PROCEEDINGS OF THE X, XI, AND XII INTERNATIONAL SYMPOSIA ON VULCANOSPELEOLOGY

Edited by
Ramón Espinasa-Pereña and John Pint

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Collapse entrance to Dahl Um Quradi in Harrat Khaybar, Saudi Arabia. Photo by John Pint.

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X Symposium
September 9–15, 2002
Reykjavik, Iceland

XI Symposium
May 12–18, 2004
Pico Island, Azores

XII Symposium
July 2–7, 2006
Tepoztlán, Morelos, Mexico

ASSOCIATION FOR MEXICAN CAVE STUDIES
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Preface

Held at the ex-Convent of Tepoztlán, in the state of Morelos, México, in July 2006, the XIIth Symposium of Vulcanospeleology was sponsored by the Sociedad Mexicana de Exploraciones Subterráneas (SMES), the Commission on Volcanic Caves of the International Union of Speleology (UIS), Grupo Espeleológico ZOTZ, the Association for Mexican Cave Studies, and the State of Morelos Section of the National Institute of Anthropology and History (INAH). It gathered thirty-eight dedicated researchers and specialists from three continents, and over twenty-eight different papers were presented.

During the symposium, the fact that no Proceedings had been published of the two previous symposia was discussed, so a request for these papers was made, with relative success. The abstracts and five papers from the 2002 symposium are therefore included, together with the abstracts and seven papers from the 2004 symposium. Together with the eighteen 2006 papers, this volume therefore includes 30 papers. Due to the success of the six field trips taken during and after the XII symposium, the guidebook is also included.

Topics range from general cave descriptions to highly specialized discussions on volcanic cave geology, archaeology, and biology. The areas covered include México (the 2006 host country), Hawaii, the Azores, the Middle East, Japan, and Iceland.

Dr. Ramón Espinasa-Pereña
2006 Symposium Convener

Cover photograph by Tim Ball.
James Begley in Flóki, Reykjanes Peninsula, Iceland.

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SUPPLEMENTARY MATERIAL ON THE CD

The CD contains, in addition to the PDF file for this proceedings volume, some material to supplement some of the articles. In some cases there are additional photographs or maps. In others, I have judged that a higher-resolution graphic of a map would be significantly more legible than the printed version. Australian Ken Grimes has provided PDF files of some of the papers referred to in an article and also a couple of nice color educational posters.—Bill Mixon, AMCS Editor

Folder **2002 Grimes 1**. Supplement to X symposium paper "Subcrustal Drainage Lava Caves . . . ," by Ken Grimes.

- Image file for additional map of cave H-51.
- PDF files of data forms and maps for caves H-106 and H-108.
- PDF files for referenced papers Grimes 1995, Grimes 2002a, and Grimes 2002b.

Folder **2002 Grimes 2**. Supplement to X symposium paper "A Small Cave in a Basalt Dike . . . ," by Ken Grimes.

- A PDF file of the version of this paper published in *Helictite* in 2006.

Folder **2004 Pint**. Supplement to XI symposium paper "Rare Cave Minerals and Features of Hibashi Cave . . . ," by John Pint.

- Image file of figure 3 (page 92), map of Ghar Al Hibashi.

Folder **2006 Al-Malabeh**. Supplement to XII symposium paper "Al-Fahde Cave, Jordan . . . ," by Ahmed Al-Malabeh, et al.

- Image files of the four sheets of the map of Al-Fahde Cave, figures 2–5, pages 202–204.

Folder **2006 Espinasa**. Supplement to XII symposium paper "Cueva Tecolotlán . . . ," by Ramón Espinasa-Pereña and Luis Espinasa.

- Image file of map of Cueva Tecolotlán, figure 2, page 154.

Folder **2006 Kempe**. Supplement to XII symposium paper "Geology and Genesis of the Kamakalepo Cave System . . . ," by Stephan Kempe, et al.

- Image file of map of Waipouli (Makai) Cave, figure 8, page 236.

Folder **2006 Pint**. Supplement to XII symposium paper "Surveyed Lava Tubes of Jalisco . . . ," by John Pint, et al.

- PDF file containing four additional color photograph with captions.

Folder **2006 Waters**. Supplement to XII symposium paper "Recent Contributions to Icelandic Cave Exploration . . . ," by Ed Waters.

- Image files of maps of Lofthellir (page 193) and Fjárhólahellir (page 194).
- Image files of additional maps of Burí, Hellinger, and Holgóma.
- PDF file containing four additional color photographs with captions.

Folder **Grimes posters**.

- PDF files of color educational posters prepared in 2005 by Ken Grimes, "Lava Tube Formation" and "Sub-Crustal Lava Caves."

X^th International Symposium on Vulcanospeleology

September 9 -15, 2002 Reykjavík, Iceland

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Nordic Volcanological Institute
Nature Conservation Agency
Icelandic Institute of Natural History
University of Iceland

2002 SYMPOSIUM ABSTRACTS

Compiled by Sigurður S. Jónsson

Geology of Harrat Kishb, Saudi Arabia, in Relation to the Formation of Lava Tubes

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Geologist, Saudi Geological Survey

Basaltic lava fields cover 89,000 square kilometers of western Saudi Arabia. One of these lava fields, named Harrat Kishb, has an area of 5,890 square kilometers and is located 300kms northeast of Jeddah. The nature of lava found in this area and the thickness of the flows were propitious for the formation of lava tubes one million years ago.

The lava tubes of Harrat Kishb are found in three different structural and physical positions relative to their parent volcanic cones. The three-km-long lava tube associated with the Jebel Hil volcano was formed by the emptying of the arterial tube as the lava front advanced downslope. Instead, the Ghostly Cave and Kahf Mut'eb lava tubes are found 7km from the volcano which gave birth to them and were caused by blocking of the lava flow by an older cone. The third manner of formation is seen in Dahl Faisal, where a thin part of the roof of the lava tube was sucked down to form a funnel-shaped entrance for surface air.

More than 2000 basaltic volcanoes can be found in western Saudi Arabia and many of these are associated with multiple lava flows. Because of the discovery of caves in Harrat Kishb, it is likely that many of these volcanoes have also produced lava tubes.

Data Base on Icelandic Caves

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The first list of Icelandic lava caves was compiled by Hróarsson in 1990 in his book "*Hraunhellar á Íslandi*" (Lava caves in Iceland). The list comprised a geographically sorted list of about 170 caves, mostly caves mentioned or described in earlier publications but also several newly discovered caves and caves only known to locals in the vicinity of the caves. Hróarsson's list laid the foundation for a "*dbase IV*" table with cave names, lava flow, length and other relevant data and the "*dbase IV*" file was maintained for several years. Later that format was abandoned and the whole list was imported and maintained in a large "*Excel*" spreadsheet.

The author will present a whole new design of a cave database, running on Microsoft Access®, using data and data fields from the previously existing Excel spreadsheet. Attempt has been made to simplify data input, and general

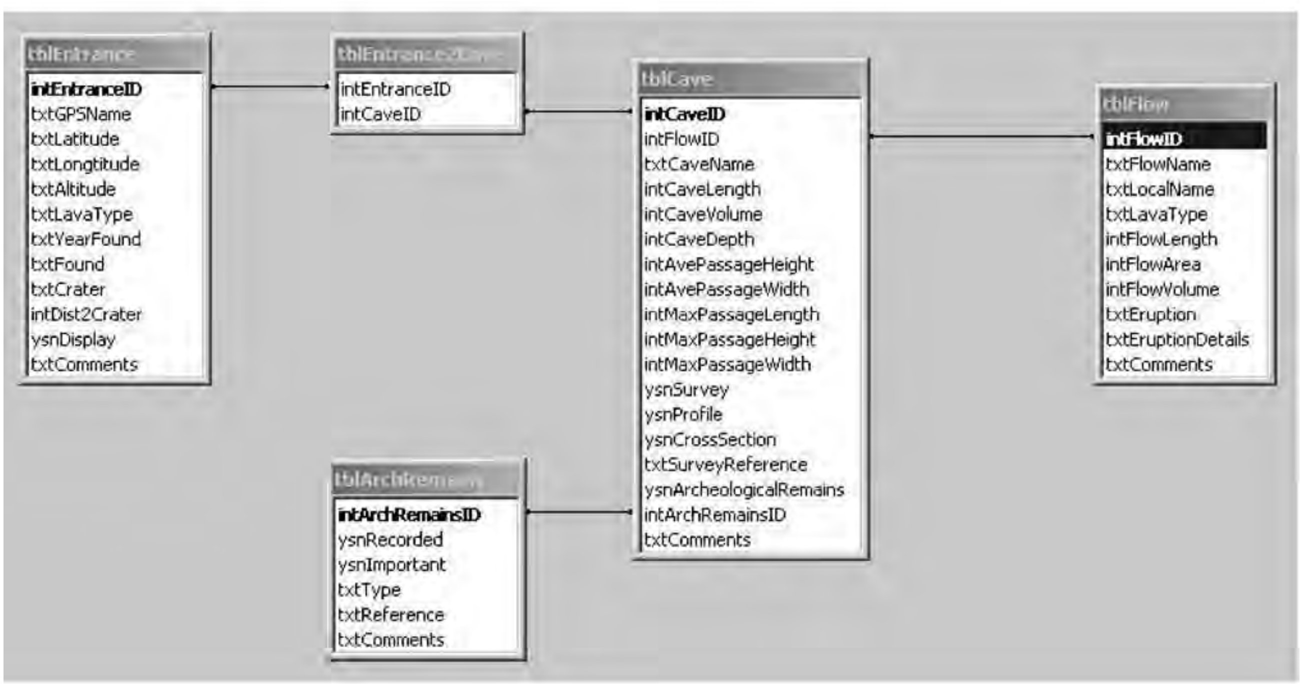

Figure 1 (Begley, "Data Base"). An example of ISS cave database table relations.

filtering, sorting and other data extraction capabilities. The ISS cave database now holds about 60 caves with known GPS-coordinates, but a large pile of data waits to be inserted into the ISS cave database.

