is Kazumura Cave (65.5 km total, 41 km main trunk length) (Hawai'i, Kilauea Volcano) and the longest duct-supported flow on Earth is the 160 km long Undara flow, site of our symposium (Atkinson & Atkinson 1995). The current Kilauea SE-Rift eruption provided ample opportunity to study pāhoehoe flows giving new insight into pyroduct formation. In parallel the Hawaiian Speleological Survey has explored and surveyed hundreds of caves on Hawai'i and elsewhere that allow to study the formation and evolution of

pyroducts from the inside. Specifically the study of roof sections is needed if we want to progress in our understanding of pyroduct formation.

It has now become clear that several modes of pyroduct formation exist:

In the "inflationary mode" lava flows grow at their distal tips where hot lava quickly covers the ground in thin sheets. The next advance will lift this sheet up ("inflation") before forming the next distal surface sheet (Hon *et al.* 1994). The process can be repeated many times, forming a primary roof with several sheets, separated by shear interfaces (only the first or top sheet displays ropy pāhoehoe surfaces). Fig. 1 gives an idealized cross-section of a roof of a cave developed by inflation and Fig. 2 gives an interpreted view of a section through an inflationary primary roof of the Huehue Cave, Hawai'i. One of the misconceptions about pyroducts (also expressed in several of the above quotations) is the suggestion

Stack of four pahoehoe sheets lifted up by inflation

pahoehoe surface

1
2
3
4

Drained primary parallel duct

breakdown enlarges the canyon upward

blocks float down-slope

downward erosion deepens the canyon

older lava flows
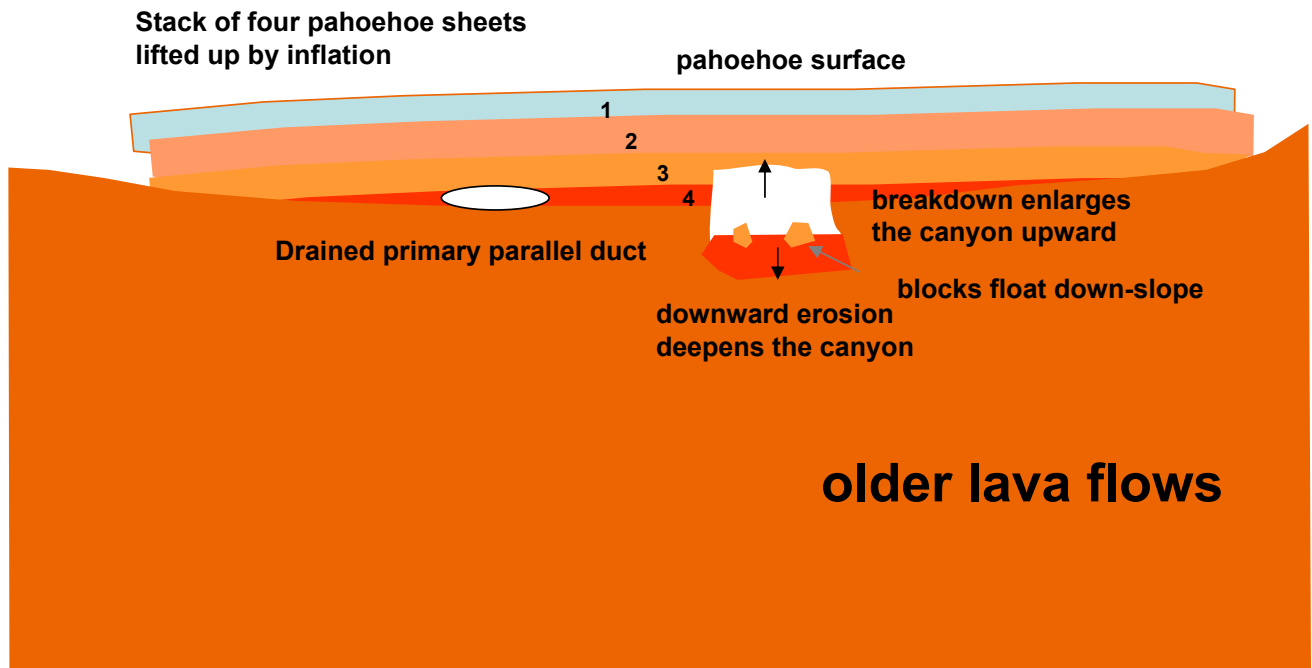
Fig. 1. Sketch of the structure of a primary roof formed by "inflation".

secondary cover by additional surface flow; note negative imprint of ropy surface flow of layer 1

1

2

3
4
5

6

primary roof with ca. 6 sheets, separated by shear planes

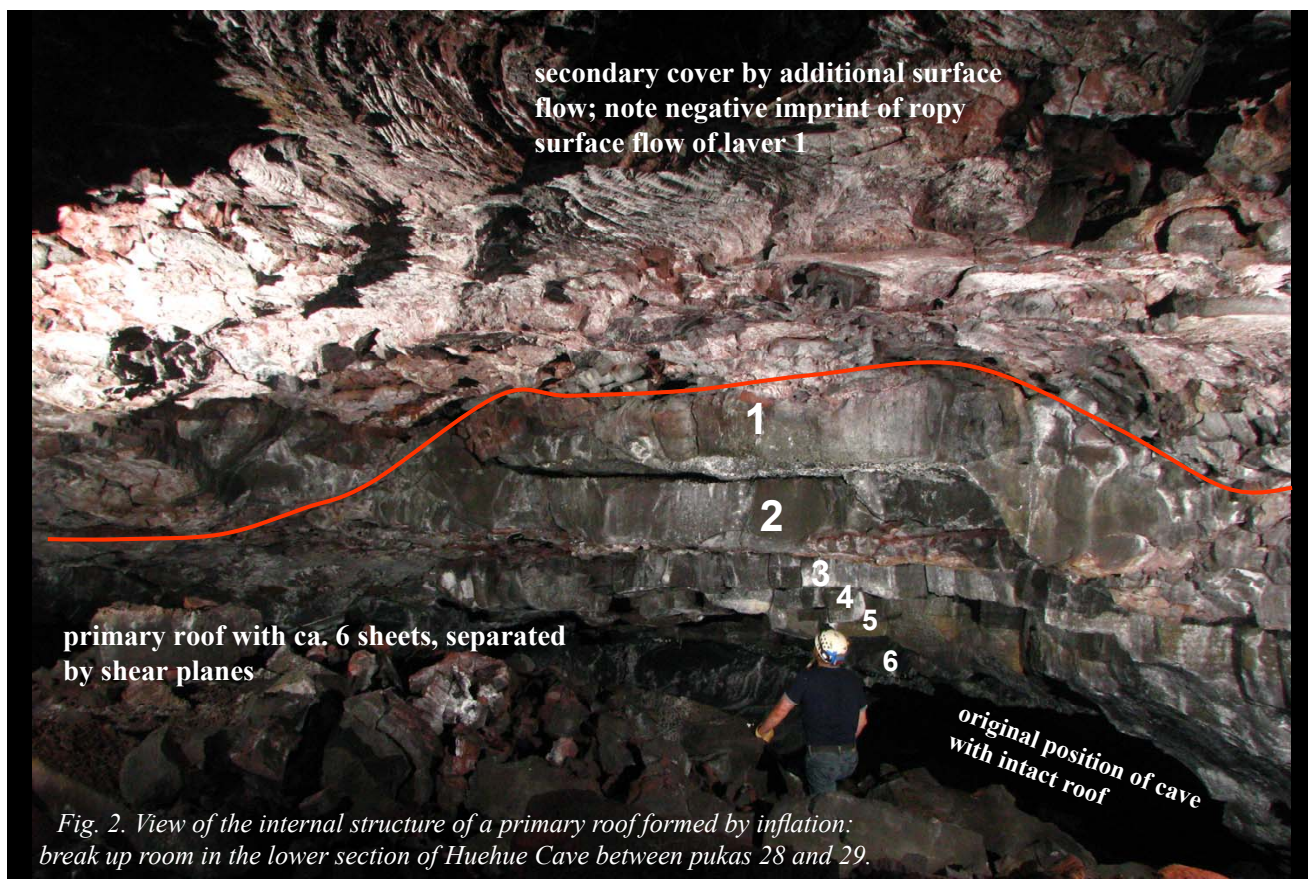*original position of cave with intact roof*

Fig. 2. View of the internal structure of a primary roof formed by inflation: break up room in the lower section of Huehue Cave between pukas 28 and 29.

that caves become only accessible after the "tube has been drained". The study of lava caves has shown that almost all of the caves have already a gas-space above the internal lava river due to massive down-cutting (Allred & Allred 1997; Kempe 1997, 2002; Greeley *et al.* 1998). Thus, even if the residual lava did not drain and solidify inside the caves, we would still be able to access them. It is also a misconception that the roof is upheld by the lava flowing below by buoyancy. Inflationary lava cave roofs hold up because they form low natural vaults with their weight resting on the walls. The internal development of pyroducts has been summarized in Kempe (2002, 2009). Fig. 3 gives some of the features that appear in a typical inflationary cave during its prolonged activity (Kempe 2010).

The so-much-described "crusting-over of channels" mode appears to have two cases: closure by "log jam" and closure by "lateral shelf growth". In the first case slabs, blocks, lavaballs and secondary clasts of already solidified lava form a "log jam" on the surface of a channelized lava flow (Fig. 4). This "jam" is highly porous and not very stable. But since it floats on the channel, it is injected by molten lava from below that forms characteristic, upward directed "squeeze balls" (Fig. 5). In this way the roof gains mass and stability. The high porosity allows air to circulate through the forming roof. It can not only oxidize the lava slabs, turning them reddish, but also freeze-out a lining originating from the top of the hot lava in the channel. This layer shows often thin lamination and can grow to a thickness of 10 cm or more, also stabilizing the roof. It is conceivable that the roof breaks up several times, forming larger agglomerations. Once it is established, it can also be reinforced by later overbank events depositing layers of pāhoehoe on top of the roof. Often this secondary reinforcement is the only stable element in the roof structure while the slab-jam collapses once the lava below recedes, depriving the roof of its buoyancy.
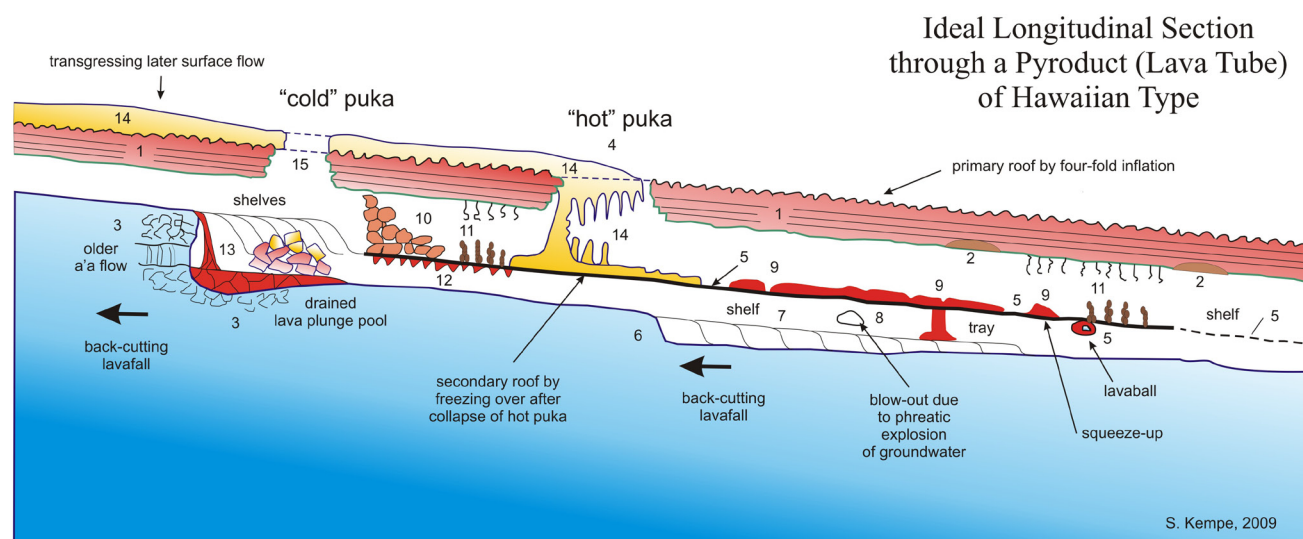

Fig. 3. Scheme of the variety of rock-speleothems tied into the evolution of a lava–pyroduct of Hawaiian type: (1) Primary roof with four inflation layers. (2) Higher passage labyrinth that was drained by the lava while the main thread of flow concentrated into a main channel that cut down into lava of older eruptions below. (3) A back-cutting lavafall has created a large underground canyon and impressive plunge-pools halls. (4) A collapse of the primary roof ("hot puka"; breakdown removed) and consecutively intruding cold air causes solidification of the lava river surface and forms a "secondary roof" (5). (6) Below the secondary roof, erosion continues and a new lavafall cuts the tube further down. (7) Back-cutting leaves curved shelves marking temporary lava fall positions. (8) Where water can enter the tube the thin and hot glazing can be expanded into bubbles, finally bursting. (9) Spills occur from below, reinforcing the secondary ceiling and seeping back through the secondary roof, to be transformed into pendants with horizontal flat feet ("trays"). Other spills form only local "squeeze ups". (10) Boulders derived either by roof or wall collapse or eroded from the floor float on the lava river and become coated spherically. Some are swept onto the secondary roof, blocking its upper end; others may get stranded below that roof. (11) The still hot primary roof extrudes residual melt that drips to the floor, being frozen by intruding cold air to form stalagmitic piles of discrete drips. Further extrusion is forming helictite-like "pig-tails" and cylindrical stalactites. (12) Final subsidence of flow and detachment from ceiling leaves cone-shaped stalactites, often consisting of many layers below ceiling. (13) The lava lake freezes-over, its last lava empties to below causing the crust to collapse. Also, the last bit of flow consolidates at the lava fall, sometimes forming irregular columns. (14) After the cave cooled, a younger flow crossed the cave and marginally flowed into the hot puka, forming a large column, stalactitic curtains and large stalactites. (15) The roof collapses again ("cold puka"; breakdown blocks preserved below), piercing both the primary roof and the later lava overlaying it. Such collapses often occur were a large hall exists underground (Kempe, 2010).
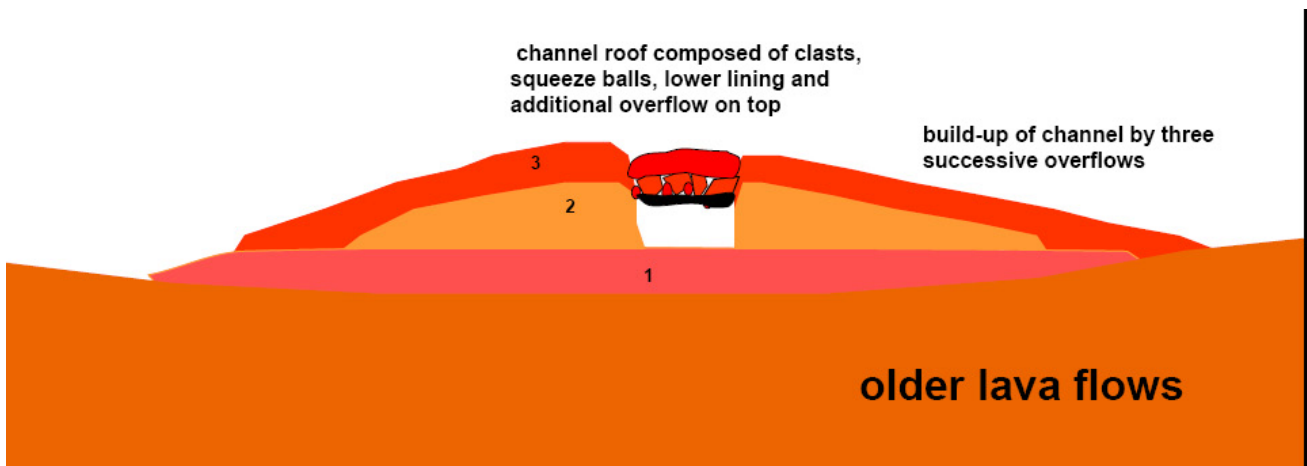
Fig. 4. Scheme of a cross-section through a roof, formed by the crusting-over of a channel by the agglomeration of floating clasts.

Closure by lateral shelf accretion (Fig. 6) on the other hand apparently needs a rather calm and steady lava flow and is therefore most probably operating in the formation of secondary roofs (Fig. 7) inside the down-cutting pyroduct and not so much in the formation of primary roofs.

3. Examples and discussion

Our investigation shows that apparently most of the long Kilauea ducts, including Kazumura, Keala, Ainahou, Keauhou Trail and others, as well as several of the Hualālai caves, such as Huehue, are of the inflationary type. Also all of the pyroducts studied in Jordan are inflation caves, sporting uninterrupted lava
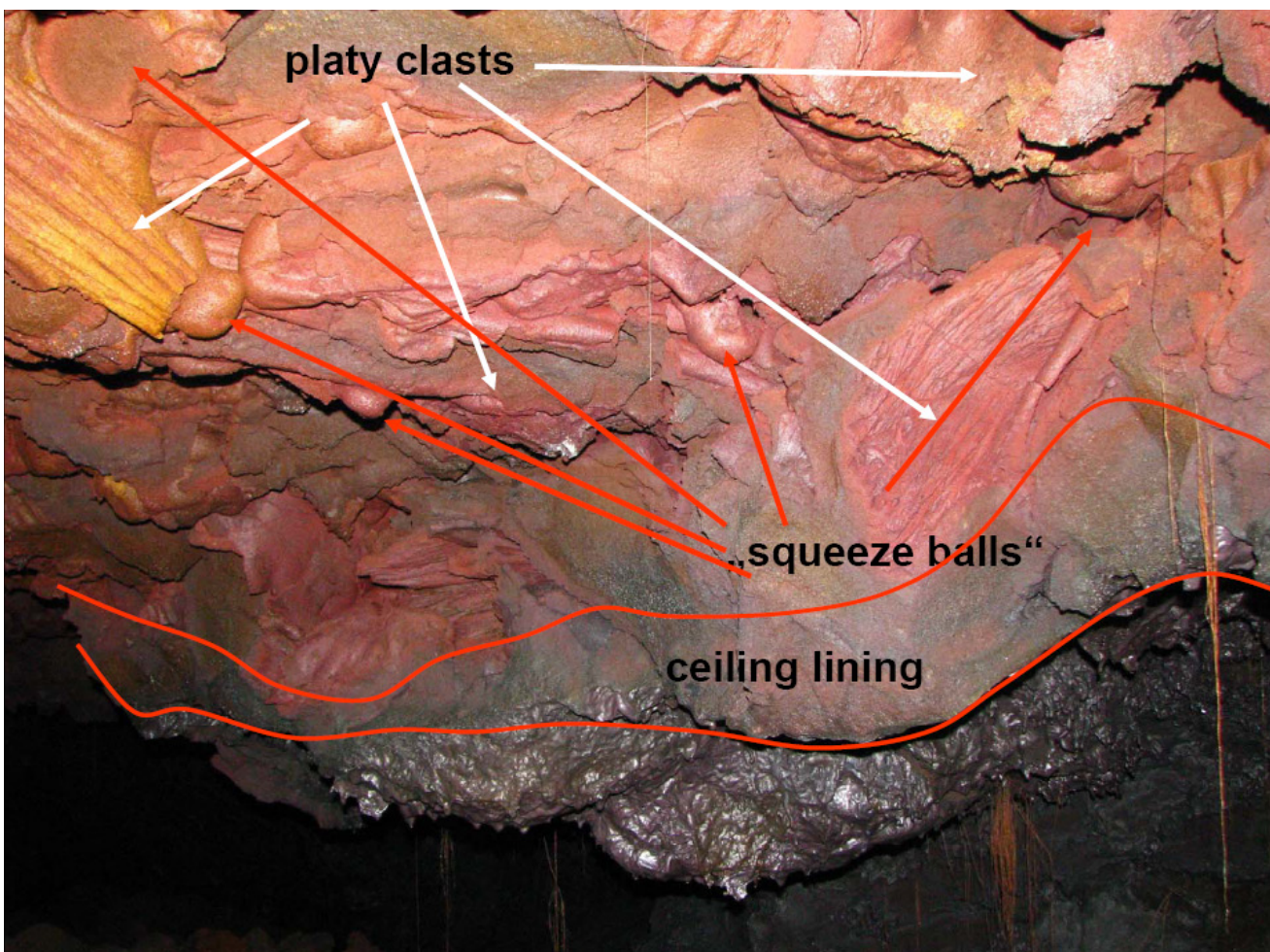
Fig. 5. Structure of a section of roof from Poha Cave, a section of Kula Kai Cavern. Individual slabs have been deposited in various orientations, some of them visibly thin pahoehoe slabs. "Squeeze-balls" were injected from below into the clasts of an agglomerated roof. The high porosity of the roof allowed air ventilation that caused recrystallization of glasses to fine-grained hematite, coloring the surfaces red. Cooling also caused the solidification of a ceiling lining.

Fig. 6. Scheme of a cross-section through a roof, formed by the crusting-over of a channel by accretion of levees.

Fig. 7. Accretionary lateral shelf growth as part of a secondary ceiling in Lost Brother Cave, Hawai'i.

sheets as roofs (Kempe *et al.* 2006).

Inspection of the Mauna Loa Kipuka Kaohina System (Kula Kai Cavern) in March 2010 by the authors on the other hand showed that it appears to have formed by the crusting-over process of the slab-jam type (Fig. 5). The syst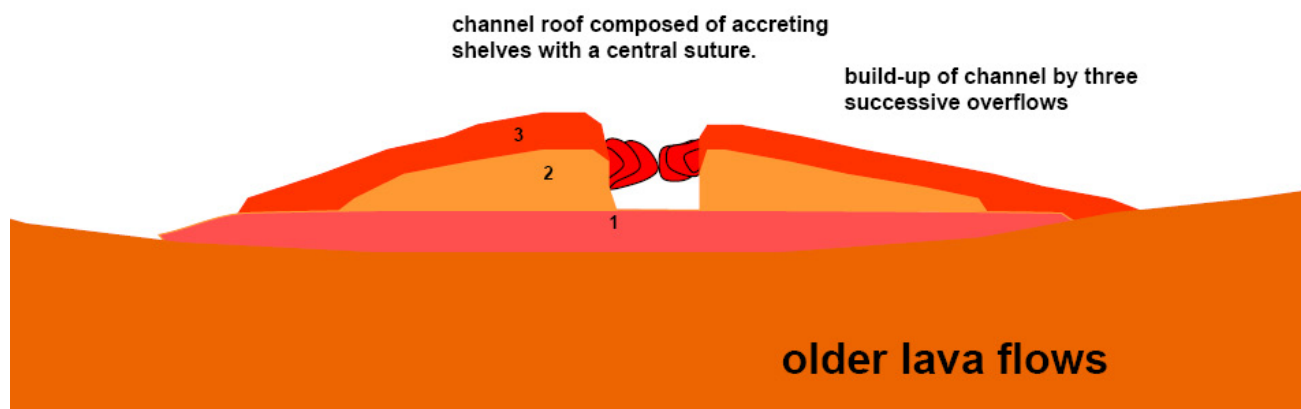em is a "multiple-trunked" pyroduct (Kempe 2009) in which passages are produced on top of each other by multiple overflows interconnected with each other also vertically. The source of these overflows seems to be a deep-seated master conduit

running NW-SE along the NW border of the system. It is itself not accessible any more. It produced a local flow ridge, that later caused the transgressing 1907 flow to split and to form two tongues on either side of this ridge. From the master conduit multiple flows issued that did not follow the direction of the master down-slope but flowed off the flank of the ridge to the SSE (Fig. 8). Lava was produced so rapidly that the lower, still active passages were buried below newer, younger ones on top. The upper passages must have been drained first and then the older, lower ones that in

Fig. 8. Detailed geological map of a section of the Kula Kai Cavern (Bienkowski 2001; Kauer 2001) overlaying cave passages (HSS). Colors mark different flows of the the same eruption event.
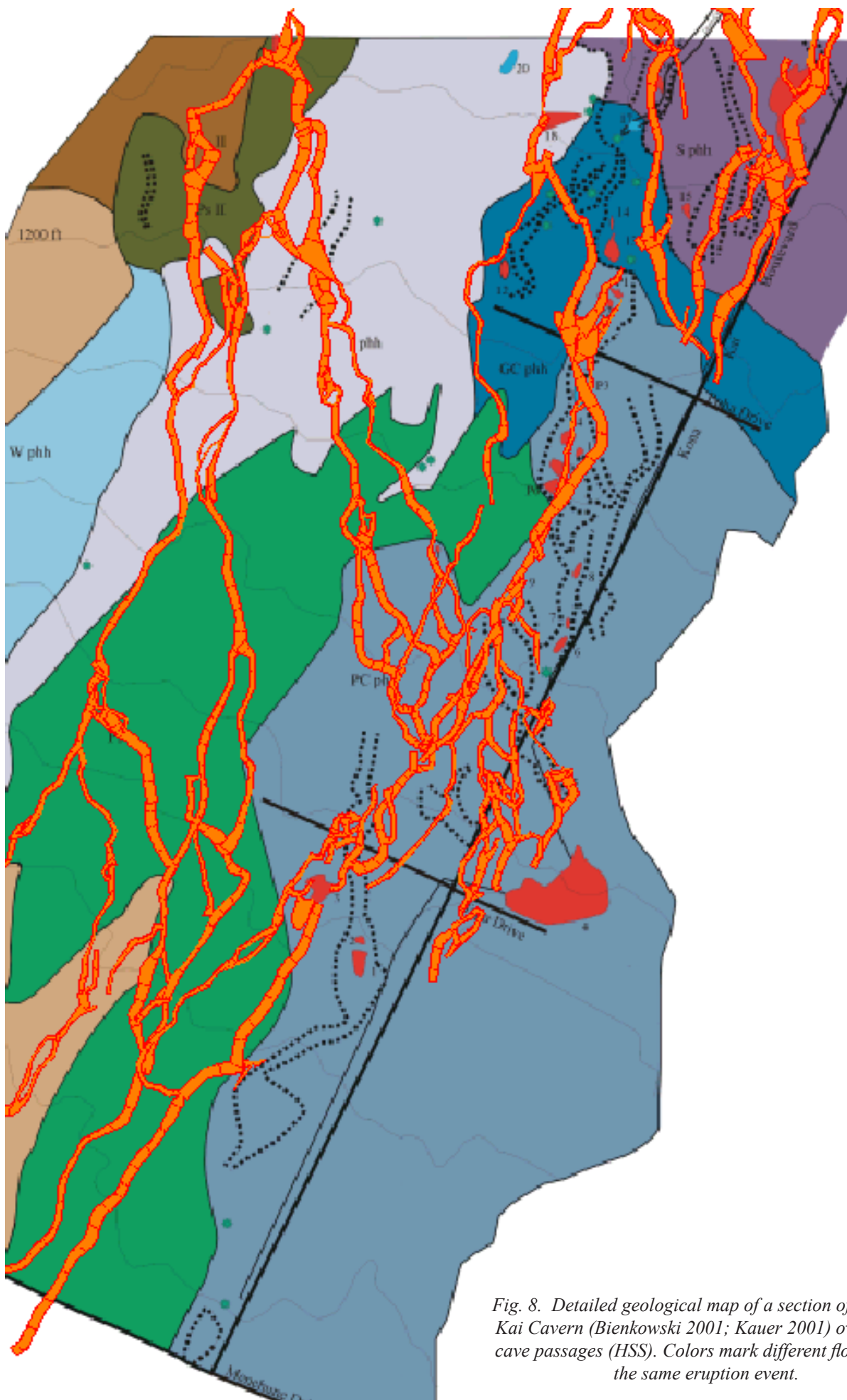
fact must have been filled up to the ceiling, in contrast to the inflation-type caves in which lava flows mostly with an open surface. Successive overflows produced more surface flows, some of them pahoehoe, others aʻa on top of the existing subterraneous maze. These flows were mapped by Michael Kauer and Robert Bienkowski in 2001 (Fig. 8) yielding a pattern not related with the conduits below due to the processes described above.

A cave with the primary roof formed by lateral growth of levees cannot be named at this time. This process is mostly seen in the formation of secondary ceilings inside the already existing pyroduct.

Certainly more detailed studies of roof structure are needed in many more caves to show what the proportions are between caves formed by inflation and by crusting-over. From the listed examples one can doubt that the majority of caves are formed by the crusting-over process, as suggested by the cited text books.

The statement of Lockwood & Hazlett (2010, p. 140-141; see above): "*On steeper slopes ... pāhoehoe flows are ... fed by well-defined channels... these channels will commonly crust over to form pyroducts. ...Where pāhoehoe flows reach more gentle terrain channel development mostly ceases and is much less important a mode of pyroduct development.*" suggesting that channel- and inflation-derived caves are caused by differences in slope, cannot be substantiated by our observations. Specifically the comparison of the Puhia Pele Channel System (Lerch 1999) with the parallel Huehue Cave (both erupted one after the other in 1801 during the last eruption of the Hualalai, Hawaiʻi; Fig. 9), developed side by side with an equal slope profile, shows that slope cannot be the governing factor differentiating between the two cave-forming processes. Alternatively, we suggest that flow rate is the important factor. The transport rate of lava through the Huehue Cave was limited by cross-sections of ca. 2 m^2 while the channel of the Puhia Pele system has a larger cross-section. Flow rate does not say anything about flow duration that may well have been much longer for the Huehue pyroduct than for the Puhia Pele channel.

4. Acknowledgments

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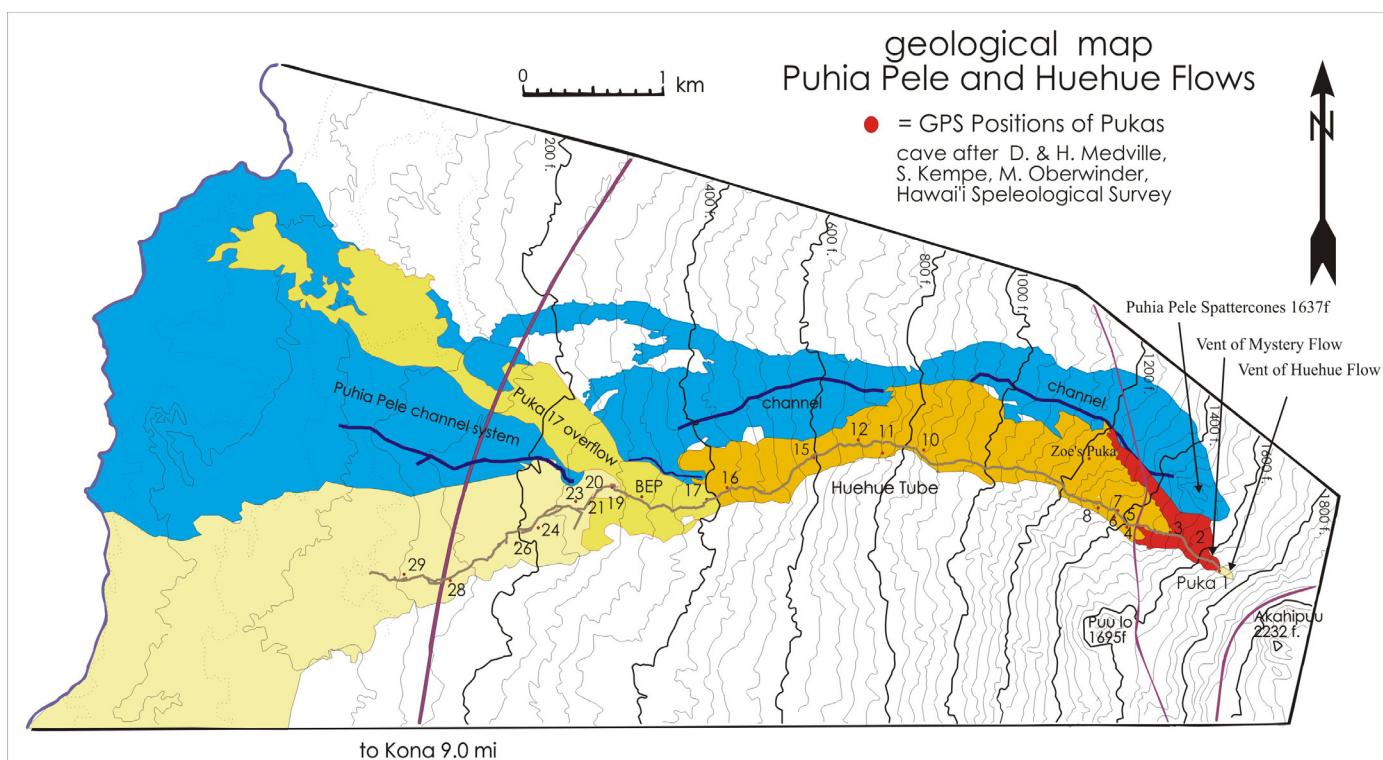
Fig. 9: Map of the flows of the 1801 eruption of the Hualalai. The Puhia Pele vent is marked by steep spatter ramparts and a km-long channel system (blue) while the lava producing the Huehue Cave (and the overlying "Mystery Lava") oozed out of the mountain side without any specific vents (Lerch, 1999; Kempe et al., 1999; Kempe 2002).

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Whitneys Cave, an Old Mauna Loa/Hawaiian Pyroduct below Pahala Ash: An Example of Upward-Enlargement by Hot Breakdown

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Abstract

Exploration and survey of Whitneys Cave has yielded astonishing insights into the processes that act to enlarge the tunnels of underground lava conduits. The current cave entrance is a cold puka (breakdown hole) situated below the Ninole Hills that represent the oldest exposed Mauna Loa lavas, possibly several hundreds of thousand of years old. The cave occurs in the slightly rolling, inclined plain below the Ninole escarpment. This plain was formed by Mauna Loa flows that came down the Ninole Hills. The plain is covered by several meters of Pahala Ash but this is not a well-defined stratigraphic unit and may represent ashes of various, albeit pre-Holocene ages. In the area of investigation it is assumed to belong to the unit "k" of the Mauna Loa Kau-Basalts, which includes the basalt of the cave. A published 14C date for a k-basalt flow near Nahalehu is 31,100 ± 900 a. This suggests that Whitneys Cave is one of the oldest yet-described caves on Mauna Loa. Another k-basalt cave is the Kamakalepo / Waipouli System. On Hawai'i only the Pa'auhau Civil Defense Cave, a pyroduct of the Hamakua Series of Mauna Kea is older.

Considering the fact that the cave does not show rapid alterations in slope, the smallest cross-sections provide "valves" regulating the maximal possible lava transport and suggesting that the larger sections of the cave could never have been filled entirely with lava. This conclusion is substantiated by the observation that the cave shows throughout its length glazed linings that are not much higher than 1 m.

In consequence, the larger halls must have been created by erosional processes, acting during the activity of the lava flow. We know of two such processes: downcutting and upward growth by breakdown. In the case of Whitneys Cave the latter process seems to have dominated. The cave must have experienced a considerable upward (and sideward) enlargement by breakdown of blocks. Roff sheets are quite thick and have generated blocks weighing tons that are now missing. Consequently, these blocks were removed through the comparatively small "valves", but without clogging the conduit. This leads to the much-debated possibility of remelting. It costs a large amount of energy to melt basaltic rocks once crystallized. In the case of Whitneys Cave however, evidence shows that the roof (both the inflation-generated primary roof and the secondary cover of surface pāhoehoe sheets) was still hot and that the blocks generated from it did not need to be heated from ambient surface temperature but could still have temperatures of above 800°C, thus saving a considerable amount of energy in the remelting process. It is interesting that the removal of the blocks must have been quite efficient, since only a few lava balls (coated fragments of breakdown) have been noticed throughout the cave.

Introduction

Post-eruptional lava flow downhill is a process that affects large areas. Yet text books do not particularly focus on this chapter of volcanism. Lava can flow across the surface in several forms, governed by viscosity. It in turn is a function of temperature, chemistry, phenocryst concentration, gas content, temperature and slope. High temperature basaltic lavas tend to flow in one of two forms: A'a and pāhoehoe (compare Lockwood, 2010). A'a flows can best be compared to glaciers, i.e. they move with almost their entire mass. At the front the rubble riding the surface is dumped and overrun, forming a bottom bed of loose or welded clasts. The whole process is reminiscent of the movement of the chains of a bulldozer. At the sides rubble is dumped as well, often forming sort of side "moraines". Pāhoehoe flows on the other hand tend

to form channels with fast running interiors or build lava conduits that hide the flowing lava from view. This "self-insulation" of the flow enables these lavas to flow down very low slopes (often <1°) and across very long distances. Thus the lava flow deposited as pāhoehoe is stationary because the lava moves only through a central conduit, depositing new lava at the distal end of the flow. Since the lava extruded there is very hot and fluid, it forms a lava delta of a thin sheet, cooling rapidly. Gas quickly exsolves and the overall rock density is diminished by vesicle formation. The next pulse of lava will therefore lift this layer up, a process called "inflation" (Hon *et al.* 1994; Kempe 2002). Thereby many sheets of lava can be deposited, with the top one being the oldest and the lowest one the youngest in the series. Once temperature in the inside of the stack remains high enough the conduit

is extended and a new series of advances and inflation is initiated. Thus a tunnel conducting molten lava is established, originally termed a pyroduct (Coan 1844; Lockwood 2010) but also known as lava tunnel or tube. This internal conduit is often active for weeks or months and can erode, thereby creating a tunnel in which the lava flows like a river in a canyon-like cave. Erosion and enlargement and the processes of lava transport inside of the pāhoehoe flows can therefore not be studied directly but vulcanospeleological studies can illustrate some of these processes that occur during the activity of the flow.

Geological situation

Exploration and survey of Whitneys Cave[1] by the authors in March 2010 yielded astonishing insights into the processes that act to enlarge the tunnels of underground lava conduits. The current cave entrance was kindly shown to us by the owner of the property, Mr. Whitney Cossman. It is situated below the Ninole Hills that represents the oldest exposed Mauna Loa lavas, possibly several hundreds of thousand of years old (e.g. Wolfe & Morris 2001) (Fig. 1). Whitneys Cave occurs in the slightly rolling, inclined plain below the Ninole escarpment, formerly used by the sugarcane industry and now replanted with Macadamia Nut trees (Fig. 2). This plain was formed by Mauna Loa flows that came down the Ninole Hills delivered by eruptions of the Mauna Loa SW-Rift in prehistoric times. The plain is covered by several meters

of Pahala Ash. However, "Pahala Ash" is not a well-defined stratigraphic unit and may represent ashes of various, albeit pre-Holocene ages (e.g., Wolfe & Morris 2001 p. 15). In the area of investigation it is assumed to belong to the unit "k" of the Mauna Loa Kau-Basalts, which includes the basalt of the cave. Lipman & Swenson (1984) published a ^{14}C date for a k-basalt flow near Nahalehu of $31,100 \pm 900$ aBP. This date suggests that Whitneys Cave belongs to one of the oldest yet-described flows on Mauna Loa. Another k-basalt cave is the Kamakalepo/Waipouli System analysed by Kempe *et al.* (2008a, b and 2009). On Hawai'i only the Pa'auhau Civil Defense Cave, a pyroduct of the Hamakua Series of Mauna Kea, is older (Kempe *et al.* 2003).

Topography of the cave

The cave entrance is a "puka" - a cold breakdown hole - puncturing the ceiling of the cave as well as the Pahala Ash that is 3 m thick here. From this puka the shorter downslope (makai) and the longer upslope (mauka) sections of the cave are accessible (Fig. 3a,b,c). The makai section was extended by a dig along one wall of the cave through ash and breakdown (St. 70-72) (Fig. 4). The ash is part of the fill of a larger puka extending from station 26 to 72 containing ash, blocks and garbage (glass bottles, china fragments). The makai passage ends at the fill of yet another puka (St. 80). The mauka section is not only much longer but also wider and higher than the makai section. In parts
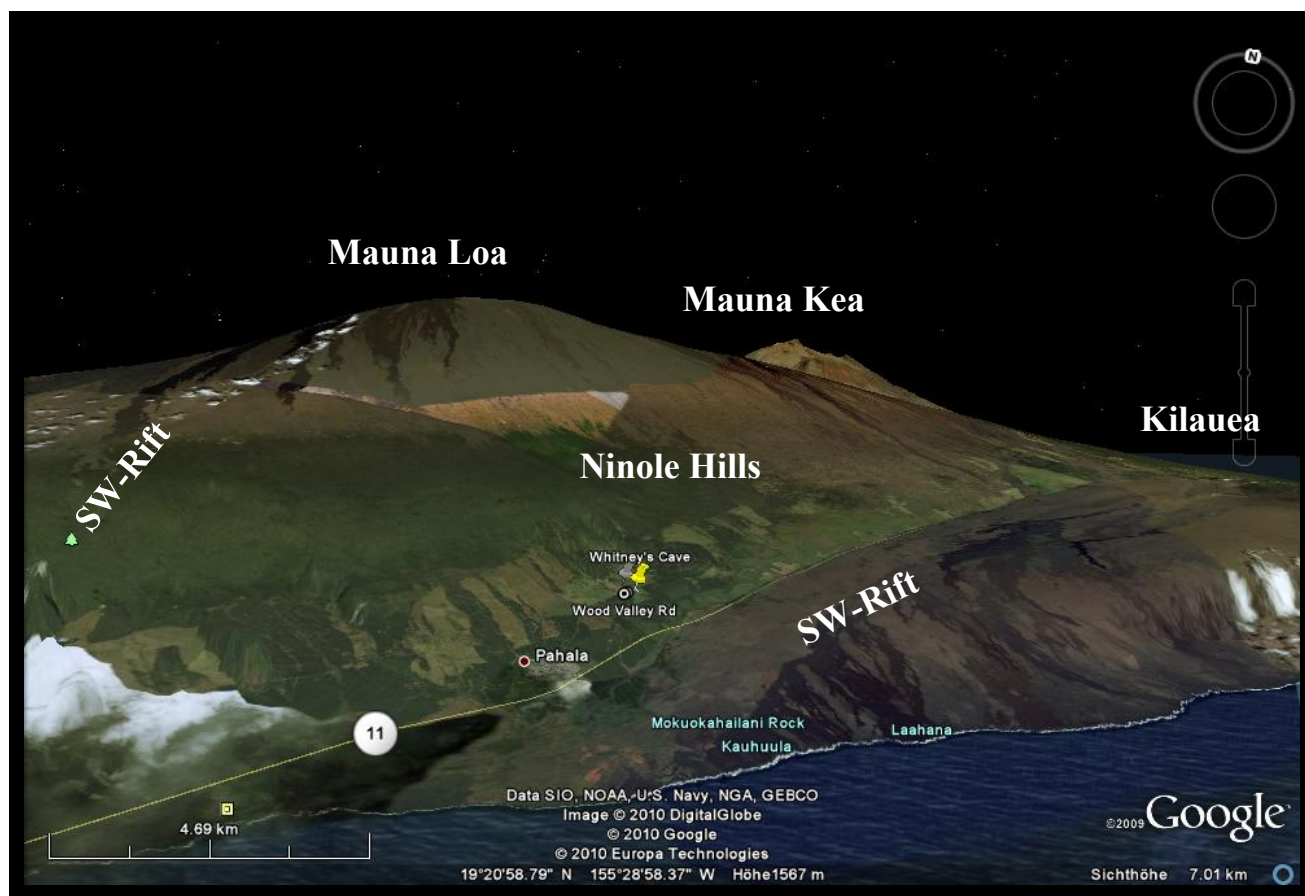
Fig. 1. General situation of Whitneys Cave on the SW Flank of Mauna Loa, Hawaii (Google Earth image).