Ranking Azorean Caves Based on Arthropod Fauna

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Endemic arthropods and in particular troglobian species were used to evaluate the conservation value of volcanic caves of the Azorean islands. For each of the 44 Azorean endemic species of arthropods recorded to caves, a rarity index was calculated, using distribution and abundance data obtained from the literature. In addition, several scoring indices based on diversity and rarity measures were used to rank 16 caves from which standardized sampling has been performed. About 47% of the 19 endemic troglobian arthropod species are "single cave endemics", that is, are known from only one cave. Based on the Jackknife estimator we estimated the occurrence of 28 (± 3) species of troglobian arthropods in the Azores, which implies that there is the need of further biospeleological surveys in these islands. The most beautiful caves based on a "Show Cave Index" are also the most diverse in troglobites ($r = 0.55$; $p = 0.01$), which means that geological diversity could be a good surrogate of fauna diversity. Moreover, there is more trogobite species on largest caves ($r = 0.66$; $p = 0.0099$). Based on the complementarity method, to preserve the Azorean arthropod troglobite biodiversity there is a need to protect at least 10 caves in order each species is represented at least once. However further caves will be needed to have each species represented at least twice. The standardized sampling provided valuable guidance for achieving the goals of practical conservation management of Azorean biological cave diversity, but further research is required to have better knowledge on the real diversity of Azorean troglobites and their distribution. There is also the need of special measures of protection for the aboveground native habitats in order to maintain the flux of nutrients for the cave environment. This study showed that cave fauna could be used to identify a network of caves for protection that are also of great geological interest.

A Data Base and Classification System for the Azorean Volcanic Caves

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The Azorean Regional Government, being aware of the importance of the volcanic caves and pits as elements of our natural heritage, created in 1998 a multidisciplinary task force to promote its study. One of the main objectives of this group was to act as a consultant to the government, by recommending initiatives concerning de conservation and preservation of these volcanic underground structures.

As a first priority, this group decided to develop a database, which could be used as a managing tool for the Azorean volcanic caves and pits. To achieve this goal it was found necessary to create a field form, to register as many data as possible, allowing a satisfactory description of the underground volcanic structures, and also that could provide the principles for the database structure.

Due to the geographical dispersion of the Azorean islands, and the number and diversity of the lava tubes, it was consider most relevant that managing decisions should be based on accurate knowledge. At that time it was settled the idea of an instrument that could organize the information, in a way it would be possible to evaluate among several parameters of each volcanic caves, to build different sorting accessions, and to produce meaningful lists. These fundaments gave origin to a computer application built over FileMaker Pro 4.0, combining both a database and a classification system.

The sorting and classifying systems presume an objectively chosen criteria set, so that the results are logical, coherent and reliable. It is also significant the possibility to generate diverse classifications based on different preset criteria, deduced from established objectives and aimed to real applications.

The Azorean Speleological Inventory and Classifying System (IPEA) incorporate six major classification issues, as follows: scientific value; potential for tourism; access; surrounding threats; available information and conservation status. Each classification comprises five classes (I to V) where the volcanic caves are sorted as a result of weight calculation upon the values given by nine criteria sets. These criteria are: biologic component; geologic features; accessibility; singularity and beauty; safety; caving progress; threats; integrity and available information. For each of these criteria were established six parameters, where 0 is the lack of information and the other five parameters are objective and clear statements that describe the cave within the criteria.

Each volcanic cave is than characterized by choosing one of the six parameters of the different criteria, that allows among other possibilities to sort the caves in many different ways and to produce relevant lists. It is expected that this application becomes a useful tool to managing Azorean caves for conservation, study and exploration.

Ranking Azorean Caves Based on Geological, Biological, and Conservation Attributes

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With the Azorean Speleological Inventory (IPEA) in a computer data base format it is possible to have a better characterization of the Azorean volcanic caves and pits, spread all over the nine islands of the archipelago. Once the existing data is often poor and incomplete, all the analysis and ranking should be considered, by now, as a preliminary approach.

The IPEA data base comprises 206 records that correspond to the Azorean caves and pits whose existence was confirmed by the team created form that purpose. It is also important to emphasise that there are several reports and bibliographic notes that allows to expect, in a near future, to raise up that number. Moreover, 57% of these 206 caves are unsatisfactorily described, in particular on their biological and geological features, and only 67 are mapped.

The Azorean volcanic caves are located at Pico (81), Terceira (66), São Miguel (17), São Jorge (16), Graciosa (11), Faial (8), Santa Maria (5), and Flores (2). About 63% are lava tubes, 13% pits, 4% fractures, 4% erosional caves and the remaining are combine or undetermined types.

Troglobic species were identified in 25 underground structures, namely the blind ground-beetle, *Thalassophillus azoricus*, which can only be seen in Água de Pau cave (São Miguel island) or the genus *Trechus* found in Pico caves. In 59 caves there are rare and uncommon geologic features, such as long lava stalagmites and sets of burst bubbles of lava, e. g. Soldão and Torres caves (Pico), and Natal and Agulhas caves (Terceira). In 12 caves severe threats were identified in the surrounding area, and thus prevention and protection measures are needed. It is recognized for 22 underground structures their high integrity status, for example Gruta dos Montanheiros (Pico), Gruta da Beira (São Jorge) and Furna do Enxofre (Graciosa).

"Gruta das Torres" Project

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In the Archipelago of the Azores there are a large quantity of lava tubes and pits, in almost every of the nine islands. At present, result of field work made during the last years by the Society of Speleologic Exploration "Os Montanheiros", by the Ecological Association "Amigos dos Açores", by the "Círculo de Amigos da Ilha do Pico", and by the Regional Services for Nature Conservation, there are 239 volcanic caves marked in the Azorean Archipelago.

This geological and biological richness lead the Regional Government of the Azores to promote, through its resolution nr. 149/98 of June 25, the creation of a working group responsible for the study of the Azorean volcanic caves. This group has already created a database and a classification system that will allow the raise of a management model for these caves. In this field of action, and taking into consideration the high speleologic value of "Gruta das Torres", its proximity to population centres and its great accessibility and therefore the facility of being visited, the Regional Environmental Services of the Azores has conceived this project and thus created a pilot experience in the Management and Exploration of volcanic caves in this Region.

"Gruta das Torres" is a volcanic cave, located in Criação Velha – Pico Island, that had its origin in *pahoehoe* lava flows expelled from Cabeço Bravo. It is the biggest lava tube known in the Azores with a total extension of 5 150m. It consists of a main tunnel of large dimensions, attaining in some areas more than 15m in height. There are also secondary ramifications of smaller dimensions where, at times, it is necessary to crawl. Its interior is full of interesting lava formations, such as lava stalactites and stalagmites, silica deposits, lateral benches, flow marks, ropy lava, and lava balls.

The walking tour inside the cave is 400m long and the access to its interior is attained through one of the cave's natural openings.

The improvements to make in the cave, namely to turn the access more easy, will be minima in order to keep the cave's aspect the most original as possible.

In the cave's interior only the ground will be cleaned, clearing out breakdown of the ceiling and walls so as to facilitate the passing through of visitors.

The visits will take place in small groups, with individual lightening system and in the presence of a guide who will give all the informations about the cave.

Besides the route inside the cave, one intends to familiarise visitors with the local geology, flora and fauna, through a briefing given at the cave's support installations, as well through the creation of complementary routes to be explored at surface near the site.

References:

Borges, P.A.V., Pereira, F. & Silva A., (1991), Caves and Pits from the Azores with some comments on their geological origin, distribution and fauna. 6th International Symposium on Vulcanospeleology. Hilo, Hawaii, pp. 121-151.

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Costa, M.P. & Barcelos, P., (2001), Cavidades Vulcânicas dos Açores, Congresso Internacional sobre Património Geológico e Mineiro, Beja, Outubro, 2001.

Costa, M.P & Verissimo, E.F. (2002), Projecto Gruta das Torres, 2nd Pico Island Internacional Volcanological Meeting, Abril, 2002.

Subcrustal Drainage Lava Caves; Examples from Victoria, Australia

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Most documented lava caves are large, linear or anastomosing tubes formed by roofing of lava channels or development of major feeder tubes within a flow. However an increasing number of small shallow caves is being recorded that have simple to complex patterns of interconnected low chambers and small passages that form by a different process.

In reviews of active volcanoes in Hawaii, Peterson & others (1994) and Hon & others (1994) proposed two distinct models for the formation of lava tubes: firstly by the roofing over of linear surface lava channels; and secondly by the draining of still molten material from beneath the solidified crust of pahoehoe flow lobes. This paper will concentrate on the second type: the smaller, but occasionally complex, caves formed by localisation of flow beneath the crust of thin flow lobes or sheet-flows, and subsequent partial draining - as illustrated in Figure 1. More recently Halliday (1998a & b) has described two types of small lava cave: His "sheet flow caves' and 'hollow volcanic tumulus caves' which he regards as being distinct. I will argue that these are just two of several possible end-members of a continuum of forms which I will refer to as "Subcrustal drainage lava caves". Examples are drawn from the basaltic Newer Volcanic Province of Victoria, Australia.

Subcrustal drainage caves involve a broad array of styles ranging from simple single chambers (Figure 2) to multi-level, complexly-interconnecting systems of tubes and chambers (Figure 3). However, while we can identify distinctive types at the extremes, there are many that fall in the middle ground and are hard to classify. All members of the group have in common the dominance of shallow, low-roofed, irregular chambers and small-diameter tubes running just below the surface of the host flow. They also grade (and possibly evolve over time) into larger and more-linear tubes. In long-lasting lava-flow systems, continuing evolution of these small caves in the upstream parts of the flow could produce larger "feeder-tubes' which would converge on the form of, and be difficult to distinguish from, the large "roofed channel" type (eg. the proximal end of H-53, Figure 3).

The simplest caves are small chambers; typically only 1m high with a roof about 1m or less thick, that occur scattered through the stony rises and have been called "blister caves" in Victoria. These can be circular, elongate or irregular in plan; up to 20m or more across but grading down to small cavities only suitable for rabbits. In section, the outer edges of the chamber may be smoothly rounded or form a sharp angle with a flat lava floor. The ceiling may be arched or nearly flat, with lava drips, and can have a central "soft" sag that would have formed while the crust was still plastic. Alternatively, the thin central part of the roof has collapsed and we find only a peripheral remnant hidden behind rubble at the edge of a shallow collapse doline (e.g. H-78, Figure 2). The more elongate versions grade into small "tubes" (e.g. H-31). These caves generally are found beneath low rises (with or without the central fissure required to class them as "tumuli"!), though some have no surface relief at all.

Larger systems show more evidence of directed flow beneath the crust, either radially from a central feeder (H-33, Figure 2) or laterally from the breached levee of a lava channel (Figure 3). They are commonly branching systems with complexes of low passages that bifurcate and rejoin, or open out into broad low chambers. The form suggests draining from beneath the thin solidified roof of a series of coalesced flow lobes.

A Small Cave in a Basalt Dyke, Mt. Fyans, Victoria, Australia

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The Volcano: Mt. Fyans is a volcano within the Newer Volcanic Province of Victoria, Australia. The age of the province dates back at least 5 million years, but this is a youthful eruption, undated, but possibly less than 100,000 years old – judging by the well developed "stony rises" (remnants of the original hummocky lava surface) and minimum soil development. The volcano is a broad shield of basaltic lava with a low scoria cone at the summit and possibly a crater - though an extensive quarry in the scoria makes the original form difficult to deduce!

The scoria at the summit has a thin cap of basaltic lava, and ropy patterns on the underside of this are well-exposed on the southern margin of the quarry. The loose scoria has been intruded by two large basalt dykes up to 12 m across (which would have fed the lava cap) and a number of smaller pipe or finger-like basalt bodies, some of which have been partly drained to leave small cavities. The quarry operations have worked around the large dykes, but damaged the smaller intrusive features (which is how we know they are hollow!).

The dyke cave: A small horizontal cave occurs within the largest dyke. It lies close to the west edge of the dyke and runs parallel to it (see map). Entry is via a small hole broken into the roof. The cave is about 17 m long and generally less than one metre high. The roof and walls have numerous lava drips. The floor is a horizontal ropy pahoehoe surface which rises gently towards the northern end – but the ropy structures suggest a final flow direction from south to north. The drainage points for the lava are not obvious. Both roof and floor have common patches of pale-cream coatings over

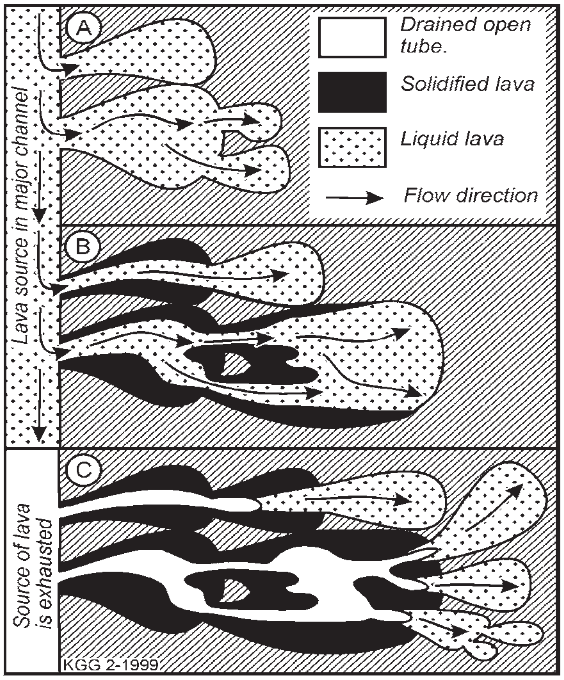


Figure 1: Development of subcrustal caves by partial drainage of successive lava lobes

Figure 2: Examples of small subcrustal caves.

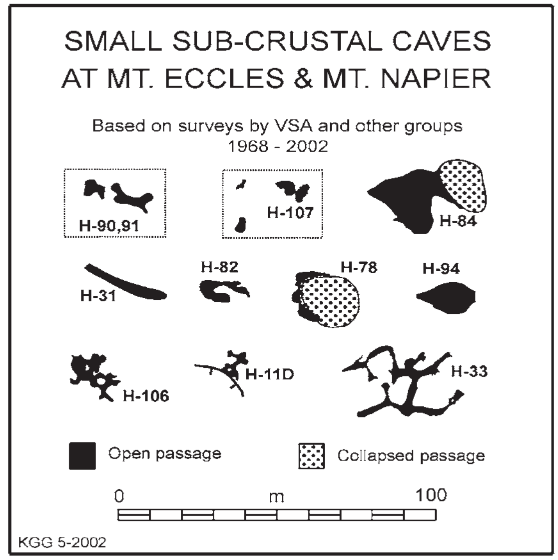
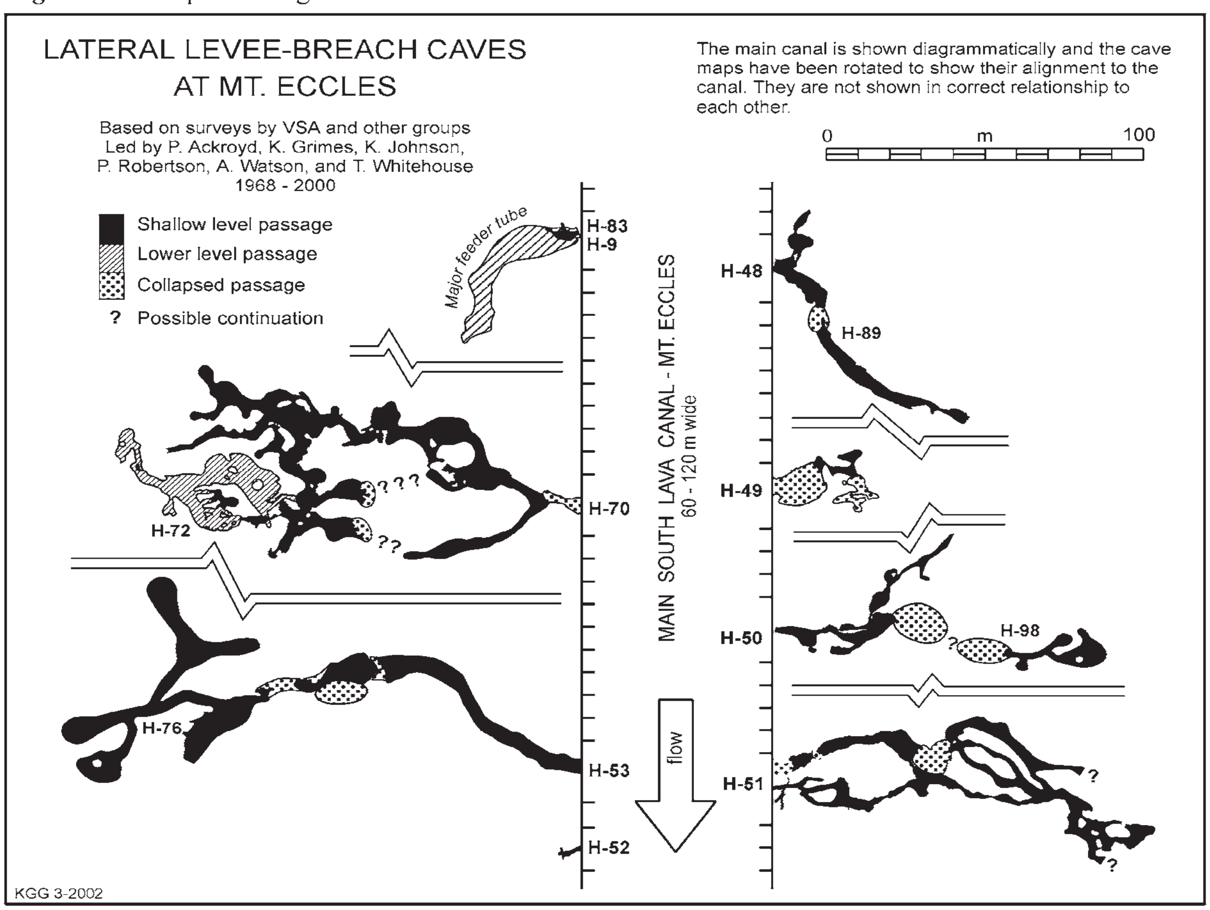


Figure 3: Examples of larger subcrustal caves formed in thin overflows from a lava channel.