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[1] Also dubbed Whitneys Dolphin Cave because of a dolphin-like lava ball at Station 46.
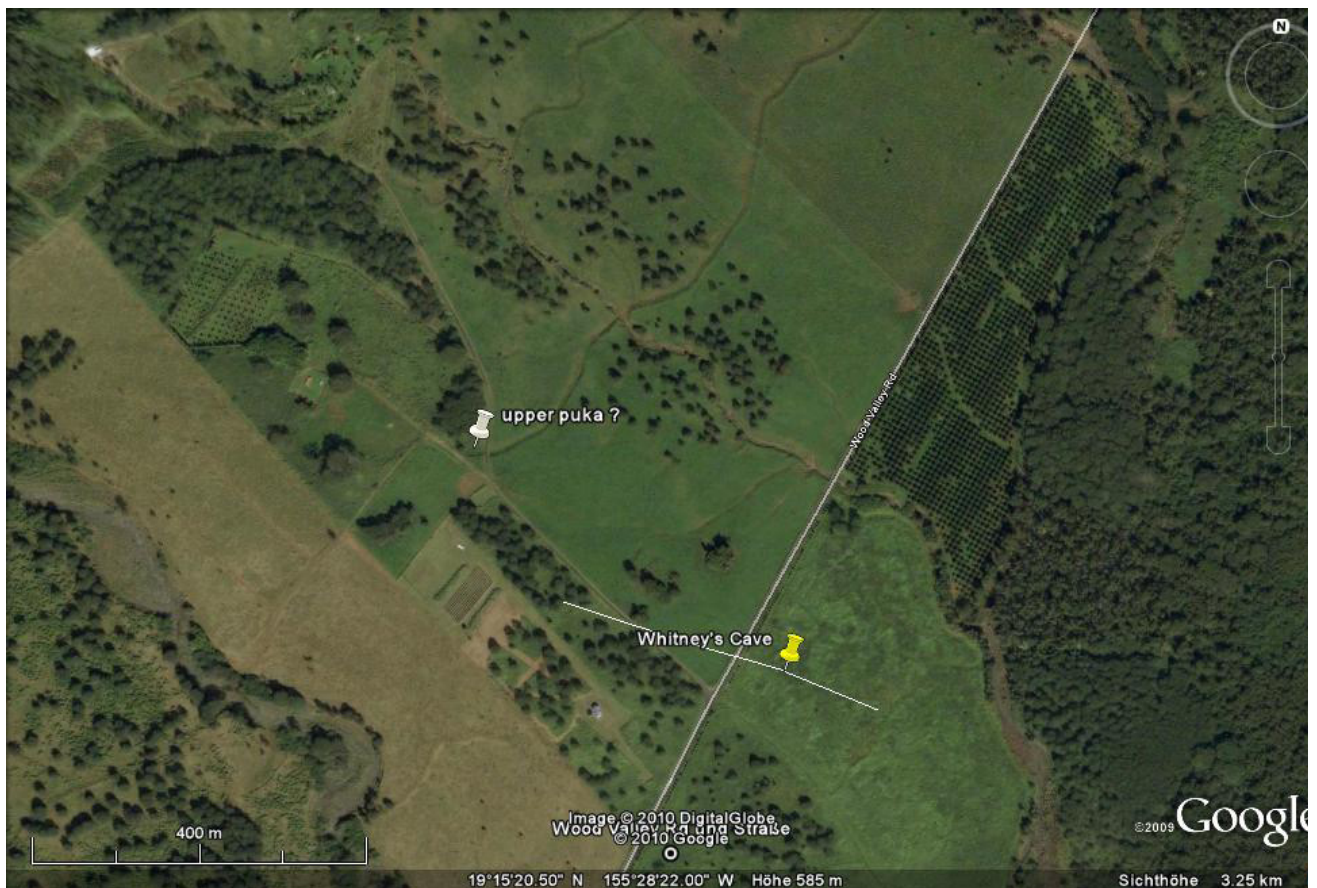
Fig. 2. Trace of Whitneys Cave below former sugar cane country. Note puka mauka of Whitneys Cave that served as a sink for water from sugar cane fields and that might mark a former upper entrance to the cave (Google Earth image).
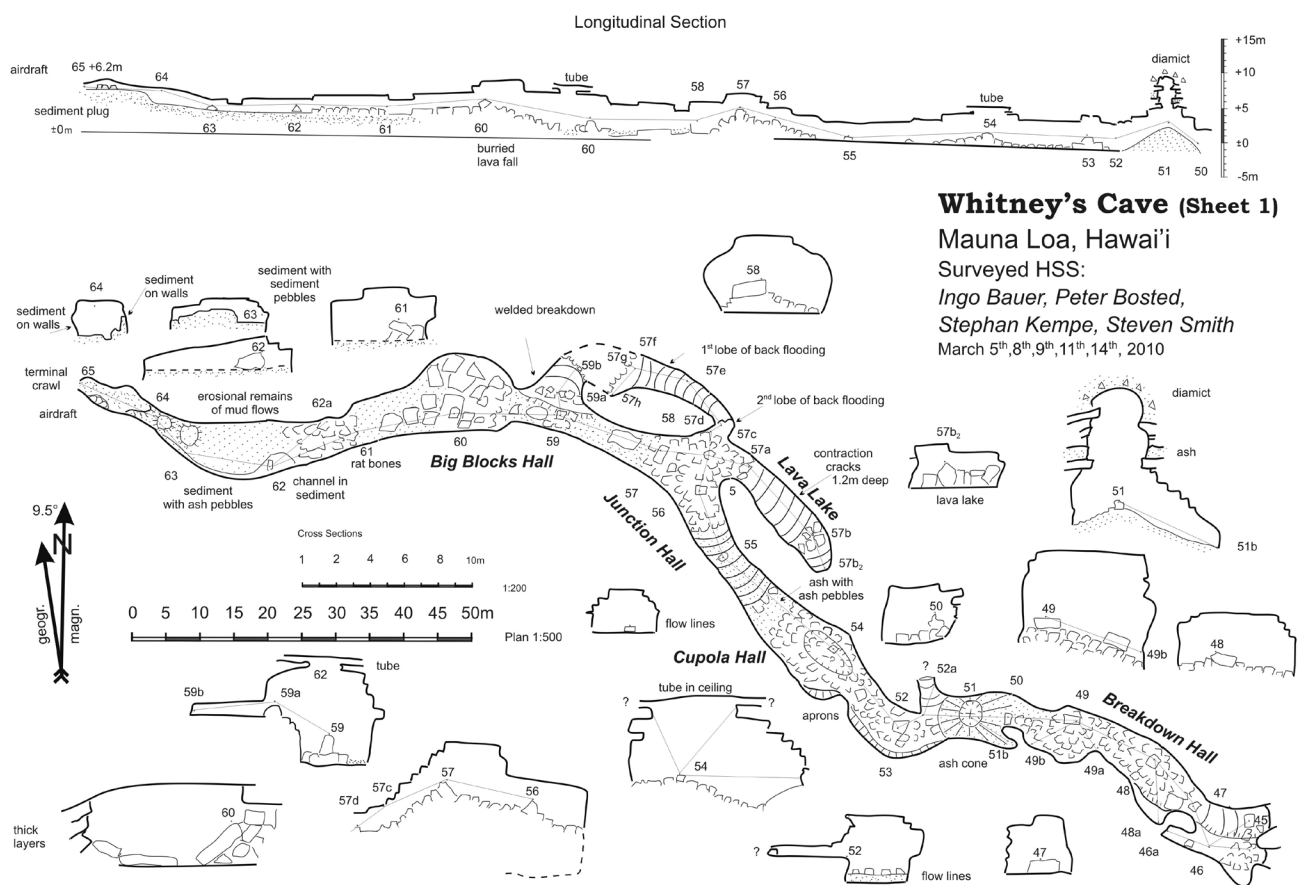
Fig. 3a. Map of Whitneys Cave with longitudinal- and cross-sections; Sheet 1.

Whitney's Cave (Sheet 2)

Mauna Loa, Hawai'i

Surveyed HSS:

Ingo Bauer, Peter Bosted,
Stephan Kempe, Steven Smith
March 5th,8th,9th,11th,14th, 2010
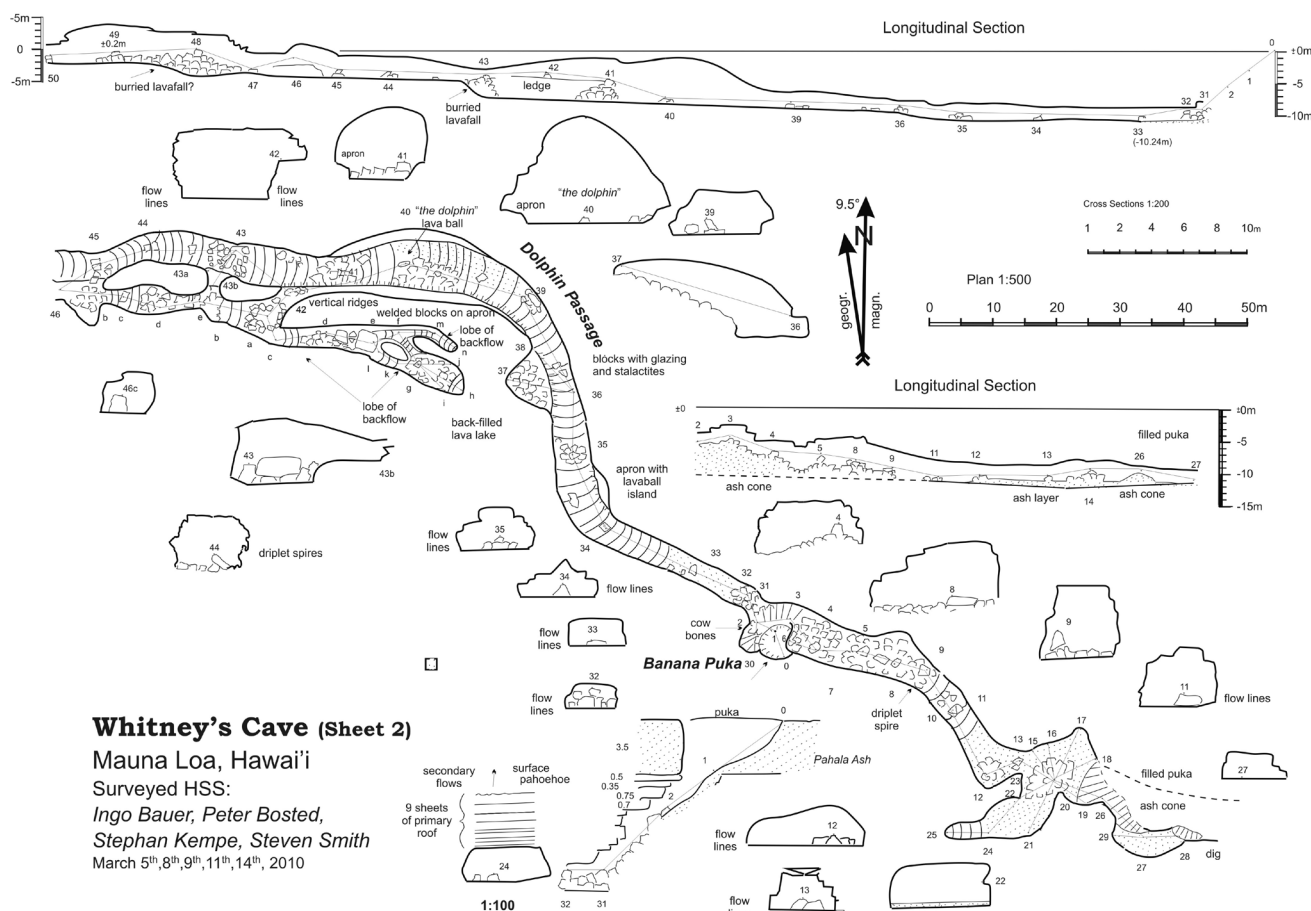
Fig. 3b. Map of Whitneys Cave, with longitudinal- and cross-sections; Sheet 2.

Whitney's Cave (Sheet 3)

Mauna Loa, Hawai'i

Surveyed HSS:

Ingo Bauer, Peter Bosted,
Stephan Kempe, Steven Smith
March 5th,8th,9th,11th,14th, 2010
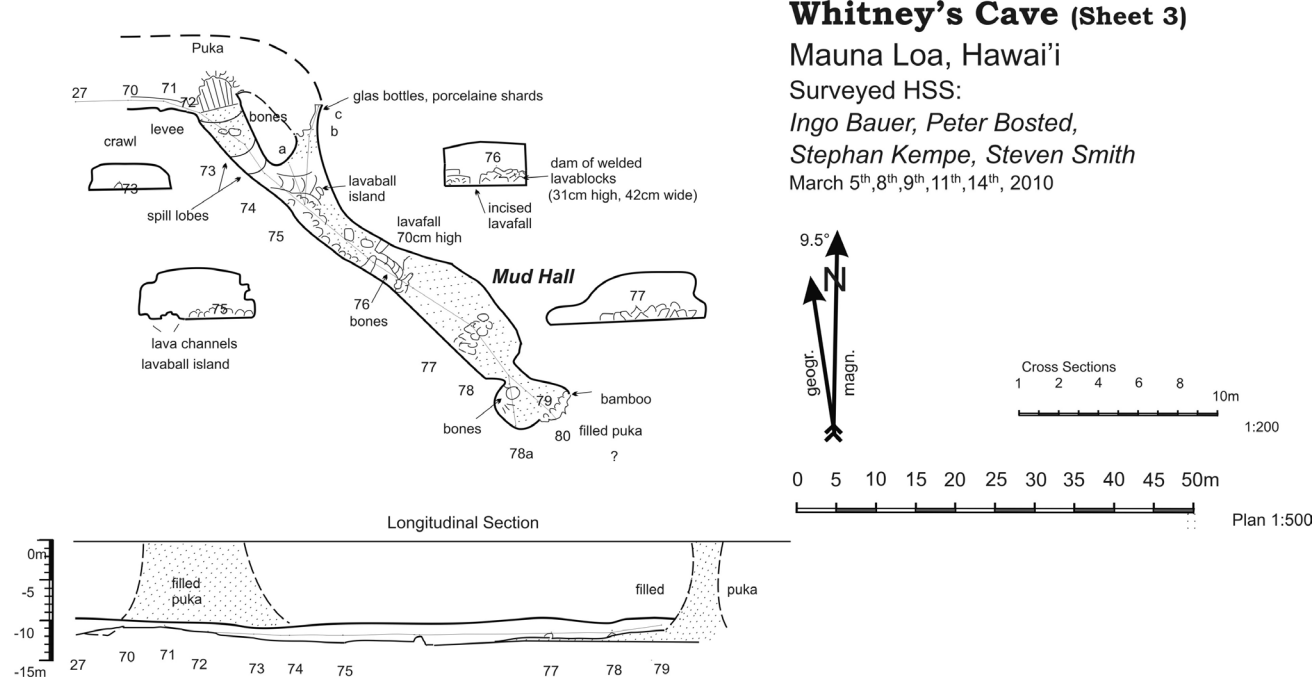
Fig. 3c. Map of Whitneys Cave, with longitudinal- and cross-sections; Sheet 3.

substantial breakdown occurred, throwing big, up to 3 m long pāhoehoe slabs to the floor of the cave (Fig. 5). Where the original floor is visible it is composed of rough pāhoehoe often sharp-edged like aʻaʻ rubble. In many parts sediment (washed-in ashes) covers the floor thinly. Towards the mauka end, these also contain rounded pebbles of consolidated dark red ash (Fig. 6)

and small fragments of rock, transported by water into the cave. The mauka end of the cave is filled with a 1.5 m thick body of sediment (Fig. 7), possibly a mud flow containing larger pebbles and lithic fragments. It is now eroded by water, washing the finer particles further downslope. Here also bushy, mauka-directed coralline (possibly calcite) mineral speleothems occur

Fig. 4. Dig along the flank of a sediment cone filling a puka to open the lower section of Whitneys Cave.

Fig. 5. Upper section of Whitneys Cave with very large (for lava caves) breakdown blocks.

Fig. 6. Rounded pebbles of an ash deposit washed into the upper end of cave (note tape case for scale)

Fig. 7. Sediment plug of the upper end of Whitneys Cave.

Fig. 8. Calcite (?) bushes at the mauka end of Whitneys Cave, indicating (former ?) airflow.

(Fig. 8). At the end a draft is felt from fractures in the pāhoehoe. The cave points towards a puka, noticed about 200 m uphill at a road fork (see Fig. 2). Into it the sugar plantation had directed its runoff from a large sugarcane field, thus explaining the encountered fill of the cave at its terminal end.

Table 1 lists the main survey results. Main trunk length (horizontal) is 502 m and total length is 643 m (which is variable depending on which sections of side passage shots are included). At Station 31 the floor of the cave is reached at 10.7 m below the surface. The deepest point is 13.5 m below the entrance at St. 76, and the highest point of the floor is at the mauka

Table 1 Main survey results (March 2010) of Whitneys Cave (magnetic declination 2010 Hawaii = 9.5° E).*

Length with side passages	real (m)	horizontal (m)	
Makai	190.22	188.88	
Mauka	461.43	454.02	
Total	651.65	642.9	
Main trunk length	real (m)	horizontal (m)	Vertical (m)
Makai St. 2-80	154.47	153.23	-5.75
Mauka St. 2-65	355.04	349.06	11.51
Total	509.51	502.29	17.26
Extension	W-E (m)	S-N (m)	"beeline" (m)
Makai	121.26	72.16	141.1
Mauka	274.06	118.02	298.39
Total	395.32	190.18	438.68
Directions	mag N.(°)	geogr. N.(°)*	
Makai	300.75	291.25	
Mauka	293.3	283.8	
Sinuosity	1.145		
Slope	1.97°		

end of the cave which is 6.21 m above the surface at the entrance. Concatenation of the entire main trunk survey line yields a vertical difference of 17.3 m (both end points are on ash fills and are similarly high above the real floor of the cave). This yields a general slope of the cave of (tan^{-1} 17.26/502.29) of 1.97°. The sinuosity calculated by dividing the main horizontal trunk length by the "beeline" (distance between the mauka and makai endpoints of the cave) yields 1.145. Both slope and sinuosity are comparable with other caves mapped on Hawaii (compare Kempe 2009, Table 1).

Table 2 lists the average heights and widths for Whitneys Cave. Heights and widths are the sums of the up and down and right and left measurements recorded at the stations along the main trunk passage. Because not all stations are in or near the centre of the passage, the height data may be smaller than the actual largest height of the passage while the width measurements are more closely representing actual widths. Also height is modified by various layers of ash fills, reducing the actual height of the passage. Nevertheless the data illustrate a substantial variation along the course of the main passage of the cave. In general the cave is much wider in the mauka section than in the makai section. It is widest at St. 60 (11.2 m) but widths of more than 10 m are also reached at stations 57 and 54. Overall the height (mean 3.22 m) shows more variation than the width (mean 5.64 m). The minimal width listed in the Table 2 is for Station 74 and is that of a side passage (main passage closed because of collapse and later filling from the surface), so that the minimal width of the main passage is found at station 64 (one station below the ash-filled mauka end = 2.8 m) and at Station 31, 32 (3.3 and 3.0 m, resp.). At these stations also the ceiling height is not very large (1.9, 2.0 and 1.5 m, resp.). Since at these stations the cross-sections are more or less square, the minimal passage cross-sections amount to 5.3, 6.6 and 4.4 m^2 (in fact these are upper values since the passages are not exactly square). In contrast to this the largest cross-sections are something in the order of 50, 40 and 30 m^2 for those stations mentioned above with the largest widths. Considering the fact that the cave does not show rapid alterations in slope (the survey lines do show considerable ups and downs, but this is mostly caused by the necessity to overcome breakdown piles) the smallest cross-sections provide "valves" regulating the maximal possible lava transport and suggesting that the larger sections of the cave could never have been filled entirely with lava. This conclusion is substantiated by the observation that the cave shows throughout its length glazed linings that are not much higher than 1 m (Fig. 9).

Table 2. Average heights and widths of Whitneys Cave, for heights Stations 51 (cupola into Pahala Ash), 26 (ash cone) and 70 and 71 (dig stations) were taken out of the calculation and for widths stations 14 (hall) 26 (ash cone) and 70 and 71 (dig stations) were left out.

Value	Height (m)	Width (m)
Max	6.75	11.17
Min	1.01	2.65
Mean	3.22	5.64
Stand. Dev.	1.46	2.12
Coef. Of Var	45.3%	37.6%

Fig. 9. Levee in the hall of station 14, showing that the lava was never standing more than about 80 cm high. The cavity above it must have been created by breakdown.

Erosion by breakdown

In consequence, the larger halls must have been created by erosional processes, acting during the activity of the lava flow. We know of two such processes: downcutting and upward growth by breakdown (e.g. Allred & Allred 1997; Kempe 1997, 2002, 2009). In the case of Whitneys Cave the latter process seems to have dominated.

The evidence comes from three lines of observations:

Downcutting is very often associated with backcutting lava falls. In Whitneys Cave only one small lava fall is visible (at Station 76; it cut through a dam of welded breakdown in the final phase of activity and has a height of only 0.4 m). There may be two more, but buried under breakdown at Station 43 and between 49 and 47. Backcutting lava falls created plunge pool

rooms that typically have a large width mauka and taper out makai. This pattern is not seen on the map of Whitneys Cave. Downward erosion also drains the side passages, leaving them high above the final floor. In Whitneys Cave the differences between the floors of the side passages and that of the main passage is small. At station 52, where a side passage joins the main passage, it is in the order of 1.2 m which is probably a good measure of how much the main passage has actually cut down. This small amount of downcutting cannot explain the generation of the large halls.

Upward enlargement on the other hand by breakdown can only become a major process if the roof of the cave is thick enough. Whitneys Cave appears to have been created by the process of inflation (Hon *et al.* 1994). During this process (Kempe 2002, 2009) a stack of pāhoehoe sheets is created, with the oldest on top (having the typical ropy surface morphology) and the younger sheets below (having shear plane contacts). This structure of the primary roof is seen at several places, best at Station 25 (Fig. 10) where the primary roof has nine layers, between 6 and 44 cm thick, and ends 2.7 m above the floor of the side passage entering
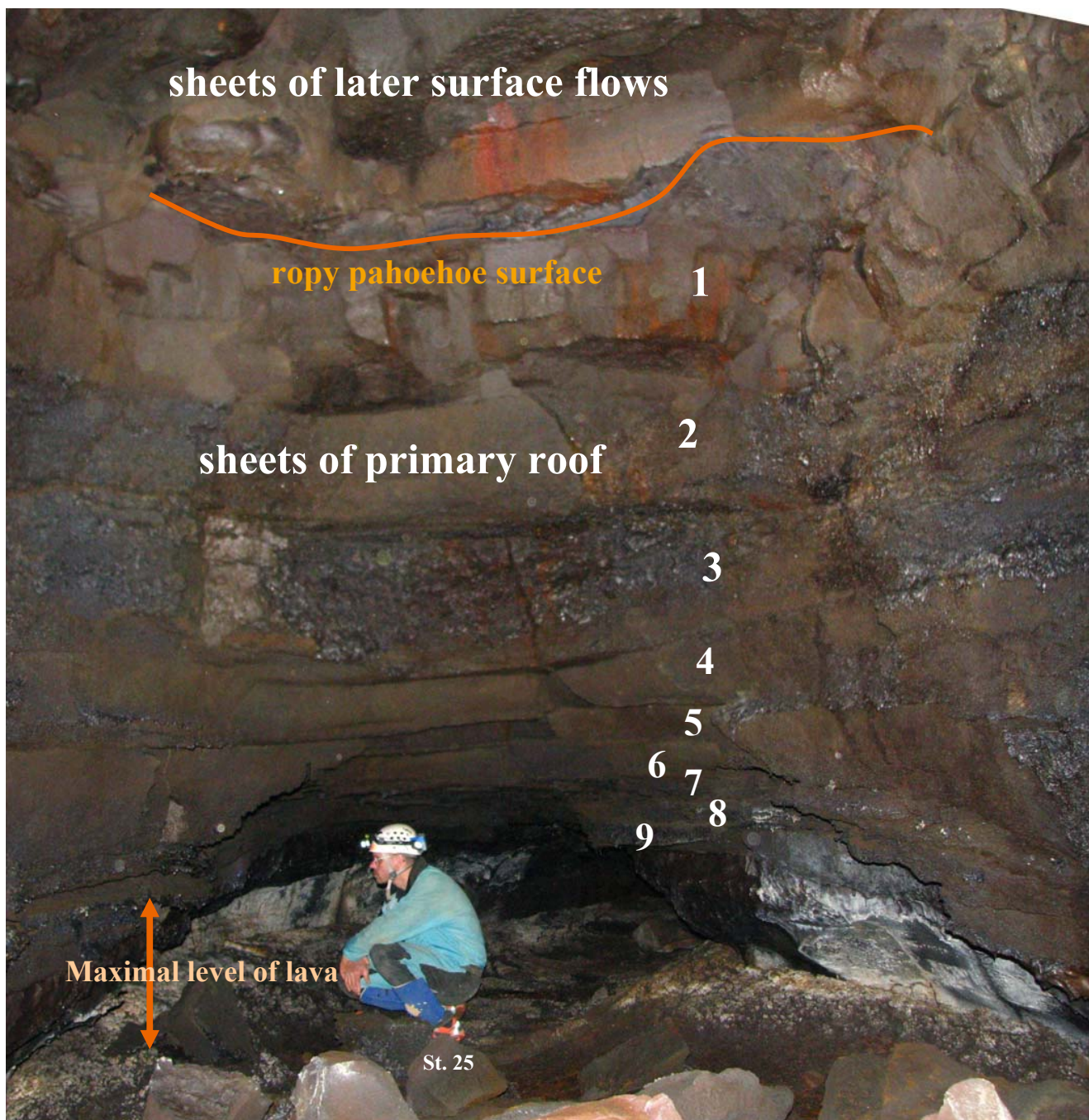
Fig. 10. *View mauka from Station 24 with the nine inflationary sheets composing the 2.7 m thick primary roof. Sheet No. 1 is the oldest, carrying pāhoehoe ropes at its surface. The layers decrease in thickness toward the bottom because the upper inflationary layers were less hot when emplaced. Layers above sheet 1 were secondarily placed there by surface flows contemporary to the conduit activity. Note the "bleeding" of lava from within the sheets of the primary roof and of the secondary sheets. Note also the reddening of the upper layers by invading air into the hot stack of lava sheets.*

at this station. Above are much thicker pāhoehoe sheets, each with a ropy surface. These must have been added secondarily on top of the primary roof as surface flows, with the youngest one on top. At stations 54, 59 and 60 these sheets have even generated small conduits, exposed in the ceiling by breakdown. Thus the roof became several meters thick. At the entrance it is about 6 m thick. At station 51 (where the roof is punctured by breakdown and the ceiling is composed of ash) the entire pāhoehoe roof is about 5 m thick (see cross section in Figure 3). Consequently the roof was thick enough to allow considerable upward enlargement of the main passage by breakdown in the observed range of passage heights.

The third evidence for the importance of enlargement of the cave upward is the observation that the pāhoehoe sheets that were added to the primary roof are in fact contemporaneous with the activity of the flow. This evidence comes from the observation that these sheets all still were extruding residual melt that oozed out of the contacts between the sheets or from beginning contraction cracks forming various patches of black glazing (Fig. 11) ending in stalactites or creating small driplet spires on the ledges of walls (Fig. 12). Also the walls, from which the blocks of the collapsed pāhoehoe sheets derived, appear to be smoothed over by heat. They did not acquire a black glazing but they certainly must have been quite hot when collapsing.

Fig. 12. *Lava stalagmite made of lava that dripped from ceiling. Note that the site where it grew is on glazing that showed the lava level during the activity of the cave. Thus the lava was still hot even after the main activity ceased.*

Conclusions

These observations together show that the cave must have experienced a considerable upward (and sideward) enlargement by breakdown of blocks from both the primary roof (which was removed entirely in many places) and from the secondary overburden of thick surface pāhoehoe sheets that were derived from the same flow event. These secondary sheets are quite thick and have generated blocks weighing tons (as seen by the blocks now littering the floor in many parts of the cave).

However, this conclusion leads to yet another question, and that is how the big breakdown blocks were removed through the comparatively small "valves" without clogging the conduit. This leads to the much-debated possibility of remelting. It costs a large amount of energy to melt basaltic rocks once crystallized. In the case of Whitneys Cave however, evidence shows that the roof (both the inflation-generated primary roof and the secondary cover of surface pāhoehoe sheets) was still hot and that the blocks generated from it did not need to be heated from ambient surface temperature but could still have had temperatures of above 800°C, thus saving a considerable amount of energy in the remelting process. It is interesting that the removal of the blocks must have been quite efficient, since only

Fig. 11. *View of the side wall of Whitneys Cave with lava oozing out of cracks.*

a few lava balls (coated fragments of breakdown like the block that looks like a dolphin) have been noticed throughout the cave.

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The Vatnshellir Project - a first for Iceland

Árni B. Stefánsson

Abstract

Vatnshellir ("Water Cave") in Snæfellsnes, Iceland, is a 205 m long lava cave/tube on three levels. The uppermost part (first level) is the "original" Vatnshellir, from where the farmers at Malarrif, a farm and a lighthouse, 3 km to the SSW, fetched water for their livestock. This part of the cave is partially collapsed, just under the surface and 35 m long.

The lower part is on two levels (floors) and in a surprisingly good condition. It is accessible through a skylight, or funnel, in the downfall basin of Vatnshellir. This part of the cave has been named Undirheimar (Underworld). The middle level (floor) is 12-20 m under the surface and about 100 m long. At the southern end of the middle level is a 12 m high vertical lavafall, leading into the 12 m deeper lowermost level. This part of the cave is about 32 m below the surface, almost horizontal and just over 70 m long. In December 2009 a platform was built over the entrance funnel leading into Undirheimar. In May 2010 an 8 m high spiral staircase was put up, leading into the 100 m long middle floor. This part of the cave was opened to the public on 15 June 2010 as "the first 20 vertical metres of the route to the centre of the earth" (alluding to the fact that Jules Verne placed the start of the journey in this vicinity in his 1864 novel, Journey to the Centre of the Earth). In October 2010 a second spiral staircase, now under construction, will provide access down to the lowermost level, to about -32 m. (Then there will be just 6,370 km to go!)

It is an interesting project; the first of its kind in Iceland. It is done with humility, wit, nature protection and service to the community in mind. The mayor of the community, a renowned architect, the head of the ruine (collapsed buildings due to earthquakes, etc) rescue school in Gufuskálar and his son, Lions, some members of the Rotary Club and the rescue squad at Hellissandur are taking part. Among other things some 28 cu metres, or 60 tons of rock, volcanic ash and soil has been hauled from a depth of 10-12 m. The Environmental Institute is financing about 1/3 of the cost, the platform over the funnel and the two spiral ladders, the rest is voluntary labour and donation. Vatnshellir is within the Snæfellsjökull National Park, the park manager and the management have wholeheartedly supported the project from the very beginning.

Four broken spatter stalagmites found in Vatnshellir have been repaired and put back. Vandalism to two of these, The Twins, was in fact the spark that lead to the development of the cave into a tourist cave. Replicas of the 37 stalagmites (now all gone) that decorated the end of Borgarhellir in Hnappadalur, when found in 1957, were put up in a sheltered corner in the north end of the middle floor, to give people a feeling of how the great caves, a world that was, once looked.

Just another cave / Is there something we can do?

Introduction

This paper was not intended to be one - not in that sense. It is more like a story. It is the latest part of a never-ending story. It came about when Greg Middleton asked me to report what I was doing. You must excuse me talking in first person, it is not that I am so self-centred, (which I am!) or that I am trying to imply I did everything myself (which I did!) – it is just easier that way. I can hardly express my gratitude for the trust I have enjoyed, and for the unselfishness and courage of a great number of people taking decisions and lending a hand, that helped making the Vatnshellir adventure come true. The Vatnshellir project is done with service to nature and that given, service to the community, in mind.

The emphasis is on wit humour and children. On the children who inherit what we adults leave behind. Some of you may not know it, but latest research has shown that no one has left this earth alive, nor has been able to take anything along.

I have been interested in caves since I can remember. I came to love these natural wonders at a very young age and have spent a great deal of my life looking for lava caves, exploring them, thinking himself into them, trying to understand how they are formed. Although not widely distributed I have been writing about them for almost 30 years and through the years contemplating more and more, how on earth to preserve them. At a very young age I learned that the great caves of Hallmundarhraun were being damaged. I listened to how they were damaged. I felt the sorrow of Stefán, who found Stefánshellir in 1918. Stefán was heartbroken because of the fate of "his" once beautiful cave. "I don't want to go there anymore", he said, "everything has been broken and damaged". By that he meant the formations.

In 1957 reports came about a new cave find in Gullborgarhraun. Some of the caves were very well decorated. "It won't take them long to be damaged", the older people said. I was only eight years old at the time. They were wrong, it did take a long time. It took fifty years to clean out all the stalagmites in Borgarhellir and the other Gullborgarhraun caves.

This exception was because Guðmundur Albertsson, a local farmer, who found the caves as a young man and Sigurður Þórarinsson, (a geologist renowned for introducing tephrochronlogy) did everything in their power, except to gate, to protect the caves. Icelandic lava caves are usually cleaned out in a much shorter time.

I have been wondering all my life why this happens to be so. I have spent a great deal of time thinking about how to open people's eyes, how to reach a consensus on what is needed, how to get public or private support and funding for the necessary intervention.

Of course we all know the cave environment is sensitive and that people damage caves. Minimal impact caving codes are intended to minimise the impact of human visits. Humans have to restrain themselves, or restraints have to be put on humans to minimise damage. As the humans are the cause, human nature has to be studied to understand damage.

There are several reasons for the damage to Icelandic lava caves:

- Open and sparsely inhabited country;

- More or less free public access to land and caves;

- Icelanders are independent, anti-authority and don't like to follow rules;

- The lava caves are vulnerable, relatively easy to access, once the location is known and for the most part horizontal;

- For the most part no special equipment or techniques are needed;

- The formations of the lava caves are almost invariably small and fragile, prone to accidental breakage, removable and/or within reach of curious or collecting hands.

I do not see damage as acceptable; never did. Once found, caves and their inventory need to be documented and classified. Access to the sensitive caves, or cave sections must be restricted and some caves must be closed to practically all traffic. To prevent damage compromises have sometimes to be made. This paper reports about ongoing damage to Stefánshellir, Víðgelmir and Vatnshellir, and tells the story about a compromise.

Stefánshellir

Stefánshellir was found (in the modern era) and explored in 1919. Fragile formations were soon severely damaged and most of the larger stalagmites more or less removed. In 1957 only a few "minors" were left, and they are now almost totally gone. The study on Stefánshellir is by no means exhaustive.

On four trips in 2008-09, I, my wife Gunnhildur, grandchildren and a few friends collected some 25-30 kg of thrash. Mostly old lighting gear, like sticks, cloth, wire, oil cans, broken bottles, flashbulbs, candles and wax. We also found newer remains like chewing gum, cigarette filters, chocolate wraps and carbide dumps.

In one 60 m section (1/25 of the total length of the cave), we counted the bases of 76 broken stalagmites. The cave roof was, according to Stefán (who found the cave), quite decorated in places with lava straws and helictites, the remnants of which can be found lying between lava ropes on the floor. Only sad remnants hang where the ceiling is at the highest, 4+ m. In the downflow section we found the bases of five, up to 60 cm wide driblet spires I vaguely remember having seen in 1963. The highest was as far as I remember, about 60 cm high. No photographs of the formations of Stefánshellir exist.

Víðgelmir history

Víðgelmir was first explored by Matthías Þórðarson, the manager of the National Museum in Iceland, in 1909. In an article in *Skírnir* (Þórðarson 1910) he describes the curious artwork of nature, asks the readers to take care not to do any damage, tells about his intention to have the cave declared a national monument and mentions if damage is done the cave should be closed. Worthy as this intention was, the cave never was declared a national monument. Between 1957 and 1963 (when I was aged 8-14) I heard people talking about increasing damage. Some said the cave should be closed but nothing was done.

In December 1972, just before an ice plug closed the cave, Mills & Wood (1972) (also in a letter to the Institute of Natural History in Iceland) recommend some sort of conservation measure be taken to preserve this unique cave. In the fall of 1991 the ice plug opened and the cave became accessible again. Shortly after the Icelandic Speleological Society gated the cave and subsequently handed the keys over to the owners, the farmers at Fljótstunga (Jónsson & Hróarsson 1991). I criticised leaving the responsibility solely with the owners who, incidentally, hardly knew the cave. At the same time I recommended that a work group be established within the ISS to help the owners take care of Víðgelmir (Stefánsson 1991). No contact was established to ensure the preservation of the cave and no consensus was reached on a work group. Access has been limited to guided parties and "responsible" groups. When we surveyed Víðgelmir in 1995/1996 I fitted several pieces of "almost fitting" fragments of broken stalagmites together and re-erected them on former bases (Stefánsson 1995).

Víðgelmir count

In December 2009, we inspected a 400-500 m section, downflow from the gate and identified the bases of 374 broken stalagmites. Almost no fragments, or remains, could be seen and not a single remaining stalagmite could be found. From this we estimated that over 1000 stalagmites must have been broken and removed from the cave.

In July 2010 we finished the count. In all, 1093 stalagmites have been broken and most of the fragments, around 90%, have been removed. Almost all large stalagmites have been removed and the few remaining are in the innermost 200 metres of the cave; the largest high on the walls. Of the 20 stalagmites I had repaired in 1995, seven had been broken again. The remnants of one had been removed.

527 stalagmites over 5 cm long are remaining in the inner half of the cave. Most of them are small, average height 12 cm, max. height about 40 cm. Average height of all stalagmites over 5 cm originally in the cave was probably a little over 20 cm.

The soda straws and helictites have been severely damaged, the accessible ones hanging from shelves, were damaged by humans before 1970. The ones out of reach, were blown away by a shock wave, created by a huge collapse in the innermost section of the cave in the early seventies.

Vatnshellir, introduction

At the 13th International Symposium on Vulcano-speleology on Jeju Island in Korea I reported about ongoing damage to four lava caves in Iceland (Stefánsson 2008; Stefánsson & Stefánsson 2008). One of these caves was Vatnshellir. Vatnshellir is one of the oldest lava caves in Iceland, 8-10,000 years old. The Twins, two 60-70 cm high stalagmites (Fig. 1) were vandalised around the turn of the century. When we found the remains of The Twins (Fig. 2) and three fragments of one of the largest stalagmites in an Icelandic lava cave (Fig. 3), in 2007, I could not keep

Fig 1. The Twins, prior to being vandalised.

Fig. 2. The broken pieces of The Twins, as found in Vatnshellir in 2007.

Fig. 3. Fragments of The Thumb, one of the largest lava stalagmites known from an Icelandic cave.

quiet and sent a report to the Environmental Institute and Environmental Ministry, with the suggestion, or demand, the cave be closed. In light of how interesting the cave is, I also suggested the cave be developed into a tourist cave. I offered to lead the job and also offered to restore and reinstall the broken stalagmites.

April 2007-January 2009

I decided to wait for things to evolve and hid the fragments of the stalagmites in the cave in April 2007. Late in 2007 the Snæfellsjökull National Park manager decided to support the idea of gating the cave and making it a tourist cave. In January 2008 a renowned architect, Hjörleifur Stefánsson, stepped aboard and agreed to design the necessary structures for free. In May 2008 a meeting was held with the park

staff and some staff members expressed their concern about human intervention. Somehow some "innocent" people tend to think human behaviour is changing for the better and in their innocence are unable to foresee the inevitable. In November I gave a Natural History Society lecture on the conservation and preservation of lava caves, based on the presentations in Korea two months earlier.

An application for an equilibrium grant in the field of tourism was turned down in February 2009.

January 2009-August 2010

In January the Environmental Institute decided to put some money into Vatnshellir. The money was limited, but the grant meant the institute accepted something needed to be done. Which was in my mind the main thing. It was clear that the job would largely have to be done on a voluntary basis and a team was needed. In March 2009 the Snæfellsjökull National Park and the Lions Club at Hellissandur invited me to give a lecture on lava caves and preservation. A little later the park manager told me that Þór Magnússon, the chairman of Lions and the householder of the Ruine Rescue School at Gufuskálar, a very able man, was interested and wanted to help. In May I was notified the allocated funds had to be spent before the end of the year. In June an application to the Pálmi in Hagkaup Nature Preservation Fund was turned down.

Fig. 5. Removal of material from the entrance pit of Vatnshellir.

There was not much use waiting. In July I surveyed the cave with my wife Gunnhildur, with an emphasis on the funnel, the entrance to the lower part of the cave (Fig. 4). Hjörleifur finished his first proposal in the
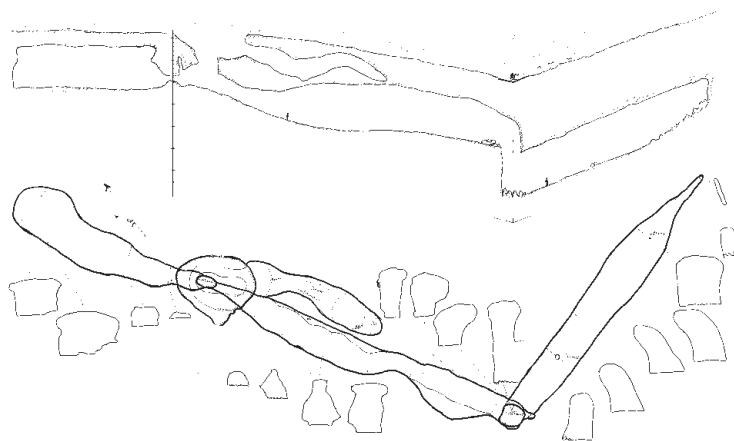

Fig. 4. The Stefánsson survey of Vatnshellir, July 2009

beginning of August. Late August we introduced our plan to the park manager, some of the park staff and most importantly, to the then uninterested mayor of Snæfellsbær, Kristinn Jónasson, who had reluctantly decided to come along. Upon entering the cave he fell for it and got kind of jolly and enthusiastic. I did not realise it at the time, but we had hit the jackpot.
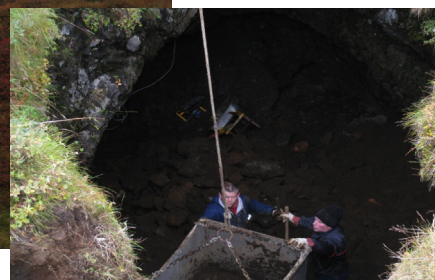
September 2009-December 2009

The plans were accepted in late September. The Lions and other community groups, with Kristinn and Þór leading, offered to help. Hjörleifur not only designed the structures, he also became an important part of the manual labour team. Svanur and Tómar, members of Lions and owners of a ground work [earth-moving] firm, were just as delighted as Hjörleifur when they were told we had no money. The team worked like an old crew from the very beginning. It had a free mind of its own, initiative and a strangely positive mentality.

According to my original plans it would be enough to remove about 3 cu meters of debris from the entrance, i.e., from the bottom of the funnel (pit) and I had intended to do it manually. The group mind decided to do it otherwise. A hauling system was constructed on a digger and landing vessel used to haul the material out (Fig. 5). In all 28 cu meters, or about 60 tons of rocks (some of them huge), ash, and debris were manually dug up, put in the landing vessel and hauled out of the entrance, from a depth of 10-12 meters.

At the beginning of November we got an extremely reasonable bid, based on goodwill, for a supporting frame and for an eight metre high spiral staircase. However reasonable the bid was, it was double the funds available. I accepted but told the firm half the cost would have to wait for our 2010 funding.

In the light of how things evolved the Environmental Institute decided to double

the 2009 allowance. Snæfellsbær [local council] decided to pay the material cost of the stairs down into the south passage. Lions and the other benevolent from Snæfellsbær built the stairs in November-December. Hjörleifur was very flexible and regularly altered his plans to suit the environment and the group mind. Late in October Þór, with two others, set up a working platform. Subsequently Hjörleifur took measurements for the supporting frame. On 21st November the carrying structure was put up and we finished pouring concrete into the moulds for the supporting pillars. During the next few days we had frost down to -10°C but the concrete held out. At the end of November-beginning of December we had northerly gale winds with a heavy snowstorm. An underpressure was created in the cave and it sucked the snow in like a vacuum cleaner. The 8 m deep entrance was filled with snow and the working platform collapsed under tons of snow. The carrying structure however held out. Two weeks later, after an intense thaw period, the group managed, just before Christmas, to cover the carrying structure with a 22 mm watertight plywood and tarred felt.

Stalagmites, Sept. 2009-May 2010

Because of the immense damage done to stalagmites and other formations in Icelandic lava caves I have often reflected on various methods of remaking stalagmites and reinstalling them into damaged caves. In September 2009 it came to my mind that I should try to make casts.

Parallel to the work in Snæfellsnes I collected The Twins and the large stalagmite, The Thumb, from the hide in Vatnshellir, got "back" formations I had known about since 1991, collected from cave looters in 1967. I also took out three stalagmites in my own possession. I found them broken in a cave in 1966 and collected them with the reflection: "I better take them before someone else does".

Late September I had two rather expensive silicone moulds made from two of the stalagmites I found in 1966 and subsequently experimented with casting materials and colours. By December I had found suitable materials and colour composition. Then I set out to reconstruct the 37 stalagmites that decorated the end of Borgarhellir in Hnappadalur when found in 1957 (Stefánsson 2008; Stefánsson & Stefánsson 2008). To be able to do that I repaired the over two dozen, for the most part broken and fragmented stalagmites retained in 1967, with epoxy glues mixed with powder colours. Subsequently I made moulds of seven of these. At the end of January I had managed to produce around 70 stalagmites, 39 of which were intended for Borgarhellir (Figs 6a, 6b). Reflecting on the "treatment" of Víðgelmir, inspected a month

Fig. 6a. Some original (repaired) lava stalagmites, left, and Fig. 6b, some of the replicas made from them, right.

before, I changed my mind. Rather than put them up in Borgarhellir, I decided to put them up in a secluded corner in Vatnshellir.

In February I reconstructed The Twins from the collected fragments as well as I could, with the help of enlargements of a photograph I had taken in 1996 (Fig. 7).

The Twins and the 37 replicas were set up in Vatnshellir in May. The three fragments of The Thumb were too heavy for removal from the cave and were repaired in situ. The pieces were drilled through, the bottom one with a 60 cm long, 18 mm drill and all three with

Fig. 7. The (reconstructed) Twins (cf. Fig. 2.)

a 80 cm long, 14 mm drill. A 50 cm long galvanized 16 mm iron rod was used to fasten the bottom piece to the ground and two 100 cm 12 mm rust-free rods were used to fasten the pieces together. A two component Hilti epoxy glue was used to fasten the rods and fit the pieces together.

January 2010-June 2010

In January we applied for a generous grant from the Icelandic Tourist Board. We were pretty sure we would get it, but in March we were turned down. Apart from the entrance pit being almost totally filled with snow, (Fig. 8) this was the best thing that could have happened. The task was now even more impossible than when we started. Impossibilities are just challenges. The prerequisite is to be stupid enough not to realise the impossibility.

Fig. 8. The entrance depression partially filled with snow and the working platform destroyed — a minor setback.

In late February I managed, with Þórs help, to finish the survey Gunnhildur and I had begun the summer before. While we were surveying the deep part of the cave, it so impressed us that we decided not to sleep or rest until we had secured the finance for a second spiral staircase, leading down there. Subsequently, early March, I managed to finish a three dimensional map with Snæfellsjökull in the background.

The map was intended to be the basis of an information sign. The map, the argument "the group has done such a good job, it deserves some more", the fact the Tourist Board had turned us down, the fact Þór offered to lead setting up the spiral staircase and Kristin's support, lead the Environmental Institute in late March to take the

gallant decision to finance the second spiral staircase. Having the financial situation in Iceland at this time in mind, this was by no means natural, or self evident.

In late March the work group in Snæfellsbær launched an attack on the snow in the pit and managed to dig 5 m down, through snow and timber and free the plinth of the spiral staircase. In late April the team spirit changed its mind about the stairs into the downfall. Instead of wooden stairs they made rock stairs from large 20-30 cm thick pieces from lava in the vicinity. A very large rock 2m x 1.5m x 0.6 m, misplaced in the downfall, got the name 'stubborn', as it was being manually put in place. The attack on the snow in March enabled us to put the spiral ladder down on 13th May. The blacksmiths at Stálprýði gave their work and the 200 km transport. Late May-beginning of June Hjörleifur and Sæmundur finished the platform (Fig. 9) while I finished "downstairs".

Fig. 9. Work on the platform advances and the cover over the spiral staircase is in place.

On 15th June 2010 the Preservation Plan for the Snæfellsjökull National Park was signed in the entrance of Vatnshellir (Fig. 10) and the cave was formally opened to the public.

Fig. 10. The Minister for Environment signs the preservation agreement for Snæfellsjökull National Park at the official opening of the cave.

Rough compilation of the voluntary work

(Minimal numbers)

Work	966 hrs
Driving	198 hrs
Driving	10,950 km
Towing truck and digger	53 hrs
Transport truck	46 hrs
Tractor digger	26 hrs
Motorsaw	16 hrs
Generator	130 hrs
Various electrical tools	xyz hrs

N.B. Architectural work, work by ÁBS April 2007-September 2009, stalagmite repair and administrative work are not included.

Postscript, Late October 2010

During the first summer over 1000 guests have visited Vatnshellir. Entrance fee for adults was about US $9 and free for children. Trips were run two days a week except one week in August when the cave was open every day. People had to book in advance. Most who did so were able to enjoy the cave, which, according to the park staff everybody did. Icelanders are not especially prone to planning their holidays in advance. Therefore some were quite disappointed. The summer of 2009 was regarded as a test summer. The cave and the park staff more or less passed the test. Next summer more staff will be needed.

The second spiral staircase, 12 m high, was set up during the first two weekends in October 2010. The entrance bridge to the spiral staircase was then under construction. In the middle of October it was decided to change the wooden exit stairs because of the creosote smell. New stairs made of galvanised steel are under construction and will be put up in the beginning of 2011.

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Vatnshellir map, May 2010 - with Snæfellsjökull ('Snow Mountain') behind —
where Jules Verne located his entrance for the "Journey to the Centre of the Earth".
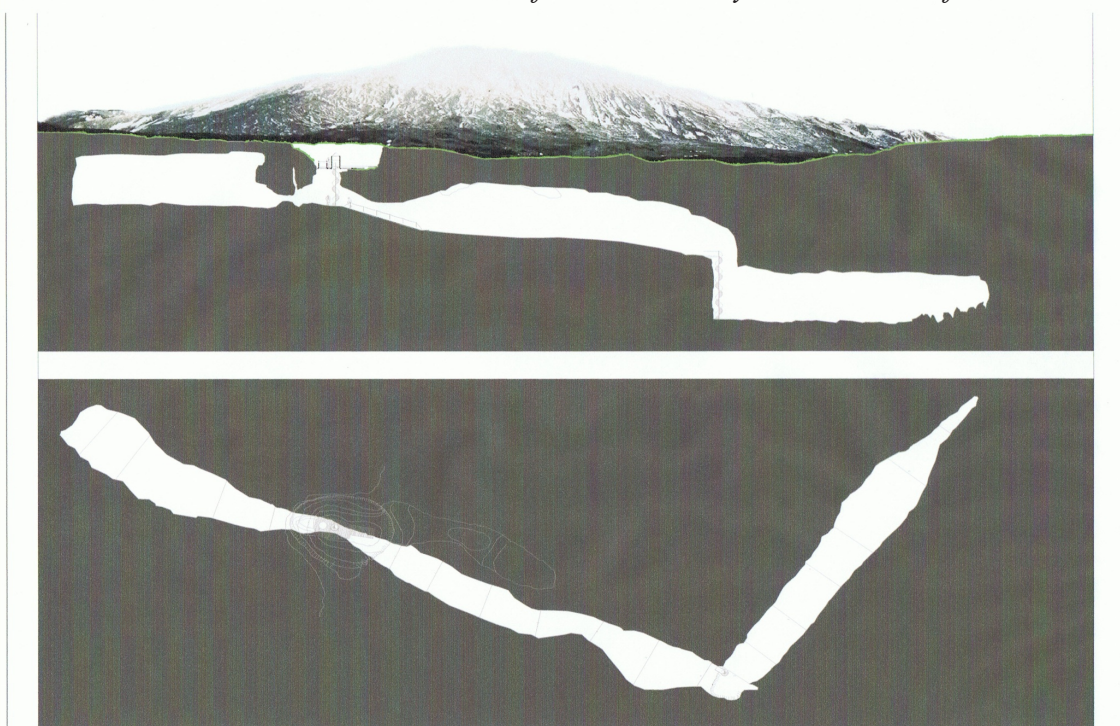
Volcanic Centres and Lava Caves in China

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Abstract

There are many active volcanic centres in China that occur in contrasting geotectonic zones and some of these are known to possess basaltic lava flows and lava tube caves. The volcanoes in the east of the country, which are products of the collision of the Indian and Eurasian tectonic plates, are little explored, and it is regarded that their magma chemistry may not be suitable for the formation of cavernous lavas. In contrast the volcanic centres in the northeast and south of China have erupted large volumes of basalts in which lava caves are known to occur. Nevertheless, accessible information on these cave areas is limited and so this paper makes a first attempt to record the presence of lava caves in three locations: the volcanic fields of Wudalianchi and Jingpo Hu in Heilongjiang province, northeast China, and the Leiqiong volcanic field in Guangdong and Hainan provinces, south China. The caves presently known to occur in these volcanic fields have not been mapped and are relatively short (up to 500m), nor have these lava fields been systematically explored for caves. Adding interest is speculation that a long lava tube cave may exist at Jingpo Hu, while the Leiqiong field may eventually reveal substantial cave networks. Beyond these three sites, there are other basaltic volcanic fields that in the future may reveal significant cave finds.

Introduction

Few people are aware that there are volcanoes in China, while in fact there are many, located across this vast country in contrasting geotectonic environments. Furthermore, it is known that in a number of these areas basaltic volcanism has emplaced extensive lava flow fields, some of which contain evidence of lava caves. This paper briefly locates China's principal volcanic centres and describes three areas which are known to contain lava caves. The paper is not definitive because the volcanic geomorphology of many of the Chinese volcanic centres has not been described, and if it has, publication has been in the Chinese language and in relatively inaccessible local publications. In addition, while there has been extensive exploration by Chinese and international speleologists of caves in China's outstanding karstic terrains, virtually no exploration of potentially cavernous lavas has taken place. There is therefore a good potential for prospecting for lava caves and their subsequent mapping will aid a better understanding the emplacement history of these lava fields.

China's volcanoes

Figure 1 shows the distribution of the fifteen volcanic centres in China that have been active in the Holocene (i.e., the last 10,000 years), based on evidence from the Smithsonian Institution's Global Volcanism Programme (http://www.volcano.si.edu) and papers by Liu (1999) and Liu (2000), These volcanic centres occur in contrasting tectonic environments and therefore display a wide variety of magma chemistry, not always effusing lavas capable of tube-fed flow. Practically all of the centres possess multiple historic eruptive vents, many numbering tens of vents, with associated lava flows.

Complex ocean/ocean - ocean/continental plate subduction: The only active subduction zone in China is at Taiwan. Eight Holocene volcanoes have been recorded here, to the north, west (Penglu Islands) and south. The volcanoes consist mainly of andesitic submarine and terrestrial stratovolcanoes and domes. While there are some basaltic lava flows, the writers are not aware of any caves being reported (although there will be many sea caves).

Continent-continent plate collision: Collision between the Indian and Eurasian continental plates caused deep subduction of the Indian plate beneath the Tibetan plateau, producing extensive volcano clusters in the Xinjiang (Tianshan and Turfan volcano groups), Tibet (Kunlun volcano group) and Yunnan (Tenchong volcano group) provinces. These volcanic areas are extensive and usually have erupted a mixture of basalts, andesites and trachy-andesites, not generally known for producing caves.

Back-arc volcanisms (i.e., volcanism occurring behind plate subduction zones, on the Eurasian
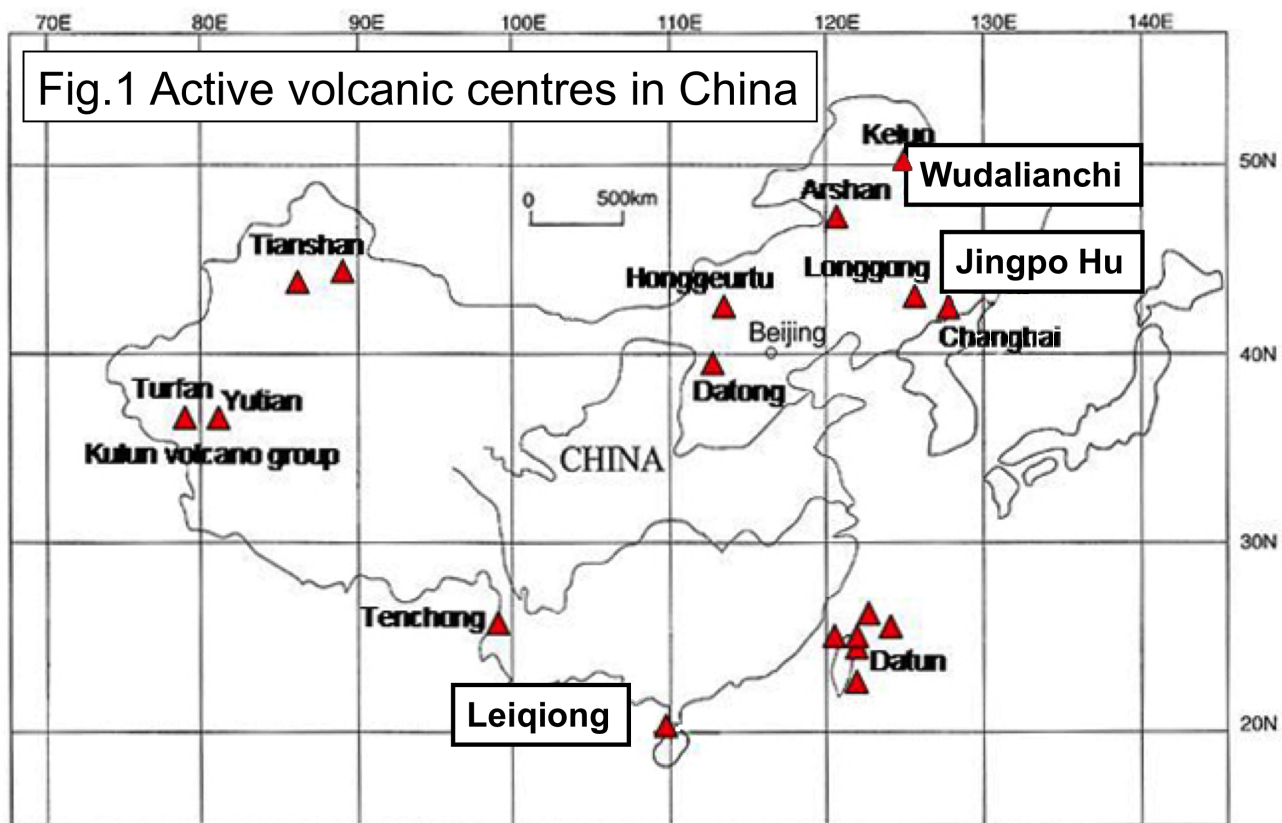
Fig.1 Active volcanic centres in China

Fig. 1. Distribution of the fifteen volcanic centres in China that have been active in the Holocene. Lava caves are known to exist in the Wudalianchi and Jingpo Hu volcanic fields in northern China's Heilongjiang province, and in the Leiqiong volcanic field in Guangdong and Hainan provinces.

tectonic plate): back-arc volcanism in China occurs in the near back-arc (back-arc basin) and far back-arc (intra-continental) environments.

Near back-arc or back-arc basin: one of China's largest volcano clusters, known as the Leiqiong volcanic field, occurs on the Leizhou peninsula, Guangdong province, and Hainan Island, in the South China Sea. Over 100 vents have erupted copious amounts of potentially cave-forming basalt in the Pleistocene and Holocene.

Far back-arc or intra-continental: volcano groups in central and northern China all lie a considerable distance (1000-2000 km) behind the Pacific plate/Eurasian plate subduction zone. With the exception of Changbai, which is a large Holocene stratovolcano, all of these sites are monogenetic volcanic fields that erupted large amounts of K-rich basalt. Lava tube caves have been found in some of these fields and they all hold the potential for new cave finds.

To date, and to the knowledge of the present authors, lava caves are known to exist in the Wudalianchi and Jingpo Hu volcanic fields in northern China's Heilongjiang province, and in the Leiqiong volcanic field in Guangdong and Hainan provinces. There may be reference to other volcanic cave sites in the popular literature, but because of language translation problems, the diversity of locations, and immense scale of the task, a full literature search has not been undertaken, and so this paper will describe the three sites of which the authors have some personal knowledge.

Caves at Wudalianchi National Park and Global Geopark

Wudalianchi (literally 'five connected lakes' - Figure 2) is a monogenetic volcanic field located in northern Heilongjiang Province, 251 km south of Heihe City and the China/Russia border marked by the Heilong or Amur River. It consists of 25 volcanic vents, all being small lava shields, with 14 surmounted by pyroclastic cones. It is believed the volcanic field formed in seven phases in the last 2.1 million years, the last eruptions being of the volcanoes Loaheishan and Huoshoashan in 1720-21, although there was a small additional eruption of Laoheishan in 1776. The Wudalianchi activity has consistently erupted K-rich basaltic magma (a variety of phonolite) which because of its unusual chemical properties has been given the local name Shilongite. This eruption effused large amounts of lava, building an extensive plateau (known locally as the Shilongite plateau) of about 60 km² in extent, and blocking the N-S flowing Shilong River in four places to form the string of five lakes.
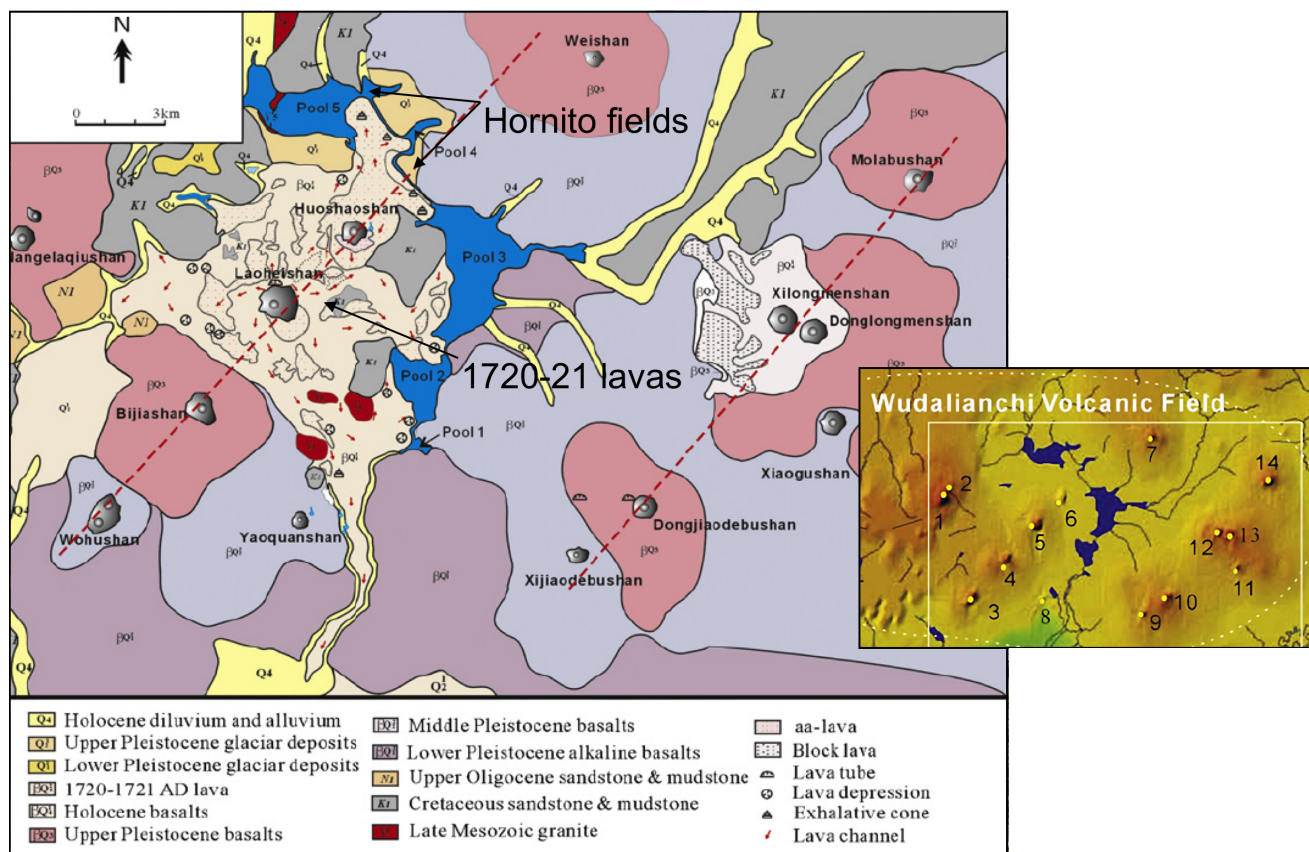
Fig. 2. Geological map of the Wudalianchi volcanic field (after Xiao & Wang 2008)

There are four lava caves so far known at Wudalianchi, all being lava tube caves. Fairy Palace Cave and Waterfall Palace Cave are both found in the new (1720-21) lavas close to the base of the Laoheishan crater, while Ice Cave and Underground Ice River Cave are located in the much older lava (dated about 0.70-0.88 Ma) erupted from the East Jiaodebushan volcano.

Laoheishan volcano

Fairy Maidan Palace Cave: This cave is approx. 225.5 m in length and is located on the lava plateau about 1000 m north of the Loaheishan cone. It was formed in the lava fan that had developed at the north-west outflow from the crater and its entrance is at the end of a boardwalk trail from the visitor car park at the base of the cone wall. The entrance occurs in a collapse pit. Inside, just beyond the entrance, the cave branches into two sub-parallel passages, lying 15-30 m apart, with the east branch being about 5 m lower than the more easterly one. A connecting passage with sub-branches occurs between a point 93.5 m down the west branch and 69 m down the east branch.

The western branch is about 103.5 m long, trends generally 330°N, and has a slope of 2-5°. This branch is 3-6 m wide, rising to a maximum width of 7.8 m, and 1.5-4 m high, rising to a maximum of 6 m. About 36 m in from the entrance there is a small hole in the roof, allowing daylight into the cave. The east

passage is about 106 m long, and initially has a width of 3-4 m, and a height of 1 -12 m, although about 32 m in the width changes to 5 m and height 3-5 m. This passage divides with one branch connecting to the west passage and the other to the surface through a small portal. The sub-branch connecting to the east passage makes the connection via a circular pit, about 3.5 m deep, represented by a hole in the roof of the western branch, The cave has minimal breakdown and a clinkery floor, in winter covered by sheet ice. Lava sags and drapes and conical stalactites decorate the roof and walls.

Waterfall Palace Cave: This is a short cave with a steep gradient (28°) located at the base of the NW slope of Loaheishan cone. Its length is 26 m and the passage is 3.8-4.5 m wide, and 1.5-2.5 m high.

East Jiaodebushan volcano

Underground Ice Cave: This cave has a total length of 515 m, and may be the longest lava cave so far known in China (accurate mapping of caves at Jingpo Hu or Hainan Island may prove that some may be longer). The lava is dated as 0.512 Ma. The entrance of the cave is 1.4-1.8 m wide and 6-7 m high, although the ceiling becomes higher inside the cave. There is a hall 206 m beyond the entrance with a width of 26.8 m, broken by two rock pillars, each c.3.2 m high and a diameter of 4.5 m. In the main part of the cave sheet ice about a metre thick covers the floor, which has a

general gradient of 2-5 degrees. There are stalactites on the roof and small amounts of breakdown. This is a very cold cave with a temperature between 0-5°C.

Ice Cave: This cave is more than 150 m long and has a vertical range of 23 m. The entrance is 0.6 m in height and 1 m wide. An initial steep slope becomes one of about 12 degrees inside the cave. 25 m from the entrance is a hall 8 m high and 12.4 m wide. The walls are covered by ice crystals, and decorated with lava drapes and stalactites.

Driblet cones

One of the very special features of the newer lavas at Wudalianchi is the large number of driblet cones and driblet dishes (also known as hornitos). In total there are 1537 of these features, all well-formed and quite large, and together they form an outstanding example of volcanic geomorphology. The site is comparable with the hornito fields of Jorullo Volcano, Mexico (Siebe *et al.* 2009) or those of the Aðaldalshraun, NE Iceland (note the paper by Gadanyi 2008), presented at the 13th International Symposium on Vulcanospeleology). Some hornitos have hollow centres and can be descended for several metres to a basal chamber. It is considered the hornitos formed where the mobile lava flow advanced across wet ground during the period when the lava-dammed lakes were being created.

Caves at Jingpo Hu National Park and Global Geopark

The Jingpo Hu (Jingpo Lake) protected area (Figure 3) is located in the upper-middle reaches of the Mudanjiang River, in southeast Heilongjiang Province. It is 110 kilometres south from Mudanjiang City. The park covers an area of 1400 km². The first author was drawn to investigate this area because Chinese geologists and some tourist websites had stated that there was a long lava tube cave that was over 35 km in length. It now seems to be unlikely that a single cave of this length exists, although there is at least one long lava flow in the area that has a string of cave segments down its length and the original feeder lava tube from which these caves formed may well have had a length in excess of 50 km.

The Jingpo Hu volcanic field is Pliocene-Holocene in age and the scenic Jingpo Hu ("Mirror Lake"), which is a major

tourist attraction, was formed when lava flows blocked the Mudan River (Mudanjiang). The location of many volcanic vents was influenced by the important NE-striking Dunhua-Mishan fault. A large number of volcanoes and basaltic lava flows are distributed in and around the lake, while many Holocene trachybasaltic or basanitic cones and lava flows lie atop plateaus along the Mudan River. In total the lavas cover an area of approximately 500 km². The youngest cluster of vents comprises of 13 impressive craters, located in remote mountains, at about 800-1000 m above sea level, in the north-west corner of the park. Lava flows that effused from the youngest craters travelled in a south-easterly direction down a tributary valley of the Mudanjiang, the lava eventually blocking the Mudanjiang where it entered the main valley, about 60 km from the vent. This event created the beautiful Jingpo Hu lake and a most impressive waterfall, known as Diaosuilou. The most recent lavas from the craters have been dated by radiocarbon method and given ages of 3430-3490 BP and 2470 BP.

Four of the recent volcanic vents possess large and impressive craters, accessible to the general public. They lie in an area known as the Crater National Forest Park, which is also known as the "Underground Forest" because of the lush primeval forest that flourishes in the craters. The largest crater lies at an elevation of 1070 m and is nearly 500 m in diameter and 132 m deep. Two of the craters are connected by a short cave through which it is possible to walk from the interior of one crater to another.
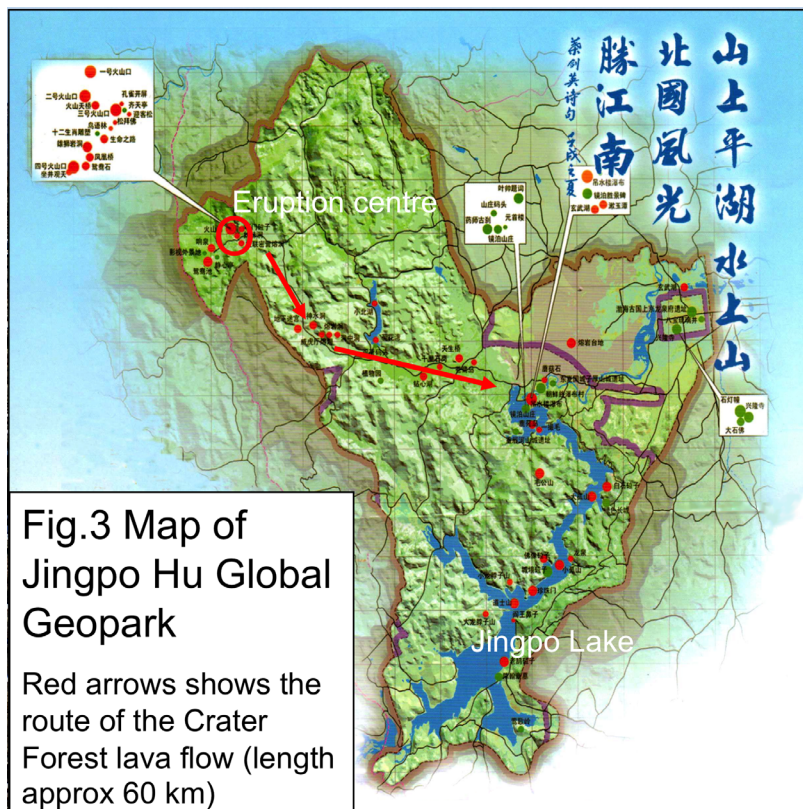

Fig.3 Map of Jingpo Hu Global Geopark

Red arrows shows the route of the Crater Forest lava flow (length approx 60 km)

Fig. 3. Map of Jingpo Hu Global Geopark

The important lava caves lie as a series, aligned down the narrow, valley-confined lava flow that extends from the craters to the lake. These caves are mostly accessible from the forest park highway, which is the route used by the buses taking tourists to the craters. The caves are presumably segments of an axial lava tube system that probably formed along the whole length of the narrow lava flow, but while some caves have been explored and mapped, the complete series of caves and the spatial relationships between them are not known. Several of the caves have been developed to receive tourists.

The caves currently recorded in the crater forest lava field are described below. These descriptions are shortened versions of ones that appear in a web publication by the park authority (http://www.jingpohu.com.cn/dizhi/Eshow.asp?id=117), and while cave lengths are not given, one cave (Longyandongtian) of at least 500 m in length has been briefly investigated by the authors.

Weihuting Cave: This cave can be found 100 m north of the 5.2 km point from the entrance gate to the crater forest park highway. The cave entrance is 7 m wide and 1.7 m high, although the passage height increases to 2.0 m farther into the cave. The ceiling is densely packed with conical lava stalactites. The wall surface is smooth and there are layers of protruding glaze. The floor is patterned pahoehoe. There are also floor driblets of different sizes. It is a spacious cavern, like a large hall.

Longyandongtian Cave (Dragon Rock Cave): Access to this cave lies about 9.2 km up-flow from the entrance gate to the crater forest park highway. There are 10 collapse entrances in this area, the largest and best-formed providing access to the most complete lava cave segment. Progress along the passage is easy, past colourful walls and beneath a ceiling of stalactites, with lateral benches and as many as three shelves protruding from either wall. The floor is pahoehoe, with impressive floor patterns.

Shenshui Cave (Driven Water Cave): The entrance to this cave lies 200 m southeast of Longyandongtian and it divides the cave into two parts. The northern passage is 1.8 m wide, 1.7 m high and more than 50 m long. The southern one is 2.0 m wide, 1.8 m high. The two passages have the same structure and character, with an arched form. The surface of the walls and ceiling is a grey purple-sorrel glaze, with densely distributed small conical lava stalactites (1 to 2 cm). The surface of the wall is smooth and the lava has sagged and dripped forming layers of protruding glaze. In the northern cavern, clean and drinkable water collects all year round and is the reason the local people have called it Shenshui Cavern.

Gubingdong Cave (Ancient Ice Cave): Access to this cave lies about 15 km up-flow from the entrance gate of the crater forest park highway. There are 3 collapse pits overlying a cave that branches in two, the northern branch being known as Gubingdong. This cave has a passage diameter of about 8 m. In summer surface water seeps into the cave through ceiling cracks and runs to the low-lying places in the cave, where it freezes in winter. The ice remains frozen through the summer.

Jiemei Cave (Sisters Cave): Access to this cave lies 13.3 km from the gate of the crater forest park highway. This is two lava caves, separated by a small collapse pit. The northern cave is 3 m wide and 2 m high and the southern one is 7 m wide and 4 m high. They have the same structure and character. Each has an arched ceiling and the surface of the walls is a smooth glaze. The ceiling displays abundant short conical lava stalactites, the largest being about 4 cm long.

Kanlianmiying Cave (Anti-J Allied Army Secret Camp): The entrance to this cave lies 19 km up the crater forest park highway. During the anti-Japanese period, anti-J soldiers were positioned here, and remains of their encampment are still present in the cave. The cave therefore has great historical significance.
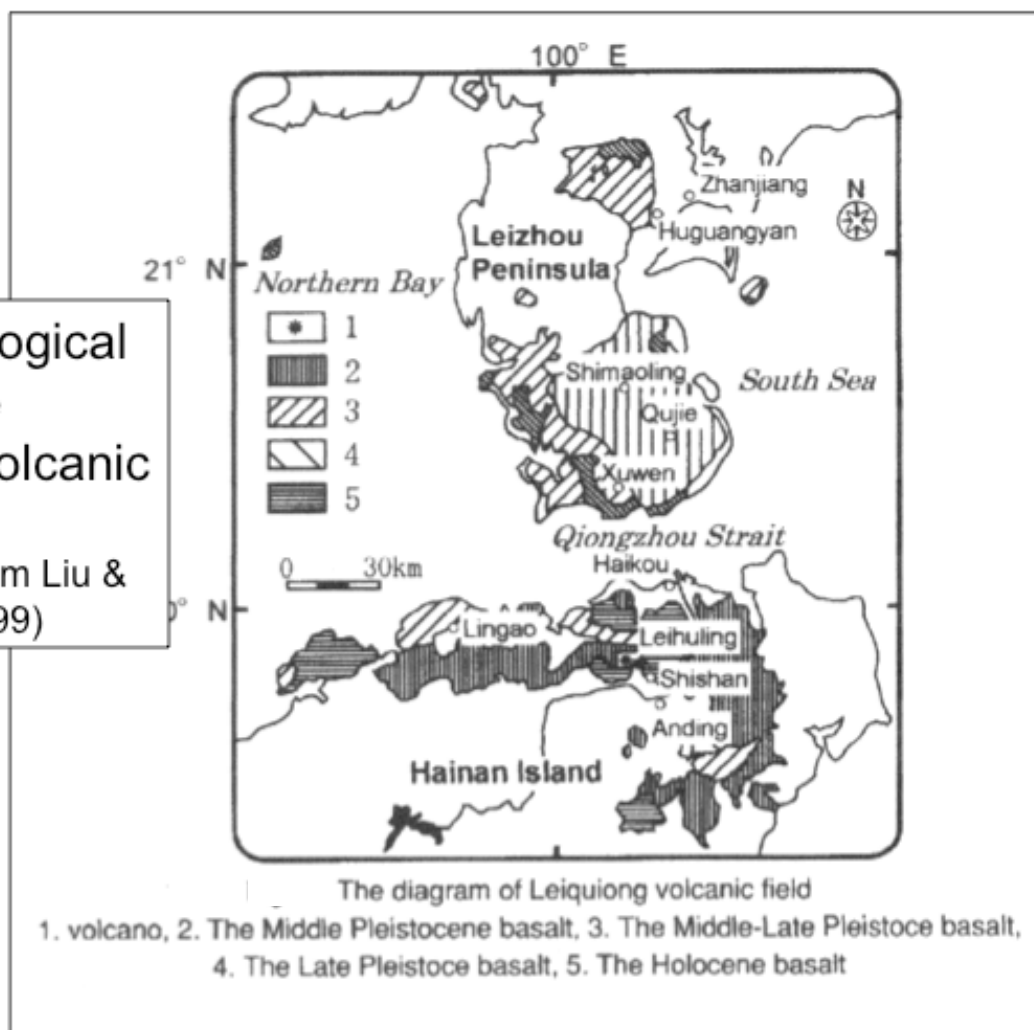
There remains great potential for further discovery, exploration and mapping of lava tube caves at Jingpo Hu, particularly in the long crater forest park lava flow. While the flow is covered with dense mixed broadleaved and conifer forest, aerial or satellite photography of the flow taken in winter when the leaves have dropped from the trees may reveal many more collapse entrances and their relationships one to another along the length of the flow. The rumoured 30+ km lava tube cave still remains to be found.

Caves at Leiqiong Global Geopark

The Leiqiong volcanic area is a 7300 km² basalt-basanite plateau (Fig. 4), which extends across the Leizhou Peninsula, Guangzhou Province, and the northern part of Hainan Island, either side of the Qiongzhou Strait, in south-east China. The whole area was designated a volcanic Global Geopark in 2006. The area belongs to the so-called Leiqiong Rift Volcanic Belt, and is the largest area of exposed basalt in southern China. Volcanic activity may have commenced in the Oligocene, but was most extensive during the Pleistocene, declining in the Holocene. Early volcanism produced flood type fissure eruptions of quartz tholeiites and olivine tholeiites, while later phases were dominated by central type eruptions of alkaline olivine basalts and olivine tholeiites.

Fig.4 Geological map of the Leiqiong volcanic field
Abstracted from Liu & Taniguchi (1999)

The diagram of Leiqiong volcanic field
1. volcano, 2. The Middle Pleistocene basalt, 3. The Middle-Late Pleistoce basalt,
4. The Late Pleistoce basalt, 5. The Holocene basalt

The volcanism was influenced by N-S crustal extension related to the opening of the South China Sea Basin, and the area is considered to be a back-arc basin. Much of the volcanism consists of Pleistocene-Holocene volcanic cones, forming an extensive monogenetic volcanic field with an estimated 177 small volcanoes, although Yingfengling and Tianyang are two Pleistocene stratovolcanoes. The youngest cones are Ma'anshan and Leihuling, and members of 30 or more cones in the Shishan and Yongxing regions of Hainan. The latest eruptions occurred in northern Hainan in 1883 and 1933.

There are abundant basaltic lava flows, but the literature makes no reference to caves, except those that have been opened for tourists in the Hainan or Qiongbei Volcano Geopark (that part of the Leiqiong geopark lying in the northern part of Hainan Island - confusingly this area of Hainan has also been called Haikou Crater Cluster Geopark and Haikou-Shishan Volcanic Group Geopark). The Haikou-Shishan district is said by tourist literature to have "more than 40 volcanic cones and 30 volcanic caves." Some of the caves can be explored by tourists in Shishan Park. The Lonely Planet Guide notes that here "the Seventy Two Cave Lava Tunnel ... is said to be hundreds of meters long, 20 m wide and 15 m high."

The Leiqiong volcanic field, both on the Leizhou Peninsula and northern Hainan Island, is undoubtedly a place that will reveal many more lava caves in the future, both through a careful search of local knowledge and more scientifically-based physical exploration.

Prospects for the future

China's volcanoes hold great promise of some major lava cave discoveries in the future. Apart from Wudalianchi, whose lava fields are quite well investigated, many of the other volcanic fields hold the possibilities of new cave discoveries. Lava flows at Jingpo Hu and in the Leiqiong volcanic fields must be a priority for investigation. At Jingpo Hu a thorough scientific investigation of the 60 km long crater forest lava flow may reveal more and possibly longer caves and if these are systematically mapped and plotted on a map of the flow field, they may reveal a substantial amount about the form of the original master feeder tube system. A necessary start to look for caves on the Leizhou Peninsula and the northern part of Hainan Island will be to record all known cave locations from literature sources and local knowledge, which can then be followed-up by physical exploration.

There are other volcanic fields in China that may hold the promise of lava caves. High on the list must be Long'gang in Jilin Province, NE China, which has 160 volcanic cones scattered over 2000 km², with extensive alkali basalt lava flows. Other possibilities are the recently discovered Arshan volcanic field in Inner Mongolia, which contains 40 volcanic cones, with long Holocene lava flows that blocked the Halahale River, and the Honggeertu volcanic field, which contains 12 cones and lava flows of Holocene age. Little is known about the volcanic fields of Tibet and Xinjiang, but a cavernous lava found here might well hold one of the highest lava caves in the world.

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Lava Cave Investigations, Anjouan, Comoro Islands, April 2009

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Abstract

Investigations were undertaken on the island of Anjouan, Union of Comores, Indian Ocean, with a view to finding and documenting lava caves and any palaeontological material they might contain. Some small sea caves were noted, but only two true lava tube caves were located. Due to the age of the lavas and the development of deep soils, few lava tube caves probably remain. No palaeontological material was located. Some lava tube caves were revisited on the island of Grande Comore but palaeontological prospects were rated low due to unfavourable conditions for preservation of vertebrate material.   A brief visit to the island of Mayotte located only one large sea cave.

Background

Greg Middleton commenced speleological investigations in the Comoro Islands - at the suggestion of Dr Bill Halliday - in 1997 (Middleton 1998a, 1998b). Further investigations on Grande Comore were undertaken in 1998) resulting in the documentation of 27 caves with lengths up to 810 metres), together with an unsuccessful visit to the island of Moheli, but the island of Anjouan could not be visited due to the outbreak of a civil war (Middleton 1999, 2005).

An opportunity to return to investigate caves on Anjouan did not arise until 2009 when hostilities were apparently over and relative normality was restored to the civil administration of the islands. Even a few weeks before we were to go to Anjouan, however, public protests broke out due to fuel shortages. Continuing civil unrest in neighbouring Madagascar made it impossible to transit through that country as was originally planned.

Originally there was to be a team of four, but in the end only the present authors undertook the trip. We were fortunate to have a British contact on Anjouan, Hugh Doulton, who was working with the environmental NGO Action Comores, provided us with reports on conditions on the island and arranged vital contacts for us.

The islands

Geographically, the Comoro Archipelago comprises four main volcanic islands: Grande Comore (Ngazidja, 1025 sq.km.), Anjouan (Ndzuani, 424 sq.km.), Mohéli (Mwali, 211 sq.km.) and Mayotte (Maore, 374 sq.km) (Fig. 1). Politically the first three make up the Union of the Comoros, while Mayotte remains a French overseas territory – but it is about to become the 101st 'department' of France.
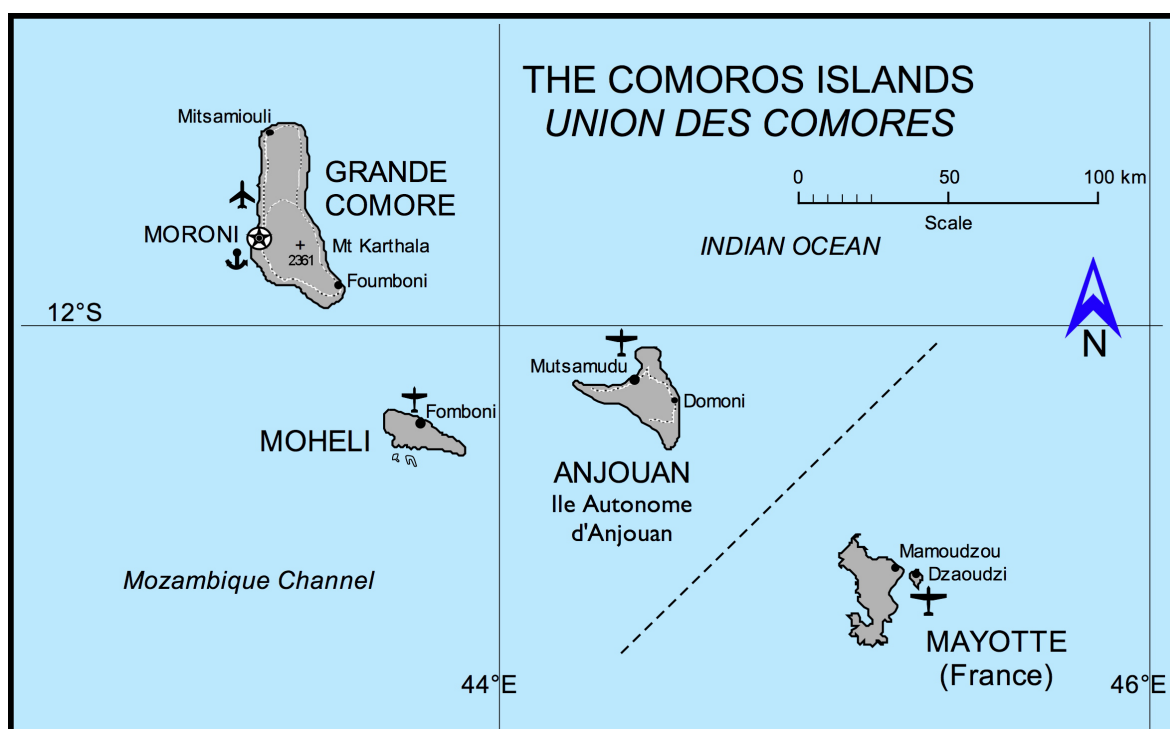

Fig. 1. Map of the Comores Archipelego

Mayotte is the oldest of the islands, followed by Moheli, Anjouan and Grande Comore which still has an active volcano, Mt Kathala (2360 m), said to have one of the largest craters in the world.

Getting there

Getting to the Comoro Islands is never an easy undertaking – and getting around them, even more uncertain. Having decided to avoid politically unstable Madagascar, our alternate route involved transit through the French department of Réunion and the French overseas territory (soon to be a department) of Mayotte. We flew to Moroni, the capital (on grande Comore) 17 April. Our first price surprise was the new tourist visa issued by Comores – €60 each, payable in Euro on arrival.

We visited the Centre National de Recherche Scientifique (CNDRS) to see if we could get a permit to "look for caves" should that be necessary. Despite our best efforts we were unable to get such a permit and – given the new relative autonomy of Anjouan – it may not have done us much good anyway.

On 18 April we flew with "Aviation Comores International" to Anjouan. At 09:45, with some relief, we touched down at Ouani airport. From there it is a short taxi ride to the capital, Mutsamudu.

Action Comores

At noon we visited the Action Comores office in the hills above the capital and met Hugh Doulton for the first time. He explained that the organisation is involved in comprehensive studies and monitoring of the biodiversity of Anjouan, with particular emphasis on the endangered Livingston's fruit bat, *Pteropus livingstonii*. Hugh's function is to organise community aspects of the program which involves education and modification of agricultural practices to minimise impacts on biodiversity.

He introduced us to the staff of Action Comores, including Nassnuri Toilibou and Halidi Ahmed. They set up a meeting so we could discuss our plans with guides who know the island, and had been asked in advance to get together any information they could on caves. Communication was not easy as our French is pathetic and only a couple of them had any English. It transpired that they knew of perhaps only five caves between them. A plan was agreed to visit these over the next three days. Then came the important issue of costs; we were told the guides would cost us €20/day, the driver €10/day and the minivan €60 or a car €50/day, plus petrol! This was going to seriously tax our resources unless we could get more cash.

The *Lonely Planet* guide acurately warns "… Mutsamudu remains smelly and filthy. Shells of burnt-out cars and piles of rubbish litter the streets, choking the shoreline and the river that runs through the town ... Cattle live on the garbage ..." (Andrew *et al.* 2008). The result is beaches no one would want to walk on, a filthy waterfront grazed by cows and goats, creeks flowing with rubbish and heaps of rotting garbage everywhere. The roads around the town don't seem to have received any maintenance for many decades so traffic moves slowly, dodging potholes. Perhaps surprisingly, the main roads around the island are tarred and in reasonable condition.

Birds around the town were scarce but fruit bats *(Pteropus seychellensis)* were numerous and evident even during the day – obviously they are not part of people's diets here.

Sunday 19 April

The minivan with driver and guide turned up just after 07:00 and we drove back towards the airport, then turned south into the spectacular central mountains. We descended to the east coast at the large village of Bambao and continued to Domoni (see map, Fig. 2) where we picked up our second guide, Ishaka Saïd.

We continued to the small village of Chaoueni in the far south. From there we followed paths steeply down towards the coast but, having been told we were within sight of our goal (which, it was becoming more evident, was to be a sea cave) we were overtaken by a gentleman who turned out to be the Mayor of the village. He was concerned that we didn't have 'authorisation' to be there. Our guides tried to convince him that we should be allowed to proceed, but to no avail. From within sight of the cave (even if only a sea cave) it was galling to be forced to climb back up to Chaoueni. Perhaps this setback demonstrated the need for the official 'permit' to go cave exploring …

We then drove down to the coastal village of Moya - with its own, rather run-down tourist hotel! and clean sandy beach!! We walked down to the beach and around a rock platform below the hotel to a filthy pebble beach. At the back of the beach was a small sea cave (Fig. 3). Not particularly impressed, Greg carried out a rough survey and we returned to the road. The cave was 28 m across the mouth, with a maximum depth of 10 m; it was 5.3 m high at the dripline. We tried to explain to our guides that we were looking for deeper caves than this.

On our way back across the island we were shown a waterfall plunging into a pool where the stream made a full right-angle turn. We were told the stream went into a cave but it was impossible to get to a position where one could see where the 'cave' might be. We were not convinced but in any case, accessing a cave if there was one would require climbing gear.
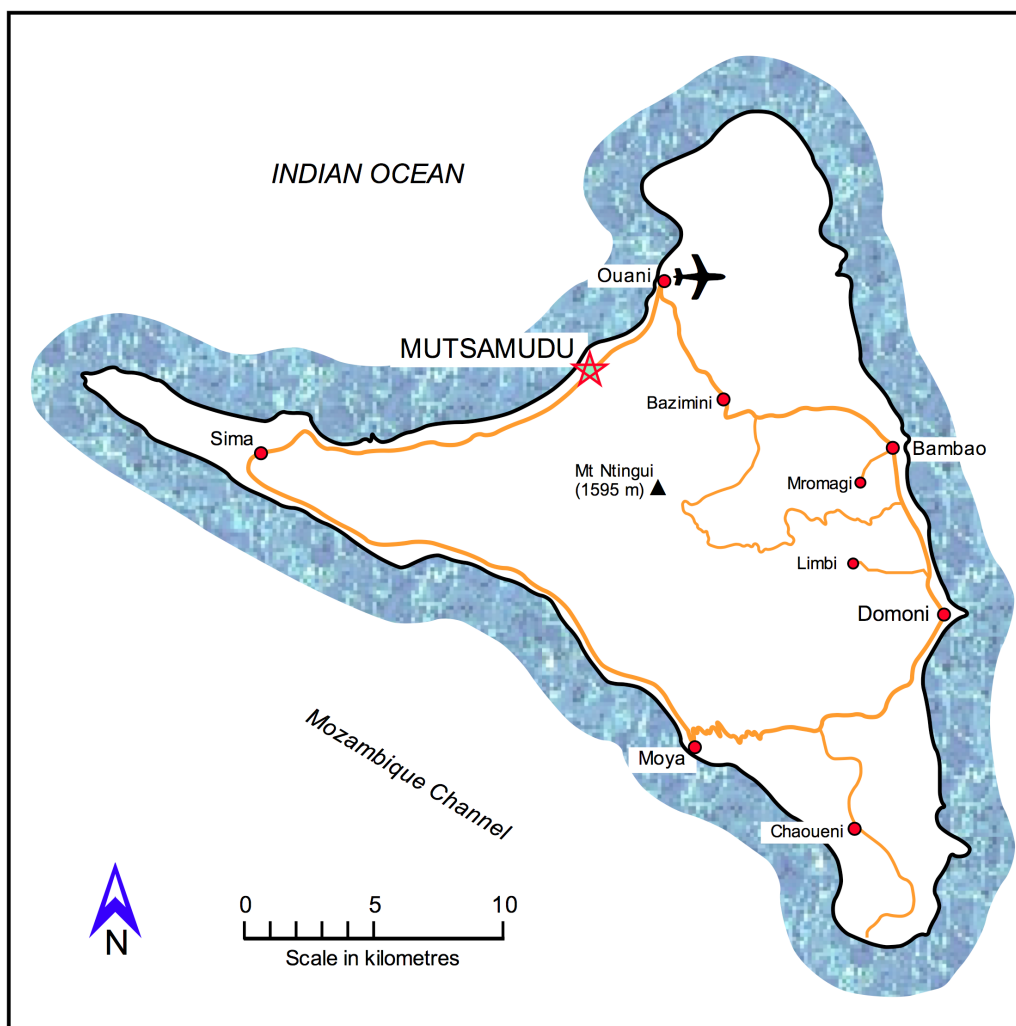
Fig. 2. The island of Anjouan, showing principal roads and places mentioned in the text.
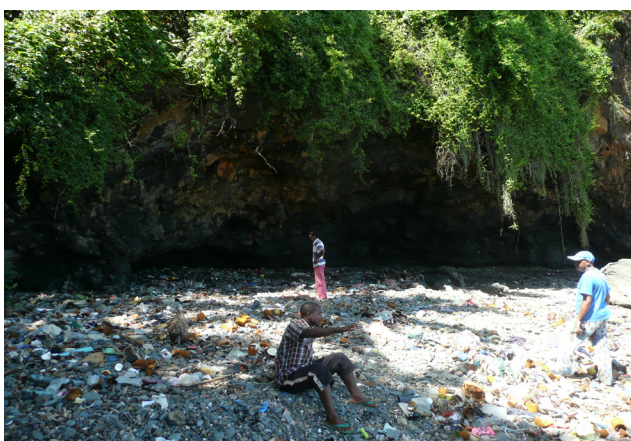

Fig. 3. The rather shallow sea cave at Moya (with garbage).