Figures for Grimes "Subcrustal Drainage Lava Caves."

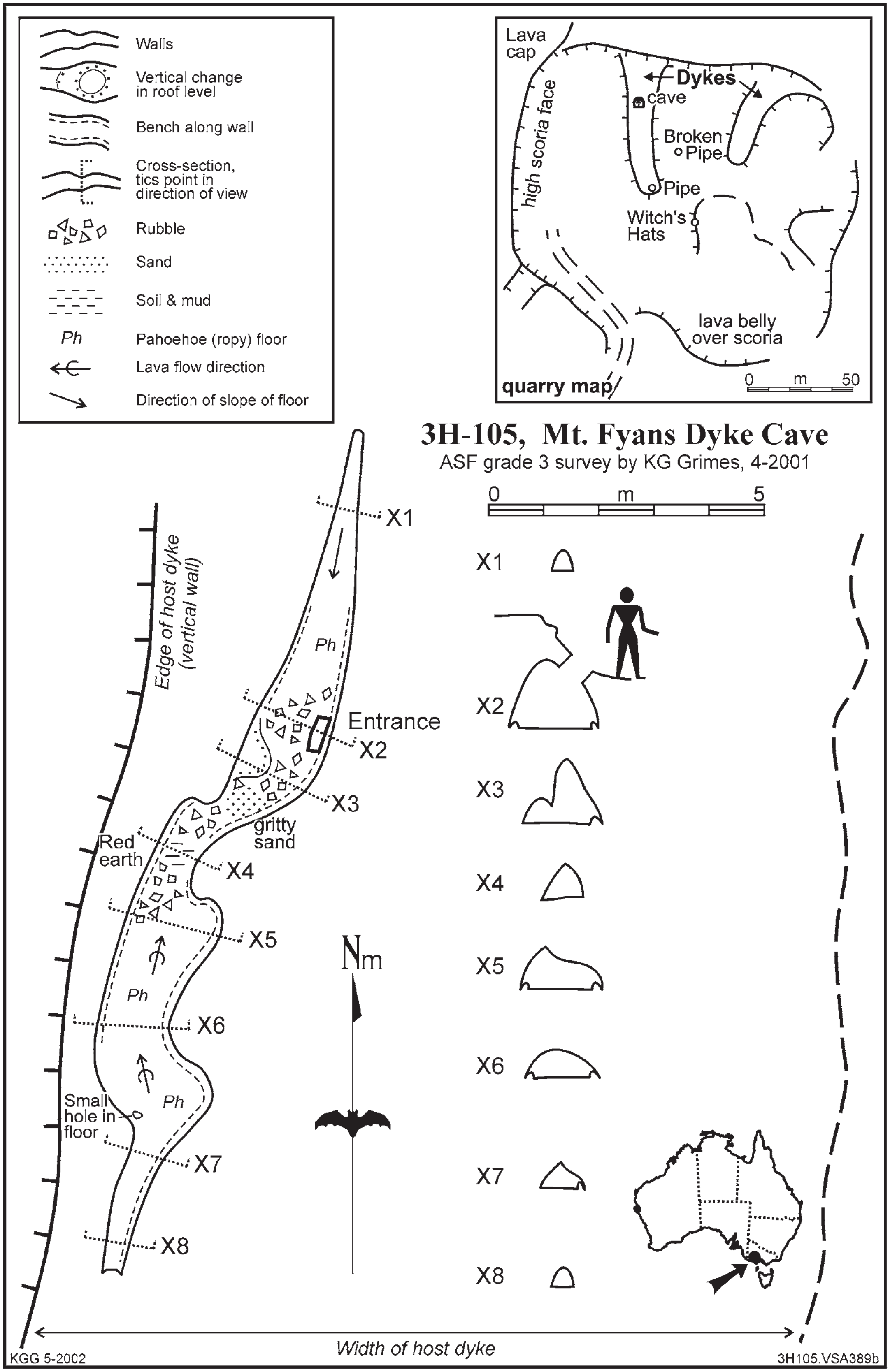


Figure for Grimes "Small Cave Mt. Fyans."

the basalt – possibly fumerolic alteration? There are well-developed rolled benches (10 cm diameter) along the edges of the floor. One small hole in the roof, near the entrance, opened into broken scoriaceous material.

Related features: As well as the cave, the main dyke also has a drained vertical pipe at its southern end – this has been broken into by the quarry operation and we found the upper part lying on its side 20 m to the NE. This pipe had spatter and dribble patterns on its inside walls. Elsewhere in the quarry there are intrusive pipes and smaller fingers of basalt that have pushed up through the loose scoria. Several of these have drained back after the outside had solidified so as to leave a hollow core, some with lava drips. Probably the most distinctive are conical "Witch's hat" structures.

No other volcanic caves formed in dykes have been reported in Australia, but a larger one has been reported from the Canary Islands (Socorro & Martin, 1992).

Genesis: The dykes and other bodies would have been intruded into the loose scoria towards the end of the eruption, would have cooled and partly solidified, and then as pressure was lost those liquid parts that were still connected to the main feeder channels would have drained a little way back to leave the cavities. There may have been some oscillation to form the rolled benches in the dyke cave.

Reference:

Socorro, JS., & Martin, JL., 1992: The Fajanita Cave (La Palma, Canary Islands): A volcanic cavity originated by partial draining of a dyke, in Rea, GT., [ed] *6th Int. Symp. Volcanospeleology*. National Speleol. Soc., Huntsville. pp 177-184 [in spanish].

Preliminary Data on Hyalocaves in Iceland: Location, Formation, and Secondary Mineralogy

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Hyalocave is a new type of volcanospeleological phenomena. *Hyalo-* is a word derived from Greek and means glass. Hyalocaves are associated with subglacial volcanic eruptions and are the result of entrapment of large ice-fragments inside or atop volcanically generated gravity flows and pillow lavas.

Evidence of basaltic subglacial eruptions have be found in Iceland, British Colombia in Canada and Antarctica. Subglacial eruptions form very distinctive geomorphological mountains called "*tindar*" (hyaloclastite ridges) and "*stapi*" (steep sided tuya). Interaction between magma and meltwater produces pillowlava or fragmented volcanic glass, depending on the hydraulic pressure inside the glacier. Scientist tend to associate subglacial eruptions with englacial lakes. Formation of basaltic subglacial eruption is often divided into three stages: 1) Magma under hydrostatic pressure, pillowbasalt is formed, 2) hydrostatic pressure is low - explosive face; volcanic glass is formed when magma comes into contact with water, gravity driven currents flow down the slopes of the mountain and 3) the main magma feeder is blocked from the water and subaerial lavas starts to flow. Lavas may flow into the englacial lake forming flowfoot- or foreset breccias.

Hyalocaves have been found on the Reykjanes peninsula (Stapafell), Mosfellssveit (Mosfell), Laugarvatn-area (Laugarvatnsfjall, Hlodufell, Mosaskardsfjall, Kalfstindar), Snaefellsnes (Songhellir in Stapafell), Eyjafjallajokull glacier and Thorsmork. Most of them are small: only few meters in length, width and height, although few are tens of meters in size.

These formations haven't been given much attention, due to lack of understanding of basaltic subglacial structures and their chaotic fashion. Hyalocaves are clear evidence of ice in the system. They can help scientists to estimate the waterlevel in the "englacial lake". They also indicate that the mountain was "roofed" by ice during the formation of the particular sediment- or pillow-pile. In the future hyalocaves might even help sedimentologist to estimate the density of gravity flows in subglacial environments.

Two new minerals in Iceland are associated with hyalocaves, these are *monohydrocalcite* ($CaCO_3*H_2O$) and *weddellite* ($CaC_2O_4*2H_2O$). Monohydrocalcite has been found in basaltic lava tubes in Hawaii, limestone caves and lake sediments in salty environment. Weddellite has been found in few limestone caves in Australia and Namibia in Africa. Weddellite is often associated with urea and feces of bats, birds, rats and other mammals. Ideally monohydrocalcite needs the following conditions to form: pH>8, Mg/Ca >1, temperature <40°C, water droplets or aerosol, salt, bacteria or algae. Formation of monohydrocalcite in Iceland is associated with oceanic originated precipitation (pH 5,4) that becomes isolated from the atmosphere as soon as the water seeps into the hyaloclastite and comes into contact with volcanic glass. Volcanic glass is ten times more easily dissolved then crystalline rock. Elements from the glass are dissolved by exchanging positive ions from the glass (Mg^{++}, Ca^{++} et. al.) while hydrogen ions go into the glass. Due to this hydrogen loss the pH increases and ends in 8-9. Micro-organism are know to exist in basaltic glass. Bacteria was seen in thin-sections made from the site where monohydrocalcite was found. Monohydrocalcite was only found in selected hyalocaves and only in the entrance with clear evidence of great leakage and moss growth (*Hymenostylium recuroirostrum*). Minerals formed only in the roof and on walls. The crystals are very small and form thin layer on pillow-fragments or 1-3 mm knobs on both the pillow-fragments and the glassy matrix. The color is white to light-brown. Weddellite is white and powdery. It is located both on walls and ceiling. Its occurrence is associated with sheep feces and urea, but they use the caves for shelter. Weddellite is the first organic mineral described from an Icelandic cave.