Apart from giving us some views of the spectacular topography of the island, our first day was rather disappointing.

Monday 20 April

We visited the two main banks on the island but learned that cash advances on credit cards could not be obtained. As we had brought limited cash, we were now in major financial difficulties. Action Comores obtained an "Authorisation de Recherches" for us as "Explorateurs des Grottes Volcaniques" approved by a Directeur Général of the Ministere de la Production, de la Peche, de l'Environnement, du Tourisme et de l'Artisanat of the Ile Autonome d'Anjouan. Hopefully this would save us from upsetting any more local officials.

Again we went south but stopped short of the divide, in the village of Bazimini. We were introduced to the Mayor who was happy for us to visit but asked for a report on our findings. Abderemane Maoulid, a local man working with Action Comores, led the way

Fig. 4. Abderemane looks on as Julian takes a closer look into Ngama Gombeni.

down narrow paths between small plots and within 15 minutes we were standing in front of what was indisputably a breakdown entrance to a lava tube cave! (Fig. 4) This hole, about 3 x 4 m, opened on the side of a steep gorge. We were told it is called Grotte (or Ngama) Gombeni but our guide could not explain the significance or origin of this name.

An easily climbed drop of a couple of metres brought us to the floor of the tube. The cave was blocked in the direction of the gorge by sediment (and probably a lava seal) but in the opposite direction it descended steeply for about 60 m into the hillside, ranging in height from 0.6 m to 4.5 m (Fig. 5).

Fig. 6. The Anjouan Miniopterus microbat.

Fig. 5. Inner part of Ngama Gombeni with highest section of roof; numerous microbats flying about, observed by our guides (who relied on us for light).

There were signs of ceremonies having been performed and offerings left at the downflow end of the entrance chamber. There were lots of grey and grey/tan microbats, which appeared to be the endemic (as yet undescribed) Anjouan Miniopterus, *Miniopterus* sp. (Fig. 6) and black and white cave crickets (Fig. 7). The tube ends in a lava seal with a murky black guano pool (Fig. 8). What appears to be a small on-going lead is blocked by apparently back-flowing lava (Fig. 9).

Greg surveyed out with Julian's help (see Fig. 10)

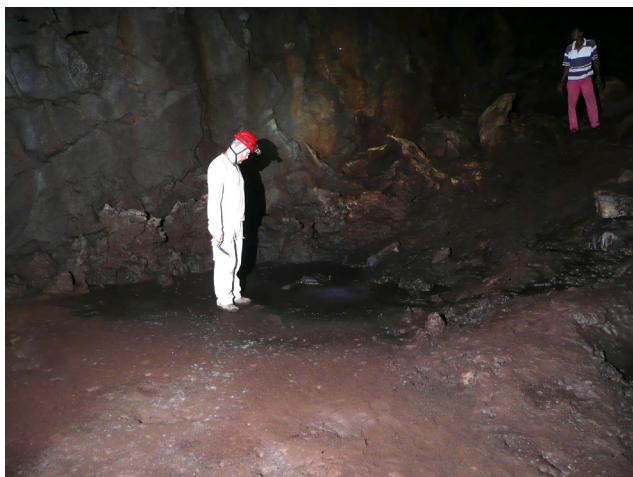*Fig. 7. Ngama Gombeni cave cricket.*

Fig. 8. Julian at black pool at end of Ngama Gombeni; poor conditions for bone preservation

Fig. 9. Apparent back-flow of lava, filling potential crawl at end of Ngama Gombeni.

Fig. 10. Plan of Ngama Gombeni, near Bazimini

and took a few photographs. Julian could find no bones and was not impressed by the prospects of their preservation in the prevailing very damp conditions. Lots of what was evidently old broken pottery was strewn across the floor among breakdown boulders. We had finished our inspection and recording by 12:30 p.m., delighted at having recorded our first lava tube on Anjouan.

Hopefully Ishaka now understood what we meant by a "grotte" or "caverne"; he assured us he could show us another as we drove down to the coast again at Bambao. We then turned inland and followed the road to the village of Mromagi. We started walking, gently up this time, and soon crossed a small river. Ishaka had to stop and scout around a few times and consult some locals but after about an hour he brought us to an unmistakable lava tube cave entrance (Fig. 11).

Ishaka informed us it was called Ngama Mapoudrou. We explored and surveyed down the fairly smooth tube to a terminal pool about 30 m in (see Fig. 12) (Fig. 13). The walls and roof were remarkably smooth and there was surprisingly little breakdown and little mud. Again, there were sacrificial items just in from

Fig. 11. Ishaka at entrance to Ngama Mapoudrou.

the entrance (Fig. 14). There were a few hundred bats in the cave. One obliged us by flying into the water. It wasn't a bad swimmer but had little sense of direction. Julian gingerly picked it out and identified it as *Mormopterus acetabulosus* (Fig. 15).

We had finished by 15:40 and were back to Mromagi village about 16:00. We dropped Ishaka in Bambao and returned to our hotel.

Hugh paid us a visit that evening and we told him what we have found, that the prospects (particularly in terms
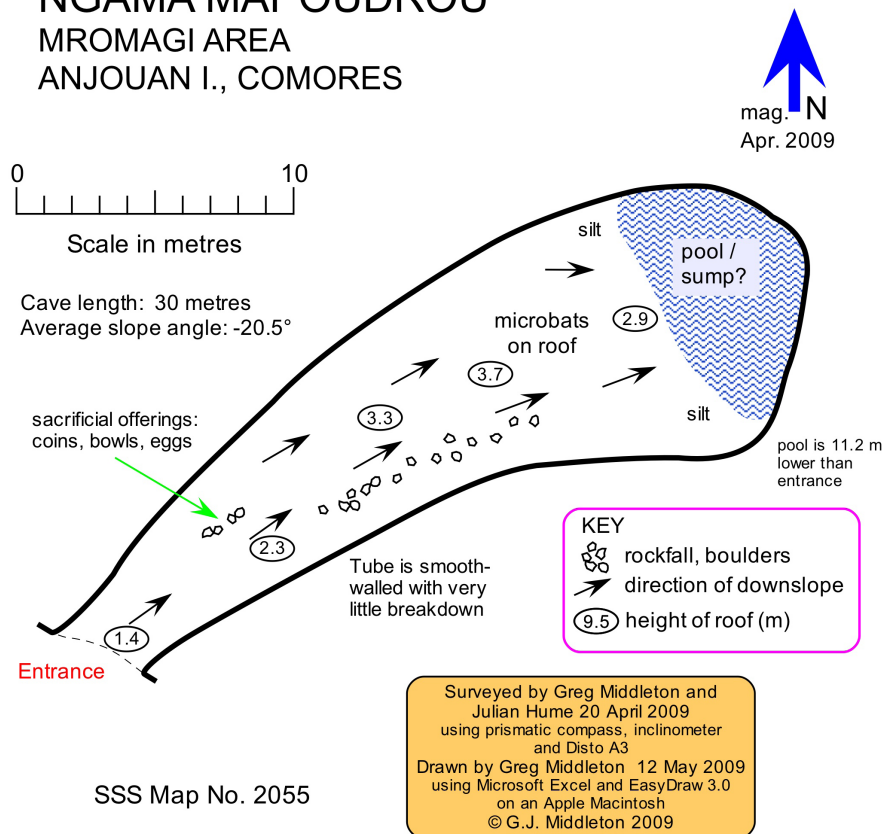
NGAMA MAPOUDROU
MROMAGI AREA
ANJOUAN I., COMORES

mag. N
Apr. 2009

0   10

Scale in metres

Cave length: 30 metres
Average slope angle: -20.5°

sacrificial offerings:
coins, bowls, eggs

silt

pool /
sump?

microbats
on roof

2.9

3.7

3.3

silt

2.3

pool is 11.2 m
lower than
entrance

1.4

KEY

⬡⬡ rockfall, boulders

→ direction of downslope

9.5 height of roof (m)

Entrance

Tube is smooth-
walled with very
little breakdown

Surveyed by Greg Middleton and
Julian Hume 20 April 2009
using prismatic compass, inclinometer
and Disto A3
Drawn by Greg Middleton 12 May 2009
using Microsoft Excel and EasyDraw 3.0
on an Apple Macintosh
© G.J. Middleton 2009

SSS Map No. 2055

Fig. 12. Plan of Ngama Mapoudrou, near Mromagi.

Fig. 13. Terminal pool (sump?) Mapoudrou.

Fig. 14. Sacrifices just inside Ngama Mapoudrou.

of fossil bone preservation) did not look good and that, as we were fast running out of cash, we would leave on 22nd if we could get seats with Aviation Comores. We discussed our options for paying for the vehicle and guides.

Observations on the caves.

It had become apparent to us from the lush vegetation (sadly most of it introduced, at least at lower levels), the deep soils and the steeply eroded mountainsides, that this is not a "recent" volcanic island. The many thousands of years it takes for such soils to form and erosion to occur on a volcanic island are sufficient for most of the lava caves that were probably there to have collapsed or have been filled with soil and debris. A few small caves survive but, compared to the much more recent and barely eroded Grande

Fig. 15. Rescued Mormopterus acetabulosus.

Comore, Anjouan appears to be a lava cave "desert". Unfortunately, also, the heavy rainfall means that conditions in the caves are virtually continuously damp, providing less than optimal conditions for the preservation of ancient bone material. Thus the lava caves of Anjouan seem unlikely to reveal any major records of the island's past vertebrate fauna.

Tuesday 21 April

We had asked to be shown the bat roosting site called "Hi Ros" (by Sewall, Granek & Trewhella 2003). We took the usual road east and south and turned inland just north of Domoni to reach the village of Limbi. From there, guided by Ishaka, we walked up into the mountains for about half an hour to a waterfall beside a large overhang which provided a roost site for the

Fig. 16. The large feature we called Rousettus Overhang beside a 10 m waterfall. Although clearly the roosting site for many hundreds of R. obliviosus, *(on left) this may not be the "Hi Ros" site.*

endemic fruit bat *Rousettus obliviosus*. The site identified by Sewall *et al.* (2003, p. 348) as "Hi Ros" was described by them as a cave with an entrance 1 m x 0.5 m "behind a water-fall of an intermittent stream". The distance to the back of the cave could not be determined, nor could the ceiling roost area, presumably because this required passing through the waterfall. This did not fit the site we had been brought to, though there were similarities. In our case the roost was a large overhang 12.4 m high, 15 m deep and about 35 m long with probably a few thousand *Rousettus oblivi-osus*, beside, not behind, a waterfall (Fig. 16). The overhang was readily accessible and the number of bats could very easily be estimated by a specialist. The "emergence estimate" provided by Sewall *et al.* (2003), was 100 bats, in July 2001. The number we saw was many times this.

Greg did a rough survey (Fig. 17) and had a swim in the plunge pool. The valley was too steep-sided and narrow at the actual site to get a GPS reading, so we had to be content with one a couple of hundred metres downstream where the valley widened a little. The altitude was given as 340 m, though altitudes with that GPS are notoriously inaccurate. Sewall *et al.* gave the altitude of their site as 600 m.
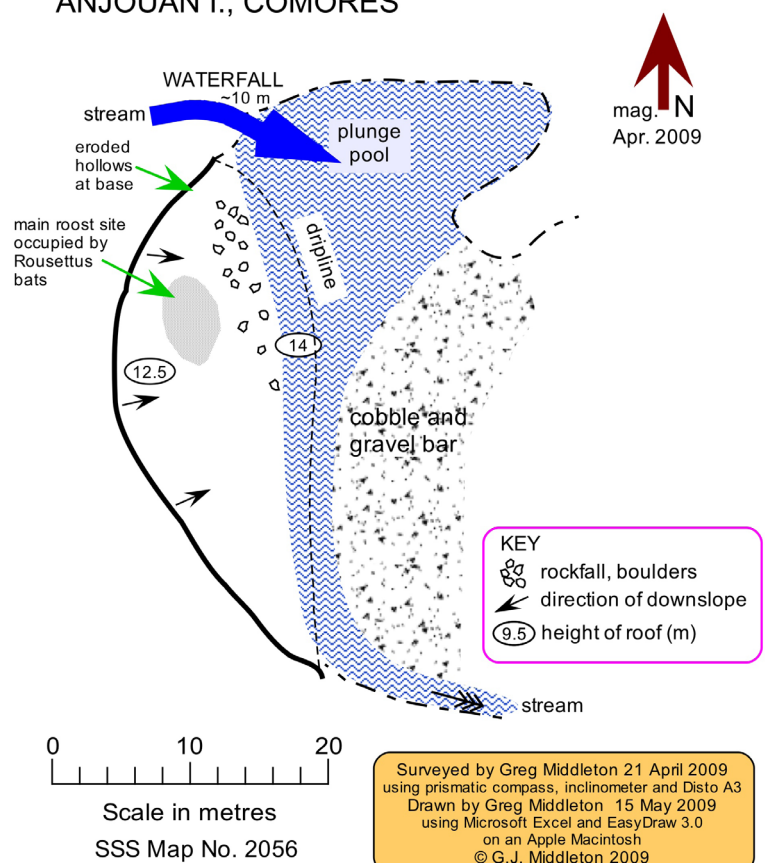

Fig. 17. Plan of Rousettus Overhang, waterfall and environs.

We walked back to Limbi, drove back to the main road, north to Bambao and inland to Mromagi. Greg rested while Julian, determined to see a roost site of the rare endemic Livingstone's fruit bat, went with Ishaka and Bacar, UP behind the village. They returned 2½ hours later after a very steep climb; Julian was exhausted. We returned to Mutsamudu.

Anjouan to Grande Comore – 22 April

At 08:30 on 22nd we took a taxi to the airport and caught the 11:00 flight to Moroni. After much frustration and negotiation we managed to bring forward our return flights to Reunion and even obtained a cash advance from the single, occasionally operational, Visa machine in the country.

Grande Comore – 23 April – Panga Betini and coastal cliffs

Despite his finding that the lava caves of Anjouan were unlikely to yield useful palaeontological material, Julian was keen to investigate the much more recent caves of Grande Comore. Accordingly we hired a taxi for the day and drove north to the Hahaya area, near the airport. From his knowledge of the caves Greg selected one with a good "trap"-type entrance, loaded the GPS coordinates into his Garmin and set out for Panga Betini (Middleton 1999). The vegetation on the lava flow was thicker than it had been 11 years earlier but it was not difficult going.

We came upon a fenced hole with bananas, which Greg didn't initially recognise. We checked out the cave – it went for over 100 m to the west and around 50 m to east; we saw no interesting bone material and no silt deposits which might contain palae-ontological material. Noting this hole for possible survey, we continued on to the Betini entrance Greg remembered, with little difficulty. At the classic collapse entrance (which Greg had designated HH7 – see Fig. 18) we climbed down the tree (Fig. 19), which was bigger and more leafy than it had been

in '98 – now it almost obscures the hole. We went through the cave (Fig. 20) looking for bones, but found little: very recent rodent, goat and cattle; no birds or bats. Conditions were fairly damp, which is not good for preservation of bones. We did notice, however, some striking bright blue lava stalactites (Fig. 21) and there were masses of hairy black roots hanging from the ceiling – these would be ideal for planthoppers but we could not spot any. We came out the small exit from the north-western passage (HH11), followed the collapsed depression to another small entrance (HH12 - all as shown on SSS Map No. 964, Fig. 18) and went in, looking for the "7 m pit" on the left (HH13).

PANGA BETINI, HH7-10-11 [#16-21- 22]
& CAVE HH12-13 [#23-24]
HAHAYA CAVE AREA, GRANDE COMORE
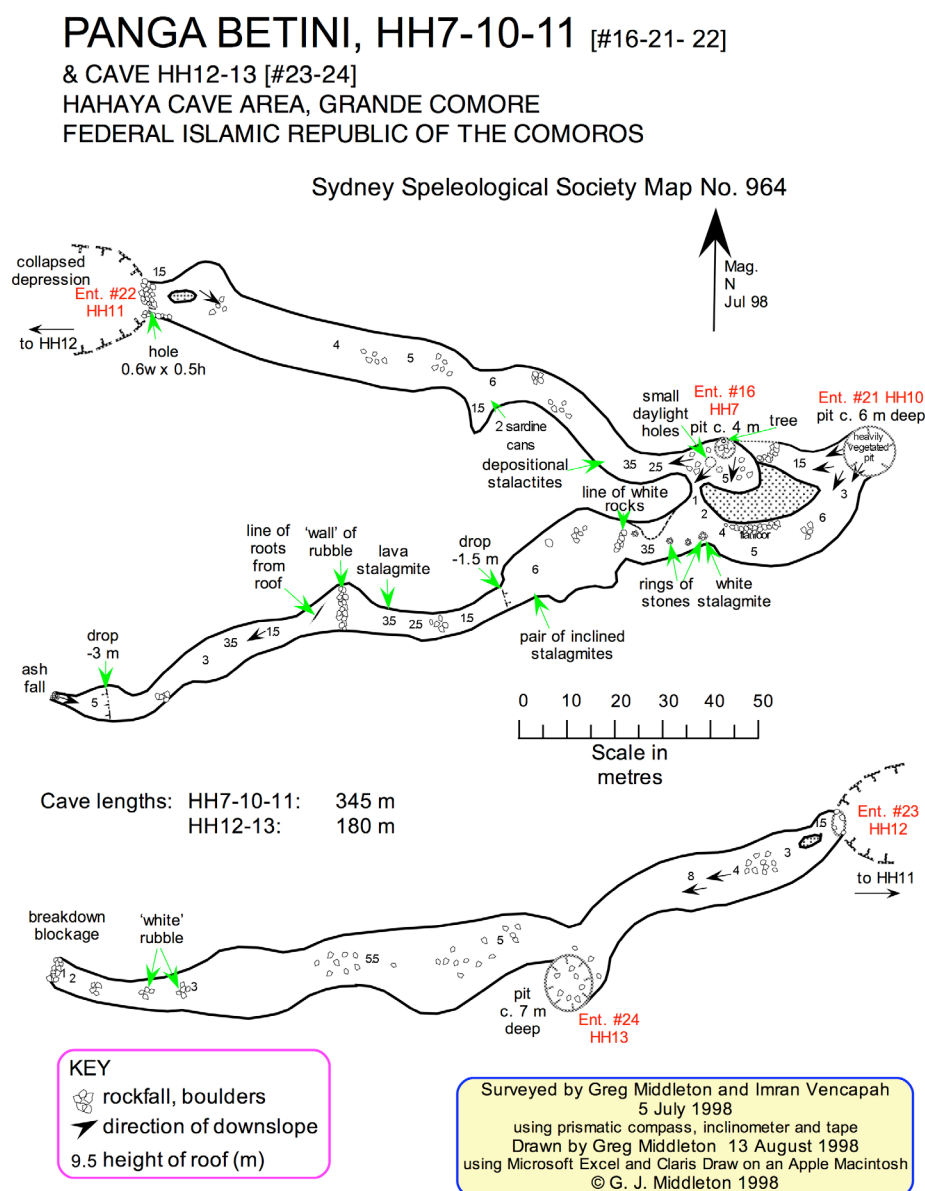### FEDERAL ISLAMIC REPUBLIC OF THE COMOROS

Fig. 18. Plan of Panga Betini HH7-10-11 and Cave HH12-13- prepared in 1998.

When we reached it Greg realised it was the hole we had found earlier in the day. (In 1998 he had only seen this hole from inside the cave as he surveyed; he hadn't bothered to climb out, so he didn't recognise it
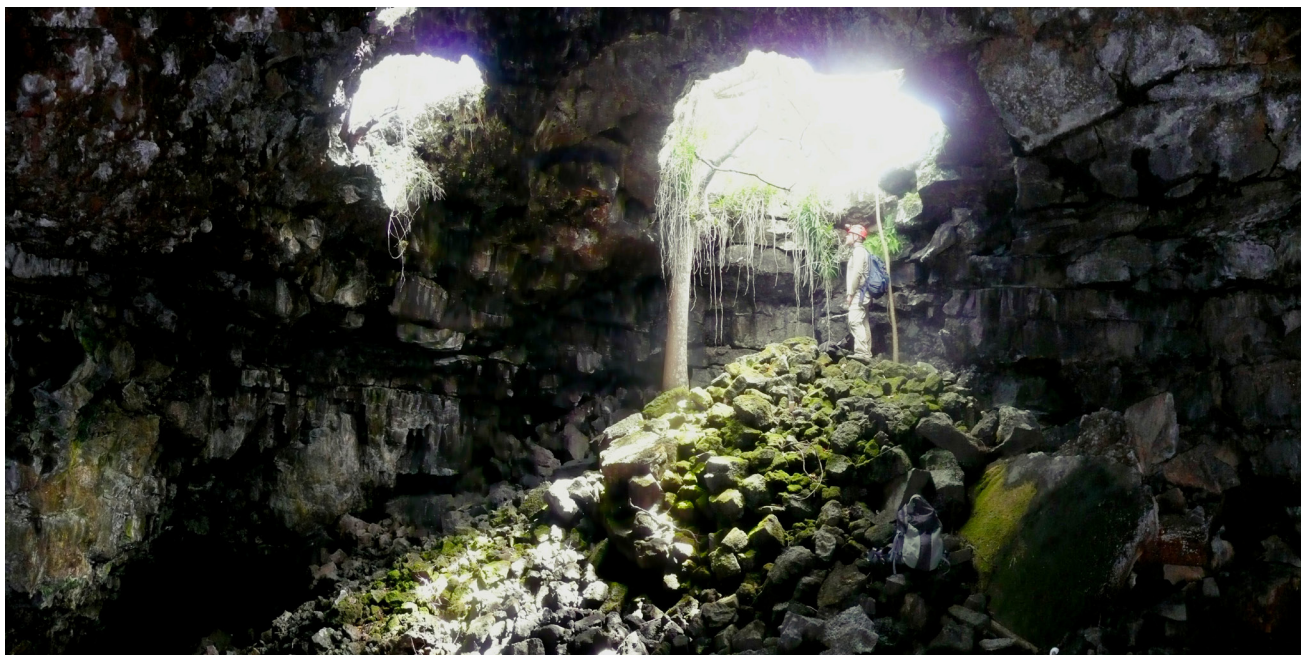
Fig. 19. The HH7 entrance to Panga Betini. Julian stands under the tree which facilitates access.

Fig. 20. Main passage in Panga Betini.

Fig. 21. Unusual blue lava stalactites.

from the surface. We returned to the small entrance (HH12). Julian had seen enough to convince him that the chances of finding anything of palaeontological interest were minimal so we headed back to our waiting taxi.

The taxi was not where we left it so Greg went looking for another cave he knew existed beside the main road. he found it but could not convince Julian it was even worth a look. When our taxi returned; we asked him to take us north to the first track to the coast north of the airport. From his earlier visits and other reports Greg was aware that there were apertures in the cliffs immediately west of the airport – some of which we had seen when coming in to land (Figs 22, 23) – and he was keen to try to check these out.

Figs 22, 23. Sea caves north of Hahaya, Grande Comore, from the air.

At the first road we found a barrier and a security guard but fortunately he was quite happy to let us through. The track ended at a navigation beacon in line with the runway. We left the taxi there and walked a couple of hundred metres to the coast, keen to see if we could find lava tubes opening in the steep sea cliffs. We walked north along the clifftop, observing eroded inlets backed by holes in the cliffs but all appeared to be sea caves. It is possible that lava tubes provided points of weakness which waves have then opened out into the large sea caves now apparent; we could not clearly see to the back of the overhangs to determine whether any vestiges of lava tubes remained. (It is of interest that there is a legend that the first Moslems to settle Grande Comore reached the island from the sea by way of a lava cave. Vérin (1994) locates it "to the north of the run-way at Hahaya" – see postscript to Middleton 1999). We found a way down to a wave-cut platform which exists along a small part of this coast. This gave better views into a couple of the openings (Fig. 24) but still no lava tubes were obvious, apart from some very small openings in the cliff.

with rodent and some snake bones - Julian strongly suspected a barn owl was responsible, but we did not see it. There was obvious white guano below roost sites. Greg made a few measurements and took some photographs. The opening is 17 m wide and 13 m high; it extends about 10 m into the hillside. There are some deeper hollows but no sign of a lava tube or passage. The parent rock appoears to be a coarse-grained tuff or volcanic conglomerate.

Back at the ferry terminal we negotiated with a taxi-driver for a 2 hour trip around the island for €30. We drove down south and across to the western side, through the town of Sada and back to Mamoudzou. Apart from a lot of luxuriant vegetation we saw nothing particularly striking except for the volcanic neck of Mt Choungui in extreme south, a different (grey) baobab and very few birds.

We concluded – as we had anticipated – even from such a brief reconnaissance – that, largely due to the age of this island, it is highly unlikely to contain any lava tube caves of any significance.

Fig. 24. Large sea caves in the cliffs adjacent to the airport. Note, for scale, Julian descending on left.

To Mayotte – 24/25 April

On 24 April we flew Air Austral to Dzaoudzi (Mayotte). On 25th we caught the ferry across to the capital, Mamoudzou, on Grande Terre. The rather grand offices of the "Comite du Tourisme" were shut so we found a travel agent where a woman responded a very definite "Non" to my question as to whether there were any caves on Mayotte. We assumed she meant tourist caves but as it is a very old volcanic island, she may be correct in the more general sense. Nevertheless, we had seen a large sea cave from the ferry (Fig. 25) so we walked down to the waterfront and around the cliffs to this obvious marine-eroded cavern. We found the steeply-sloping floor littered

Ile de La Réunion – Mauritius – 25/26 April – Conclusion

In the afternoon of 25 April we flew back to Reunion and, on 26th, back to Mauritius. This concluded our brief and only partly-successful visit to the Comores.

At least we had established that lava tube caves do persist on Anjouan – but our observations of the conditions led to our forming the opinion that they, and those already recorded on Grande Comore, are unlikely to preserve much of the past vertebrate fauna of these islands.

Fig. 25. Sea cave, Pointe Mahabou, Mamoudzou harbour, Grande Terre, Mayotte

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Geomunoreum Lava Tube System, Jeju Island

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Abstract

The lava tubes associated with the Geomun volcano on Jeju Island (Korea) are amongst the longest and most spectacular on the island. The tubes were formed some 200 000 to 300 000 years ago and today are, arguably, the most significant element of the volcanic province World Heritage site on Jeju, which also includes the Hallasan Nature Reserve (encompassing the highest peak in Korea) and Seongsan Ichulbong, an eroded tuff cone on the eastern coast of Jeju.

The lava tube system, comprising at least eight separate caves separated by infilled lavas and breakdown, trends for some 15km in a north-northeasterly direction from the crater to near the northern coast of Jeju.

During field trips for the 13th International Symposium on Vulcanospeleology in 2008, participants visited three caves in the system (Manjanggul, Gimnyeongul and Yongcheongul) and this paper focuses on some of the features observed on those field trips.

Introduction

In 2008, the 13th International Symposium on Vulcanospeleology was held on Jeju Island, located off the southern coast of the Korean Peninsula.

During Symposium field trips, a considerable amount of time was devoted to studying some of the lava tubes in the Geomunoreum system (*oreum* is the Korean word for volcanic cone).

Jeju is approximately 70km long and 30km wide and is composed almost entirely of lavas and volcanic ash. There are more than 300 volcanic cones scattered across the island and many of them are visible from the largest cone, Hallasan, located near the centre of the island (Fig. 1). At 1950m, Hallasan (Mt Halla) dominates the island and is Korea's highest mountain.

There are many spectacular and unusual volcanic features on the island, including numerous lava tubes.

Fig. 1. Many volcanic cones can be seen from the upper slopes of Hallasan, Korea's highest mountain.

Such is the importance of this volcanic province that parts of the island were designated as a UNESCO World Heritage site in 2007, the first natural World Heritage site designated in Korea.

The Jeju Island Volcanic Province World Heritage Area covers an area of approximately 1885 hectares and comprises the (1) Hallasan Nature Reserve, (2) Seongsan Ichulbong (an eroded tuff cone) and (3) the Geomunoreum Lava Tube System (see Fig. 2).

finally, Woljeongnamjimidonggul near the down-flow end. This latter tube is of note as it was detected by remote sensing methods and subsequently penetrated by drilling in June 2009 (Park, 2009). It apparently has considerable secondary calcite speleothem development.

This paper will now look at three of the caves (Manjanggul, Gimnyeongul and Yongcheongul) in more detail.

Fig. 2. Map of Jeju Island showing the location of the three components of the Jeju Island Volcanic Province World Heritage Area.

Arguably, the Geomunoreum complex is the most important part of the World Heritage area.

The Geomunoreum was active 100,000-300,000 years ago and resulted in the formation of some of the most spectacular and famous lava tube systems on Jeju. The lava flow in which the caves formed trends in a north-northeasterly direction for about 15km from the crater to the northern coast of Jeju (see Fig. 3).

The tubes include Manjanggul, Gimnyeongul, and Yongcheongul tubes, visited on the Symposium field trips. Other tubes in the system include Bengdwigul, an extraordinarily complex tube system with more than 4.4km of passage; an unnamed short vertical lava tube near the crater; Bugoreumdonggul, a small lava tube; Dangcheomuldonggul, a simple tube just 110m long, but packed with secondary calcite decoration; and

Manjanggul

Manjanggul is longest and most spacious tube in the Geomunoreum system. It has 3 entrances, two main passages levels and a total of about 7.4km of passage (Fig. 4). Passages range in size up to 23m wide and 30m high and contain a wide and spectacular range of lava features.

Symposium delegates visited Manjanggul (gul = cave) (Fig. 5) on three separate occasions over the course of the symposium and had opportunities to inspect most of the system.

A section of Manjanggul, approximately 1km long and up-flow from the middle entrance has been developed as a self-guiding show cave. Entry is via a large flight of stone steps (Fig. 6).

Figure 3. The Geomun area showing approximate locations of the crater (large horizontal pink arrow), the 3 lava tubes covered by this paper: Manjanggul, Gimnyeongul and Yongcheongul (blue arrows). Other tubes in the system include Bengdwigul (large pink arrow) and several smaller tubes (smaller purple arrows).

Fig. 4. Schematic diagram of Manjanggul, modified to show the approximate extent of the upper level section.

After the long flight of steps into the cave, it is an easy walk on an almost-level smooth lava floor.

The show cave section is electrically lit, with many of the lights camouflaged by fibreglass structures textured to look like piles of rock (Fig. 7). The light housings are arranged so that the lights face into the cave. This gives visitors a better view on the way in, but makes it harder to see on the way out.

In places grey coloured shotcrete has been sprayed onto the cave walls and ceiling, presumably to bind the surface and reduce the risk of minor rock fall. With subdued lighting in the cave, the shotcrete is not very obvious, but it does stand out in photographs, unfortunately (Fig. 7).

The main hazards along the show cave route are drips and resulting puddles of water. The drip problem can be overcome by wearing a rain jacket or carrying an umbrella and cave management has addressed the

Fig. 5. Symposium delegates approaching the Manjanggul visitor centre.

Fig. 6. Stephan Kempe, Kyung Sik Woo and Gunnhildur Stefansdottir entering the show cave section of Manjanggul.

puddle problem by strategically placing loose concrete stepping stones along the wettest sections of passage (Fig. 8).

The show cave section ends at an impressive lava column, more than 7m tall, where lava flowing along an upper level passage (no longer accessible) has dribbled down to the main level and more or less frozen in situ (Fig. 9).

Towards the end of the Symposium, the field trip program was amended so that participants could return

to Manjang to visit the long up-flow section beyond the end of the tourist trail. The goal was to see the full 3km of passage beyond the lava column (Fig. 10). To see it all was an 8km round trip from the tourist entrance; a full day trip.

The up-flow passages are generally quite spacious but there are some lower sections (Figs 11-13). There are also extensive areas of breakdown, where the roof lining has collapsed, which at one point provides access to an upper level section. The upper level is an important roost site for a population of long-Winged bats (*Miniopterus schreibersii fulginosus*). This colony, with an estimated population of 30,000 bats, is the largest known bat colony in Korea. Manjang is also an important site for invertebrates and more than 38 species have been identified.

The cave ends at a large collapse entrance. This up-flow entrance was used at one time as an access point to the cave, but the only evidence for this now is a large block of concrete that apparently marked the mid point of a flight of stairs (Fig. 14).

On the second visit to Manjanggul, delegates made their way to the bottom of the show cave steps and turned left into the lower (main) level of the down-flow section. It is a relatively short section (less than 1km long) with easy walking on a flat lava floor (Fig. 15). For most of its length down-flow from the show cave entrance, Manjanggul has two levels. Access to the upper level is gained by walking halfway down the stone access steps from the show cave entrance (Fig. 16) and pushing through a narrow gap between the steps and the passage wall.

Fig. 7. Marjorie Coggan in the show cave section of Manjanggul.

Fig. 8. Manjanggul show cave section, note the flat lava floor, concrete 'stepping stones' and fibreglass light housings.

Fig. 9. A 7m tall lava column marks the end of the show cave section.

Fig. 10. Symposium delegates heading beyond the show cave section (and lava column)
to explore the up-flow sections of passage.

Fig. 11. A lava toe and minor breakdown in Manjanggul.

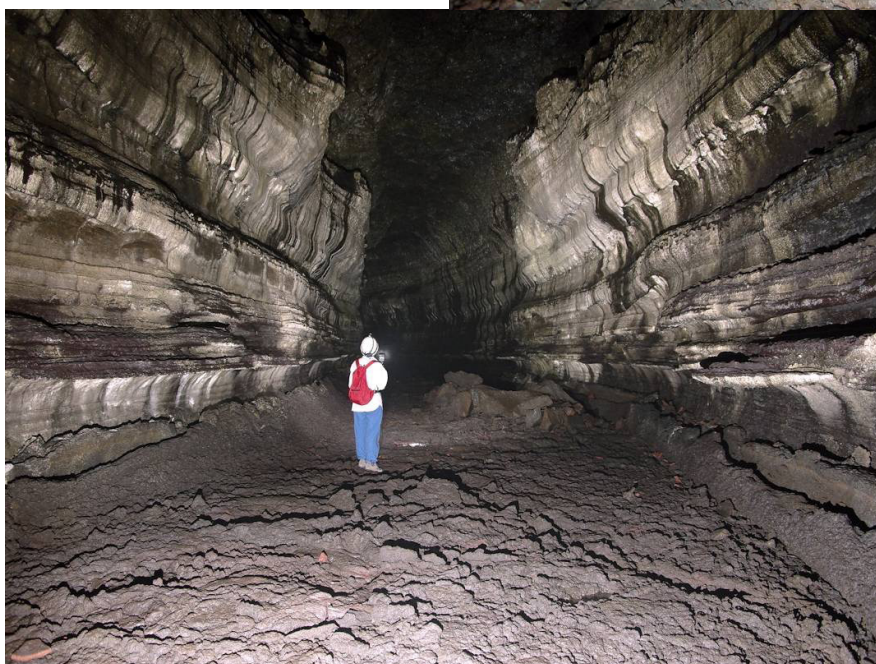*Fig. 12. Low section of passage with lateral flow lines.*

Fig. 13. A section of passage with lava benches, flow lines and a small amount of breakdown.

Fig. 14. Vertical entrance at the up-flow end on Manjanggul. A good spot for a lunch break

Fig. 15. Typical passage morphologies, Manjanggul lower level, down-flow section.

The upper, or balcony, level has quite a different character to the lower level passage referred to above. It has large areas of collapsed lava floors (Fig. 17) and lava bridges (Fig. 18) where sections of floor have partly collapsed (tube in tube structures).

Fig. 16. Manjanggul main entrance viewed from the upper (or balcony) level of the down-flow section of cave.

The balcony level of Manjanggul also has large areas of pahoehoe (ropey) lava (Figs 19 & 20) and, towards the lower end, areas of bright red lava (Fig. 21) where the iron content has oxidised to ferric iron.

Fig. 17. Marjorie Coggan and Claude Mouret on an extensive section of collapsed lava floor in the upper level section of Manjanggul (down-flow end).

Gimnyeongul

The next cave down-flow from Manjang is Gimnyeon. It is a mostly spacious cave about 700m long. Passage dimensions range up to 12m high and 5m wide.

The passage goes in two directions from the large collapse entrance. The short down-flow section of passage is a fauna reserve and was not entered on the symposium field trip.

The main up-flow section of passage is accessed via a flight of stone steps, now vegetation covered, (Fig. 22) that apparently date from its time as a show cave. The cave was open from 1962 to 1991 and plans are afoot to reopen in 2012.

The first 100-150m of up-flow passage has a floor of white calcitic sand (Figure 23). The sand has blown in from nearby coastal areas and is apparently responsible for choking off the short down-flow section. The sand is also the source of calcite for secondary speleothem growth in several of the Geomunoreum lava tubes. More about that below.

Towards the up-flow end, there is a 2m high lava fall (Figure 24) and above that, passage dimensions are quite small (Figure 25). The passage soon pinches out and at that point, it is just 90m to Manjanggul. However, as both passages end in solid lava, and there is an area of collapse in between, it seems unlikely that an underground connection will ever be made.

Yongcheongul

Yongcheongul is just a short distance down-flow from Gimnyeongul.

The cave was accidentally discovered in 2005 when excavations for a new power pole broke through into the tube. Somewhat

Fig. 18. Lava bridge/ collapsed floor in the upper level of Manjanggul.

Fig. 19. Horst-Volkel Henschel on Pahoehoe (ropey) lava floor, Manjanggul balcony level. The green netting in the background is a simple rock fall monitoring system.

Fig. 20. Amos Frumkin and Marjorie Coggan inspecting a pahoehoe (ropey) lava floor.

Fig. 21. Red lava floor towards the down-flow end of the balcony level in Manjanggul.

Fig. 22. Symposium delegates pushing through thick vegetation towards the Gimnyeongul entrance.

Fig. 23. White calcite sand floor in the outer section of passage in Gimnyeongul.

Fig. 24. Small lava falls near the up-flow end of Gimnyeongul.

Fig. 25. Marjorie Coggan, Stein-Eric Lauritzen and Birgit Stav above the Gimnyeon lava falls.

disconcertingly, entry to the cave is now down beside the offending cement power pole, around and under the bottom of it and then down a wobbly 10m aluminium extension ladder.

The cave has impressive lava features, extensive calcite speleothem development and contains important archaeological artefacts. In view of its values, it was designated as a National Monument in 2006, just months after its discovery and it now forms a key part of the Jeju Volcanic Province World Heritage Area. The entrance is right beside a major road and is protected by an alarm system, a padlocked stainless steel plate (Fig. 26) and under this, a securely locked gate.

The cave has about 2.5 km of passage, is generally 7-15 m wide and 1.5-20 m high. Most of the passage (approx 75%

Fig. 27. Cathy Plowman, David Butler and Kyung-Sik Woo in the up-flow section of Yongcheon.

In the more delicate up-flow section, a trail has been delineated with large reflective markers (Figs 28-30). In places the markers are several metres apart, leaving the precise route open to interpretation. Happily, visitor numbers are very low as access is very tightly controlled. In addition to the permanent (but unfixed) reflective markers, several other protective measures were implemented specially for the visit by symposium delegates. These included several lengths of temporary plastic sheeting (see Fig. 29) and the use of protective overshoes (Figs 31-33) in particularly sensitive areas.

Fig. 26. Lifting the lid on Yongcheongul. The well-protected entrance is right beside a major road.

is down-flow from the entrance. The shorter up-flow section has more modest passage dimensions but has more calcite speleothem development (Figs 27-34).

Calcite speleothems in Yongcheon result from solution of surficial deposits of sand that have blown in from the nearby coastal areas.

There are several lava falls in the cave (Fig. 43), including one that has a thin coating of calcite (Fig. 29), and one that has an elevation change of 10m in two stages.

Fig. 28. Calcite straws are in abundance and the longest are an estimated 5 m long.
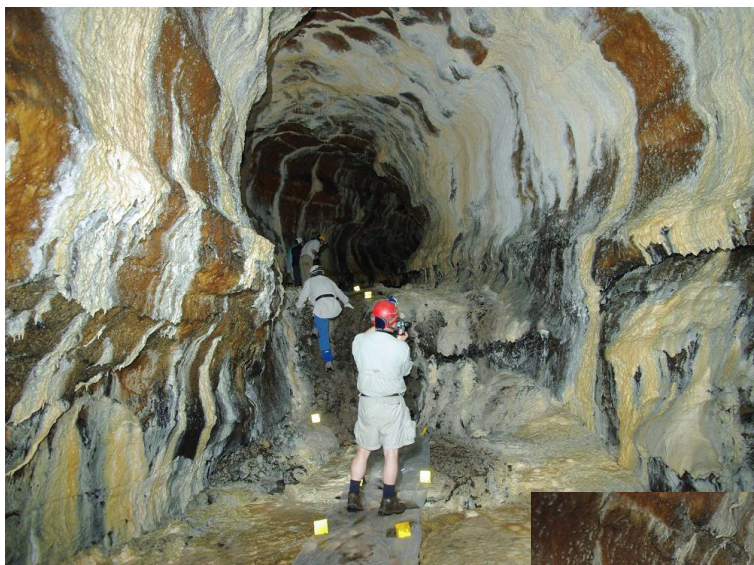
Fig. 29. David Wools-Cobb, Marjorie Coggan, Greg Middleton and Julia James near calcite coated lava falls. The temporary plastic matting was specially laid for symposium delegates.

Fig. 30. Passage above the calcite-covered lava falls.

Fig. 31. The wide range of calcite speleothems in Yongcheon Cave includes flowstones, stalagmites, straws, cave corals, oolites and microgours.

The party was also split into several small groups, each with a local leader.

Many artefacts such as iron tools, pottery fragments, large animal bones, abalone shells and the remains of wooden torches have been found throughout the cave. Radio-carbon studies suggest the artefacts date from 500-600AD and this is apparently consistent with the pottery styles found in the cave. Some artefacts apparently been removed for protection or for research purposes, but many can still be seen in the cave (Fig. 35).

The artefacts point to an earlier period of human access through an entrance that is assumed to be now sand/soil covered.

Down-flow from the entrance pitch, there is less calcite speleothem development, but there are some impressive lava features including flow lines (Figs 36 and 37), lava falls up to 10 m tall, tube in tube structures (Fig. 38) and lava stalactites.

Fig. 32. Marjorie Coggan standing beside a nice lava roll; forest of straws above.

Fig. 33. A small lava bridge marked the end of our upstream investigations. The passage continues for a short distance, but is constricted and does not have a marked trail.

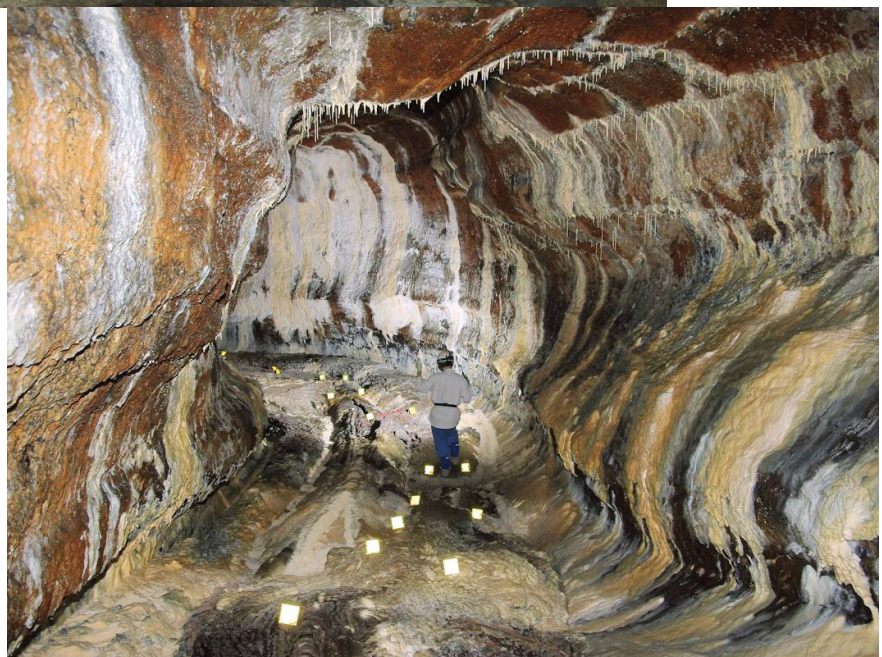*Fig. 34. Marjorie Coggan heading back towards the entrance.*

Fig. 35. Artefacts in the cave include pottery dating from 5-600AD.

Calcite speleothems are more common towards the lower end of the down-flow section of the cave. Thin calcite layers on walls, straws and small stalagmites are common (Figs 39 and 40). In some parts of the cave, the floor calcite is redissolving (Fig. 41), suggesting more acidic percolation waters in areas where the overlying calcite-rich sands are depleted.

Fig. 36. Impressive flow lines down-flow from the entrance.

Fig. 37. Lava features predominate in much of the down-flow section. The white 'straws' are tree roots.

Fig. 38. A collapsed lava crust, or tube-in-tube structure.

Fig. 39. Typical calcite decoration in the down-flow section of Yongcheon Cave.

Fig. 40. Calcite and lava speleothems near the terminal lake.

Near the lower end of the cave, a lava fall drops 5m into the terminal lake. The first pool of the lake is only a few metres across and has been bridged with an aluminium ladder (Fig. 42). From a vantage point near the end of the horizontal ladder, the main section lake disappears from view around a bend, but is apparently some 200m long and up to 15m deep.

Conclusions

The range of features observed in the Geomunoreum lava tubes, and the Yongcheon tube in particular, is truly remarkable. As such, the tubes form a fitting and prominent part of the Jeju Island Volcanic Province World Heritage Area. Apart from the show cave section of Manjang, there are strict access controls on all caves in the Geomun system and entry to Yongcheon Cave is very tightly controlled. Symposium delegates were privileged to be granted access and the organisers of the Symposium (and various Korean officials) deserve special thanks for making it all possible.

*Fig. 41.
Floor calcite is
redissolving
in parts of the
downflow section.*

*Fig. 42. Crossing
a horizontal ladder
over a pit (a lava
fall) that drops to
the terminal lake.*

Fig. 43. Marjorie Coggan and Greg Middleton climbing a small lava fall on their return journey to the entrance.

Fig. 45. Passage near the entry ladder, which is vaguely visible through the build up of condensation

Fig. 46. Jan-Paul van de Pas and party (David Butler, Marjorie Coggan, David Wools-Cobb and Jean-Pierre Bartholeyns) returned safely to the surface, thanks to the Dolharubung (Grandfather figure) warding off evil spirits.