Proposals for Future Vulcanospeleological Research in Iceland

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Icelandic speleology has contributed enormously from foreign expedition during the last 3-4 decades. Prior to that, very scant information was available on Icelandic caves, and only the general public knew a few caves. Furthermore Icelandic geoscientists have always rather reluctantly approached speleological topics for whatever reasons. An accurate chronology of foreign cave-expeditions to Iceland is not available, but an effort can be made to expose the highlights.

The first expeditions are not very well known and it can be that the main purpose of those journeys was general travelling around Iceland. The British Shepton Mallet Caving Club was active in surveying the larger known Icelandic caves in the seventies, and so were Jay R. Reich and his associates. Spanish, Dutch and French cavers are also known to have visited the country and some have produced important data.

The highly successful expeditions to the eastern part of the Skaftáreldahraun (Eldhraun) in 2000 and 2001 were jointly planned by the Icelandic Speleological Society and foreign participants and organizers. (Wood 2002. this volume). Main role of the ISS was to propose a potentially prominent area for speleological studies with acceptable remoteness and road-access

The main purpose of the poster presented is to raise attention for two sites, considered to be of great vulcanospeleological interest, and offer cooperation in logistical planning and research program. The ISS has some preliminary information about the two sites.

The first site proposed is the western part of the Snæfellsnes peninsula, mostly Holocene lava flows on the flanks of the Snæfellsjökull glacier but also unexplored flows of similar age further ease along the peninsula. The ISS has conducted several short reconnaissance trips and small-scale surveying trips mostly in the Purkhólahraun and Neshraun lava flow in recent years, but also in Saxhólshraun and Klifhraun. Only few caves have been mapped, but a large number of caves and conduits await further research.

The other site is a large lava shield northeast of lake Thingvallavatn, called Þjófahraun (Thjófahraun). The ISS has organized two reconnaissance trips to the area in recent years and concluded that there is a wealth of speleological features to be explored and surveyed. Many un-surveyed caves are known, both braided tube systems and pit-like structures.

What Is a Lava Tube?

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Variances and imprecision in defiing the term LAVA TUBE have led to its application to a wide range of features, some of them far removed from the ordinary meaning of the word TUBE: "a hollow body, usually cylindrical, and long in proportion to its diameter..." The current American Geological Institute definition helpfully limits the term to roofed conduits and requires that they be formed in one of four accepted mechanisms. However it provides little guidance on whether a variety of injection structures traditionally termed LAVA TUBES actually are undrained or refilled examples or are entirely dfferent phenomena.

Ideally, lava tubes and lava tube caves should be defined as discrete structures with definable parameters which differentiate them from all other volcanic features, e.g., aa cores, lava tongues, tumuli, sills and related injection masses. The defining characteristics should be compatible with:

1) the common meanings of TUBE and CAVE;
2) the presence of solid, liquid, and/or gaseous matter within them;
3) observations of all phases of their complex speleogenesis, e.g., crustal and subcrustal accretion and erosion;
4) their tendency to form braided and distributory complexes, and multlevel structures of at least two types;
5) their propensity to combine with or produce other volcanic structures, e.g., lava trenches, rift crevices, tumuli, drained flow lobes, lava rises, dikes, etc.

The ideal may not be achievable at the present state of knowledge and technology. However, new concepts of flow field emplacement and drainage offer a notable opportunity to shape a clearer definition of this elusive term. I propose that the Commission on Volcanic Caves of the IUS develop such a definition, in collaboration with the AGI and other concerned agencies and organizations, for consideration at the 2005 International Congress of Speleology.

Caves of the Great Crack of Kilauea Volcano, Hawaii

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The Great Crack ("17 Mile Crack") is the most prominent feature of Kilauea volcano's Southwest Rift Zone. Rather than consisting of a single crevice, much of the "crack" consists of en echelon crevices of various widths in a strip locally more than 1 km wide. Numerous grabens and collapse pits are present.

Detailed studies of this complex have been begun only in the past decade. Some of the participating geologists have requested support and some leadership by speleologists in investigating cavernous pits at the bottom of steep talus slopes. The Hawaii Speleological Survey of the National Speleological Society consequently has cooperated with University of Hawaii and U.S. Geological Survey researchers in investigating cavernous pits in the principal axis of the crevice complex.

The first two such pits yielded minimal findings, but the third—labelled Pit H by University of Hawaii geologists—immediately was seen to require SRT expertise. In 2001 it was explored and mapped to a depth of 183 m. Despite extensive breakdown, accretion by laterally flowing lava was identified on several levels. A total of 600 m of passage was mapped.

In a similar crevice passage at the bottom of Wood Valley Pit Crater (which is nearby but off the principal axis of the rift zone), tube segments have been found along the crevice at a depth of almost 90 m.

No such tube segments have been found in Pit H Cave, but numerous other pits remain to be investigated along the Great Crack.

Investigation on Discharge Mechanism of Lava-Tube Cave

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Discharge mechanism of lava-cave has been proposed and discussed based on Bingham characteristics of lava flow in the tube(T.Honda,2000,2001). A simple model of steady state isothermal laminar flow in circular pipe were used for analysis.

Flow characteristics were studied as a function of parameters such as tube radius, viscosity, yield strength of lava and inclination of down slope. A critical condition was obtained for determining the discharge parameters in which the yield strength plays a dominant role. Some existing data base form the observation of lava cave were introduced to the critical condition and yield strength can be obtained. This model was applied to lava cave of Mt.Fuji, Etna, St.Helenes, Suchiooc, Kilauea, etc., and some deduced yield strength of lava of the caves for these area are found to be good accordance with yield strength estimated by other methods.

General flow equation of Bingham fluid can be shown as,

$$f(t)=(t-f_B)/v_B \quad (t>f_B, \text{ or } r>r_B),$$
$$f(t)=0 \quad (t<f_B, \text{ or } r<r_B).$$

Here, f_B is Bingham yield strength, v_B is Bingham viscosity, which takes specific value depending on the materials. t is shearing stress at r.

For laminar flow model in circular tube on the slope, the equation of the distribution of flow speed u of Bingham fluid are shown as follows:

For tw =(d g sin a)R/2>f_B,

$$u=(R-r_B)^2(d\ g \sin a)/4v_B \quad (r<r_B),$$
$$u=[R^2-r^2-2r_B(R-r)]\ (d\ g \sin a)/4v_B \quad (r>r_B).$$

For tw= (d g sin a)R/2<f_B, u=0.

Here, tw is shearing stress at wall, a is angle of slope or inclination of tube, d:density of the fluid, g: gravity acceleration, R :radius of the tube, r_B :radius of the flowing position where Bingham yield stress takes f_B.

Here, (d g sin a)R/2=f_B is the critical condition to determine if the fluid in the tube can be drained out. For given and known relation between slope angle and diameter (height)of the tube, this critical condition can give the yield strength f_B. This critical condition means that when the yield strength f_B of Bingham fluid is higher than the shear stress at the wall, there is no flow of fluid, as a consequence, no discharge of fluid from the tube. Relations between slope angle and height of cave for Mt. Fuji, Mt. Etna, and St. Helenes are shown in Table 1 – Table 3. Obtained yield stress from slope angle and height of some lava caves are shown in the Table 4 together with the yield stress obtained by other methods.

References:

T. Honda: “On the formation of Subashiri-Tainai cave in Mt. Fuji”. The 26th annual meeting of the Speleological Society of Japan, 2000, August, p.64

T. Honda: “Investigation on the formation mechanism of lava tube cave”. The 27th annual meeting of the Speleological Society of Japan, 2001, August, p.11

T. Honda and T. Ogawa: “On the formation process of Inusuzumi-yama lava cave ”. The 27th annual meeting of the Speleological Society of Japan, 2001, August, p.37

T. Honda: “Formatin mechanism of lava tube caves in Mt. Fuji”. The 2001 Fall meeting of the Volcanological Society of Japan, 2001, 0ctober, p.66

On Lava Stalactite Formation in the Hollow of Tree Molds of Mt. Fuji

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At the north-east flank of Mt.Fuji, lava stalactites are often found in the hollow located adjacent to the lava tree molds. These stalactites have a periodic distribution on the surface with 3–6 cm pitch on the roof of hollow and have almost same diameter (4–8mm) at the edge of the lava stalactites. There had been no scientific and systematic study on the formation process of this kind of stalactite in the hollow adjacent to the tree molds before long.

The author proposed a possible formation mechanism of this stalactite and a model to explain the final structure of stalactite (T.Honda, 2000). The author have investigated the initiation of the formation process of stalactite by stability/instability problem (H.Lamb, 1954) of melted liquid layer on the surface of hollow under the action of gravity force. Limit of stability/instability of this layer is determined by balance between surface tension and density of lava. Period of wave of small perturbation on this layer for this stability limit can be determined as, $Pc=2\pi(s / g\ d)^{1/2}$. Here, Pc is critical period of wave, s is surface tension, d is density of lava, g is gravity acceleration. This period is believed to be also a pitch of stalactite location .

As surface tension of lava (I.Yokoyama et al,1970): $10x10^{-2}$Kg/m(1000deg) to $6.5x10^{-2}$Kg/m (1400deg), and density of lava 1.5to2.5g/cm^3 are used for this study.

For surface tension s=$6.5x10^{-2}$Kg/m and d=1.5–2.5g/cm^3, Pc=3.2–4.1cm. For surface tension of lava s=$10x10^{-2}$Kg/m and d=1.5–2.5g/cm^3, Pc=5.1–6.6cm. Measurement by a scale shows 3cm–6cm pitch which has a good agreement with above estimation.

As for a study on the structure and diameter of lava stalactite, the author used the Bingham flow model to explain the formation mechanism and structure of lava stalactite. From the diameter of edge of stalactite, yield strength of lava was determined. From this yield strength, the temperature of this stalactite when it was formed can be estimated.

General flow equation of Bingham fluid can be shown as,

$$f(t)=(t-f_B)/v_B \quad (t>f_B, \text{ or } r>r_B),$$
$$f(t)=0 \quad (t<f_B, \text{ or } r<r_B).$$

Here, f_B is Bingham yield strength, v_B is Bingham viscosity, which takes specific value depending on the materials. t is shearing stress at r. For laminar flow model in vertical set circular tube with pressure difference P1-P2 for stalactite length L, the critical condition is tw=(P1-P2)r/2L=f_B. Here, (P1-P2)/L=dgL/L=d g. So the limiting radius for lava discharge is r=2f_B/d g. For density d =2.5 g/cm^3, when r=2–4mm, f_B=2.5–5x10^2 dyn/cm^2. For density d=1.5g/cm^3, when r=2–4mm, f_B=1.5–3x10^2 dyn/cm^2. This low yield strenght suggests that the lava was in rather high temperature condition when surafce is re-melted before re-solidified.

References:

T. Honda: "The formation process of lava stalactite in the of tree molds of Mt. Fuji". The 26th annual meeting of the Speleological Society of Japan, 2000, August, p.4

T. Honda: "The investigation on the formation process of the lava tree-molds structure of Mt. Fuji". The 2000 Fall meeting of the Volcanogical Society of Japan, 2000, September, p.110

H. Lamb: Hydrodynamics, Dover 1945, p.19

I. Yokoyama et al: "Measurement of surface tension of volcanic rocks". Technical Report of Hokkaido University, 1970, p.56-61.

Table 1. *Relation between Slope angle and height of lava cave in Mt.Fuji.*

Name of lava cave	*Slope angle*	*Height*
Subashiri-Tainai Cave Upper area	20 degree	1m
Subashiri-Tainai Cave Lower area	15 degree	2m
Shoiko-Fuketsu Cave-1	10 degree	3.3m
Mujina-Ana Cave	8.5 degree	5m
Bannba-Ana Cave	4.8 degree	5m-10m
Mitsuike-Ana Cave	3.2 degree	10m

Table 2. *Relation between Slope angle and height of lava cave in Mt.Etna.*

Name of lava cave	*Slope angle*	*Height*
Tre Livelli Cave	15.3 degree	3m
Serracozzo Cave	9.8 degree	2m-3m
KTM Cave	8.9 degree	5m
Cutrona Cave	6.4 degree	6m
Immoacolatella-I Cave	3.8 degree	10m

Table 3. *Relation between Slope angle and height of lava cave in St.Helenes.*

Name of lava cave	*Slope angle*	*Height*
Little Red River Cave	4.5 degree	9.1m
Ape Cave	3.3 degree	11.6m
Lake Cave	2.6 degree	15.5m
Ole's Cave	2.1 degree	7.6m

Table 4. *Yield strength obtained from the critical condition.*

Name of volcano which has lava tube caves	*SiO_2 fraction of lava*	*Yield strength obtained from the limiting condition (yield strength obtained by other method in paranthesis)*	*References*
Mt.Fuji	49.09~51.3%*	2.5~5x10^4dyne/cm^2	*H.Tsuya(1971)
Mt.Etna	48%	5x10^4dyne/cm2 (7x10^4dyne/cm^2*)	*G.P.L.Walker et al(1967) *G.Hulme(1974)
Mt.St Helenes	50.12~50.28%*	1~2.5x10^4dyne/cm^2	*R.Greely&H.Hyde(1972)
Mt. Suchiooc	51.23~51.35%*	7.5 x10^4~1x10^5dyne/cm^2	*R.E.Perena(1999)
Mt.Kilauea	46.46~50%	1x10^3dyne/cm^2 (1x10^3dyne/cm^2*)	*H.R.Shaw et al(1968) *G.Hulme(1974)
Mt Piton de la Fournaise	47.98%*	5x10^4dyne/cm^2	*A.Lacroix(1936)
Mt.Cameroon	43.5%*	1x10^5dyne/cm^2 (~1x10^5dyne/cm^2*)	*J.G.Fitton et al(1983)

Tables for Honda "Discharge Mechanism"

Air Quality Measurements in Lava Tubes

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Air quality in lava tubes is not normally recorded or investigated. Thus in some instances discomfort from poor air quality may have been misinterpreted as resulting from stress from high temperatures or high humidity. Only two gases have been recorded are ammonia from bat caves and carbon dioxide. The former is unlikely to reach hazardous levels and later has been known to reach hazardous levels in at least one lava tube. This paper will focus on the possible sources, concentrations, distribution and movement both spatially and temporally within lava tubes. The importance of air analyses including oxygen, nitrogen and water vapour will be stressed in order to establish the source of carbon dioxide. Analysis of trace gases, for example, hydrogen sulfide and methane, can also give additional information as to a CO_2 source. Simple CO_2 tests available to the exploration caver will introduced and assessed. The practical aspects of the exploration lava tubes found to contain poor air quality will be discussed. The advantages and disadvantages of using scrubber gases, oxygen re-breathers and scuba will be presented. The paper will include examples of where poor air quality has been identified from volcanic activity and will feature the author's experience with the Chillagoe Caving Club in Bayliss Cave, Undara the longest lava tube found in Australia.

The Mapping History of the Surtshellir/Stefánshellir Cave System

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The nearly 2 km long cave Surtshellir is the best know lava tube in Iceland and is mentioned in many early manuscripts and publications of domestic and international origin. The cave is mentioned in the Icelandic Sagas and folklore and tales are associated with the cave. The cave has provoked many early travelers' attention and curiosity and many explorers visited the cave in past centuries. The first mappublished of the cave was the work of native explorers Eggert Ólafsson and Bjarni Pálsson and published in Denmark in 1772. Eggert and Bjarni's fieldwork is believed to have been carried out in the summer of 1755 but they also toured the same region in 1773. The next map that follows is the work of German traveler/explorer Zugmeyer published in 1902.

The presentation is an overview of the work carried out is Surtshellir and the adjacent and upflow continuation of Surtshellir, Stefánshellir but they upflow segment is divided from Surtshellir with an unpenetrateable boulder-choke which also contains perennial ice. The maps presented are both of Surtshellir and Stefánshellir individually and of the both. It can be concluded that early travelers were not aware of the upflow continuation since not mention is made of its presence.

Surtshellir is in the Hallmundarhraun lava flow in West-Iceland and was formed in historical times (10^{th} century), just after the settlement of Iceland in 874 AD. Surthellir bears large and extensive remains of human habitation, but the archaeological remains have not been cared for by Icelandic archaeological authorities, and are now more or less ruined – or at least seriously affected. The Icelandic novelist Halldor Laxness had pieces of bones ^{14}C-dated in the fifties, and the dating gave grounds to conclude that the remains where of 10^{th} century origin. This has recently been confirmed by later ^{14}C datings.

Altogether 11 maps of different grades and quality are presented and each map's history is briefly discussed.

25 Years of Icelandic Cave Surveying – Jay R. Reich's Maps

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The Pennsylvania born caver Jay R. Reich has contributed a lot to Icelandic speleology and his work on Icelandic caves is summarized. Four large and detailed maps are presented and light is cast on Jay's enthusiasm and fine work in cave mapping and drawing, as well as his enormous interest in Icelandic caves. His first visit to Iceland was early in 1969 when he made his first attempt to survey Surtshellir but hostile weather and other logistical problems prevented him from achieving his goal at that time. He was in Iceland three more times, and completed his map of Surtshellir/Stefánshellir in 1973. His next major project was the exploration and mapping of the extensive cave system of Kalmanshellir in 1993, also in the Hallmundarhraun lava flow. The map of the roughly 4 km cave system with vast details was finished the same year.

The Icelandic Speleological Society collaborated with Jay in the mapping of Víðgelmir, also in Hallmundarhraun, and fieldwork was carried out in 1996. The map was drawn by Jay Reich, checked and corrected by ISS members and it was finished in 1998. During the Kalmanshellir expedition Jay had in collaboration with ISS members and US cavers completed a map of the recently discovered nearly 1 km long cave of Leiðarendi in 1993. In the last 30 years Jay and his collaborators have surveyed all three of the big caves of the Hallmundarhraun lava flow in Western Iceland and Jay has completed maps of over 10 km of cave passage.

Conservation of Volcanic caves in Iceland – Status and Update

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Since the founding of the Icelandic Speleological Society (ISS) in 1989 it has been the society's goal to enhance and further collaboration and cooperation with governmental bodies in the field of cave conservation and general preservation of volcanic phenomena.

A bold and brave step was taken in 1974 by the Nature Conservation authorities, when all protruding and hanging lava formations (stalactites and stalagmites) were subject to an "automatic" and undisputable conservation as a Natural Monument, in accordance to the Nature Conservation legislation valid at that time. The speleothems were protected regardless of their position in the cave and if the cave itself had any direct or indirect conservations status and if it was known or unknown. The speleotheme conservation is formation oriented and bears resemblance to protection of bird species – i.e. the protection is broadly aimed at the form and occurrence but not at an in-situ individual formation.