Acknowledgements

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Footnote: This paper was presented as a slide show at the 14th International Symposium on Vulcanospeleology at Undara in August 2008 and has been reformatted for the Symposium Proceedings. Apologies if the great pics don't look as good as they do in the ppt version – Ed.
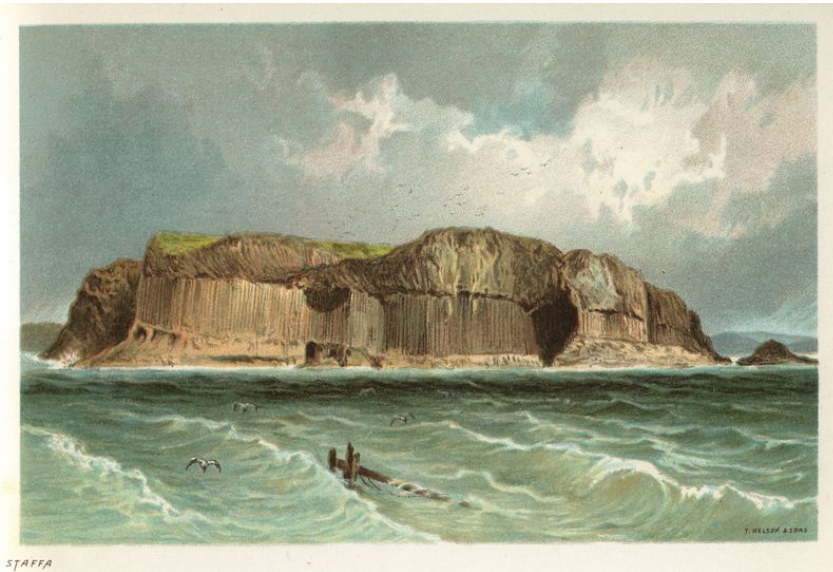
Fingals Cave, Staffa

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Abstract

Fingals Cave, the world's most famous basalt cave, is to be found on the island of Staffa in the Inner Hebrides, off the west coast of Scotland. The cave was "discovered" by Sir Joseph Banks in 1772. The circumstances of its "discovery"; prior history; earliest illustrations from 1772; the island's depiction on early maps and its promotion and as an object of scientific study and picturesque grandeur, particularly during Victorian times, are discussed. Many famous people are recorded as having visited the cave, including Queen Victoria and Felix Mendelssohn in 1829. In 2005 and 2006 the first detailed speleological investigation of the island and its caves was carried out and some of the findings are detailed.

The island of Staffa, showing Fingals Cave – Thomas Nelson & Sons, 1891

Introduction

Fingals Cave is on the island of Staffa, off the west coast of the Island of Mull, off the west coast of Scotland (Fig. 1). It is reached by sailing from Oban to Mull and then driving the 31 miles (50 km) down to Fionnphort and sailing out to Staffa. There are several boat operators who offer tourist sailings to Staffa throughout the summer months and usually, weather permitting, a landing is made and approximately an hour to an hour and a quarter can be spent on the island. This allows enough time to visit Fingals Cave and walk round the top of the island.

It is volcanic in origin with the famous columnar basalt lying over layers of compacted ash. This in turn is topped by subsequent lava flows which also show signs of formation of columns but these are broken, twisted and jumbled. Dr J. MacCulloch (1814) in Vol. II of the *Transactions of the Geological Society* refers to reports of a sandstone bed which can be seen at low water on the south western side of the island but he had not seen it himself. During the Grampian
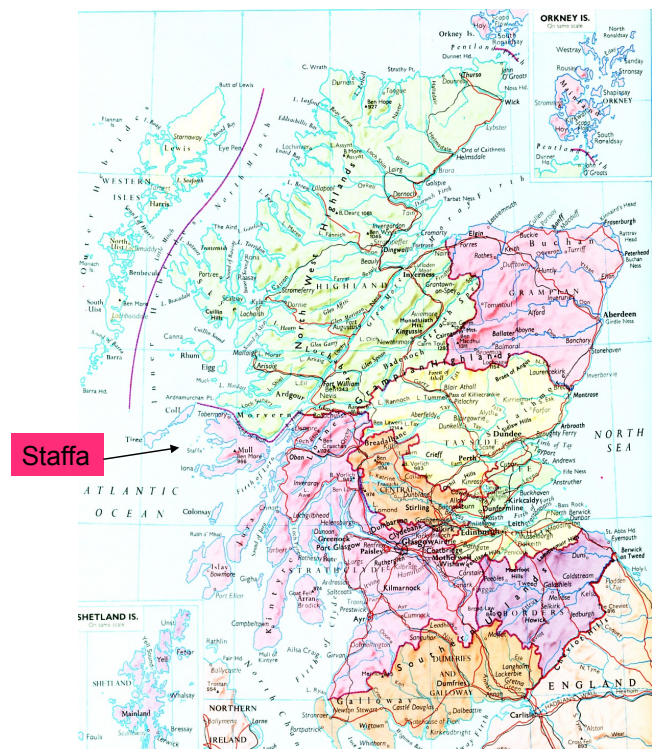

Fig. 1. Location of the island of Staffa.

Speleological Group's recent exploration of the island some of the caves were dived and again there were no reports of sandstone being found. The island is thought once to be part of the neighbouring island of Mull and part of the volcanic region which extends from Skye and the Shiant Isles in the north to the Giants Causeway in County Antrim, Northern Ireland, to the south where similar basalt columns can be seen.

Staffa is a small island being just under ¾ of a mile (1.25 km) long, ¼ of a mile (420 m) wide, 1½ miles (2.5 km) in circumference, with an area of 71 acres (29 ha) and the highest point is 135 ft (50 m) above sea level. Apart from Fingals Cave there are a number of other well-known caves on the island, including Clamshell Cave, Goat Cave, Boat Cave, McKinnons Cave and Cormorants Cave, the last two of which are linked (Fig. 2).
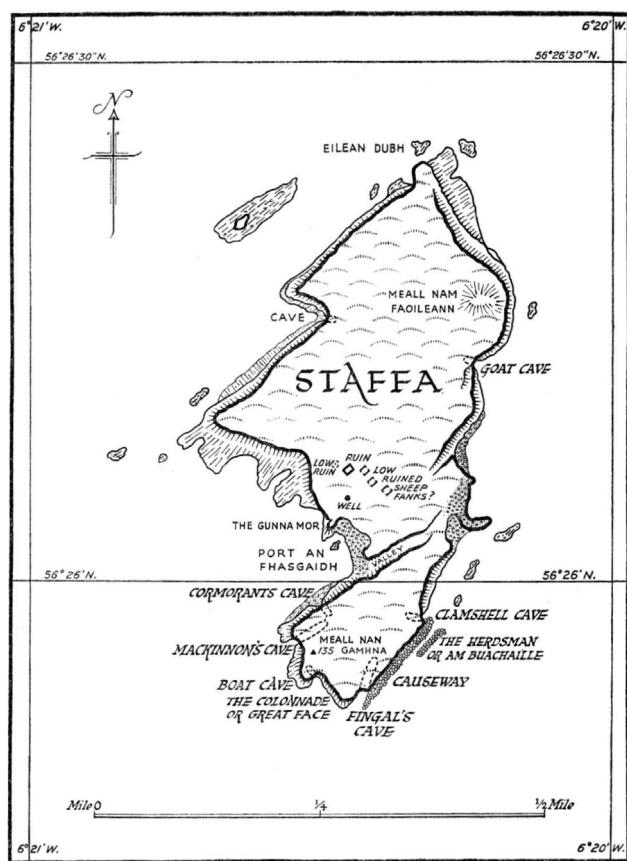

Fig. 2. MacCulloch's map of Staffa (1814)

Discovery

Martin Martin was born on Skye, probably in the late 1660s and was employed as a tutor or governor by two major landowning island families. As a Gaelic speaking islander with valuable social connections he proved to be a useful researcher and collector on behalf of the Royal Society. He published *A Late Voyage to St Kilda* in 1698 and *A Description of the Western Islands of Scotland* printed in London in 1703 [329pp.] He visited and describes at least 24 islands, together with Orkney and Shetland which appear

possibly based on the writings of others, and produced *A New Map of the Western Isles of Scotland.* The most glaring omission in Martin's perambulations round the Hebridean Islands which included Mull and Iona, was not to visit nearby Staffa. If he had he would have surely reported Fingals and the other caves and history would be different.

One of the first mentions of the island is in Thomas Pennant's (1774) second "Tour in Scotland" when he "sailed past this interesting island" on 11th July 1772, but "due to sea conditions, did not land". However Joseph Banks (later Sir Joseph) (Fig. 3) did land on the island on 13th August 1772 and "discovered" Fingals Cave. He was en route to Iceland with a party which included Dr Uno von Troil when he had to take shelter in a storm. He accepted an invitation ashore and met a Mr Leach who told him that nearby was an island with pillars of rock like those of the Giant's Causeway. Banks visited the island the next day and declared Fingals " .. one of the greatest natural curiosities in the world…" and he then set about publicising this natural wonder.

Fig. 3. Sir Joseph Banks,
'discoverer' of Fingals Cave.

Dr Samuel Johnson, with James Boswell, in 1773 reached Mull on 19th October during their "Journey to the Western Islands and A Tour to the Hebrides". Johnson wrote "We saw the island of Staffa at no very great distance, but could not land on it, the surge was so high off its rocky coast."

However the island, and therefore the cave, was undoubtedly already known to locals and other passing boats, not to mention the Vikings. The name *Staffa* dates from the Viking occupation of the West Coast of Scotland from about 890 to 1266 AD and is derived from the Old Norse words *Stafr* meaning pillar or post and *Ey* meaning island, hence *Pillar Isle*. When Banks first visited the island he found a house and signs of

habitation by a lone herdsman, probably seasonal. By 1782, according to the *Parochial Register,* the herdsman had acquired a wife and child, and by 1784 the island population reportedly consisted of sixteen people, probably in two families, but by 1798 it was no longer inhabited throughout the year but was certainly still used for grazing in the summer months.

Putting Staffa on the Map

Nearly two centuries before Banks' "discovery" Timothy Pont, in the period between graduating from St Andrews University and being ordained as a Church of Scotland Minister in the Parish of Dunnet in Caithness, surveyed the whole of Scotland. His surveys consisted of compass traverses of the rivers and valleys and he recorded the vast number of place names associated with each area. This was a remarkable achievement considering he probably only worked during the summer months. His manuscript maps are not dated and only 36 sheets survived after his death some time between 1611 and 1614. Pont's original sheet covering Staffa has not survived so we do not know if he actually visited Staffa but his map showing Staffa was included in Joan Blaeu's *Atlas Novus*, published in Amsterdam in 1654 (Fig. 4).


Fig. 5. Earliest illustration of Staffa, by John Frederick Miller, 1772

The First Illustrations

There are a great many illustrations of Staffa and Fingals Cave, the earliest we know of being that of John Frederick Miller in 1772 (the same year as its "discovery") (Fig. 5). Thomas Pennant may have missed out on the "discovery" but in the account of his *Tour of Scotland* (part 1) (1774), he included engravings based on the sketches made by John Cleveley Jnr. (Fig. 6), who was part of Banks' party.

Other examples of engravings included are by Antonio di Bittio, c. 1780 (Fig. 7), two by F. Bertuch, 1798 (Figs 8, 9), T. Garnett in 1800 (Fig. 10), C. Horney (Fig. 11) also in 1800, Jean Claude Nattes in 1801 (Fig. 12) and two more of his from 1804 (Figs 13, 14), and Josiah Whimper in 1849 (Fig. 21).

William Daniell, a famous artist and engraver, commenced a tour around Great Britain in 1813 at Land's End and travelled clockwise round the coast. Initially he was accompanied by a companion, Richard Ayton, who was to provide the text to accompany his illustrations, but who dropped out in 1816 just after reaching

Fig. 4. Timothy Pont's map of Mull, showing Staffa, published 1654.
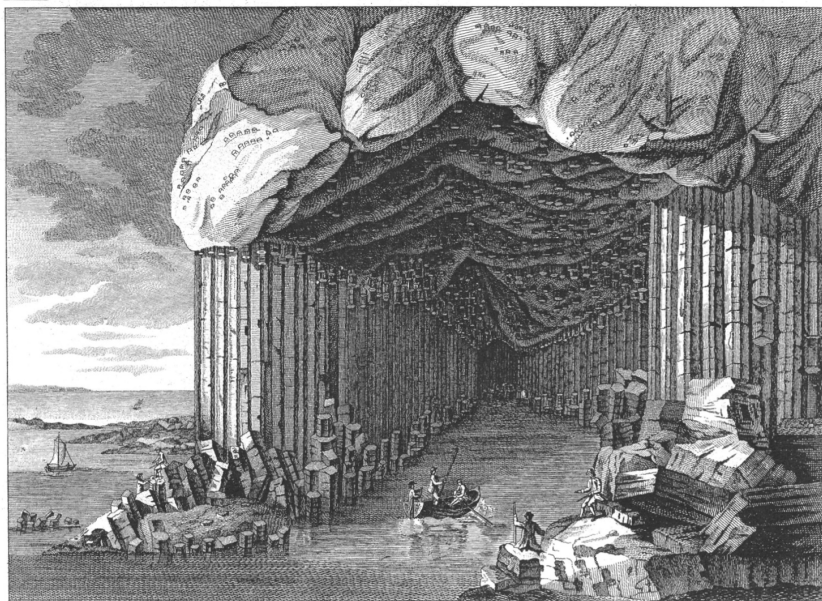
FINGAL'S CAVE IN STAFFA.

Fig. 6. Pennant's engraving from John Cleveley Jnr.'s sketches, published 1774 (image reversed).
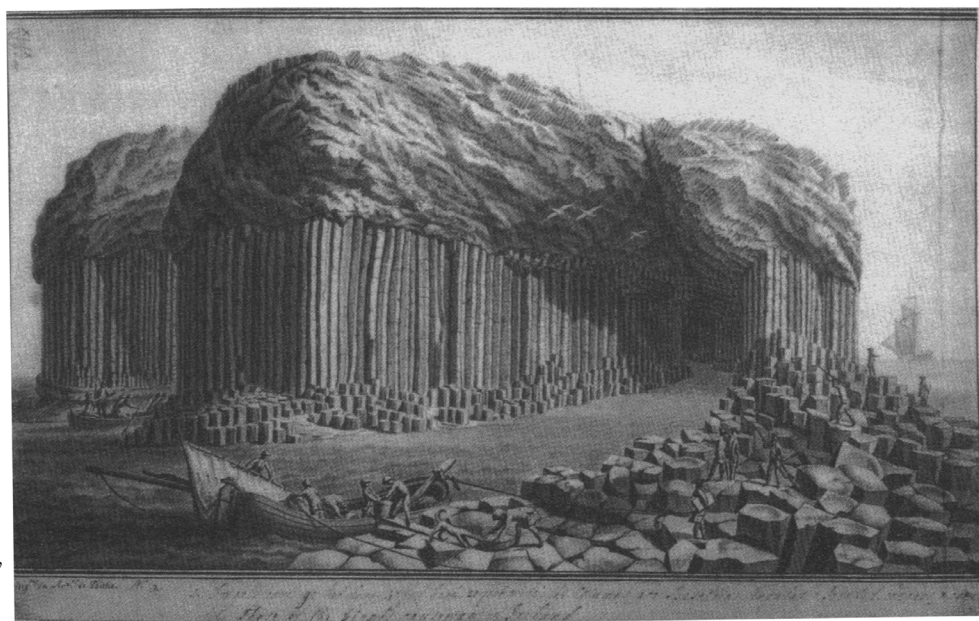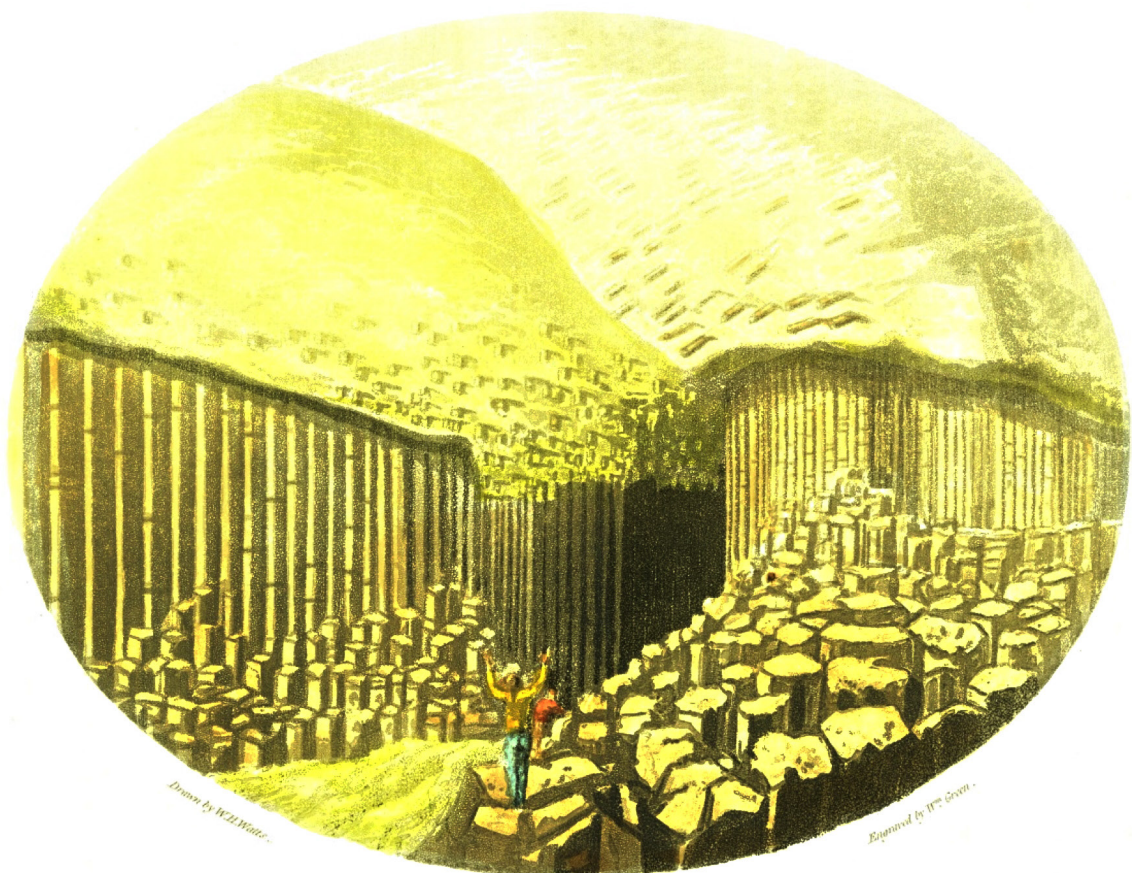

Fig. 7. Staffa engraving by Antonio di Bittio, ca. 1780

Fig. 8. "The Basalt island of Staffa" by F. Bertuch, 1798.

Fig. 9. Close-up illustration by F. Bertuch, 1798, showing Fingals Cave detail (image reversed, as Fig. 6?)

Drawn by Wm Watts.   Engraved by Wm Green.

Fingals Cave

Fig. 10. Fingals Cave by T. Garnett, 1800.

Fig. 11. View of Staffa from the south – C. Horney, 1800.

Fig. 12. Jean Claude Nattes, 1801 – View looking out of Fingals Cave.

Fig. 13. Another view out of Fingals Cave by Jean Claude Nattes, 1804 in 'Scotia Depicta'.
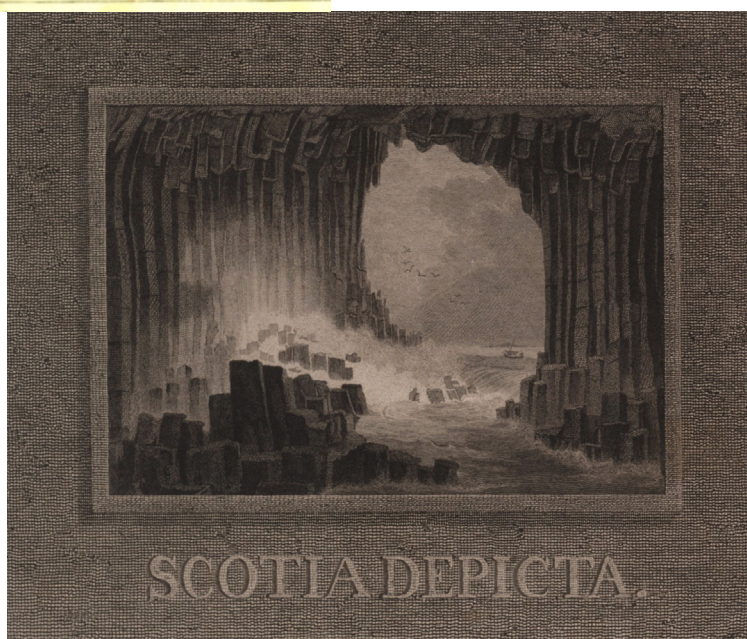
Fig. 14. A view of tourists disembarking into Fingals Cave by Jean Claude Nattes, 1804.

Scotland and thereafter Daniell provided his own text. He completed 577 water-colours and drawings of which 308 were published, along with accompanying text, in his eight volume *Voyage Round Great Britain* between 1814 and 1825. Staffa appears in Volume III published in 1818 and it is thought that he visited the island in the summer of 1817. All the aquatints were hand coloured by trade colourists from his notes. In 1818 due to anticipated demand from increasing tourism, a separate volume, *Illustrations of the Island of Staffa, in a Series of Views, accompanied by Topographical and Geological Descriptions* was published separately, with slightly revised text and amended sequence from that in Volume III of his "Voyage".

The nine aquatints of Staffa comprise:

The Island of Staffa from the South West.

The Island of Staffa from the East.

View from the Island of Staffa. (Fig. 15)

Clamshell Cave. Iona in the distance. (Fig. 16)

Exterior of Fingals Cave, Staffa. (Fig. 17)

Entrance to Fingals Cave, Staffa. (Fig. 18)

In Fingals Cave, Staffa. (Fig. 19)

Staffa near Fingals Cave.

The Cormorants Cave, Staffa. (This is actually McKinnon's Cave). (Fig. 20)

Fig. 15. William Daniell – View from the island of Staffa, 1818

Fig. 16. William Daniell – Clamshell Cave; Iona in the distance, 1818.

Fig. 17. William Daniell – Exterior of Fingals Cave
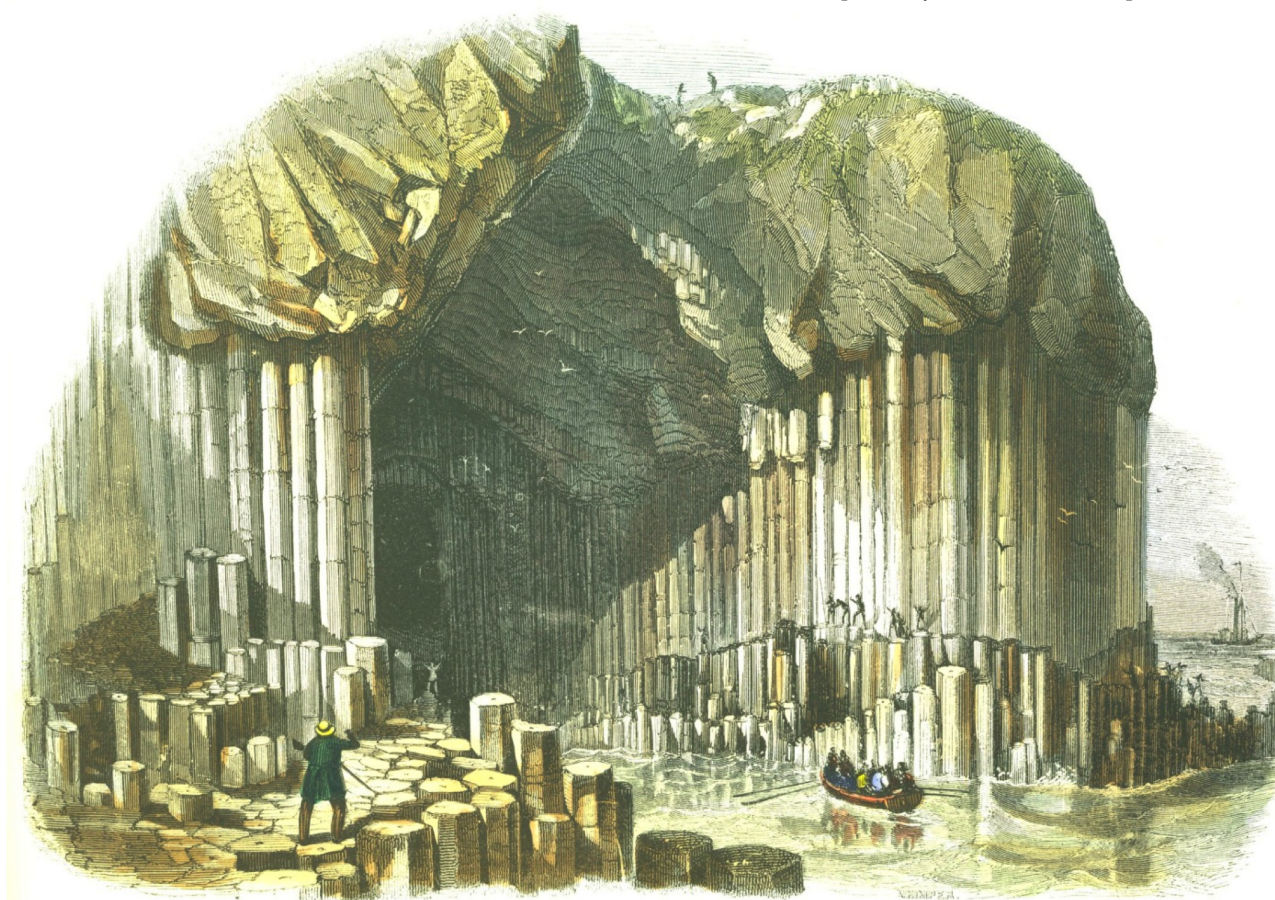

Fig. 18. William Daniell – Entrance to Fingals Cave

Fig. 19. William Daniell – In Fingals Cave, Staffa

Fig. 20. William Daniell – "Cormorants Cave"
[actually McKinnons Cave]

FINGAL'S CAVE.

Fig. 21. Josiah Whimper: Fingals Cave – from "Phenomena of Nature" 1849

In this volume on page 6, Daniell includes the following interesting historical anecdote about Fingals Cave:

"The roof of the cave, to a spectator far advanced within, excites both wonder and apprehension. It was mentioned by one of the boatmen, while the present view was taken, that the shooting parties, whom curiosity sometimes induces to extend their excursions to this spot, occasionally venture to discharge their pieces within it. The effect is described as awfully grand, but it must be attended with considerable peril, because the concussion occasioned by such an explosion cannot but tend to affect, perhaps to loosen, some of the ponderous fragments in this pendant ceiling, and these, if detached, might in their fall send the boat and its crew to the bottom. It was not stated that any accident of this kind ever took place."

Famous Visitors

After Sir Joseph Banks had "discovered" Fingals Cave many famous visitors made their way there having added it to their itinerary on their Grand Tour of Scotland. Barthelemy Faujas de Saint Fond, the French geologist visited the island in 1784 in the company of James Smithson then a geologist and mineralogist, who later funded the Smithsonian Institution in Washington, of which more later. They were accompanied by the artist William Thornton (Fig. 22).
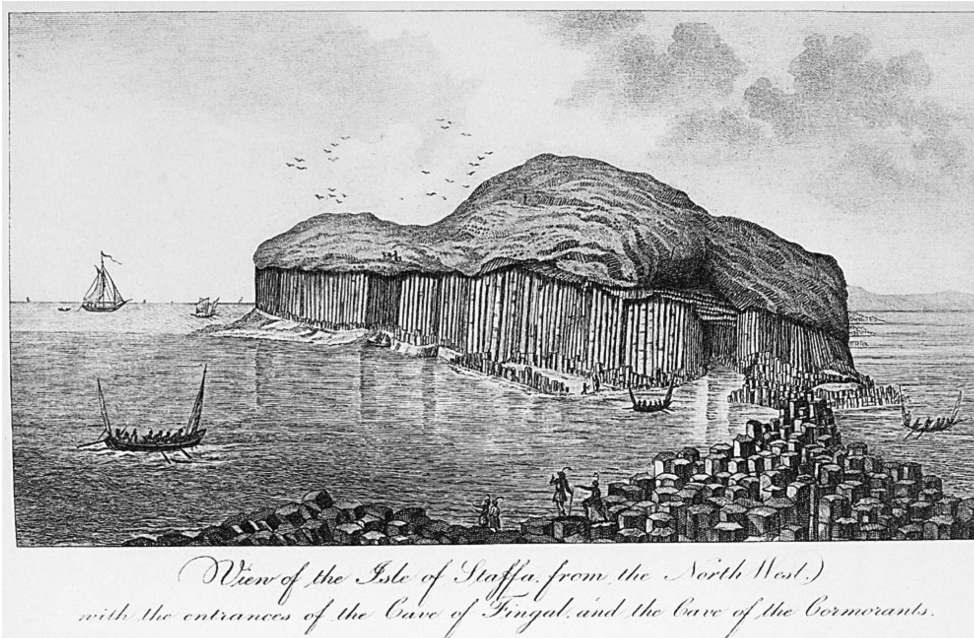

Fig. 22. View of the Isle of Staffa from the north-west, William Thornton, 1784

Sir Walter Scott made trips to the island in 1810 and 1814 and declared it to be "…one of the most extraordinary places I ever beheld." He made all his knowledge of Scotland available to William Daniell as to where to go and what to see during his "Voyage".

John Keats, the poet, visited in July 1818 and wrote

On visiting Staffa. William Wordsworth visited in 1835 and Alfred Lord Tennyson in 1853.

J.M.W. Turner, the painter, made the journey in 1830 as part of a commission from Sir Walter Scott to provide drawings to illustrate *The Lord of the Isles* and C.L.F. Panckoucke also visited by steamer in 1830 (Fig. 23).

One of the visitors who left a lasting legacy was Felix Mendelssohn (Fig. 24) who, aged 20, sailed with his companion, Klingemann, on 7th August 1829. Despite being violently seasick the opening bars of a piece of music came into his mind. He returned to Germany where he developed the sketch into an overture *The Lonely Island*. Later

Fig. 24. Composer, Felix Mendelssohn

he rewrotethis and it became The *Hebrides Overture (Fingals Cave) Opus 26*. Without doubt this is the best known piece of cave music in the world and it contributed to the increased popularity of the island and the cave. Staffa and the picturesque grandeur of Fingals Cave went on to become the object of scientific study, particularly in Victorian times.
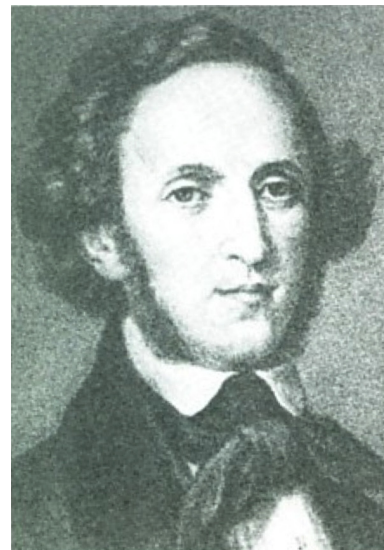
Jules Verne visited in 1859 and some years later he published *Le Rayon Vert* or *The Green Ray* in which the climax of the story takes place on Staffa. Robert Louis Stevenson visited the island more than once, including in 1885.

There were also Royal visitors: the King of Saxony visited in 1844 and Queen Victoria and Price Albert sailed to Staffa in the Royal Yacht on 19th August 1847, Queen Victoria recording in her diary "…when we turned the corner to go into the renowned Fingals Cave the effect was splendid, like a great entrance into a vaulted hall…" (Fig. 25).
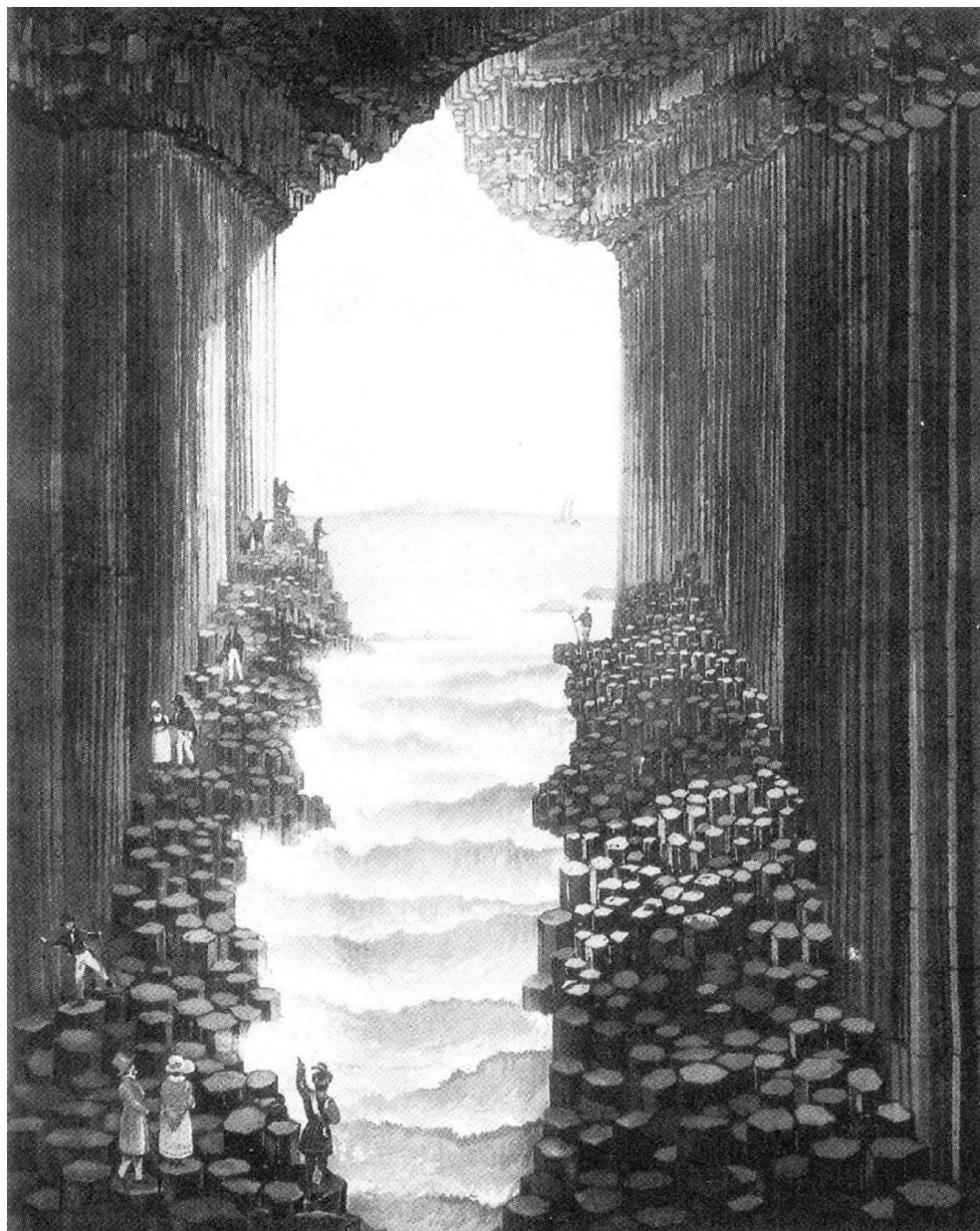
Fig. 23. Panckoucke: Interior of Fingals Cave with figures in foreground, from 'Voyage Pittoresque aux Îles Hebrides' Paris 1831.

The royal party visits Fingal's Cave.

Fig. 25. The royal party visits Fingals Cave.

Mass tourism (Fig. 26) began in the 1820s when a paddle steamer, based in Glasgow, started making weekly voyages with 300 passengers being put ashore in the ship's boats. At the height of the Victorian era a piper was employed to play in the depths of the cave to give additional "atmosphere". In 1935 an 800-passenger turbine steamer landed passengers on calm days by ferrying them in launches. The landings ceased in 1967 due to the time it took and the anxiety about rock falls.

On 29th August 1884, two tourists were washed off the narrow causeway in Fingals Cave, by heavy seas which caught them unawares, and drowned. They happened to be at the lowest point of the causeway with their backs to the cave entrance when a large wave swept their feet from under them, and they slipped under the lower guide rope and over the edge of the causeway. At that time there were no life-saving appliances in the cave, and the tourists had been landed from the paddle steamer *Chevalier* at the North end of Staffa. Consequently there was no boat at hand; otherwise they might have been rescued. They were Scotland's first recorded caving fatalities.

Some Early Geological Investigations

Bartelemy Faujas de Saint Fond was the first to recognise the volcanic nature of the basaltic columns of Fingals Cave in 1874. He studied law at Grenoble and became an *avocet*. Although he had a wide general scientific knowledge he was first and foremost a geologist. In 1778 he established his reputation with a treatise on the volcanic nature of hills. It was the account by Joseph Banks of Staffa that Thomas Pennant had included in his *Tour of Scotland* that stimulated him to set out for Scotland. Towards the end of August 1784, with William Thornton, a
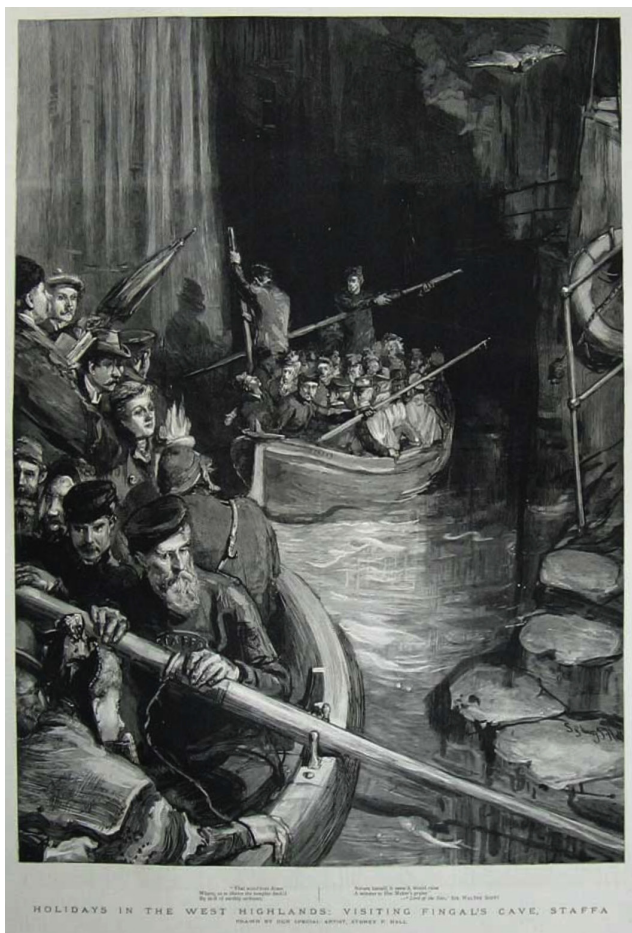
Fig. 26. Mass tourism at Fingals Cave - from The Graphic, 1892

wealthy American (who drew the illustrations for Faujas' account) and two others, left London in three post-chaises. In late September Faujas landed on Staffa and with local guides visited Fingals Cave. To avoid slipping he took off his shoes and made his way barefooted to the back of the cave, measuring as he went and not forgetting to break off geological specimens. He conscientiously measured the length and breadth of the cave, its height from sea level, the depth of the sea inside the cave and the roof thickness. All measurements were taken with a piece of thread-tape, painted and waxed, divided into French *toises*, feet and inches, and rolling up into a leather case which he had specially made in London.

"I have seen many ancient volcanoes; I have described and made known some superb basaltic causeways and fine caverns in the midst of lavas; but I have never found anything which comes near this one, or can be compared to it, for the admirable regularity of the columns, the height of the arch, the situation, the forms, the gracefulness of this production of nature, and resemblance to the master-pieces of art: although art has had no place here."

Faujas' book with engravings was published in Paris in 1797 and in London in 1799. The delay in publishing was due to losing all his geological specimens which

sank in the Channel, together with the outbreak of the French Revolution!

Although there had been various descriptions of Staffa published by naturalists and tourists, including Saint Fond detailed above, the first geological account was by John MacCulloch MD, FLS, Chemist to the Ordnance, Lecturer on Chemistry at the Royal Military Academy at Woolwich, and Vice President of the Geological Society of London. He was born in 1773 and was one of the outstanding geologists of his day. After a brief spell as a practising physician, he became Chemist to the Board of Ordnance, and in this capacity, and later as Geologist to the Trigonometrical Survey, he undertook a series of geological surveys in Scotland which gave him a detailed knowledge of Scottish geology. He wrote "On Staffa" in the Geological Society's Transactions, Volume 2, published in 1814. Of the 24 papers in that volume, nine are by him. From his paper on Staffa:

"It is superfluous to attempt a description of the great cave. The language of wonder has already been exhausted on it, and that of simple description must fail in an attempt where hyperbole has done its utmost. I may however remark, that its dimensions appear to have been over-rated, in consequence of the mode of measurement adopted, and that the drawings of it which have been engraved, give it an aspect of geometrical regularity which it is far from possessing. Its superiority in point of effect to the greatest efforts of architecture, might admit of dispute if there were any disputing about feelings. …… Large fissures are seen above this cave, with an incipient detachment of considerable masses, threatening a ruin which is perhaps not far distant. Beyond this there is still another cave which appears to pass through the promontory in which it lies, but equally or even more difficult of access, and still involved in uncertainty. Many other caves of less note are to be seen in various parts of the cliff around the island, into which the sea breaks with a noise resembling that of heavy and distant ordnance."

He was undoubtedly a man of talent and he wrote many papers published by the Geological Society. He died in 1835.

William Daniell in 1816 quotes extensively from MacCulloch, whose work he describes as "a very able paper". He even includes a resume of the theories to date as to the mode of formation of columnar basalt and adds his own views:

"Respecting the formation of these masses, it may not be uninteresting to cite the hypotheses which have been proposed, without, however, presuming to decide as to their merits, or to enter into the general

discussion of a question which belongs to philosophers alone. M. Desmarets, an eminent mineralogist, is said to have been one of the first who considered basaltes as a volcanic production, and gave it as his opinion that they were produced by currents of volcanic lava. From all the circumstances which he had observed in the course of an extensive tour, he concluded that basaltic columns were formed by the gradual refrigeration of a mass of fluid lava during its slow and retarded progress over the subjacent soil. In the year 1776, Ferber declared, that from every examination of volcanic productions in which he had been engaged, he had been led to the same conclusion. Mr Raspe, in the same year, gave it as his opinion that prismatic basaltes should be looked upon as currents of lava, cooled by sea-water, or cooled of themselves under ground. It was likewise the opinion of Buffon that when a current of lava arrived at the margin of the sea, the water, by its immensity, by the resistance of its cold, and by its power of arresting and extinguishing fire, soon consolidates the torrent of burning matter, which can proceed no farther, but rises up, accumulates new strata, and forms a perpendicular wall. Here it will be asked, by what law of nature could this consolidation of a river of liquid fire assume the characteristics of crystallization. Aggregates of basaltes are in this instance, as well as in that of the Giant's Causeway, and many others, found near the sea, but they occur also in situations at a remote distance from it, where such a process of refrigeration could not take place. The difficulty arising from this consideration has been disposed of, by concluding that basaltic prisms have been formed by lava, or a matter similar to it, in fusion in the bowels of the earth, and left to cool slowly. The matter, when cooled and indurated, is supposed to have contracted or split into several parts. 'A mass of lava' says Dr Garnett, 'in the interior parts of the earth, cooling gradually, contracts and forms these pillars; they seem to have been produced exactly in the same way as prisms of starch, to which they bear a strong resemblance. As the water evaporates or escapes, the prisms of starch are formed by the contraction of the mass; and as the caloric escapes from a mass of fluid lava, prisms of basaltes are produced.' This author, therefore, deems it probable that the island of Staffa is a small relic of a subterraneous collection of pillars, which have been laid bare by the violence of the sea, or perhaps by some of the adjacent parts giving way. He justifies this supposition from the general appearance of the island, which is that of having sloped gradually to the water's edge, until the disruption of its sides was effected by the continual beating of the Atlantic. The pillars, he observes, are not confined to the exterior surface of the island, which would have been the case had they been formed of lava cooled by flowing into the sea; they extend into the great cave as far as it has been explored, and probably the whole island consists of them."

Much later that century, in the 1880s, some unconventional alternative geological theories were put forward. F. Cope Whitehouse, a well-known American Egyptologist, at a meeting of the British Archaeological Association (BAA) in 1881, states he consulted some members privately about a paper he proposed to read before the British Association for the Advancement of Science. In the BAA Proceedings June 1886, pp.247-250 he observes that four pictures of Fingals Cave in geological works written by distinguished authors do not bear the slightest resemblance to each other or the object. After criticising each in turn he puts forward a doubt as to whether the seven holes [caves!] on all sides of the island can have been made by the sea. If not sea-caves are they artificial? And if made by man, by what race? He suggests the Society should discuss and decide such a question.

It would appear this unconventional view may have come to the attention of the United States National Museum under the direction of The Smithsonian Institution, Washington, DC as in April 1887 they asked Prof. J.P. MacLean who was intending to examine Fingals Cave to consider "It seems incredible that any one should suppose these caves to be the work of man". Prof. MacLean duly reported later in 1887 but had found nothing to support that the caves were the work of man.

Meanwhile Cope Whitehouse, who had visited Staffa in 1885, developed the subject of discovery, visits and engravings at considerable length in the *Scottish Geographical Magazine*, October 1887. He then goes on to consider the erosive power of Atlantic breakers, including observations as to the force during the construction of the Skerryvore Lighthouse in 1843/44 and concludes that it is inconceivable that the edges of the entrance to Boat Cave have been exposed to the constant lashing of the Atlantic. He then goes on to consider the major caves in turn and sets down 39 reasons why the caves are not worn by the sea, and concluded that the caves may have been excavated by the Phoenicians to harbour their galleys.

Recent Exploration

The island of Staffa was in private ownership, part of the Ulva Estate and owned by the McQuarrie family until the early 19th century after which it changed hands several times in the next 150 years. It was designated a Site of Special Scientific Interest (SSSI) in 1973 and in 1986 it was gifted to the National Trust for Scotland by the then owner, John Elliot Jnr., of New

York, as an imaginative way to celebrate the birthday of his wife who was declared Steward of Staffa for her lifetime. The island became a National Nature Reserve in September 2001, courtesy of Scottish Natural Heritage. Access to the island is restricted to outside the seabird breeding season.

Surprisingly no detailed examination had ever been made of the various sea caves round the coast although Donald MacCulloch, who wrote four guidebooks to the island between 1927 and 1975, listed eight caves.

The Grampian Speleological Group put forward to The National Trust for Scotland and Scottish Natural Heritage a proposal to survey and photograph five sea caves and examine some of the columnar detail around Fingals Cave. Permission was granted for 5 days camping on the island in the summers of 2005 and 2006. The first party consisted of Bob Mehew, the late Tony Jarratt, Vern Freeman, Tony Boycott, Duncan Butler and John Crae and the second Bob Mehew, Tony Boycott, Duncan Butler, John Crae, Lucas Goehring, a Canadian PhD student, and Martin and I joined them for three days on our way home from a visit to Iceland. The island is very busy during the day between 10.00 am and 4.00 pm when the various tourist boats have landed their passengers, but once they leave in the late afternoon it is extremely peaceful sitting out in the heather in the evening sunshine.

Fig. 27. The Grampian Speleological Group party on the Staffa jetty, 2006.

During the first visit the main caves were located, photographed and surveyed although not all of the lesser caves were named and surveyed until the second visit. All features were noted, including rock shelters and natural rock arches. Access to the caves was not always easy as not all were accessible round the shoreline even at low tide, so a number of methods were used including swimming, boating and even setting up a 'tyrolean' across the entrance to Fingals Cave (Fig. 28). Life jackets were added to personal caving kit and other useful equipment included an

Fig. 28. J-Rat using the Tyrolean traverse across the mouth of Fingals Cave.

extending sectional metal ladder to move more easily up and down some of the sea cliffs and to reach the upper levels of McKinnon's Cave where normal climbing methods had been ruled out due to excessive amounts of seabird guano on the ledges (Fig. 29).

Fig. 29. Looking at the upper levels of McKinnons Cave.

Apart from the well-known caves, Fingals, McKinnons, Cormorants, Clamshell, Boat Cave, Horse Cave, Gunnar Mor (Fig. 30a, b) and Gunshot Cave, a further 7 caves and 8 rock shelters, a couple of short passages and a natural rock arch were noted and surveyed (Fig. 31). Many of the basalt columns were also measured and photographed, leading to the production in 2006 by the Grampian of a 2CD set: *The Sea Caves of Staffa: A Baseline Report V1a.*

It was a great privilege to be invited to join the second visit to the island and an experience to be long remembered. The scenery on and from the island is magnificent (Figs 32, 33), the campsite chosen was idyllic. There is a freshwater spring which is usable with care and this would have allowed previous occupation of the island.

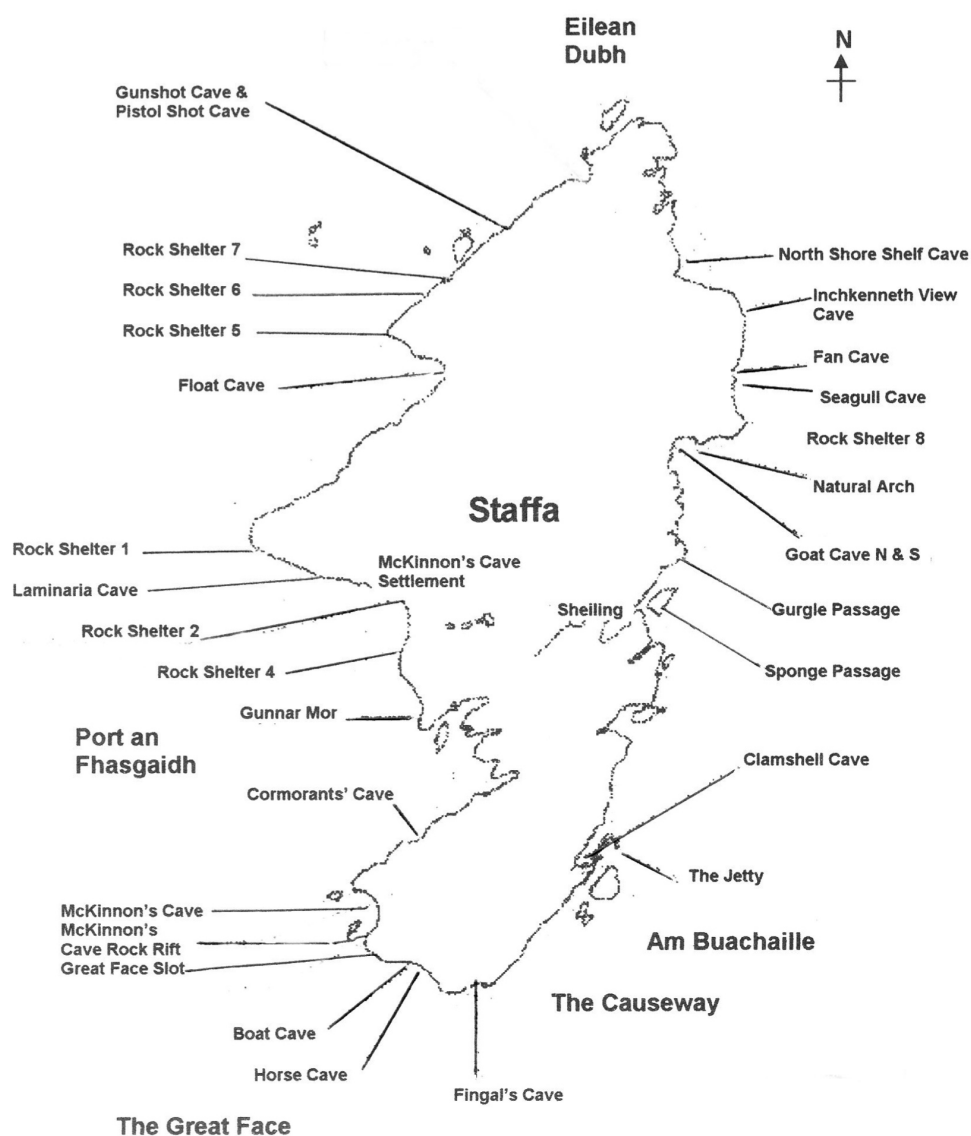*Fig. 30a, b. Gunnar Mor, Staffa – might this be Scotland's only lava tube cave?*

Fig. 31. Map showing results of cave exploration and documentation on Staffa in 2005 and 2006 by GSG.

Fig. 32. View along cliffs to Dutchmans Cap in distance.

Fig. 33. Boat Cave & Horse Cave entrances from the sea.

Sadly all too soon it was time to pack up and leave for home. Thankfully the crossing this time was not as rough as on the way out.

We did wonder what would have happened had Fingals Cave been either more easily accessible or for that matter, more remote. Would it still have been part of The Scottish Grand Tour or hardly visited at all?

This presentation came about from a comment at the XIIIth International Symposium at Jeju Island, South Korea in 2008, that the UK does not have any lava caves. However it does have the most famous basalt cave in the world.

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Caves Formed in the Volcanic Rocks of Hungary
Part I: Caves formed in Rhyolite, Rhyolite Tuff, Rhyodacite Tuff, Dacite, Andesite, Andesite Agglomerate and Andesite Tuff

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Abstract

Organised research into the non-karst caves of Hungary, relating to the study of caves formed in volcanic rocks, began in 1983 with the launch of the Volcanspeleological Collective. Their comprehensive activities are still ongoing. The organisation, led by István Eszterhás, consists of a nucleus of 15 persons, who are occasionally joined by several more cavers. They have listed 894 non-karstic caves, and surveyed 741 of them. In 40 caves they have dug and discovered nearly 1000 m of new cave passages. They have studied the development of the non-karstic caves, and have determined new types of cave development (consequence caves, holes formed by alkaline solution, fumarole cavities). They have identified and described speleothems previously unknown in Hungary, such as silica stalactites and isingerite discs. They have solved the problem of ice development in low elevation basalt caves. They have classified 200 species of animals and 18 species of fungi (some of them are unusual) which are to be found in the caves. The results have been summarized in 7 separate volumes and in 160 articles mainly in Hungarian, but occasionally in German or in English. The majority of the non-karst caves in Hungary, numbering 669 caves, developed in volcanic rocks. The study reviews, in two parts, the most important achievements resulting from research on these caves. The first part presents the caves formed in rhyolite, rhyolite tuff, rhyodacite tuff, dacite, andesite, andesite agglomerate and in andesite tuff.

1. Introduction

In Hungary as well as 2800 karst caves, 894 non-karst caves are listed (Bertalan 1958, Eszterhás 2005, Eszterhás & Szentes 2004-2009, Ozoray 1952). Among the non-karst caves, 669 have developed in volcanic rocks. The first part of this study summarizes the 531 non-karst caves, which have formed in rhyolite, rhyolite tuff, rhyodacite tuff, dacite, andesite, andesite agglomerate and in andesite tuff. The majority of the caves are between 2 and 10 m long, but some are more extensive and have developed in an atypical manner. The longest non-karst cave in Hungary, the 428 m long Csörgő Hole in the Mátra Mountains, has developed in rhyodacite tuff. Detailed information on the caves in rhyolite, rhyolite tuff, rhyodacite tuff, dacite, andesite, andesite agglomerate and in andesite tuff can be viewed on the website http://geogr.elte.hu/non-karstic using either Netscape or Mozilla browsers. The list is updated every year (Eszterhás & Szentes 2004-2009).

2. Geological locations of the rhyolite, dacite and andesite formations

The main landscape of Hungary consists of the Great Hungarian Plain, the Small Plain, the North Hungarian Mountains, the Transdanubian Central Mountains, the Transdanubian Hills and Island Mountains and the pre-Alps. In the present study we discuss only those landscapes where caves are to be found in the volcanic formations. The Devonian, Permian, Jurassic and Cretaceous quartz porphyry, diabase and dolerite occurrences in the Bakony, Mecsek and in the Mátra Mountains are negligible as regards cave development.

Significant andesitic volcanism took place in the Middle and Upper Eocene, which resulted in the formation of amphibole andesite, andesite agglomerate and tuff in the Velencei and in the Mátra Mountains. The caves of the Pázmándi Cliffs in the north-eastern part of the Velencei Mountains formed in andesite agglomerate. Volcanic activity in the Miocene produced extensive rhyolite, dacite, andesite masses and their tuffaceous formations in the Visegrádi-, Börzsöny-, Mátra- and in Eperjes–Tokaji Mountains. The majority of the caves are to be found in these sequences. Part of the Cserhát Mountains and the Bükk Region are also composed of similar sequences (Fig. 1).

The key horizon in the North Hungarian Mountains is the Lower Miocene Ottnangian light grey pumiceous rhyolite tuff referred to as Lower Rhyolite Tuff in geological literature. In the Carpathian and Badenian Stages significant andesite volcanic activity and tuff deposition occurred. The rhyodacite tuff, referred to as Middle Rhyolite Tuff divides the Lower and the Middle Andesite Formations. The final stage of andesite volcanism is characterised by dark grey piroxene andesite. Andesite volcanism was accompanied by rhyolite intrusions in the Mátra and Eperjes-Tokaji Mountains. Little Miocene dacite occurs in the Börzsöny and Mátra Mountains.

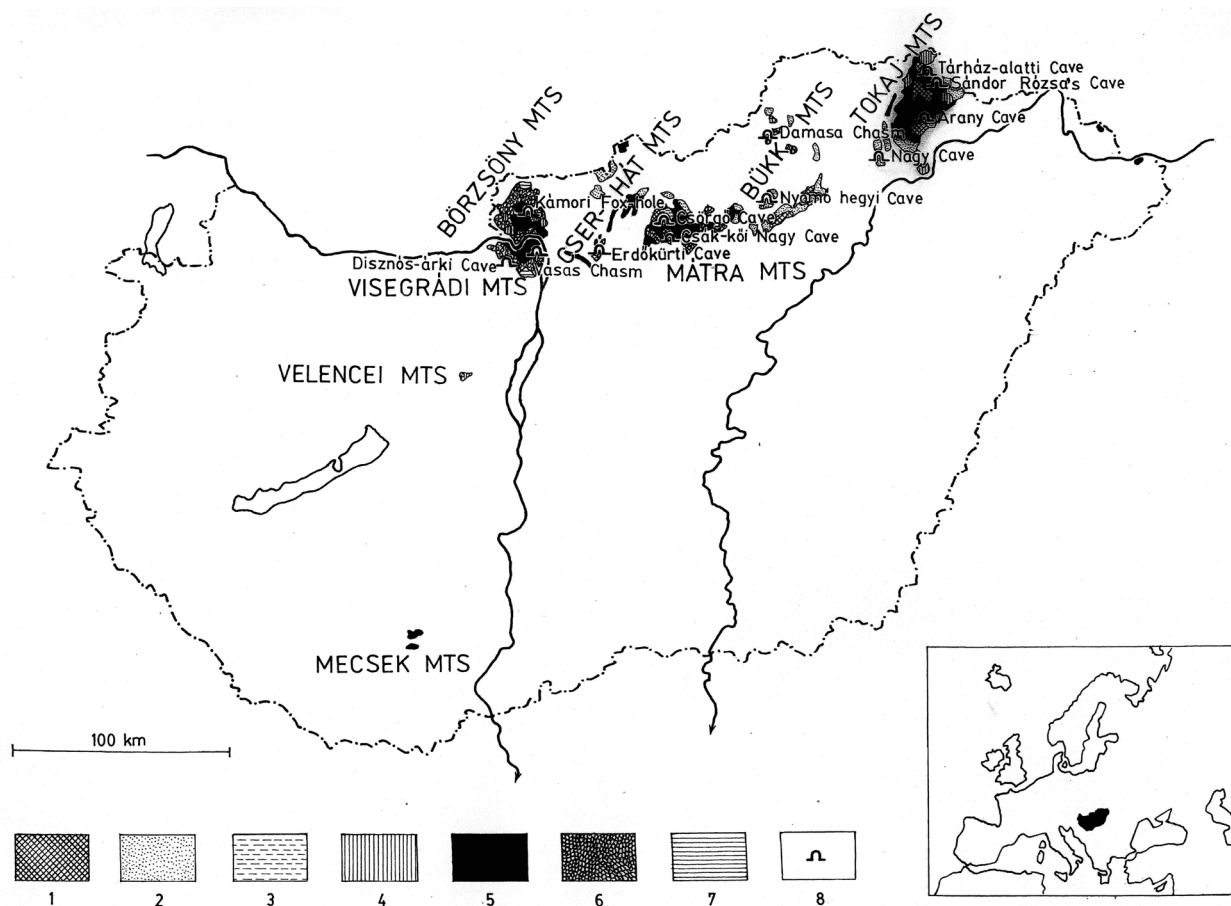The Visegrádi Mountains have formed from a Miocene

Fig. 1. Caves formed in rhyolite, dacite, andesite and in their tuffs in Hungary, showing the most remarkable caves in the formations. 1. rhyolite, 2. rhyolite tuff, 3. rhyodacite tuff, 4. dacite, 5. andesite, 6. andesite agglomerate, 7. andesite tuff, 8. remarkable cave

stratovolcano which has been strongly denuded and dissected along fault lines. It is composed of andesite agglomerate, andesite tuff and subordinately compacted andesite. The Börzsöny Mountains are mainly made up of the denuded residual of a Miocene stratovolcanic blanket. In the middle section a collapsed caldera can be proved. The major part of the landscape consists of low hills formed of sediments. In the middle and eastern areas of the mountains andesite rift volcanoes, andesite agglomerate and andesite tuff appear. The base of the Medves-Ajnácskői Mountains is composed of a denuded Miocene sedimentary formation. The mountains have witnessed a great deal of basalt volcanic activity, though this activity began with two andesite laccolith intrusions. The Mátra Mountains comprises of a stratovolcanic group with several eruption centres. The eruptions happened in the Miocene and have resulted in various formations of lava rocks and pyroclastics. Volcanic tuff deposition has covered large areas in northern Hungary. Thick tuff and the andesite agglomerate layers have accumulated in the margins of the karstic Bükk Mountains, and it is here that several non-karst cave caves have developed. The andesite agglomerate also outcrops also on the rim of the Sajó Basin. Intense volcanic activity took place in the Eperjes-Tokaji throughout the Miocene.

The oldest sequence is composed of andesite, andesite agglomerate and tuff, while the younger formation is of rhyolite, rhyolite tuff and subordinate dacite and dacite tuff (Juhész 1987, Fig. 1.).

3. The most significant caves and their genotypes which have formed in rhyolite, dacite, rhyolite tuff and rhyodacite tuff

Three caves have formed in rhyolite in the Mátra Mountains, one small crevice cave, one small pseudo cave and the Csák-kői Big Cave. The Csák-kői Big Cave can be found in a former millstone quarry near the village of Gyöngyössolymos. It consists of a large cavity in hyolite, caused by breakdown and thus is a consequence cave (Fig. 2; Fig. 3). There are two distinct parts to this cave. The southern part is the original quarried chamber and consequently this is an artificial cavity. On the other hand the northern part, a long labyrinth, has resulted from natural breakdown and has developed as a natural cave. There are six entrances to the artificial cavity and to the natural cave. The length of both parts is 113 m.

Thirty one caves between 2 m and 40 m long have formed in rhyolite and perlite in the Eperjes-Tokaji

CSÁK-KŐI BIG CAVE

PLAN

Surveyed by: 07 - 11. 07. 1991.
I. Eszterhás,
I. Gönczöl,
T. Gönczöl,
Á. Katapán,
Zs. Sivó,
Gy. Szarka

Enclosing Rock: Rhyolite
Length: 133.0 m
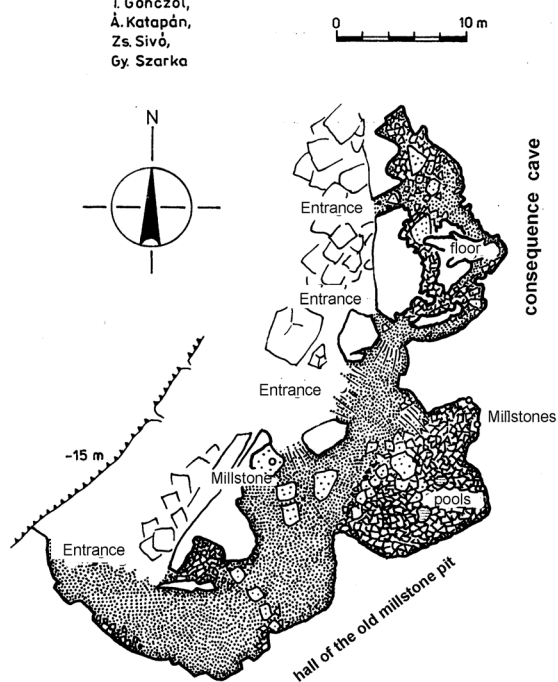Level difference: 14.5 m

0   10 m

*Fig. 2. Survey of the Csák-kői Big Cave in rhyolite
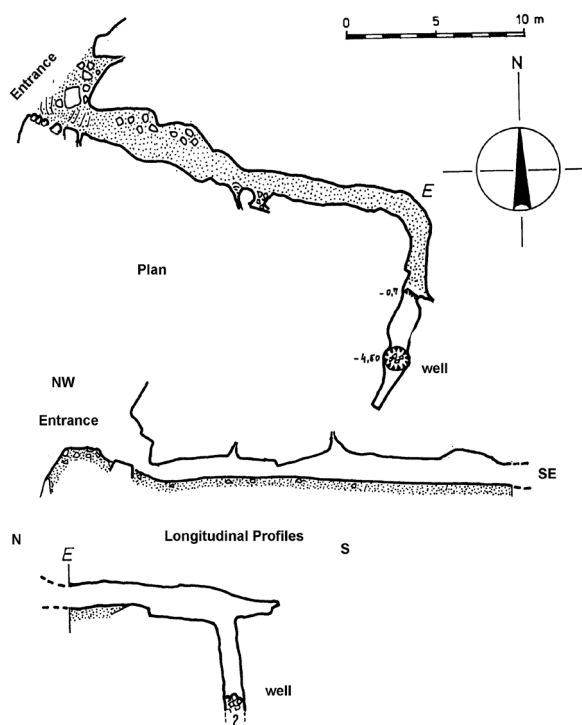Mátra Mountains.*

CAVE OF THE REGÉCI CASTLE

*Fig. 4. Survey of the Cave of the Regéci Castle,
Eperjes-Tokaji Mountains.*

Fig. 3. Csák-Kői Big Cave in rhyolite, Mátra Mountains

Mountains. The 13 m long Cave Beneath the Garnet near the village of Füzér developed along fault lines as a result of movement. The 29 m long Iván Cave to the north of Erdőbénye village has formed as a result of extension, which was caused by the termination of lateral pressure in the rock masses. Small rock shelters developed as a result of lateral erosion, for instance the 2-3 m deep Rock Shelter below the Castle of Kőkapu.

*Fig. 5. Cave of the Regéci Castle in dacite,
Eperjes-Tokaji Mountains*

Only in the Eperjes-Tokaji Mountains have caves formed in dacite. There are 28 caves between 2 m and 40 m in length. The longest cave in dacite is the 40 m long Regéci Castle Cave (Fig. 4, Fig. 5). Only the first 20 m is natural cave passage, formed as a result of weathering along the fault line. The rest of the cave has been artificially widened and a well has been dug at the end. The 11 m long through cave, Desem Cave was formed by rock extension (Eszterhás 1993).

In northern Hungary, 38 caves have formed in rhyolite tuff and rhyodacite tuff. The petrographic difference between rhyolite tuff and rhyodacite tuff is minimal, therefore we present collectively those caves which have formed in these rocks. In the Mátra Mountains one small cave has developed in rhyolite tuff and 6 caves have formed in rhyodacite tuff. The rhyodacite tuff, referred to as Middle Rhyolite Tuff, is speleologically important because the longest non-karstic cave in Hungary, the 428 m long Csörgő Hole has formed in rhyodacite tuff (Eszterhás 2003a). The Csörgő Hole is an atectonic labyrinth (Fig. 6).

CSÖRGŐ HOLE

Fig. 6. Survey of the Csörgő Hole, the longest non-karst cave in Hungary, Mátra Mountains.

The development of the cave can be traced back to the continuous sliding of the rhyodacite tuff and the consequent aggradation. The boulders have slid south-eastwards on a 20° slope, therefore between the accumulated boulders passages have formed following a NE - SW strike. Because of the continuous sliding of the boulders, the size and form of the cavities are still subject to frequent change. This cave consists of a complicated labyrinth with several chambers, passages of varying lengths, and shafts (Fig. 7).

Fig. 7. Csörgő Hole in rhyodacite tuff, Mátra Mountains.

The 15 m long Macska Cave can be found in the Gorge of the Macska Valley. The cave was developed by rock extension in rhyodacite tuff. After the deepening of the gorge, its steep, backward sloping side lost its lateral support and thus tension occurred in the rock mass. Later the rock cracked and the blocks separated from one another, forming a cave-sized fissure. The Macska Rock Shelter is a cavity the Macska Valley. The rock shelter was shaped by erosion in rhyodacite tuff below a waterfall.

Nearly one thousand artificial caves, mainly former cave-dwellings and cellars, have been excavated in rhyolite tuff in the Bükk Region. Ten small natural caves have been formed in rhyolite tuff. The biggest is the 16 m x 18 m Nyomó-hegyi Cave (Fig. 8), which has formed as the result of fragmentation of rhyolite tuff . There are also tectonic caves such as the 13 m long Haramia Pit.

Twenty two caves have formed in rhyolite tuff in the Eperjes-Tokaji Mountains. The most spectacular

Fig. 8. Nyomó-hegyi Cave in rhyolite tuff, Bükk Region.

is the 50 m long Arany Cave (Fig. 9; Fig. 10) near the village of Tállya. The entrance to this partly collapsed horizontal cave has developed in a complex manner. Originally it was formed along a fissure by an underground stream. The natural passage was widened to accommodate a mining tunnel in the 17th century when ore prospecting was in progress. Later, the first part of the tunnel collapsed but was subsequently re-opened in 1993. There is a slow running, knee deep, stream in the cave. The roof is nicely decorated with a large number of 20-40 cm long silicate stalactites.

Fig. 10. Arany Cave in rhyolite tuff, Eperjes-Tokaji Mountains.

Fig. 9. Survey of the Arany Cave, Eperjes-Tokaji Mountains.

Alkaline solution has been responsible for the formation of ten caves in the Miocene rhyolite tuff of Mount Fuló near the village of Legyesbénye. There the 25 m long Big Cave, and the 13 m long Small Cave are the most spacious. The seeping alkaline hot spring

water has resulted in siliceous precipitation in the rhyolite tuff. After the pH of the water exceeded 9 the process was reversed, and the precipitated silica was dissolved. As a result of this, natural holes developed in the tuff. The Somosi Hole, near the village of Golop, despite being a cellar, can be considered as a natural cave in the rhyolite tuff, because the break down of the cavity displays the initial phase of consequence cave formation.

4. The most significant caves and their genotypes which have formed in andesite, andesite agglomerate and andesite tuff

Four hundred and thirty-one caves in Hungary have formed in andesite, andesite agglomerate and andesite tuff.

Two caves have developed in compact andesite in the Visegrádi Mountains. The 13 m long Dömörkapui Cave is a consequence cave, which is a result of the break down of a mining tunnel. The 4 m x 8 m wide Csódi-hegyi Cave is believed to be a syngenetic cave. Five smaller caves have developed in andesite in the Börzsöny Mountains. The most significant is the 10 m long Andesite Cavity in the Rózsa Mine. The cave is a syngenetic crystal cave, which was opened by ore mining operations to a depth of 92 m. Five caves are to be found in andesite in the Cserhát Mountains. As a consequence of intense Miocene volcanic activity, the syngenetic caves of Függő-kői Cave, Double Hole and

the Sámsonházi Bubble Cave are syngenetic caves, which were formed by steam explosion (Szentes 1971). The Sárkányfürdő Cave was developed in andesite by the lateral erosion of the Cserkúti Creek.

Twenty-one caves open in compact andesite in the Mátra Mountains (Eszterhás 1996). There are two different types of syngenetic holes. In the abandoned and flooded Gyöngyösoroszi Mine, four crystal caves were found at a depth of several hundred metres. The caves were formed on the edge of an ore dyke and the tracyandesite as a result of the influence of the ascending hot solutions. The cave walls were covered with spectacular crystals, mainly of amethyst. Unfortunately after their discovery the crystal caves were looted and filled with debris. Gas bubble cavities, the Gyula Cave, the Kis Gyula Cave and the Vidróczki Cave are to be found in andesite near the villages of Mátrakeresztes and Mátraszentimre. The Gyula Cave has archaeological significance. The other caves in andesite are 2–5 m long crevices or rock shelters (Eszterhás 2003b).

One hundred and ninety-eight caves have formed in andesite in the Eperjes-Tokaji Mountains. The majority of these caves are between 2 m and 5 m long. Three andesite caves are longer than 20 metres. The longest is the 45.6 m long Rózsa Sándor Cave. The cave was developed by rock extension. The 31.5 m long Difficult Through Cave is a combined fissure which developed along several vertical crevices near the village of Háromhuta. The smaller caves exhibit some interesting characteristics regarding their formation and subsequent development.. Only one syngenetic cave, the Upper Cave, is to be found in this locality, and this is in Sárospatak town. This cave is a fumarole shaft. The 14 m long Bárány-hegyi Cave near the village of Boldogkőváralja has developed as a the result of rock fragmentation. Several caves have been formed as a consequence of loosening of the rock, along the bedding planes. These caves include Lőállás Cave near the village of Mogyoróska and Holyca Cave in the Tekeres Creek Valley. There are also some pseudocaves, such as Boldogkővári Hole and Labyrinth Cave near the village of Középhuta.

Many caves have formed in andesite agglomerate in the andesitic mountains, but in the Börzsöny and Visegradi Mountains only a few caves are to be found in andesite tuff.

Six caves have been found in the Eocene andesite agglomerate of the Velencei Mountains. The 7 m long Szedres Cave and Crevice Cave are tectonic caves near the village of Pázmánd. The 7 m x 6 m wide Maléza Cave and three other small caves are pseudocaves which were formed amongst the boulders at the above-mentioned location.

Sixty two caves have formed in andesite agglomerate in the Visegrádi Mountains. The longest cave is the 60 m long Disznós-árki Cave near the village of Pilisszentkereszt, which formed as a result of the sliding of broken rock layers and the consequent aggradation (Fig. 11). Nine other caves are longer than 10 metres. There are also syngenetic fumarole tubes, such as the Maria Cave, Ablakos Cave and the Csikóvári Tube Cave.
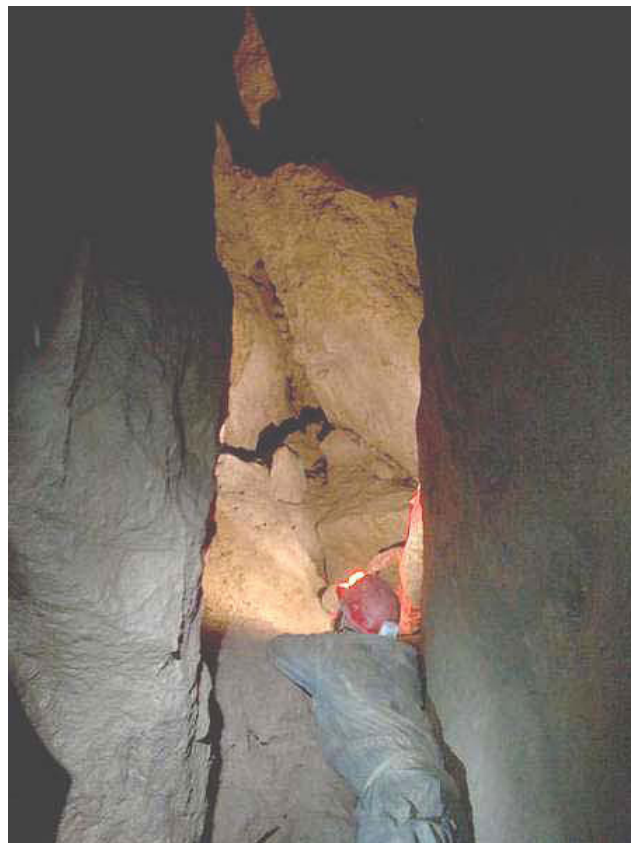

Fig. 11. Disznós-árki Cave in andesite agglomerate, Visegrádi Mountains.

Many different types of postgenetic caves have been identified. These include four caves between 25 m and 50 m long in the Vasas Chasm (Fig. 12; Fig. 13), whilst at Mount Kő, near the settlement of Dobogókő, the Egres Cave and the Bubia Cave have formed as a result of tectonic movement. The Őz Cave is a pseudocave located in the agglomerate boulders. The Rock Shelters of the Rám Chasm are typical erosional caves. Ten caves occur in andesite tuff. Sas-kövi Cave near the town of Szentendre is 63 m long, but the origin of the cave is in dispute as some say it is an artificial hole. The 16 m long Domini Cave is a pseudocave located in the andesite tuff boulders. The Karolina-árok Caves are lateral erosional caves.

Seventy-five caves have formed in the andesite agglomerate of the Börzsöny Mountains. These caves are generally small cavities, their average length being 4 m. Only 4 caves are longer than 10 metres. The thirty metre long Hermit Cave above the
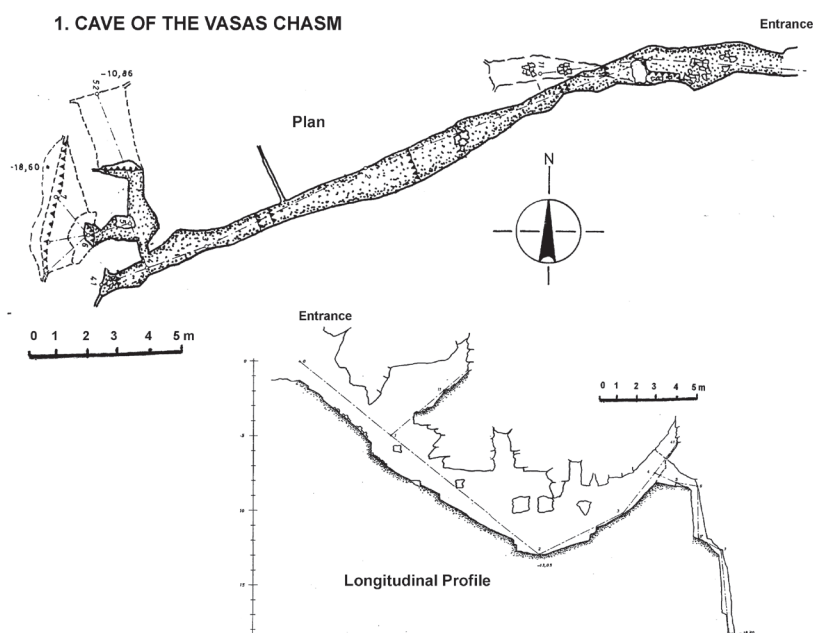
Fig. 12. Survey of Cave No. 1 of Vasas Chasm, Visegrádi Mountains

origin. Most of the caves in the Börzsöny Mountains are postgenetic. They were formed in andesite agglomerate by tectonic movement (Alsó-Rab Hole, Jancsi-hegyi Cave), either as a result of collapses along the bedding planes (Pléska Fissure Cave) or by the lateral erosion of a creek (Rakottyás-patak Cave, Pogány-völgyi Rock Shelter). Five caves occur in andesite. These are rock shelters, which were formed by lateral erosion, as instance the Itató-vízesési Rock Shelter.

One cave is known in andesite agglomerate in the Cserhát Mountains. The 21 m long Erdőkürti Andesite Cave opens in a quarry (Fig. 14; Fig. 15). It appears to be a syngenetic cave. On the swampy moorland falling hot volcanic gravel heated up the swamp water, pressure of the steam which was generated as a result of this caused a hollow to form in the andesitic gravel.

Fig. 13. Cave No. 1 of the Vasas Chasm in andesite agglomerate,Visegrádi Mountains.

village of Nagymaros has been artificially widened. The eighteen metre long Holló-kői-lámpás Cave is a pseudocave, formed amongst large boulders. The syngenetic Kámori Fox Hole was formed by the expansion and dissolving effect of ascending hot solutions in the semi-plastic lava rock. It is a 11.5 m long tube forming a horizontal cavity. The only 2 m long fumarole tube, Jókofág Cave, has a similar

Fig. 14. Survey of the Erdőkürti Andesite Cave, Cserhát Mountains.

Fig. 15. Erdőkürti Andesite cave in andesite agglomerate, Cserhát Mountains.

Twenty-five caves open in andesite agglomerate in the Mátra Mountains. The caves are small, less than four metres long fissures or rock shelters. The Tekeres-kői Rock Shelter near the village of Abasár and the 5 m long Holló-kői Fissure Cave should be noted.

The tuffaceous sequence of the Bükk Region partly consists of significant andesite agglomerate accumulation. The eleven caves of Damsa Chasm are atectonic caves, for example the 56 m long Táncterem-Lepkés-ág Cave, the 24 m long Hollow Fissure and the 21 m long Deep Fissure, where the formation is the result of a landslide in the andesite agglomerate near Bánhorváti village. The length of the other eight caves are between 3 metres and 13 metres.

One cave is known in the Sajó Basin, in the hill country to the north of the Sajó River, the Nagy-kő Hole. It opens in the northern hills 1 km from the village of Sajókaza. The 2.9 m long and 1 m high cave has developed as a result of tectonic movement in an andesite agglomerate cliff, which rises from its tuffaceous environment.

No caves were found in either andesite agglomerate or in andesite tuff in the Eperjes-Tokaji Mountains.

5. Mineralogical, Hydrological, Climatological, Biological and Archaeological Observations

Generally the non-karst caves in Hungary are poor in mineral content, but in some caves formed in volcanic rocks various mineral formations occur. The andesite cavities from the influence of the ascending hot solutions in the Mátra and Börzsöny Mountains were found during mining operations. Their walls were covered with large brilliant individual quartz, amethyst, baryte and celestite crystals and disseminated pyrite. Unfortunately, immediately after their discovery, the caves were looted.

In the Upper Cave near the town of Sárospatak, in the Hermit Cave near the town of Gyöngyös and in the Ablakos Cave near the village of Dömös, silicate encrustation (albite, anorthite, kaolinite) occurs. Many spectacular 5 cm -10 cm in diameter and 20 cm – 40 cm long, tridymite containing silicate stalactites are to be found in the Arany Cave in the Eperjes-Tokaji Mountains. In twenty andesite caves (e.g. Galériás Cave, Függő-kői Cave, Smirgli Cave and Alsó-Rab Hole) 3 mm -5 mm long butt-shaped grey silicate pisolites can be observed, composed of quartz, feldspar and mica.

Lateral erosion of the creeks has formed the Macska Rock Shelter in rhyodacite tuff, the Sárkányfürdő Cave in andesite and the Görgeteges Rock Shelter in andesite agglomerate. The Arany Cave has developed in rhyolite. From the cave a slowly flowing stream emerges. The water is acidic due to the decay of the pyrite. In the longest non-karst cave in Hungary, the Csörgő Hole. Several hydrological observations have been carried out. At a depth of 27 m the Vidróczki Spring emerges. The water shortly disappears between the blocks. The spring water was dyed with fluorescein and it appeared after 7 hours in the Vándor Spring on the surface, which lies 8 m deeper and 180 m away. When the Vidróczky Spring has a larger discharge it feeds a small lake in the Bat Chamber. The lake completely disappears at times when there is a low discharge from the spring. In the Surprise Chamber it is possible to hear the sound of a stream, but unfortunately it has not been possible to find the origin of this phenomenon.

The climatic conditions in the relatively small non-karst caves in Hungary do not show significant deviation from the surface climate. In the bigger caves the temperature is more or less constant throughout the year, relative to the annual average surface temperature. The exceptions are those caves that have developed in porous or detritic rock formations. Here evaporation on the large rock surface causes such a significant heat extraction that the surroundings are cooled below freezing point. The Csörgő Hole has formed in porous tuff blocks, therefore the average temperature in the lower part of the cave is +4ºC. The Cold Hole near the village of Pusztafalu has an average temperature +6.5ºC, because the cave has formed in porous dacite blocks. One of the five small ice caves which are to be found in Hungary is the Ice Pit in the Damsa Chasm. The cavity has developed in porous andesite agglomerate and the floor and the walls are covered with thick layers of ice. The Ice Tunnel near the village of Telkibánya is an artificial hole in rhyodacite gravel, but the conditions which have resulted in the formation of the ice are similar to those found in natural caves.

The fauna and the flora in non-karst caves do not show significant differences from those found in karst-caves, although variations in proportions found can be observed. For instance the proportions of the penicillin flora and the Lepidoptera fauna are higher than in the karst-caves. In almost every cave springtails (Collembola) occur, as do rove beetles (Staphylinidae), humpbacked flies (Phoridae), spiders (Araneidae), mosquitoes (Nematocera), small carrion beetles (Catopitae), butterflies and moths (Lepidoptera) and bats (Chiroptera). Troglophile butterflies – the herald moth *(Scoliopteryx libatrix),* the tissue *(Triphosa dubitata)* and the European Peacock *(Inachis io)* - use many non-karst caves as resting places in the daytime, as well as allowing the imago to overwinter

in the caves. Those caves, which are dens of foxes, badgers and woodland dormice, are infested with fleas (Siphonaptera). In the andesite caves, which open near water (e.g. Sárkányfürdő Cave, Pogány-völgyi Rock Shelter), the larvas of Caddisflies (Trichoptera) are abundant.

Palaeontological excavations have been carried out in only a few volcanic caves. The remains of 33 molluscs and 54 vertebrates were discovered in from the Függő-kői Cave in the Cserhát Mountains.

Archaeological remains occurred in 12 non-karst caves, which were formed in rhyolite, dacite and andesite. The oldest findings, Neolithic potsherds and lithic tools (flint obsidian), were excavated from the Big Cave near the village of Legyesbénye between 1910 and 1932. From the Big Cave artefacts from the metal ages were also discovered, as well as from the ancient times and from the Middle Ages. From the Gyula Cave in the Mátra Mountains 53 potsherds from the Bronze Age and from the 12th to the 15th century were excavated. In the Cave Beneath the Garnet at the Castle of Füzér many Middle Age potsherds originating from the castle and dating from the Middle Ages were unearthed. Neolithic potsherds and stone and metal tools were found in the Függő-kői Cave. From the Király Cave near the village of Szomolya 36 potsherds were unearthed, dating from the 12th to 13th centuries. Some caves on higher ground were modified into small fortifications or shooting boxes such as the three caves near the village of Arka in the Eperjes-Tokaji Mountains and the Lőállás Cave (Eszterhás 2003b).

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Caves Formed in the Volcanic Rocks of Hungary
Part II: Caves formed in Basalt, Basalt Tuff and Geyserite

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Abstract

Organised research into the non-karst caves, relating to the study of caves formed in volcanic rocks, began in 1983 with the launch of the Volcanspeleological Collective. Their comprehensive activities are still ongoing. The organisation, led by István Eszterhás, consists of a nucleus of 15 persons, who are occasionally joined by several more cavers. They have listed 894 non-karstic caves, and surveyed 741 of them. In 40 caves they have dug and discovered nearly 1000 m of new cave passages. They have studied the development of the non-karstic caves, and have determined new types of cave development (consequence caves, holes formed by alkaline solution, fumarole cavities). They have identified, and described, have speleothems previously unknown in Hungary, such as silica stalactites and isingerite discs. They have solved the problem of ice development in low elevation basalt caves. They have classified 200 species of animals and 18 species of fungii (some of them are unusual) which are to be found in the caves. The results have been summarized in 7 separate volumes and in 160 articles mainly in Hungarian, but occasionally in German or in English. The majority of the non-karst caves in Hungary, numbering 669 caves, developed in volcanic rocks. The study reviews, in two parts the most important achievements resulting from research on these caves. The second part presents the caves formed in basalt, basalt tuff and in geyserite.

1. Introduction

In Hungary 101 caves have developed in basalt and basalt tuff along with the 669 caves, which have formed in volcanic rocks (Bertalan 1958, , Eszterhás 2005, Eszterhás & Szentes 2004-2009, Ozoray 1952), whilst 37 caves are to be found in geyserite (Eszterhás 1987). The second part of our study deals with the development of these caves and includes those which can be considered the most significant. As well as the caves in basaltic rocks and in geyserite there are many spectacular genotypes and interesting interesting caves which have originated tectonically. Significant mineralogical and climatological observations have been carried out. Detailed information on the caves formed in basalt, basalt tuff and geyserite can be viewed on the website http://geogr.elte.hu/nonkarstic. The list is updated every year (Eszterhás & Szentes 2004-2009).

2. Geological locations of the basalt, basalt tuff and the geyserite

Basalt occurrences related to caves in Hungary are to be found in the Bakony Mountains, the Kemenesalja, the Budai Mountains and the Medves-Ajnácskői Mountains. (Eszterhás & Szentes 2004-2009). Caves do not exist either in the Cretaceous phonolite and trachybasalt in the Mecsek Mountains or in the 9 million year old basalt near the town of Sárospatak.

Caves have formed in *geyserite* in the *Tihanyi Peninsula*, which is part of the Balaton Highland in the Bakony Mountains (Eszterhás 1987a).

Sixty million years ago upper Cretaceous pyroxene and olivine phenocrystic basalt intruded 60 million years ago into the Triassic limestone in the *Budai Mountains*. A small cave traverses the intrusion (Emby *et al.* 1989).

The basalt volcanic activity in the *Bakony Mountains* can be divided into three phases. The first explosion resulted in tuff layers, which are dotted with lapilli and volcanic bombs. The second phase produced lava streams and the liquid basalt lava spread out on the surface. The third explosion phase resulted in toadstone, which is known as "bread stone" by the locals. Basalt lava layers are to be found in the Western Bakony Mountains, in Mount Kovácsi. Holes filled with calcite crystals and zeolite can be observed in the basalt.

The Tapolcai Basin is typical of the landscape of the Bakony Mountains. The region is remarkable for the whiteness buttes. Basalt and basalt tuff have shaped the truncated cones, which overlay the Pannonian sediments. Also remarkable are Mount Badacsony and the basalt columns of Mount Szent György, although the other cones are also geomorphological curiosities and several smaller caves have been listed as occurring in their basalt. The Pannonian sediments which lie between 270 m and 290 m a.s.l. are overlain, by 4 m to 5 m thick basalt tuff, the material of the first explosion phase. Basalt 40 m thick basalt covers the tuff formation, which is overlain by toadstone. Basalt tuff also outcrops on the Tihanyi Peninsula. A geological curiosity of the tuff is the large back fallen volcanic bombs, which were torn from the

depths. Some of the bombs are composed of Permian red sandstone (Juhász 1987). Following the lava flow hot steam and water geysers erupted. The precipitated hydrosilicate has formed 79 geyserit cones (Eszterhás 1987a).

In the South Bakony Mountains, basalt volcanoes overlay the Pannonian sediments, the Triassic limestone and dolomite. The highest peak of the Bakony Mountains, the 601 m high Mount Kab, is composed of basalt. Basalt volcanism also can be seen in the northern part of the mountains. The 435 m high Mount Somló is composed of Pannonian clay which is overlain by a tuff ring and basalt lava .

Northwards, in the Kemenesalja Region, in Mount Ság and in the Tuff Ring of Miske, basalt and basalt tuff are to be found above the Pannonian sediments. The basalt of Mount Ság has been almost completely quarried away. The remains of the basalt quarry outcrops demonstrate nicely the structure of the lava flow, the tuff deposition and their contact zones.

The Medves-Ajnácskői Mountains in North Hungary are composed of basalt, which is the product of the volcanoes at the end of Pliocene and at the beginning of Pleistocene. The fluid lava reached the surface through vents and spread on the surface. The extended basalt plateaux are the witnesses to this volcanic activity. The 100 km² Medves Plateau is the largest basalt plateau in Europe. The volcanic activity began with an andesite laccolite intrusion, which was followed by tuff deposition and extended basalt lava streams. The 4-5 m thick tuffaceous layers are subordinate to the basalt lava formation. As a consequence of the several eruptions the geomorphology of the basalt formation is diverse. There is dark grey thick-bedded basalt and black columnar jointing basalt. Especially spectacular are the basalt columns of Somos-kő, Szilvás-kő and Bagó-kö. The basalt formation extends northward into Slovakia and some interesting and scientifically significant caves are also to be found in the basalt (Fig 1.).