After removing an ice-plug in Víðgelmir in 1993 the ISS proposed the idea of gating the cave but it had been blocked since 1972 by the before mentioned perennial ice. The landowners were very positive towards the idea and participated in the project of building the gate. Since the installation of the gate all traffic has been controlled and the landowner now rents caving equipment and takes visitors on guided tours to the cave. The involvement of government authorities was not needed in the gating process of Viðgelmir, but proper authorities were notified of the action.

Following the discovery of the enormously decorated cave Jörundur in 1979 there was an ongoing debate about necessary efforts to protect the cave. In 1985 the cave Jörundur was legally declared a natural monument and subsequently the cave was closed by a steel-gate on the surface, leaving it only open for scientific purpose, and managed by the Nature Conservation Agency. The lock on the gate was broken several times, but no serious damage was done to the cave, except a few specks of candle wax were left on some of the stalagmites. The gate was removed by ISS in September 1999 and a new chain-gate installed in a narrow passage.

The cave Árnahellir is another specific cave-conservation issue the be mentioned. The cave was discovered in 1985 and an escalating number of visitors was experienced in due time from the day of the discovery. In 1995 the ISS took a radical step in cave conservation when after some negotiation time a treaty was signed with the land-owner giving the ISS the sole right to take necessary steps to protect the cave, including the installation of a gate. The treaty was notarized at the sheriff's office in Þorlákshöfn. Immediately, or when the action was legally binding, the ISS prepared for gating the cave. The cave has been closed since and access controlled by the ISS. This privatized conservation has been a little disturbing and irritating for the authorities but the latest development is very satisfying and encouraging for the ISS. In 2001 the ISS board signed a contract with the Nature Conservation Agency granting the ISS the right to maintain and manage all protected caves and caves enclosed on areas where specific conservation effort or actions have been taken, i.e. natural parks, recreations areas, protected lava – or volcanic fields and other reserves. This action of forwarding the authority to the ISS is a milestone for the ISS´s efforts toward cave conservation in Iceland and the Minister of Environmental Affairs authenticated the arrangement in July 2002. The ISS/land-owner treaty wassubsequently abandoned and Árnahellir legally declared a Natural Monument.

In the future the ISS will propose new specific cave conservation projects to the Nature Conservation Agency or if the matter allows, take the necessary steps unaided in power of the treaty made with the Nature Conservation Agency and Ministry of Environmental Affairs.

Vulcanospeleology as Tourism: Case Study of Samoa

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The Independent State of Samoa is located in the South Pacific region immediately east of the International Date Line. Located to the north of the Tonga Trench, the country of Samoa comprises several small volcanic islands as part of a 1200 linear volcanic chain extending 550 km from Rose Atoll in the east to the Samoan island of Savaii in the west. The Samoan islands are composed almost wholly of basic volcanic rocks such as olivine basalt, picric basalt and olivine dolerite of the alkaline basalt suite. Although the age of the rocks is poorly known, it is thought that the oldest Fagaloa Volcanics erupted in the Pliocene period. The islands are still volcanically active, with the last eruptions in Savaii of Mauga Afi in 1760, Mauga Mu in 1902 and Matavanu in 1905.

There are an unknown number of caves located within the volcanic landscape of Samoa. Most caves appear to be of subcrustal forms that have been modified by subsurface river systems. The Samoan Visitors Center advertise tours through several caves including the Peapea Cave in the Le Pupu-Pue National Park, and the Paia Dwarf's Cave below the summit of Mt Matavanu. Other caves, such as the Piula Cave Pool between the Piula Theological College and the coast, are available for visitor exploration.

This study aimed to identify as many vulcanospeleological features in Samoa as possible and to relate the location of the caves to geology and land tenure. A short inventory of the caves was undertaken by identifying physical and cultural features of significance. The use of the popular and lesser known caves for tourism was examined, and the relationship between cave tourism and local village ownership was explored. The challenges and impediments to the expansion of vulcanospeleology as part of tourism in Western Samoa was also examined.

Patterns of Lava Tube Development on the North Flank of Mauna Loa, Hawaii

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Mauna Loa is a shield volcano on the island of Hawaii with a surface area of about 5,500 sq. km and rising to an elevation of 4,170 meters above sea level. The U. S. Geological Survey estimates that about 40 percent of its surface area is covered by lava flows that are less than 1,000 years old. In the time period 1992-2001, members of the Hawaii Speleological Survey have surveyed 55 km of passage in 107 lava tubes within a 60 square km area on the north side of Mauna Loa's northeast rift zone. The tubes are found in flows ranging in age from 5,000 years BP to as recent as the historic 1935 flow. These tubes exhibit several distinct configurations. The most commonly observed tube pattern consists of a single sinuous conduit containing occasional loops and short branches. Other, more complex tube patterns are also observed in the Mauna Loa lava flows and include:

(a) *Unitary, multi-level tubes*. Some of the thicker flows are up to 20 meters deep and contain multilevel tubes in canyon like passages. These tubes appear to result from stable lava levels that partially filled the tubes. Crusting took place on the top of the lava in the tubes with molten lava flowing below. Subsequent lowering of the level of flow in the tube and crusting of the tops of the lower lava flow levels resulted in evacuated multi-level tubes with the crusted upper surfaces of the partially filled tubes remaining as intermediate ceilings when flow through the tubes ceased.

(b) *Shallow complex tubes*. The 1935 flow is only 7-8 meters thick but contains a grid-like tube complex having 4,500 meters of surveyed passages in an area that is 700 meters long and 250 meters wide. This tube appears to have been developed by multiple flow lobes advancing along the distal end of a sheet flow with the lobes diverging and converging as inflation occurred, resulting in a tubes having a maze-like pattern.

(c) *Single level tube complexes in broad flows*. Over 8 km of parallel tubes have been surveyed in the historic 1855 flow. The tubes extend across the flow in at least three parallel lines. The tubes are at about the same depth beneath the surface, appear to be in the same flow unit, and are not branches of large loops.

(d) *Giant tubes*. Emesine Cave in the historic 1881 flow is the largest surveyed tube on Mauna Loa. With a linear extent of over 8 km, a vertical extent of 436 meters, and having a surveyed length of 20.72 km, this single tube contains almost 40 percent of the total surveyed passage found in the northeast rift zone tubes. Although much of Emesine Cave consists of a unitary tube, some parts of the cave are a complex braided network of passages on more than one level.

Carvão Cave (S. Miguel Island, Azores, Portugal: An Educational Experience

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"Gruta do Carvão" (meaning "Coal Cave") is the biggest lava cave in S. Miguel Island, and one of the most impressive underground structures in the archipelago. It is a well-known cave, reported in old manuscripts since the sixteenth century, and visited by many national and international explorers.

Carvão Cave has nowadays a total acknowledged length of about 1650 m, with a general NNW-SSE trend and along three different sections, most of it more than five meters wide. However, the original path of the main channel can be traced for about 2400 m from the coastline, and it might be able to have reached more than 5 km long. This cave develops in a basaltic *s.s.* lava flow (SiO_2=45.6%; Na_2O=2.53%, K_2O=1.19%) probably extruded from the Serra Gorda scoria cone area. This strombolian cone is one of the about 200 volcanic cones pertaining to the "Picos Volcanic Complex", an area of basaltic nature that extends in the western sector of S. Miguel Island as a shallow platform, built by lava flows of *aa* and *pahoehoe* type. The lava flow of Carvão Cave is covering a pumice layer and a paleosoil, in witch some charcoal remains were found and dated by ^{14}C conventional gas counting technique, at Geochron Laboratory (USA). The ages determined were 11,880 years BP (±80y) and 12,100 years BP (±140y), pointing a Holocene age to Carvão Cave.

Owing to its size, a great variety of microstructures can be found inside the cave, which are undoubtedly an eloquent sample of the creative force of the Azorean volcanism. Among those are flow marks, lava tree molds, *pahoehoe* slabs, ropy and spongy lavas, burst bubbles of lava, branching galleries, superimposed channels and long extensions with benches at several steps. On the roof there are many fusion lava stalactites and other irregular deposition-type stalactites, sometimes over the former. Some sectors of the cave, mostly the flatter ones, were affected by sand and clay deposition, which silt them up and block the cave in some places. Thus, it was needed some removing work in recent times to allow a permanent and easy walk inside the lava tube. Carvão Cave has been used for many years as warehouse of the local tobacco factory.

Given its size and location, right in the urban area of Ponta Delgada city, close to the downtown, airport, schools and tourist facilities, the cave is the perfect spot for visitors interested in the speleological thematic, or in a wider sense, to all who want to know the natural volcanic underground landscape of the S. Miguel Island. Therefore, a project to open Carvão Cave to the general public is in progress, taking profit of the many potentialities of that cave, namely in terms of its scientific, educational and touristy value.

That project is based on well-sustained museum programme and the dynamics of several activities associated, including an exhibition area nearby the main entrance. In fact, it is believed that Carvão Cave is the perfect place to enhance the importance of the volcanic phenomena (specially of the basaltic volcanism) to the genesis and evolution of the Azores archipelago, and its influence in the Azorean way of life. This cave is also an excellent scenario for educational approaches, namely in terms of Environment Education, owing for a better knowledge of Man and Nature, calling attention to Environmental problems and creating a new behaviour. With these ideas in mind, a special attention is given to schools (with the appropriate connection with their teachers and school programmes) allowing that many students visited Carvão Cave, in what it's expected to be a fruitfully educational experience.