3. The most significant caves and their genotypes which have formed in basalt, basalt tuff and in geyserite

In Hungary only a few syngenetic cavities are known in basalt, as the youngest lava flow of the country is over one and a half million years old. Thus the cavities near to the surface, for instance the lava tubes have fallen victim to denudation.
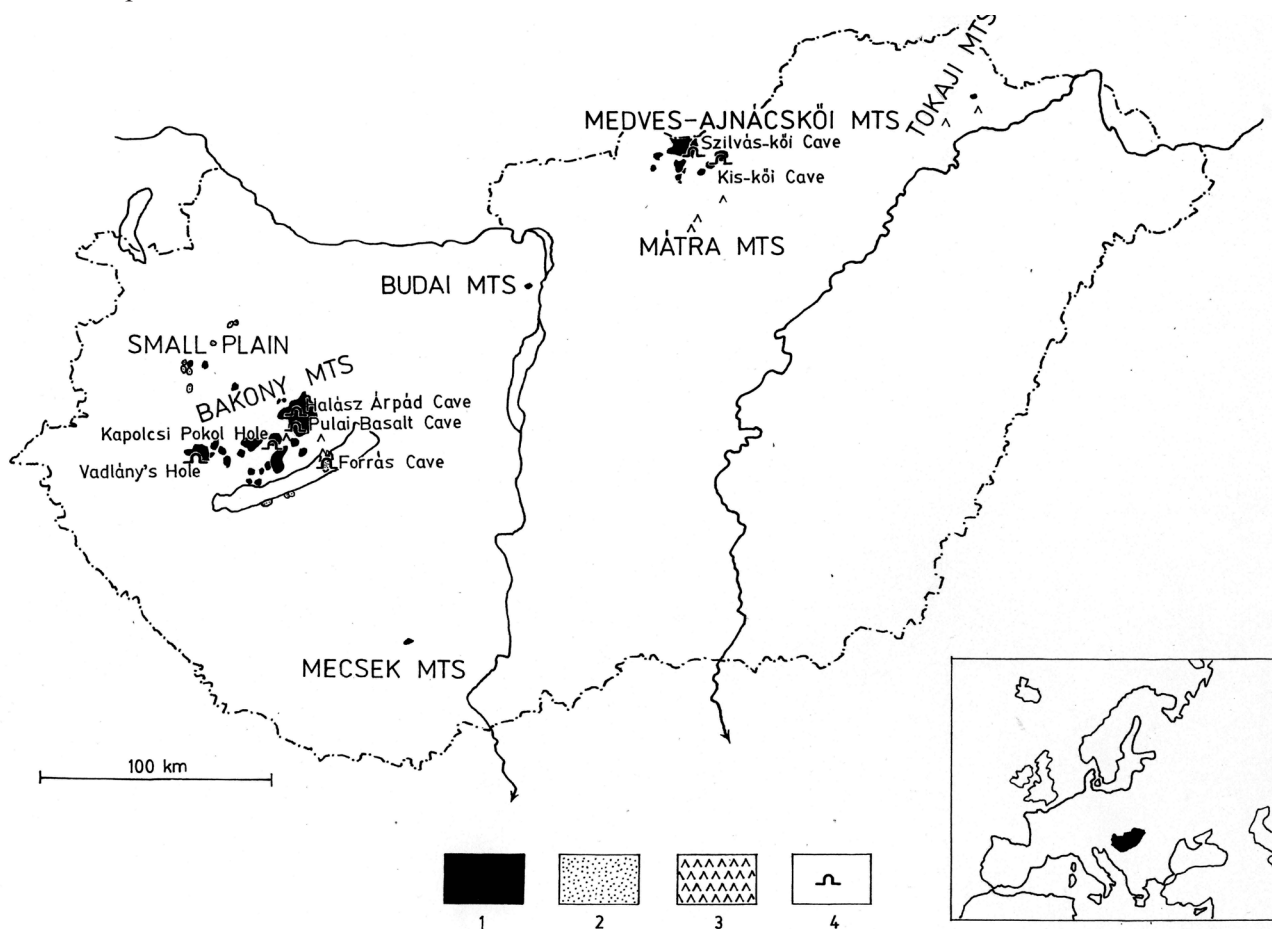

Fig. 1. Caves formed in basalt, basalt tuff, and geyserite in Hungary, showing the most remarkable caves in the formations.   1. basalt, 2. basalt tuff, 3. geyserite, 4. remarkable cave

Fifty-six caves are to be found in basalt in the Bakony Mountains. Caves occur in almost every basalt plateaux and in the whiteness buttes. Eight caves are longer than 20 m. The longest is the 151 m long Pulai Basalt Cave (Fig 2., Fig. 3). The cave is a 151 m long and 21 m deep breakdown cave. The 25-30 m thick basalt is underlain by soluble limestone. Along cracks in the basalt, seeping water has dissolved holes i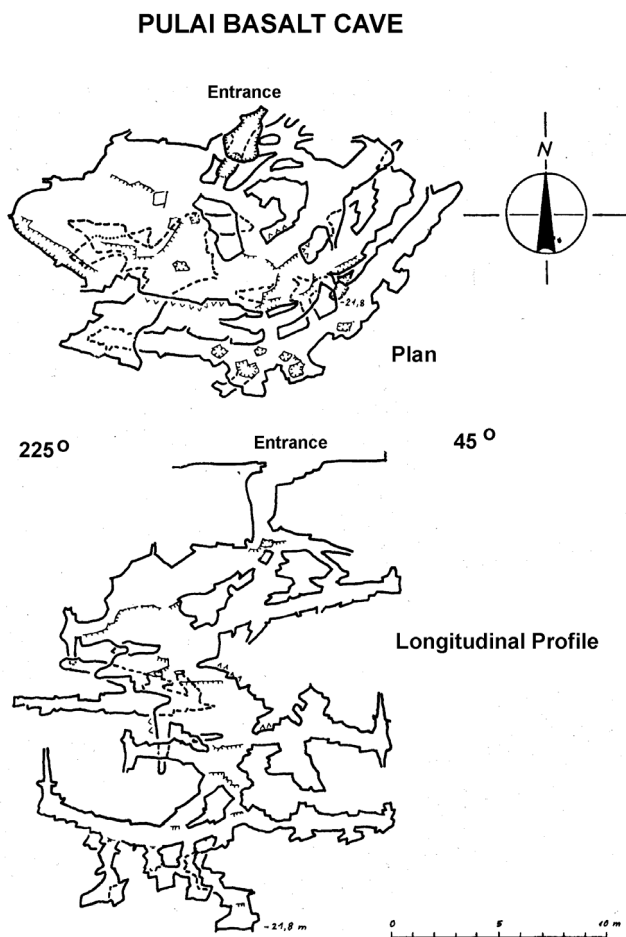n the limestone, into which the basalt layer has broken. The cave is accessible through a narrow shaft, which leads to a bigger chamber. From this chamber various small passages and shafts open in different directions. The cave wall shows clearly the different basalt layers, which are witness to several thousand years of volcanic activity. In the cave a rare silicate mineral has been found, the disc-shaped isingerite.

The flooded Halász Árpád Cave on Mount Kab is 72 m long. The cave is partly artificial, because a series of gas bubble cavities have connected with the tunnel of a mining company. The fifty-one metre long Pokol Hole is also to be found in the basalt of the Bakony Mountains (Eszterhás 1994) (Fig 4, Fig. 5). The basalt overlays a loose sandstone layer and the basalt

PULAI BASALT CAVE

Fig. 2. Survey of the Pulai Basalt Cave, Bakony Mountains
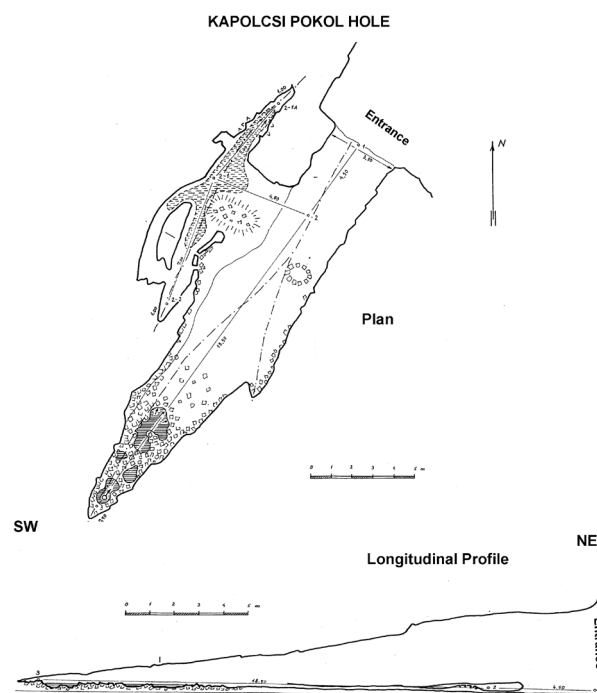
Fig. 4. Survey of the Kapolcsi Pokol Hole, Bakony Mountains

Fig. 3. Pulai Basalt Cave, Bakony Mountains

rim has broken away. The basalt blocks have not slid down the slope, but have fallen back against the bedrock, forming a leaning pseudocave. The Fissure Cave of Mount Tátika which originateed tectonically has developed perpendicular to the rim of the outcrop. The thirty nine metre long Hermit Cave near the village of Zalaszántó has formed parallel to the rim of the outcropping rock formation. Atectonic caves were formed by the equalization of tension as the rock mass moved down the slope. In the talus deposits of the basalt cones, typical extensional atectonic pseudocaves such as the Vadlány Hole in the Mount Kovácsi are to be found. The 32 m long Nagy Sárkány Ice Cave opens in the basalt of Mount Szent György in

Fig. 5. Kapolcsi Pokol Hole in basalt, Bakony Mountains

Fig. 6. Cavities between the basalt columns, Bakony Mountains

the Bakony Mountains. This cave is unique in that the annual average temperature is +10°C . The entrance is 270 m a.s.l. The cave consist of a narrow labyrinth, which has developed in the debris of the collapsed basalt columns. Many small cavities have developed between the basalt columns of Mount Szent György (Fig. 6). The twenty six metre long Araszoló Cave has formed along a fault which is parallel to the basalt rim in the Mount Szent György. The symmetrical Gas Bubble Cavity of the Castle Hill near the village of Szigliget is syngenetic in origin (Eszterhás 1988, 1993, Szentes 1971).

Seven caves have developed in basalt tuff. The longest is the 16 m long Gödrösi Explosion Cave on the Tihanyi Peninsula. The cave is the result of a steam explosion, which took place concurrently with the deposition of the basalt tuff. On the Tihanyi Peninsula some other, partly demolished, smaller caves are also known. The 22 m x 3 m wide Nyereg-hegyi Rock Shelter has formed in the outcrops of the basalt tuff and geyserite layers. To the West of Pula village in the valley of Eger Creek the Pulai Basalt Tuff Cave opens. Rock fragmentation has been responsible for the formation of this 10 m long, flat cave, which has developed as a result of variations in temperature and moisture.

On the Tihany Peninsula in the Bakony Mountains 37 caves have developed in geyserite. The caves

have formed as the result of alkaline solution. Unfortunately many caves have broken down and only some remnants are reminiscent of their former existence. The longest geyserite cave is the 16 m long Spring Cave (Fig. 7, Fig. 8). The cave consists of a single chamber and is a show cave, illuminated by electric light. It is worthwhile to mention the 2.5 m long Upper Hole of the Aranyház, the 6 m long Hármas-hegyi Through Cave, the 5 m long Csúcs-hegyi Hole and the small Csúcs-hegyi Spring Cave. A geyserite cave was also to be found in the Koloska Valley near the town of Balatonfüred, but this has long disappeared (Eszterhás 1987a).

The 200 km^2 large Kemenesalja area lies north of the Bakony Mountains. The 6.5 m long Mount Pet Cave is to be found in basalt tuff in a tuff ring near the village of Miske. It is a tectonic cave, which has formed along a fault line parallel to the rim of the outcropping tuff. The basalt cave in Mount Ság, the so called Vass Pál Cave, was the most significant cave of the area, but it was demolished in 1914 during quarrying operations. There is not no reliable information about the cave.

South of Solymár village in the Budai Mountains limestone quarrying has opened several minor karst caves. In one of the quarries, a smaller Upper
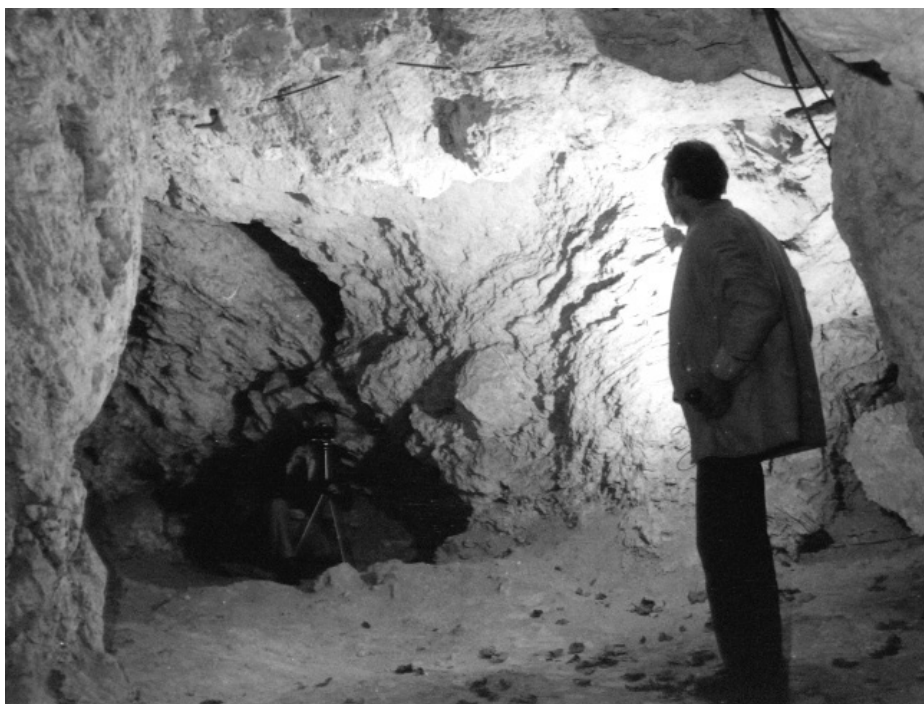
Fig. 7. Spring Cave in geyserite, Mount Szent György, Bakony Mountains, Tihanyi Peninsula.

with two andesite laccolith intrusions at the boundary of Pliocene and Pleistocene. Later basalt lava flowed on the surface from about hundred explosion centres. Between the basalt plateaux deep erosion valleys have formed. Thirty-four caves are to be found in the basalt (Eszterhás 1991). Two syngenetic caves have been discovered in the region. The 30 m long Kis-kői Basalt Cave (Fig. 9, Fig. 10) originated from steam explosion whilst the 13 m long Baglyas-kői Basalt Hole is a fumarole cave. The consequence caves represent an interesting genotype, as they have
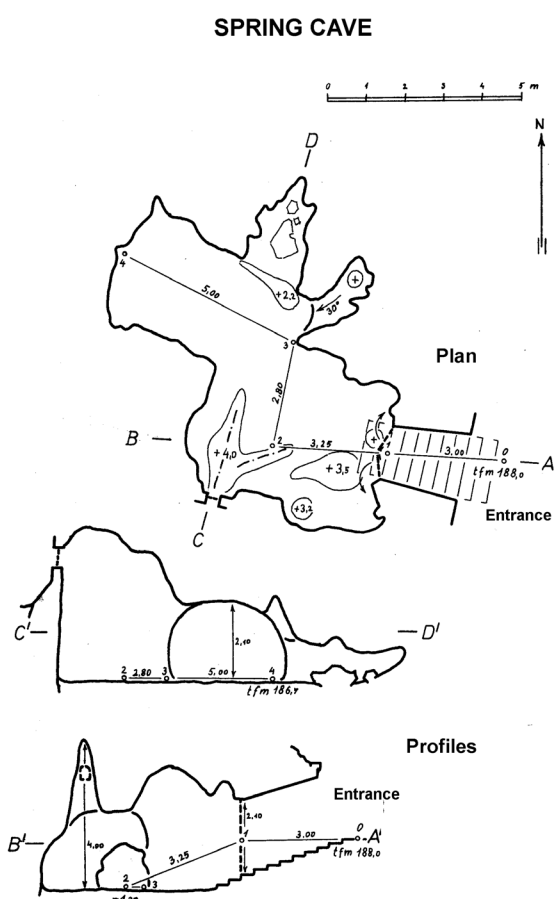
SPRING CAVE

Fig. 8. Survey of the Spring Cave, Bakony Mountains, Tihanyi Peninsula

KIS-KŐI BASALT CAVE

Fig. 9. Survey of the Kis-kői Basalt Cave, Medves-Ajnácskői Mountains

Cretaceous basalt intrusion has been revealed. Here a cave, the so called Budaligeti Basalt Cave, intersects the intrusion (Emby *et al.* 1989).

In the Medves-Ajnácskői Mountains volcanism began

formed as a result of the collapse of the abandoned coal mines beneath the region. In the early 20th Century, below the basalt, a 3 m thick coal seam was mined out. In May 1917 the mine collapsed. As a consequence of this collapse the 80 m thick basalt

*Fig. 10. Kis-kői Basalt Cave,
Medves-Ajnácskői Mountains*

layer downfaulted about 1 m and a 600 m long 20-25 m deep crevice has developed. The basalt blocks formed part of the ceiling of this fissure system and 30 known consequence caves were created with a total length of 350 m. Two caves are longer than 50 m, four caves are longer than 20 m and 24 caves are between 2 m and 15 m long. The largest cave is the 68 m long and 14 m deep Szilvás-kői Cave (Fig. 11,
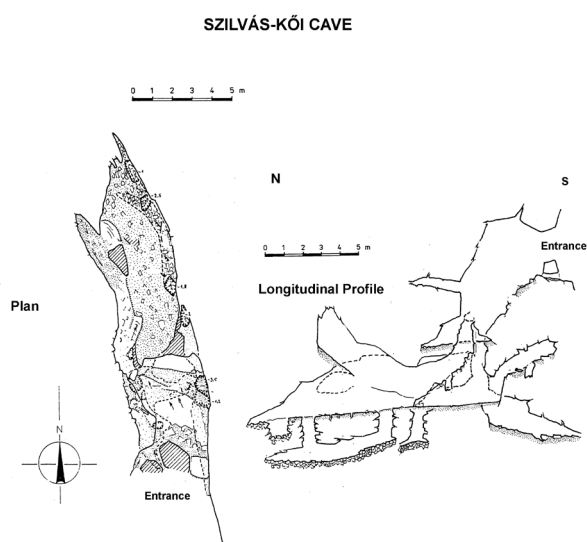
SZILVÁS-KŐI CAVE

*Fig. 11. Survey of the Szilvás-kői Cave,
Medves-Ajnácskői Mountains*

*Fig. 12. Szilvás-kői Cave, the biggest consequence
cave in the Medves-Ajnácskői Mountains*

Fig. 12). The Sárkánytorok Cave is a 51 m long and 16 m deep through cave. In the southern part of the cave compacted snow accumulates 7-8 months of the year. The twenty-six metre long Dornyai Cave has developed along a narrow crevice. The twenty metre long Kis-szilváskői Fissure Cave is to be found at the end of an open crevice Compacted snow also occurs in this cave. Near the Fissure Cave the 45 m long and 14 m deep narrow Spider Hole opens (Eszterhás 2003).

4. Mineralogical, Hydrological, Climato-logical, Biological and Archaeological Observations

Among the 101 basalt caves and 41 geyserite caves in Hungary, mineral formations only occur in 20 caves. In some basalt and basalt tuff cavities calcite precipitation can be observed. The precipitation occurs in those caves, where the seeping water dissolves lime from the overlaying calcareous rock formation. The overlaying limy sand is responsible for the white, spectacular, calcite coating in Remete Cave near the village of Zalaszántó. Less significant calcite coating is also to be found also in Pokol Hole near the village of Kapolcs. In Explosion Cave near the village of

Gödrös calcareous pisolites occur. The pisolite coating has precipitated from the hot solutions which filled the cave after the steam explosion. The amygdales in the Pulai Basalt Cave were plugged with so called second generation calcite or with kaolinite. On the wall of the Basalt Cave a large number of 2-3 cm diameter, thin discs can be observed composed of isingerite, a rarely occurring silicate mineral. Different zeolite minerals (natrolite, phillipsite, desmine) are to be found in the small amygdales on the walls in the Basalt Caves of Mount Kovácsi. Limonite coating, calcareous pisolites and opal inclusions occur in some geyserite caves on the Tihanyi Peninsula.

Only two basalt caves contain significant water masses in Hungary. Seeping water completely fills in Halász Árpád Cave. Most of the time the two shaft entrances of the cave look like lakes. Only at the end of very dry summers does the water sink the and airspace appears in the passages. In the Kapolcsi Pokol Hole the thick basalt blocks dam up the seeping water, which emerges in the cave as a spring. This spring feeds a small lake. The size of the lake varies, because after the water reaches a certain level a siphon system drains it. The lake appears mainly in the spring, after thawing.

The climatic conditions in the relatively small basalt and geysirite caves (3-5m) in Hungary do not show significant deviation from the surface climate. In the larger caves the temperature is more or less constant throughout the year, relative to the annual average surface temperature. The exceptions are those caves, which have developed in porous or detritic rock formations. Here evaporation on the large rock surface causes such a significant a heat extraction, that the surroundings are cooled below freezing point. Each of these caves has developed in porous detritic volcanic rocks (Eszterhás 1999). Three of the five small ice caves which are to be found in Hungary have developed in basalt. The Kis Sárkány Ice Cave and the Nagy Sárkány Ice Cave (Fig. 13) can be found in the basalt debris of the Mount Szent György in the Bakony Mountains at 270 m a.s.l. The caves are dynamic ice caves. The ice (ice coating, icicles) can be observed only in summer. During this time the cold air flows over the stone slope outwards from the cave. In winter the air flows in the opposite direction and the ice formations thaw. The Sárkánytorok Cave opens in slaggy basalt in the Medves-Ajnácskői Mountains at 625 m a.s.l. The cave is a static ice cave, having a minor air flow. In winter the falling snow firmificates in the cave and remains throughout the year. Because of evaporation on the large surface of the surrounding slaggy basalt walls, not even in summer does the temperature exceed freezing point. Interesting alternating air flow has been observed in some interconnecting basalt caves. In these caves the

Fig. 13. Ice formations in summer in the Nagy Sárkány Ice Cave, Bakony Mountains. The cave has formed in basalt.

direction of the air flow alternates half-yearly. As a consequence the temperature between the two caves varies 10-20ºC. It is obvious there is a connection through the debris between the two caves. Examples of such interconnected caves are the Nagy Sárkány Ice Cave and the Warm Shelter Cave on Mount Szent György and Marcinek Cave and the Dornyai Cave in the Medves-Ajnácskői Mountains.

The fauna and flora do not show significant differences from those found in karst-caves, although variations in proportions found can be observed. For instance the proportions of the penicillin flora and the lepidoptera fauna are higher than in karst-caves. In almost every cave springtails (Collembola) occur, as do rove beetles (Staphylinidae), humpbacked flies (Phoridae), spiders (Araneidae), mosquitoes (Nematocera), small carrion beetles (Catopitae), butterflies and moths (Lepidoptera) and bats (Chiroptera). Some unique species have been identified in basalt caves. In the Basalt Caves of Mount Kovácsi two rare beetle specieses *(Orobainosoma hungaricum, Hungarosoma bokori)* and a rare land snail species *(Aegopis verticillus)* occur. The rare cave harvestman *(Holoscotoleman jaquati)* and another rare spider

species *(Kratochviliella bicapiota)* have been identified in the basalt caves of the Medves-Ajnácskői Mountains.

The palaeontological findings in the basalt and geysirite caves are not particularly interesting. Only Holocene remains were discovered, and the species belong to animals still living today.

Archaeological remains occurred in three caves, formed in basalt. The most abundant remains, 79 potsherds, were found in the Kapolcsi Pokol Hole in the Bakony Mountains. The oldest finds are Neolithic, thick, black, potsherds both thrown and shaped by hand dating from the Bronze Age. Furthermore, red, unglazed thrown potsherds were unearthed dating from the Middle Ages. Above the Kis-kői Basalt Cave in the Medves-Ajnácskői Mountains there once stood a fortification, although today this is completely ruined. However, in the cave potsherds are to be found, dating from the 13th to 14th centuries. A half horseshoe, of unidentified age, was unearthed from Dornyai Cave in the Medves-Ajnácskői Mountains. The age of the findings is unidentified.

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Lava tube photography on the run

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Abstract

Precisely positioned back and side lighting, compliant assistants, sturdy tripods and endless amounts of time all help to capture that perfect lava tube image. In the real world, however, there is often insufficient time to set up tripods or multiple flashes and other members of the party may be unreceptive to overtures from photographers or they may just simply get in the way. This paper explores some methods for capturing images of lava tubes where there is a need to keep moving, where there is limited assistance available or other factors that the photographer cannot easily control.
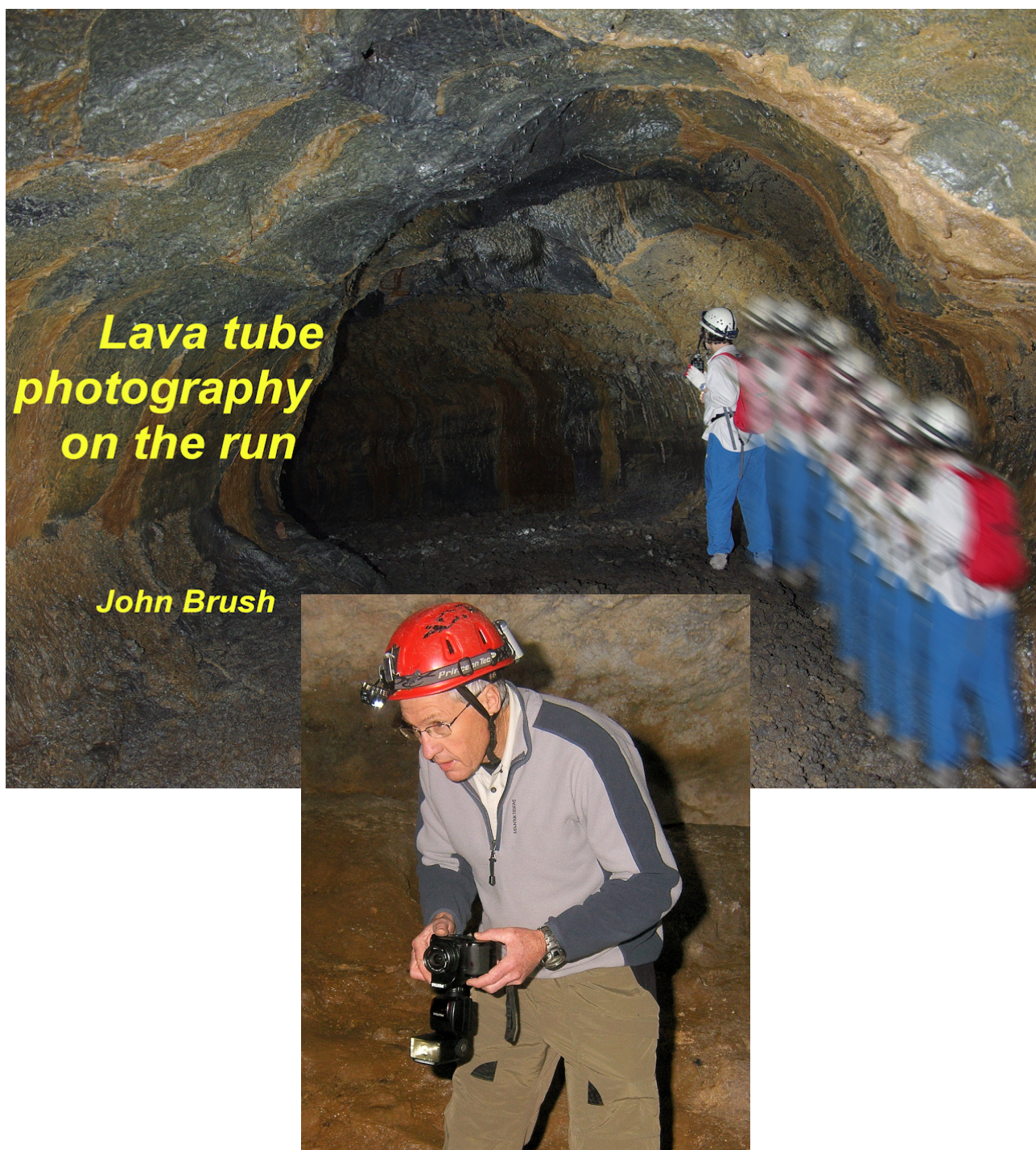
Kites and other Archaeological Structures along the Eastern Rim of the Harrat (Lava Plain) of Jordan, Signs of Intensive Usage in Prehistoric Time, a Google Earth Images Study[*]

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Abstract

Google Earth offers a unique opportunity and methodologically new approach to study geological and archaeological phenomena over large areas. We have evaluated a high resolution strip of images along the eastern rim of the Jordanian Harrat along 38°E where basaltic Quaternary lava flows override Upper Cretaceous and Lower Tertiary limestones and cherts of the Hamad.

Within this strip we recorded and evaluated statistically 44 'kites' (km-large structures of walls resembling children's kites from the air) many more than was previously known there. 'Kites' consist of km-long guiding walls ending in hectare-sized enclosures erected most probably in Neolithic times to hunt migrating gazelle. They form N-S oriented continuous chains, effectively intercepting animal migration routes. Distances between 32 kites of the easternmost chain were 1.62±0.94 km, covering 48 km N-S. The longest guiding wall found is >10 km long, the total length of all walls being >150 km. Northern, central and southern guiding walls average 2.00±1.35 km (N = 39), 0.78±0.66 (N = 25) and 2.06±1.31 km (N = 38), respectively. The enclosures, situated behind a low sill to hide them from view of approaching gazelle, are star-shaped and 1.80 ± 0.91 ha (from 4.46 to 0.23 ha) in size with circumferences of 624±195 m (1,056 m to 228 m). Enclosures have up to 14 stone circles at their tip, so called 'blinds', historically interpreted as 'hides' for hunters to shoot gazelle. However, we argue that they must have had a different use, i.e. they were the actual traps. Once the gazelle had jumped into them, they could not jump out again lacking the forward speed. The data suggest a structural stratigraphy of trap construction in the area, that began with meander walls, proceeded with bag-like traps and culminated with the construction of kite chains. Later some kites were decommissioned by extending the guiding walls of adjacent kites. This process was repeated and only 19 kites remained functioning from the original 36. Calculation of energy to construct these traps shows that they must have been highly profitable in terms of caloric return. After the hunting period, kites were partly destroyed by houses and corrals that were built by later herders. Among them are 'jelly fish/wheel' houses and other clearings. The most enigmatic structures found are 103 'circular paths', on average 43.3±17.7 m long and 31.7±13.7 m wide, that appear to be very old. All these structures form a rich heritage, unique world-wide, that is not only a challenge for further ground-based archaeological studies but also urgently needing protection against further bulldozing and the spreading of 'civilization' into this area.

Keywords: Jordanian Harrat, kites, Neolithic, hunting, gazelle

1. Introduction

1.1 Geology and geomorphology

Two very different landscapes determine the geomorphology of northeastern Jordan: The flat peneplain of the Hamad, consisting of Oligocene to Paleocene limestones, in the east and the hummocky Harrat, consisting of Oligocene to Quaternary volcanites (Tarawneh *et al.* 2000), in the west. The border between the Harrat and Hamad roughly runs N-S along 38°E (Fig. 1). The Harrat features shield volcanoes (Kempe *et al.* 2008), tephra cones (e.g., Al Malabeh 2003, 1994), >100m high strato-volcanoes (Ashgaf or the Al-Shahba volcanoes) and three or four up to 100 m long NW–SE striking fissure eruptions (e.g. Al-Malabeh *et al.* 2002) (Fig. 1). The

erupted lavas occur both as thick a'a or as thinly-sheeted pāhoehoe flows. The latter were transported through pyroducts (lava tunnels, lava tubes) for many kilometres, accounting for the wide spread of the lavas and the low slope of the south-dipping plateau (Al-Malabeh *et al.* 2006; Kempe *et al.* 2006). Post-eruptive faulting produced local ridges in the SE-Harrat (Fig. 1). Depending on age, wadis have cut canyons (Wadi Rajil). The plateau was covered with a 1 to 2 m of silty, carbonate and quartz-containing loess. Through the poorly understood process of 'stone heaving', loose rocks of the underlying lava moved up to the surface, covering the loess in a protective manner against deflation and erosion. Erosion washed loess into the depressions in the hummocky terrain producing playa flats giving the terrain a "mottled" pattern. Today, annual precipitation in the area is less than 100 mm

[*] *This paper is a much shortened version of Kempe & Al-Malabeh (2010).*
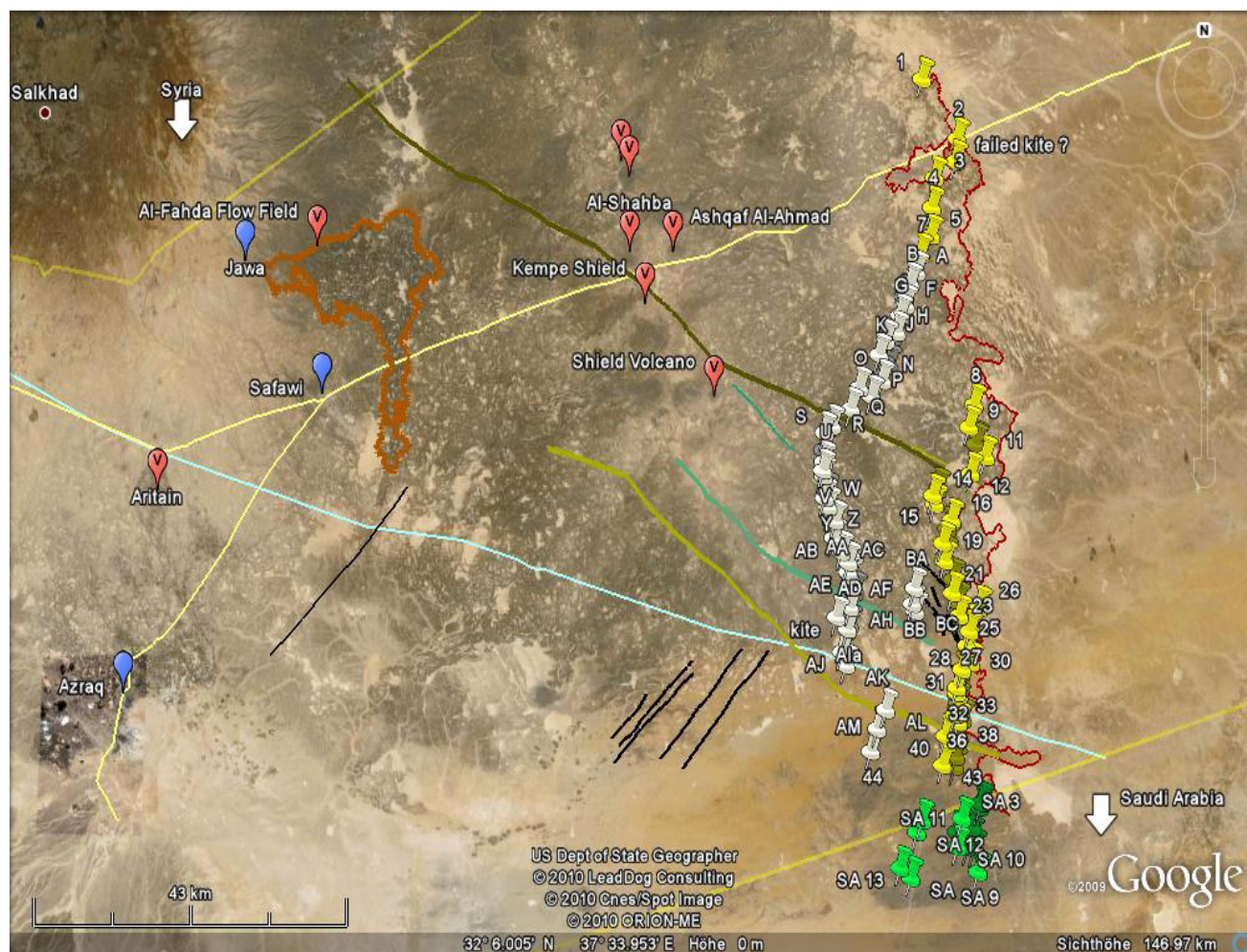
Fig. 1. Google Earth overview of the Harrat in eastern Jordan with some of the pertinent geological, volcanological and geographical features (Volcanoes marked in red; towns of Safawi and Azraq and the Bronze Age city of Jawa marked in blue. Bold, yellow lines: international borders; thin yellow lines: roads; light blue line: Trans-Arabian Pipeline; black lines: faults, colored bold lines: eruptive fissures; bold brown line: Al-Fahda flow field; thin brown line: eastern border of the Harrat. The kites studied here are marked by numbered yellow pins while the white pins with letters mark the next kite chain to the west in an area not available in high resolution. Kite positions in Saudi Arabia are marked with green pins labeled SA).

and flowing water is restricted to wet winters. A streak of a 10 km wide swath of reddish aeolian sediment almost buried some of the kites between 31°55.4'N and 31°50'N along our profile (Fig. 1).

1.2 Occupational history

Archaeological surveys began in the 1920s (Field 1960; Betts 1982, 1993, 1998a). Traces of human presence date back to Paleolithic times (Betts 1988b). During the Last Glacial the area was much wetter as documented by a high level of Lake Lisan, the predecessor of the Dead Sea (e.g., Landmann *et al.* 2002; Abu Ghazleh & Kempe 2009) when also local lakes existed in the Harrat (Rollefson 1982; Rollefson *et al.* 1997). After a sharp post glacial regression, lake levels rose again (Neev & Emery 1995) from 14–10.5 ka ago and beginning at 8.5 ka BP, probably also improving conditions on the Harrat. Excavation conducted at Dhuweila in the central

Harrat documented occupation at around 8.25 – 8.19 ka BP, 7.45 – 7.03 ka BP and 5.51 – 4.44 ka BP (Betts 1998b) (stage 1 and 2 belonging to the pre-pottery Neolithic-B, or PPNB). Jawa, an Early Bronze Age 'city' with massive basaltic defense walls, is the most impressive archeological site in the Harrat (Helms 1981; Betts 1991).

During Roman times, roads, towns and border forts were built along the Limes Arabica (e.g., Kennedy & Riley 1990) such as the fort at Azraq, the large towns of Umm Al-Jimal, Sama Al-Sirham and Umm Al-Qutain (e.g., de Vries 2000; Kennedy 1993), and the castle of Qasr Burqu' E of the Harrat (Gaube 1974), all built from basalt. Between the 1st century BC and the 4th century AD early Arabic tribes left Safaitic inscriptions and petroglyphs of camels, horses, lions, ostriches, gazelles and of various hunting (Fig. 2) and riding scenes (e.g., Ababneh, 2005), sometimes overwritten by modern inscriptions or even images of trucks.

Inscription: l ' q h g(?) y t
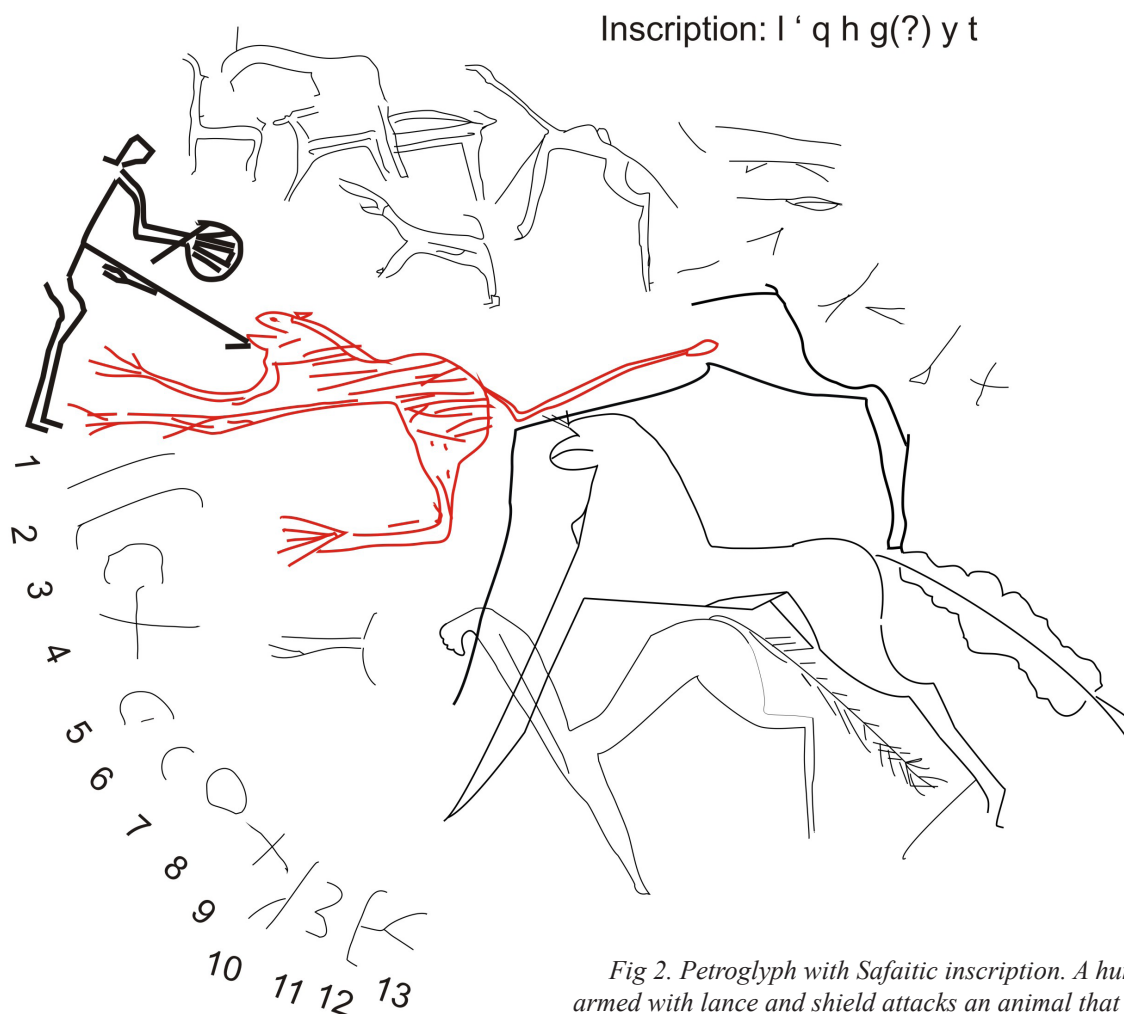
inscription: l r b t b n b g t h f r k
by rbt son of bgt

Fig 2. Petroglyph with Safaitic inscription. A hunter armed with lance and shield attacks an animal that is most probably a hyena (round head, stripped fur). Two complete horses with elaborate tails stand to the right. A third horse is incompletely drawn. In the background a herd of goats and to the right a camel (?) is seen. The hunters name probably reads "rbt son of bgt". The other parts of the inscription still need translation. The inscription dates this hunt to about 2000 BP.

1.3 'Desert kites'

First noticed by pilots in 1925 (Maitland 1927; Poidebard 1928) the 'desert kites' are the most enigmatic archaeological structures of the Harrat (e.g., Helms & Betts 1987). Kites are also known from Syria (e.g., Echallier & Braemer 1995), Saudi Arabia (Kennedy 2009), the Negev (e.g., Holzer *et al.* 2010), and from the Aralo-Caspian region (e.g., Betts & Yagodin 2000. But Jordan apparently has most kites and Betts (1998c, fig. 10.10) gives a map with about 300 of them. Most Jordanian kites consist of pairs of straight or curved 'guiding walls' that narrow down at a sill. Behind follows an irregular polygonal, star-like shape, giving the whole structure the appearance of a child's kite. At corners, small circular stone walls are placed, so called 'blinds', interpreted by e.g. Betts (1982, 31) as "*series of hides to conceal the hunters*." Further she says: "*Kites form long chains joined at their extremities of their trailing walls, the chains stretch for many kilometers across what must have been the seasonal migration routes of the desert fauna.*" Echallier & Braemer (1995) suggested that kites were used for animal herding, but most agree that the kites were used to hunt gazelle.

The PPNB camp-site Dhuweila (7th millennium BC) was association with kites (Betts 1998b) and over 90 % of the recovered stage 1 and 2 Dhuweila bones – >11,000 pieces – belong to the genus *Gazella*; domestic animals are entirely missing (Martin 1998). Furthermore >80 rock carvings recovered show horned animals, probably gazelle (Betts 1998d).

At Jawa, cattle and sheep/goat bones already dominate over gazelle, suggesting that their hunt was continued, albeit not the main protein source in Middle Bronze Age times (Helms 1981). Furthermore, the water system of Jawa succeeded kite walls, also suggesting their Neolithic age (Helms & Betts 1987, 45). Some rock carvings may show kites, some without animals,

others with animals possibly representing gazelle and hunting dogs (Betts 1998d, figs. 7.12, 7.14). Among them is the 'Cairn of Hani' (Harding 1953; Field 1960, fig. 32a) showing on one side a hunting scene with animals between guiding walls driven by a human and assembled in a kite enclosure characterized by circular 'blinds'. On the other side of the boulder an archer shoots at horned animals and a human with a whip directs hunting dogs. The rock carries also a Safaitic inscription; if it was not added later, it would date the cairn to between the 2nd century BC and the 4th century AD. Observations in the 19th century from Syria by Musil (1927 and 1928, cited by Betts 1998d, 156), demonstrate the long-term usage of kites for hunting. However, Musil reports that the gazelle were forced to jump walls with pits or ditches behind, where they would break their legs. Pits and ditches, however, have not been reported from any of the hunting kites on the Harrat (Betts 1998c). Comparison of the Harrat kites with those of the Aralo-Caspian region (dating from the 1st millennium AD) substantiates the conclusions that kites were used to intercept migrating animals occurring in large numbers, such as gazelle. No firm evidence exists that the kites were used to hunt other animals such as onager, oryx or ostriches. The most likely animal hunted is *Gazella subgutturosa marica* (Goitered Gazelle), a migrating species now extinct

in Jordan, and Betts (1993, 10) summarizes: "*The steppe was not extensively, re-used until the late Pre-Pottery Neolithic-B in the second half of the seventh millennium BC. In this period, there was emphasis on exploitation of particular resources, at this time gazelle. Gazelle was hunted in large number in the harra* (Helms and Betts 1987; Betts 1988a, 1989). *Hunting camps were located within reach of gudran* (i.e. rain pools), *but choice of site location was also influenced by the proximity of hunting ground and landscape suitable for the construction of 'kites'.... With the introduction of sheep/goat herding in the early sixth millennium B.V., open country became more useful....*"

2. Materials and methods

Here we give details of a specific set of kites, their geological context and evaluate their interrelationships, and survey the area for other anthropogenic features. We took advantage of a high resolution (about 0.5 m pixel^{-1}) strip of Google Earth images east of 37°59' (datum WGS 84) that contains a set of >40 kites following the eastern border of the basalts (Fig. 3). Distances were obtained with the Google Earth ruler and areas with the Photoshop CS4 extended program. All walls were redrawn as Google Earth vectors: guiding walls in white (Fig. 3), others in yellow. Walls
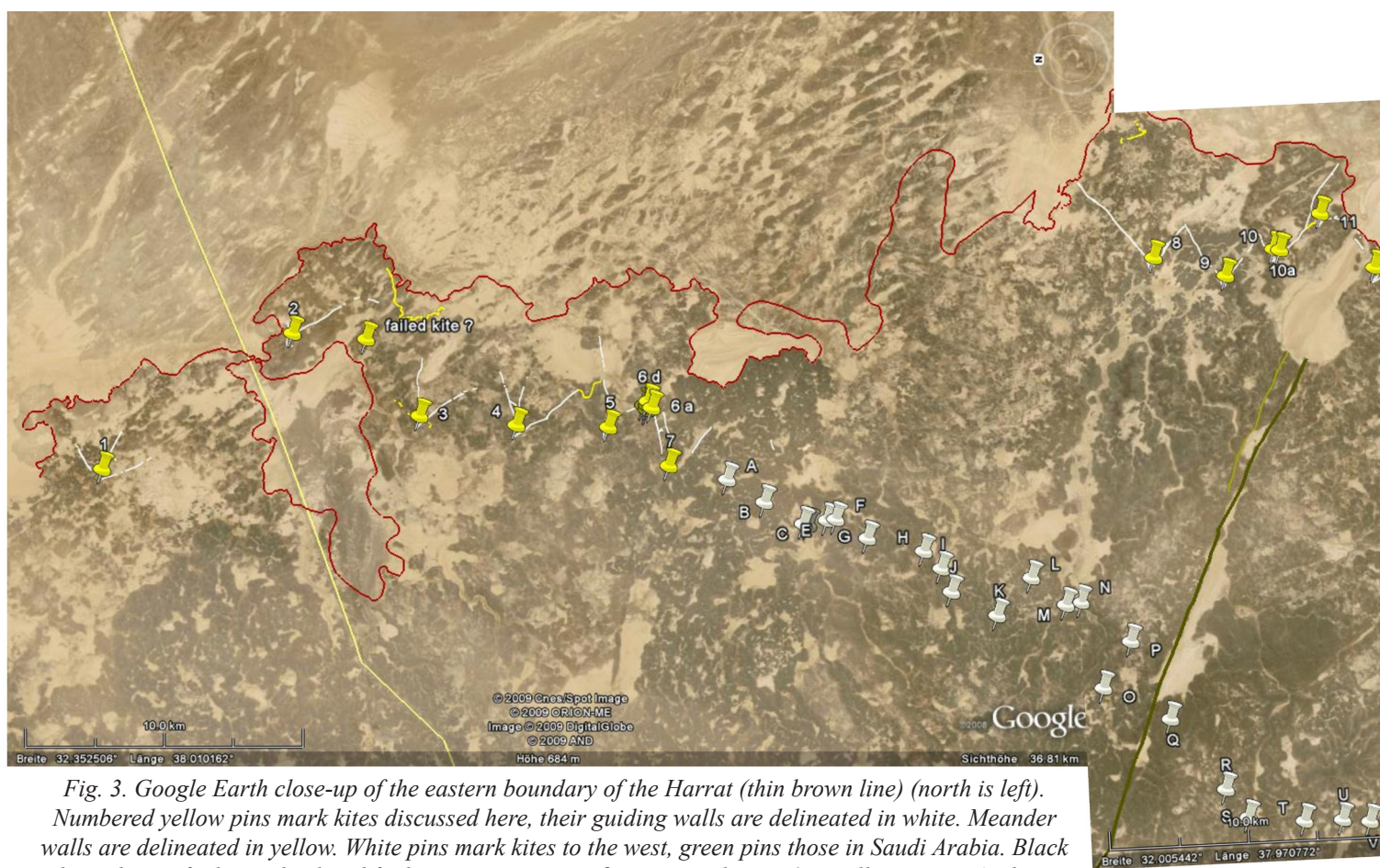

Fig. 3. Google Earth close-up of the eastern boundary of the Harrat (thin brown line) (north is left). Numbered yellow pins mark kites discussed here, their guiding walls are delineated in white. Meander walls are delineated in yellow. White pins mark kites to the west, green pins those in Saudi Arabia. Black lines denote faults, and colored fat lines trace eruptive fissures, Highway 40 in yellow, Trans-Arabian Pipeline in light blue.

appear on Google Earth as dark traces because they are erected from basalt blocks. In collecting them, the underlying loess is exposed and the dark wall is often paralleled by light lines on one or both sides of it. Where walls run across playas they are better visibly while they become obscure when running across dark rock outcrops. No kites occur in the Hamad (Betts 1993). Paths appear as light lines, four wheel tracks appear as double light lines and bulldozed trails are not only wider but also marked by rock piles on both sides or with on-echelon edges. National Road 40 (Amman – Bagdad) crosses the area in the N and the old Trans-Arabian Pipe Line in the S (Fig. 1). In February 2009 we inspected a few of the structures in the field (Kite 3 and a few wheelhouses, Fig. 4).

3. The kites

3.1 General situation and structural stratigraphy

East of 37°59' (Fig. 1) in the high resolution area within Jordan we identified 43 kites (Figs. 1 and 2, yellow pins), significantly more than the 17 kites recorded by Helms & Betts (1987, fig. 17), more than see on the published topographic maps (Royal Jordanian Geogr. Center 1997) and contradicting the assumption (Betts & Yagodin 2000) that most kites occur in the western and central Harrat. In the lower resolution area 46 further kites occur to the west (white pins).

These kites form two parallel chains, the eastern one including kites 8 to 43 (distance 47 km) and western one from 1 to 7 and from A to 44 (including a shorter intermediate chain from BA to BC) (distance 78 km). 17 more kites were found in Saudi Arabia, marked by green pins extending these chains.

Averaged distances between kites amount to:

- Kites 1 to 7 (n = 6; excluding Kite 6 because it may not be a kite at all) 5.54±2.40 km;

- Kites 8 to 43 (n = 32; excluding several kites of older generation, i.e., no. 10a, 26, 37 and 43) 1.62±0.94 km;

- Kites A to 44 (n = 38; excluding kites D and AHa because they appear to be older kites) 1.64±0.73 km (max 3.34, min 0.31 km).

The distance of 1.6 km reminds of the distance covered by 1000 double paces, i.e. that of the Roman mile (1.479 km) or the statue mile (1.609 km). Thus the original positions may have been spaced out by 1000 double paces and then the exact positions were adjusted to the possibilities the terrain offered. This close spacing was given up after some time and many of the kites were 'decommissioned' by extending the guiding walls of neighboring kites. This allows constructing a structural stratigraphy (Table 1). Column 1 lists all kites N to S, columns 2 and 3 gives the kites that supersede the original kite by
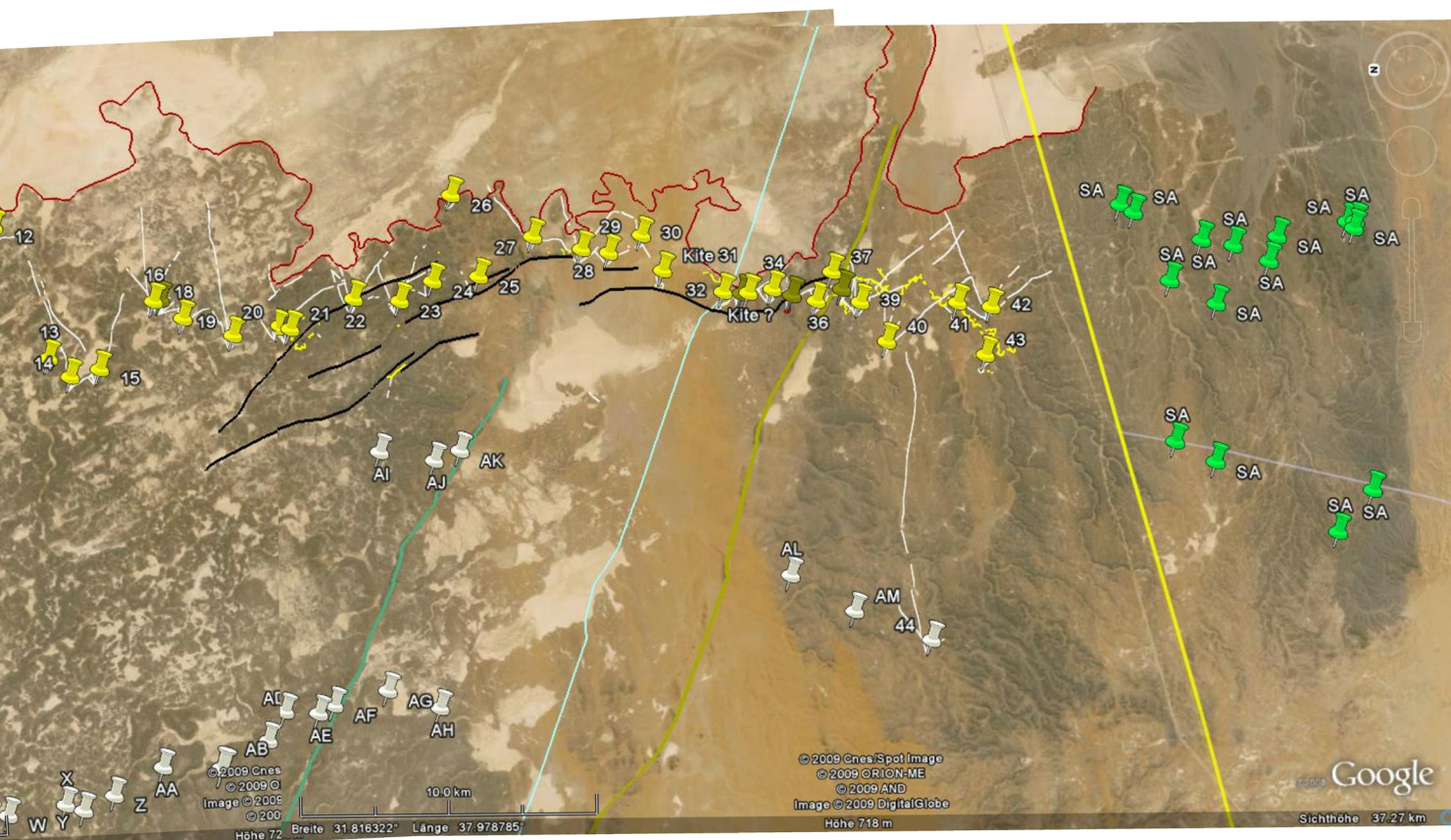
Fig. 4. Southeast-ward view of the enclosure wall of Kite #3 in the field. Note the N-guiding wall at the horizon as it approaches the gate to the enclosure (off the picture to the right). Note also the dilapidated nature of the walls and the loess strip along it from which the stones were collected to build the wall.

the extension of their guiding walls. In the northern chain all kites remained active. In the more closely spaced southern chain the number of active kites was diminished at least twice. Of the original 36 kites only 19 finally remained functioning. In case of Kite 10 and 10a (one of the least altered original kites), less than 200 m apart, 10a was completely cut off by the southern guiding wall of Kite 10 (Fig. 5). Kite 10a is one of the most original kites because it seems to have been abandoned even before obtaining its final guiding walls.

Table 1: Stratigraphy of kites.

Phase 1	Phase 2	Phase 3
1		
2		
3		
4		
5	5	
6	5	
7		
8		
9		
10	10	
10a	10	
11		
12		
13	14	
14	14	
15	14	
16	16	19
17	16	19
18		19
19	19	19
20	21	19
21	21	19
22		
23	23	
24	23	
25		
26		
27		
28	28	
29	28	
30	31	
31	31	
32		
33	33	
34	33	
35	35	
36	35	
37	35	
38	39	39
39	39	39
40	40	39
41	40	39
42	42	42
43	42	42

Fig. 5. Google Earth picture of kites 10 and 10a. Note that the southern guiding wall of kite 10 closes off kite 10a and that no traces are visible suggesting that kite 10a walls were formerly longer.
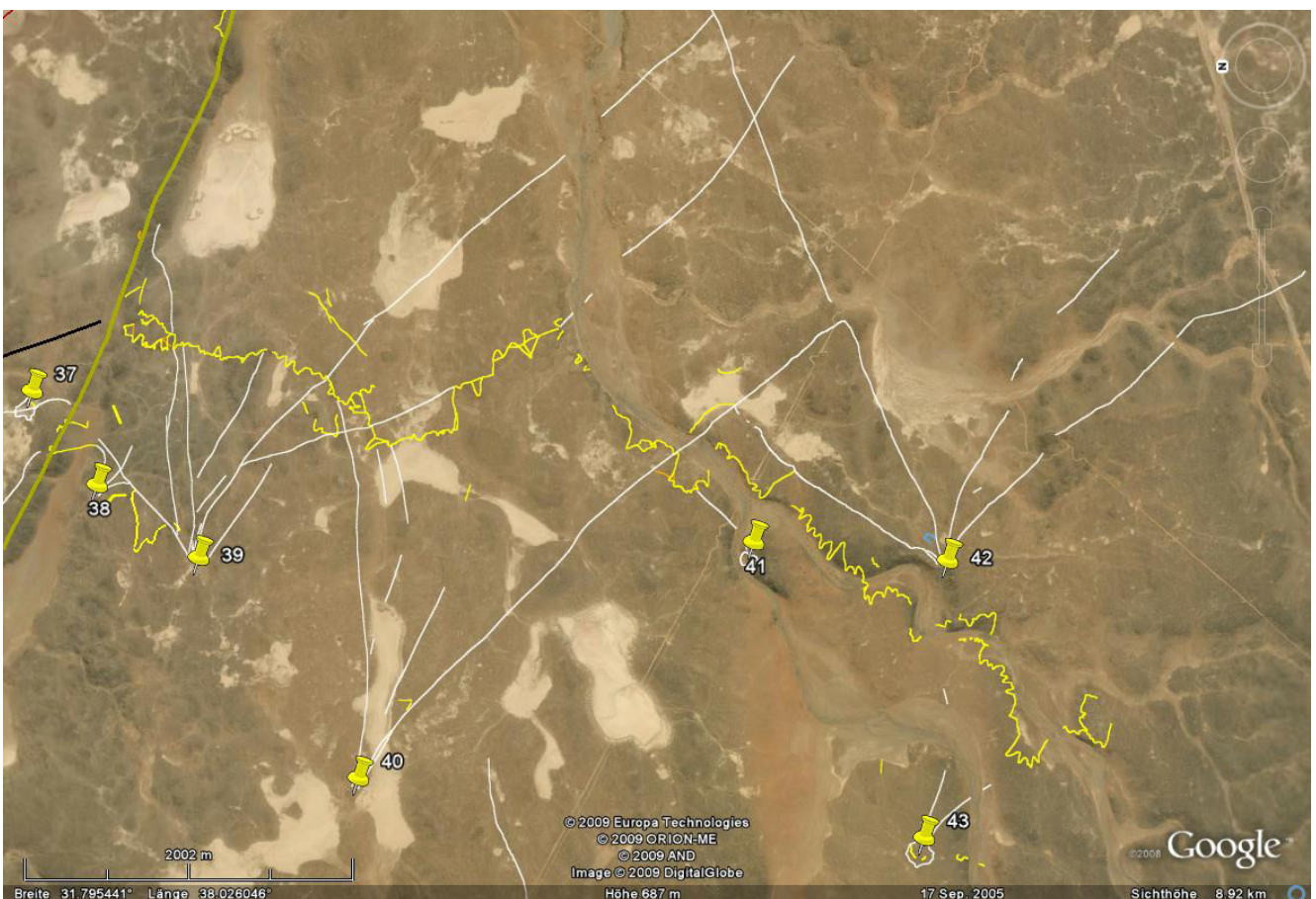
Fig. 6. Google Earth picture of meander walls (in yellow) between kites 37 to 43. In the south the meander walls follow the wadi, crossing it several times. In the north the walls cross the lava plain. Several later-erected walls cut off meanders (in orange) (north is left).

3.2 'Meander' walls

In addition to kites and their guiding walls a second class of walls is present that meander back and forth (Fig. 3 in yellow), thereby closing off dells between lava hills. They seem to funnel migrating animals into certain paths or leading then into bag-like constrictions. A km-long wall runs parallel to the Harrat border between 32°24.475'N/38°3.522'E and 32°23.383'N/38°2.530'E. A second section extends between 32°20.829'N/38°0.565'E and 32°20.357'N/38°0.759'E that forms one large W-oriented pouch erected along the crest of a lava rise that ends in four small 'fingers'. Our observations suggest that the meander walls predate the construction of the kites.

Fig. 6 shows the longest meander wall systems (>7 km end-to-end; 31°49.5'N/38°2.1'E and 31°46.3'N/38°0.4'E; between Kites 38 and 43). It runs back and forth between an escarpment (a fissure eruption) in the north and Wadi Al-Sheikh (or Wadi Ibn Waqqad) in the south. This system of walls bared a primary migration route through the Harrat between the Hamad in the east and the Azraq Basin. It exploits even small surface features, curving W where the area is flattest along a series of small playas in the center of the depression. The walls obviously served to keep the gazelle in the wadi and to hunt them at convenient constrictions and at the ends of W-oriented pouches. Fig. 6 also shows that some kite guiding walls cut across the meander walls or incorporate them into their scheme, thus proving that the kites belong to a younger and radically different hunting technique.

3.3 Guiding walls of kites

In contrast to meander walls, guiding walls run more or less straight across playas or lava knolls, changing direction at distinct angles if necessary. The longest kite guiding wall is that of Kite 44 with a length of 10.57 km, longer than any previously reported wall. It runs W from 31°48.291'N/38°0.416'E (in the high resolution area) and ends at 44 at 31°47.823'N 37°53.831'E (in the low resolution area). Each kite normally has a northern, central and southern wall. We measured all the walls in the high resolution strips and, choosing the longest of each (many guiding walls show minor or major alterations), calculated average lengths of all of the guiding walls. Kites 6, 10a, 26, 37 and 43 were excluded (10a was replaced by nearby Kite 10; Kite 26 is not in line with the main chain; Kites 37 and 43 are smaller, bag-like structures presumably of an older generation because the S wall of Kite 35 was extended to cross # 37; Kite 44 was also excluded because it belongs to the second chain to the west, but Kites 1 and 7 were included, even though their enclosures do not appear in high resolution). The northern walls have an average length of 2.00±1.35 km (n = 39), the central walls have an average length of 0.78±0.66 km (n = 25) and the southern guiding walls a length of 2.06±1.31 km (n = 38). The gape width of the kites (distance between the outer tip of the northern and southern guiding walls) was 2.17±1.15 km (n = 38). Again excluding the kites listed above and any parallel walls the total length of northern, central and southern guiding walls sums up to 73.94, 17.27 and 77.39 km, respectively and an overall length of guiding walls of ca. 150 km for the easternmost kites of the Harrat.

Playas may offer an opportunity to date these walls by ^{14}C of OSL because some of the kite walls seem to sink below the playa surface, reappearing on the other side. This indicates that they have been buried in sediment since their time of erection.

3.4 Kite enclosures

The shape of the kite enclosures appears to be either *design-dominated*, having strict symmetric and geometric pattern, or *terrain-dominated*, taking advantage of the *in situ* morphology. Kites 2 and 10a are design-dominated, forming a hexagon with four 'blinds' on the far corners and a 5-tip star, respectively (Fig. 7), but most of the studied kites are terrain-dominated. This is because they open toward the E and it was necessary to find W-inclined places behind a sill so that advancing animals cannot see (or smell) what lies beyond. Available places are further reduced by the need to build a continuous chain of kites. The W-facing slopes become steeper S-wards because there faults with W-facing escarpments occur (Fig. 1). Fig. 6 gives some kite shapes in detail. A common feature is that all have inward concave enclosure walls. The only exception is Kite 2 (Fig. 7), that also does not show any signs of later alteration and is also missing a central wall. Could this have been an early "test-kite", that proved not as effective as the other designs and was abandoned early on? The same arguments apply to Kite 10a that has never been altered.

The average size of the kite enclosure including all buildings stages (i.e., n = 69) is 1.75 ±0.85 ha (coef. of var. 48.8%). The largest kite was # 31 with 4.27 ha and the smallest # 42 with 0.23 ha. The circumference (mean 615 ± 188 m coef. of var. 31.6%) is largest for Kite 31 (1,056 m) and smallest for Kite 42 (228 m). This large number of cases, compared to the number of kites included here (n = 40; excl. # 1,6,7), is caused because many of the kites have different building stages that were evaluated individually (for complete statistics see Kempe & Al-Malabeh 2010). The entrance width varies between 10 m (# 26) and 76 m (# 37). None of the entrances show signs of having been closed in later stages or that the rocks have been
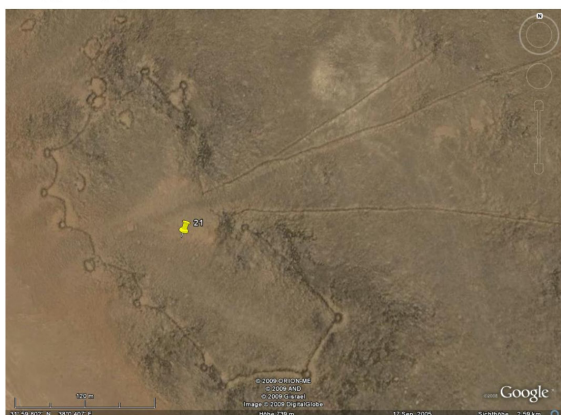
Kite 2
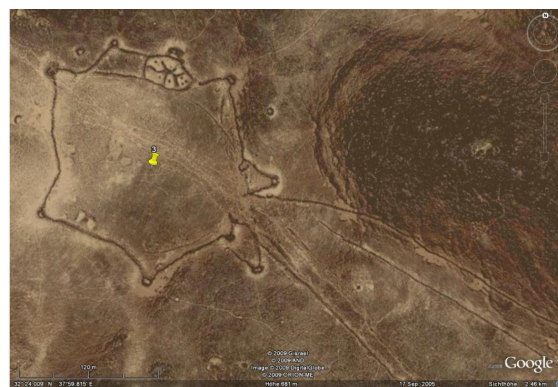
Kite 3

Kite 10a

Kite 14

Kite 21

Kite 26

Kite 36

Kite 42

Fig. 7. Selection of Google Earth images of the kites discussed here (note common 120 m scale bar at lower left. Kite 2 and 10a are examples of design-dominated ground plans. Kite 3 illustrates that wheel houses may be structures of a younger period. Kite 14 has the most blinds and is of a very regular shape. Kite 21 is situated behind a steep sill and elongated to make use the available space. Kite 26 is of an older circular design, placed directly at the border of the Harrat. Kite 36 is an even older pouch-like design, build before 'blinds' were used. Kite 42 is the one furthest south that has been enlarges, taking advantage of the morphology. It is also one with very long guiding walls and being in service even in the third phase of prolongation of guiding walls.

wheel house 29
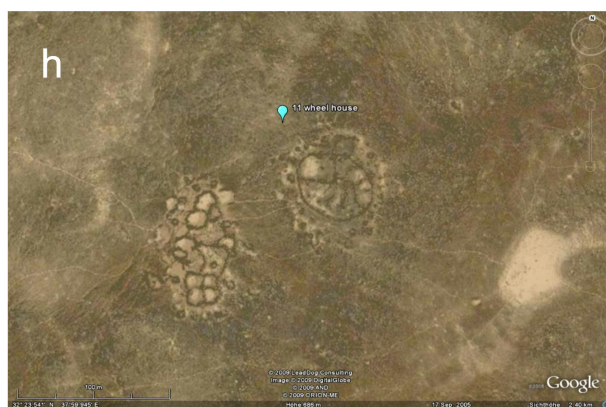
wheel house 17
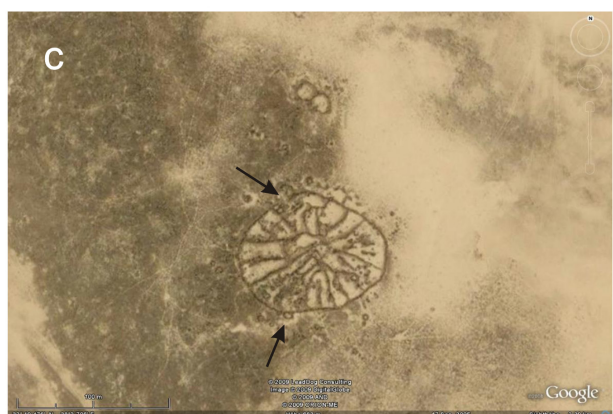
wheel house 31
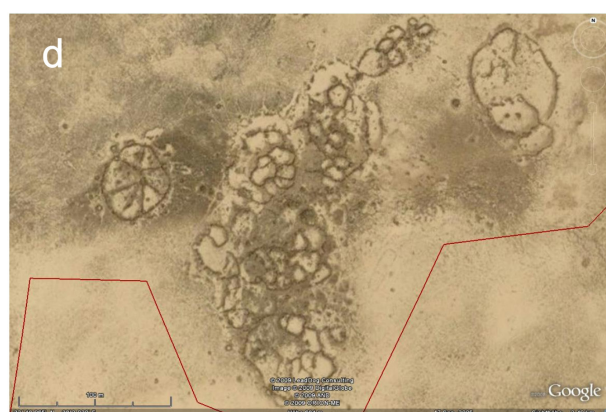
wheel house 32
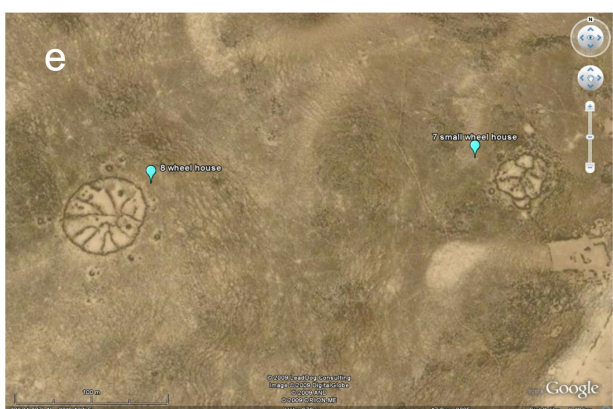
wheel house 8

wheel house 8
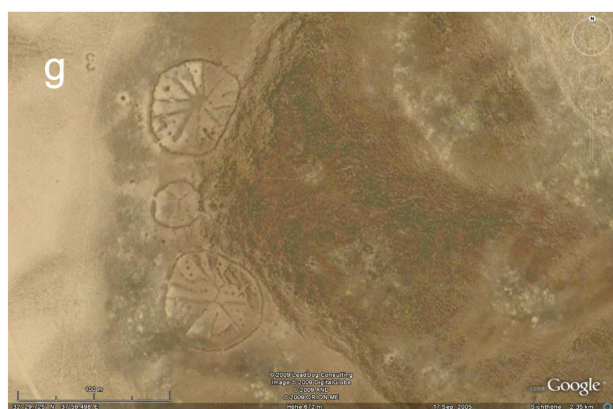
wheel houses 1, 2, 3

wheel house 11

Fig. 8. Examples of Google Earth views of wheel houses from the investigation area (all of the same scale).

Fig. 9. Panoramic view of wheel house 1 on the ground looking south (32°29.763'N / 37°59.450'E; 67 x 54 m, 12 spokes.) Image: Kempe.

removed to form temporary closures. This observation excludes the possibility that the enclosures could have been used to keep domesticated herds (as suggested by Echallier & Braemer 1995).

Kites 37 and 43 do not have any blinds and may represent an early stage of kites, succeeding the meander walls (similar to 'Type C' of Helms & Betts 1987, fig. 14). The star-like type ('type D' of Helms & Betts 1987, fig. 14) has 'blinds' at their ends and the largest number found was 14 for Kite 14. These blinds are always stone circles, 2 to 5 m across. If they are elongated, the long axis, up to 12 m long, is parallel to the enclosure wall.

Many of the kites show later alteration, enlarging them, diminishing them or adding or subtracting 'blinds'. But also location and gate width was changed. Later alterations include erection of structures inside the enclosure with or without incorporation of the kite walls. A detailed analysis of all observed alterations is given by Kempe & Al-Malabeh (2010).

4. Other anthropogenic features

4.1 Places for living

The studied area shows, apart from the km-long hunting structures, an astounding number of traces of human usage present in many different categories (used possibly for dwelling, water management, agriculture, herding, storing, manufacturing, way marking, religious ceremonies or burying). However, which pattern served for what remains often open to debate.

The terms 'jelly fish house' (Helms 1981, pl. 9) or 'wheel house' (WH) describes a circular structure with radial spokes (Fig. 8). 32 WHs are seen in the high resolution area. Their area can change by a factor of 20. On average, WHs measure 51.1(±18.0) x 42.8(±15.0) m in diameter (excluding other detached outside structures) with an average area of 1,730 m². Field inspection of some of the well preserved WHs showed that their walls could not have been much higher than a metre (Fig. 9; # 8, 32°24.804'N/38°0.015'E). Some

of the WHs have satellite rings, in size similar to kite blinds. Often they are positioned on small lava rises. They seem to be concentrated between Kites 1 to 4 and 5 to 8. One WH is built inside a kite enclosure and another inside the runway of the animals, suggesting that they are younger than the kites.

Other structures, more common than WHs, can be described as 'agglomerated houses' (AH), quasi-circular structures formed by an agglomerate of 'rooms' attached to each other. Some of these houses form elongated clusters; others are more centrally organized complexes. AH seem also to be younger than kites since some of them destroy kite features.

At an even higher number of places rocks have been moved to form clearings. Most of them lack peripheral walls, some contain stacks of rocks. Modern clearings are larger and rectangular to accommodate current Bedouin tents and their cars and trucks.

4.2 Circular paths

The most enigmatic finding of our Google Earth studies is 103 'circular paths' (Fig. 10). They also occur further W and S of the Saudi border. Some are almost circular, others elongated, one is a dumbbell and in one example there are two circles within each other (Fig. 11). On average these paths measure 43.3±17.7 m times 31.7±13.7 m. The longest measures 117 m and the largest measures 106 x 90 m. The paths have been cleared of stones and the loess below lets them appear in a lighter color than the surroundings. These paths are much more pronounced than the usual webbing of paths crisscrossing the landscape. Also, they appear to be very regular in their width, about 1 to 1.5 m wide. They encircle in almost all cases an unaltered piece of the Harrat surface. Rarely is any structure found inside them. Some circles are within stone shot of a settlement, others are several hundred metres off. Twice we found kite guiding walls running across them (Kite 36 at 31°49.76'N/38°1.62'E and Kite 42 at 31°46.167'N/38°1.835'E), suggesting that they are older than the kites. In a few other cases, circular paths are overlain by later houses.
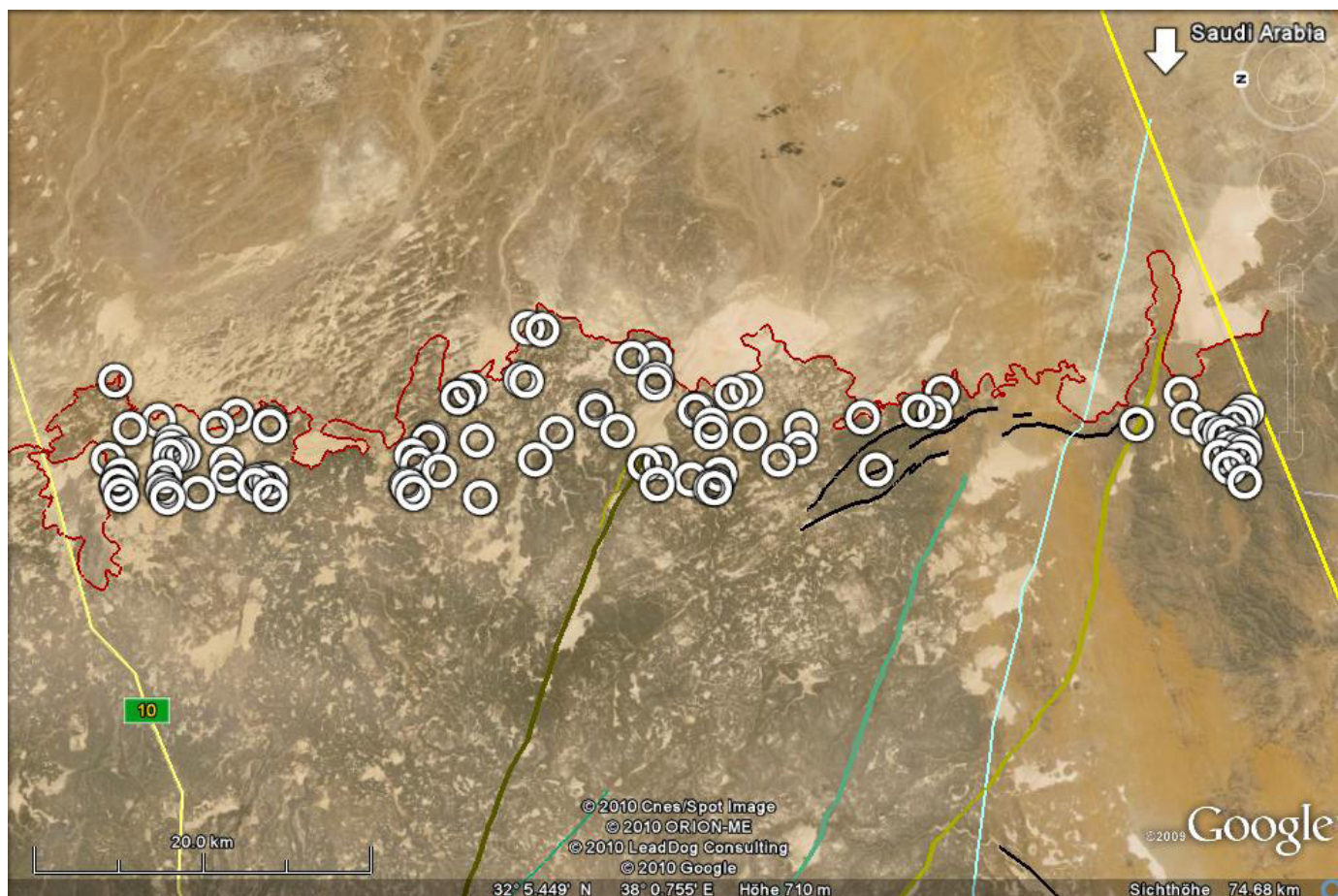
Fig. 10. Positions of circular paths along the eastern border of the Harrat in the Google Earth high resolution strip (north is left). For explanation of geological features see Fig. 1.

Why are there so many of these and what have they been made for? Many reasons come to mind; none is conclusive: training tracks for hunters or their dogs, circles to thrash wild grain harvests or religious processional courses. We may never know, but they definitely are wide-spread phenomena that add curiosity to the Harrat and its prehistoric times.

4.3 Other structures

Seven 'pearl-string enclosures' were found. They are walls formed by strings of small stone circles. The longest wall is a large rectangle, enclosing an entire playa having a perimeter of 1,700 m. Others are much smaller and circular, one is u-shaped. They could have had agricultural purposes.

'U-shaped' structures are small, with a 3 to 6 m long base and two 2 to 5 long arms. They occur in a few places along playas and may also have had agricultural purposes.

More than 20 examples of a quite characteristic feature, consisting of a large rock pile accompanied by one string (or two) of smaller mounds were noticed (Fig. 11a). They seem to be graves, associated to an older tomb of an important forefather.

The area contains also many modern structures, like corrals to keep sheep over night. Other features include forts, reservoirs, airplane orientation marks, airports (next to Jabal Aritain for example) and a multitude of bulldozed tracks.

5. Conclusions

The 'desert kites' of the Jordanian Harrat are a singular phenomenon both concerning their number and their developmental complexity. They illustrate the intensive use of a rough area, now seen as a forbidden rock desert. Archaeological investigations (Ch.1.3) suggest that they date to Prepottery Neolithic times (e.g., Betts, 1998c) and that they served for rounding up and killing gazelle in large numbers. Safaitic inscriptions could suggest that some were still used in early historic times (Harding 1953) and even later. Fundamental questions arise that concern the early building stages and the structural stratigraphy, the exact functioning of the kites and the social background of their creators.

5.1 Structural stratigraphy

Our investigations and earlier analyses (Helms & Betts, 1987) indicate that the technique to hunt gazelle evolved in several steps. The observations in our study area (particularly in its south) suggest the following stages:
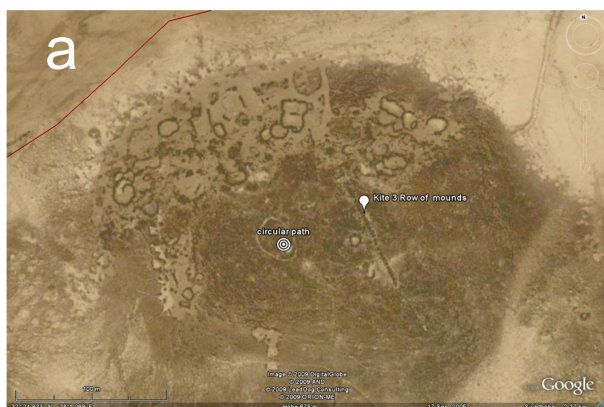
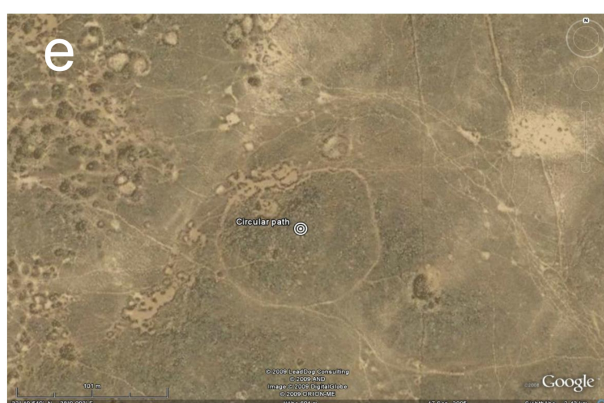Circular path #1 near kite 3
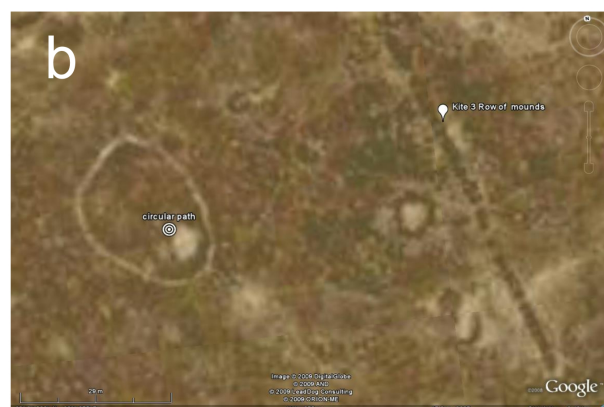
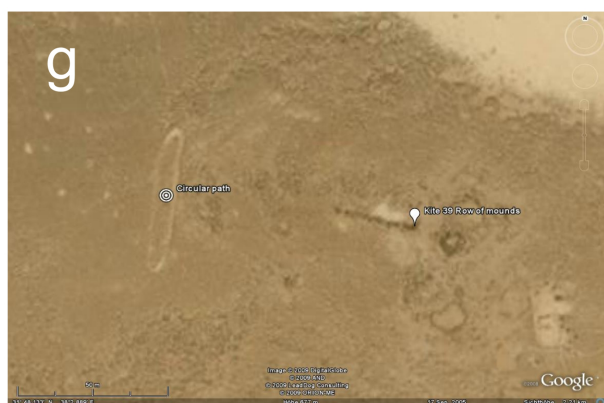Circular path #1 detail

Dumbbell path #13 near kite 3

Double circular paths #16+17 near kite 3

Largest path #27 around knoll

Circular path #66 near kite 16

Elongated path # 78 near kite 39

Circular path #93 crossed by kite wall

Fig. 11. Selection of several circular paths visible on Google Earth. Note the varying scales; (b) is an enlargement of (a).
In (h) the southern guiding wall of kite 36 crosses the circular path.

1　First was a system of meandering walls as obstacles at places of E–W gazelle migration. Multiple W-directed indentations ('pouches') possibly served as places where gazelle would collect and could be hunted easily. Other walls follow the flanks of a wadi, in order to keep gazelle in the wadi and focus them to certain hunting stations.

2　Next, bag-like walls, still without blinds (Kites 37 and 43), were erected at flat places that do not have sills.

3　Then circular enclosures were built next to the Harrat border with a few blinds such as Kite 26 (Fig. 6b). Their guiding walls were relatively short, but placed beyond a sill.

4　In the main period consecutive chains of kites were planned (by a master planner?) and erected, effectively controlling the entire eastern rim of the Harrat. The guiding walls were now straight, extending for kilometres across the terrain irrespectively of its character. Meandering walls were integrated, if appropriate.

5　The last stage of usage was the prolongation of guiding walls, decommissioning some of the neighboring kites of step (4). The walls are now touching each other and the animals following them must have arrived at one or the other kites with no chance to bypass the wall system. In the kites themselves alterations were made, adding blinds or cutting them off. In a few cases, the kite entrances were shifted.

6　With the advent of herding culture the kites were not necessary or not all necessary any more and WHs, AHs and corrals were built within the kite areas, a few of them destroying even sections of the kite walls.

The two chains of kites discussed here are not the only ones in the Harrat. Further west, several more chains exist. Chain after chain of kites was constructed. But what would be left to hunt if already the first chain was a continuous concatenation of walls?

5.2 Mode of operation

In the literature, several hypotheses are given as to how the kites were used. The most common is that the 'blinds' were 'hides' for the hunters. However, the description of 'ditch-hunting' of gazelle in historic times in Syria (compare Simpson, 1994) gives, to our opinion an interesting clue. This method involved driving gazelle along guiding walls into constrictions towards breaches with ditches across them. In their panic the animals would jump into the ditches, hurting themselves so that they could be killed in large numbers. None of the kites discussed here or those described by Helms & Betts (1987) and Betts (1998c) further W, seem to have had ditches. In the described kites, the enclosures are quite large, many hundreds, if not thousands of animals could have been trapped within. They would, in fact have made a good aim for hunters. However, the 'hides' were invariably placed at the tip of the ray-like extensions, i.e. the hunters would be stationed the furthest away from their prey. Furthermore, they would be sitting inside of stone circles and would need to scramble in and out of there if they wanted to swap stations. Therefore we suggest a different mode of operation: The 'blinds' in fact served as ditches, i.e. the animals that would collect in the enclosures because they followed the guiding walls would be frightened, so that they would dash towards the furthest points of the enclosures and jump the wall there. Instead of gaining free terrain, they would find themselves in the tight space of a 'blind'. *Gazella* (even though also called 'jumping gazelle'; Walther, 1990) do not like to jump across obstacles and presumably they cannot jump up and forward if not having a certain runway. Therefore they may have found themselves in "a tight spot" and as more and more gazelle followed, many of them were disabled and could later be easily taken out of the 'blinds'. The inward curved walls of the enclosures would allow the hunters to get close to the center of the enclosure and shoot at animals at close range, thereby setting them off in panic towards the ray-tips. This concept would, to our opinion, explain much better how the kites were operated than previous interpretations. In this way a few hunters could 'harvest' many gazelle without running high personal risk. All animals jumping the walls aside of the 'blinds' would escape and could be intercepted by the next chain of kites a few km further west.

5.3 Social structures

The building of hundreds of kilometres of walls in the Harrat, all of the same concept that result in an almost 100 % closure against animal movement must have involved an overall planning. The builders must not only have been internally organized and must have had enough man-power but they must also have had a long-term control over the area to embark on such an endeavor. We wondered if building these kite structures would actually have a high enough caloric return to justify this expenditure of man-power. We therefore calculated the calories need to build kites (calculation courtesy W. Dreybrodt, Bremen):

The weight (W) of a 1 m high (1 m = h_w), 1 m long and 0.5 m wide (A = 0.5 m²) wall built from basalt (ρ = 3000 kg m⁻³) with an airspace fraction of 0.3 (F) is equal to

$$W = A * h_w * \rho * (1 - F) = 1050 \text{ kg}.$$

The energy (E) (with G = 9.81 ms^{-2}) needed to lift this mass (i.e. each stone has to be lifted to about 1 m (h) before it can be carried to the wall and deposited there is:

$$E = W*h*G = 10,300 \text{ J}, \quad \text{or } (1J = 0.239 \text{ cal})$$

$$E = 10,300 * 0.239 \ 10^{-3} = 2.46 \text{ kcal}$$

If the stones are 10 kg each, then for 1 m of wall, 1050 kg 10 kg^{-1} = 105 stones are needed. For each stone one has to bend over and lift the body (50 kg) back up; thus additionally

$$E = 105*50kg*1m*9.81ms^{-2} = 51,500 \text{ J} = 12.3 \text{ kcal}$$

are needed. In total about 15 kcal at least are needed per metre of wall. The efficiency of muscular work is about 0.25 and thus

$$1/0.25*15 \text{ kcal} = 60 \text{ kcal}$$

are needed per metre of wall, or 60,000 kcal per kilometre. Meat has a caloric value of 1,280 kcal kg^{-1}. Thus, 1 km of wall is equivalent to 46.9 kg of meat, i.e. in the range of the usable weight of three gazelle (if, for example, a Dorca gazelle is taken as standard that has a weight of around 20 kg). Assuming that per day about 500 kcal can be invested into work (half of that assumed for very heavy work) then 1 km of wall can be erected in 120 man days. Taking the average length of the enclosure perimeter (0.62 km), northern (2.00 km) and southern (2.06 km) guide walls together (= 4.68 km) then a kite can be erected in about 562 man days; or, if ten people cooperate, within 56 days or one hunting season. The investment would then be equal to about 220 kg of meat or about 15 gazelle, i.e. it would be highly profitable even at short-term.

Thus, the kites may have been built within a few years and, if hundreds of gazelle were hunted per year, they would have returned the caloric investment within a very few years.

The extension of some kite guiding walls across the openings of neighboring kites (phase (5) above) may have been triggered by the depletion of gazelle so that fewer kites were necessary or by the decrease of the number of people still living from hunting (or both). It could also be hypothesized that the final kite chain stage was used to exclude gazelle entirely from the area so that domesticated animals had the full use of the vegetation.

Many more questions need to be asked; for example where did the people building and using the kites have their camping sites, how did they preserve the meat and how did they transport the meat to markets (if that was one of the aims of the operation)? Who was organizing the building of the kites and who designed the master plan?

5.4 Sustainability

The high density of the kites also raises the question of sustainability. How long could the kites have been used with profit without depleting the gazelle to a point that the return would not sustain the hunting community anymore? The effective barring of animal migration by multiple kite chains and gap-less guiding walls could diminish the migrating herds within a few years almost to the point of extinction. But even after a near-extinction, the number of gazelle may have recovered if large-scale hunting would cease. This would explain the use of the kites in later times as described above. We were shown a head of a Dorcas gazelle (*Gazella dorcas,* Linnaeus, 1758) in Ruweished shot recently in the area. The introduction of fire arms, non-sustainable pleasure hunting and overgrazing have finally led to the extinction of gazelle in Jordan.

5.5 Heritage issues

Our study of the Google Earth images also shows how the area and its archaeological heritage are impacted by modern man. The area is crossed by the Trans Arabian Pipeline (TAP) (Fig. 1) and the Iraqi Pipeline (passing from Karouk in Iraq through Ruweished and Safawi to Haifa). To construct the pipelines, tracks and fort-like buildings had to be built. Wide, straight, characteristic double-tracks were bulldozed through the area, regardless of archaeological structures for oil exploration seismics (King, 1990). Other single-lane bulldozed tracks crisscross the area, intended to make the area accessible to the trucks of the modern sheep herders and reservoir basins have been bulldozed into the playas. More tracks are made by pickups. But most scaring is the random bulldozing that is seen along the national road 40 that crosses the area from Safawi to the Iraqi border and it seems only a matter of time before a substantial part of the archaeological heritage is lost irrevocably.

6. Acknowledgments

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