The Grotta dei Rotoli (Mount Etna, Italy)

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Only few years ago discovered, the Grotta dei Rotoli (*cave of rolls*) develops in the flow field who was generated during the eruption of 1865. This basaltic effusion shows both pahoehoe and 'a'a flows but it is in the former morphology that the studied lava tube develops. Plan view, longitudinal and transverse sections of the cave are presented in this work.

This lava tube has a length of only 260 meters but its importance is given by big rolling-over structures drapping the walls of the cave. In his short lenght the cave bifurcates twice, in general agreement with the observation that many lava tubes show an increase in size with increasing distance from the vent (Calvari and Pinkerton, 1999).

Is supposed that the enlargement of the lava tube, join to a fast draining of lava (probably due to the opening of an ephemeral vent), promotes a slow longitudinal collapse of the still not self-supporting roof. This kind of collapse generates a downward directed bulge: because this bulge touches the floor it create the splitting of the lava tube. This partition of the transverse section works as a stoppage for the new following flow. Is in fact assumed that only a new re-filling of the tube with fresh lava can lock the collapse of the roof, giving to it more time to cool and solidificate. The successive rapid draining gives eventually rise to rolling-over structures that embrace the bifurcation.

Thanks to thin sections studying, substantial differences in porphyritic indexes are detected between rolls and roof samples, giving force to the theory of the second flow injection.

Key words: lava flow; lava tube; rolling-over structures; Etna volcano.

Growth of a Submarine Lava Tube at Ustica Island (South Tyrrhenian Sea)

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The island of Ustica is a small (8 km^2) volcanic island, located in the Tyrrhenian Sea, 60 km north of Sicily. The island rises from the bottom of the sea of 2.000 m and reaches the elevation of 248 m a.s.l..

Several authors have recognised in the island an articulated volcanic succession, with different eruptive centers, the last of wich has been active 147 ky b.p. (Cinque et al., 1988; De Vita et al., 1998; Romano & Sturiale, 1971). The morphologies of lavas cropping in the island vary from pahoehoe to pillow. Explosive activity produced large amounts of tephra, going from hydromagmatic breccias to pumice. All existing geochemical data comes from subaerial outcrops, they indicate for the volcanics of Ustica a mostly alkaline and subordinately subalkaline character.

Due to the reduced dimension of the island all subaerial lava flows reached the sea. This produced a great amount of morphologies of the transition from subaerial to submarine lava flows. The tectonic uplift wich has affected the island after its last period of activity allows us to see the submarine lavas, and the transition from pahoehoe flows to pillow breccias.

In this work we want to point out the existence of a little lava tube (14x2 m) found in one of these submarine pillow-breccia levels. Such lava tubes are considered to be very rare occurrences in submarine lavas.

The origin of this lava tube can be explained considering the formation of a mega-pillow in an advancing submarine lava flow. Its outer layer solidified protecting the inner part of the tube from the water. Inside the tube the gas expanded, probably part of this gas was provided by the vaporization of small volumes of sea water that entered the tube. The expansion of the gas caused an inflation of the walls of the tube wich were still in a plastic state. Such an inflation left a space in the tube so that liquid lava inside could develop tipically pahoehoe ropy morphologies.

Key words: lava flow; lava tube; pillow-lava; Ustica; Tyrrhenian Sea.

Lava Tubes of Harrat Kishb, Saudi Arabia

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This presentation features a Powerpoint slide show on the discovery and exploration of several lava tubes located in Harrat Kishb, a lava field located 300 kilometers Northeast of Jeddah, Saudi Arabia.

The first visit to Harrat Kishb had two goals. One was to investigate a series of collapse holes, visible in air photos, extending from an extinct volcano named Jebel Hil and suggesting the presence of a lava tube at least three kilometers long. The second goal was to try locating several shorter lava tubes seen in this area by a hunter.

A hair-raising, nearly impossible climb up Jebel Hil revealed an opening in the side of the crater, presumed to be the upper end of the long lava tube. A ground reconnaissance then gave the coordinates of most of the collapses and indicated the floor of the tube was from 26 to 42 meters below the surface.

Two days of searching the stark landscape of Harrat Kishb failed to reveal the location of the smaller lava tubes, but these were finally found with the help of Bedouins living at the edge of the lava field. One of the tubes, Kahf Al Mut'eb, was surveyed to a length of 165.8 meters and was found to contain lava levees, stalactites and animal bones. A brief look at a nearby lava tube revealed that it was "populated" by tall, shadowy figures which turned out to be stalagmites of rock-

dove guano, giving this hole the name Ghostly Cave.

During a second visit to Harrat Kishb, a survey of Ghostly Cave was undertaken. Samples were taken of the basalt and mineral coatings found on the walls and of the thick layer of choking, potassium-rich dust on the floor. The "guanomites" were photographed and sampled. During the survey, two L-shaped throwing sticks were found inside the cave. These are similar to sticks seen in the hands of figures in Arabian Neolithic rock art and may be five to eight thousand years old.

A photography session held in Kahf Al Mut'eb resulted in the discovery of a plant-fiber rope which may also be of Neolithic age.

Finally, a visit was made to a lava tube located much farther north in Harrat Kishb. Its entrance is unusual in that it is not a collapse, but apparently the result of surface air being sucked into the tube as the lava was draining from it. This cave, named Dahl Faisal, also features a "dust volcano" produced by the release of air trapped in mud during flooding.

Topographical Map of Lower Hallmundarhraun

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Hallmundarhraun is morphologically and speleogenetically one of the most interesting lavas in Iceland. Hallmundarhraun is in the authors opinion at least two different lavas. An older one, probably coming from southern main crater in Jökulkrókur and a younger one around 1200 years old, coming from the northen crater. It totally covers the older lava, except where the lavas meet east of Þrístapafell and in Laski south and south east of Þorvaldsháls. There are other separate lavas in Jökulkrókur south of the southern crater coming from craters covered by Langjökull.

A geomorhological map of the lower two quarters of the lava showing surface features and the underlying caves is presented and discussed.

The History of Lava Cave Preservation in Iceland

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The author spent several summers as a child helping out at Kalmanstunga in the vicinity og the great caves in Hallmundarhraun in the fifties and sixties. Peoples interest in the caves and that new caves were found was very stimulating. But there was an other side, a black side that was only wispered about. The damage. The dwindling bone heap in Vígishellir in Surtshellir, deliberate breaking and taking of formations from all the caves. This had a deep effect on the author. The relationship became clearer as the years went by. Every find of a new cave had been presented in the newspapers and or the radio. This stimulated interest, interest traffic, traffic damage, intentional as well as unintentional, the well known evil cicle. All caves were easily accessible. By 1982 sensitive formations in all known Icelandic caves had been either severly or totally damaged. The papes describes the steps taken after 1982 in the preservation of lava cave features as seen by the author.

Five Vertical Conduits in Iceland

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The paper describes five interesting vertical conduits in Iceland. First four are in the Gjábakka / Þjófahraun fissure system. The first three, Tintron, Pyttlur, Vambi are seen by the author as either as pure chimneys or chimneys with some overflow, on an otherwise closed vent / tube cave system. The fourth is a 24m deep very well preserved mineature volcano. A chamber with an inflow tube from below, chimney and a small outflow tube. At last the great pit crater Þríhnúkagígur is presented and discussed.

Complex Tree Mold Labyrinth found in Ken-Marubi Lava Flow in Mt. Fuji

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At the north-east flank of Mt.Fiji, the tree molds are often found in the lava flow erupted about 1000 years ago. During the field survey for tree mold in this lava flow, a very complex tree mold is found and observed (H. Tachihara,T. Makita,1998).

This tree mold is not a single tree mold, but combined labyrinth like tree molds which consist of 39 tree molds attached one after another and total lenght of the cavity (the maximum diameter is about 1.5m) penetrable by personnel is 204 m by excepting unpenetrable cavity of less than 50cm diameter. The longest tree mold cavity reported in US hitherto was 40.84m (D.G.Davis et al,1983).

The following table 1 shows length/depth and cross section of penetrables in the combined tree molds.

Combined 39 tree molds are, one vertical standing tree mold, fourteen horizontally inclined tree molds, and other unpenetrable twenty four samall tree molds of branches or creepers.

The inner surafece of some tree molds have a remelted layer of lava and lava stalactite are often observed. The remelting of the inner surface of the tree mold seems to be produced by gas burnig with oxygene by chemical reaction of carbon after carbonization of living tree or cellulose with water in the tree(T.Honda,1998). The tree molds located at the bottom area are laid down on a scoria layer and have no remelting surface.

As for details on the origin of the structure of tree mold and vegetation succession stage at the eruption time, extensive studies are still under going together with the historical dating investigation of this lava flow.

At the symposium poster session, the photos and drawings of this combined tree molds will be presented.

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Table 1 (Tachihara et al. "Complex Tree Mold Labyrinth). Depth/length and cross section of combined tree molds.

Tree mold	Depth or Length	Cross section
Tree mold A	675 cm	160x120~140x110cm
Tree mold B	2420cm	360x140~90x90cm
Tree mold D	400cm	70x70cm
Tree mold E	940cm	45x50cm
Tree mold F	886cm	70x70cm
Tree mold G	2835cm	500x120~70x70cm
Tree mold H	160cm	420x120~100x65cm
Tree mold K	2760cm	110x80cm
Tree mold L	1800cm	100x120~90x40cm
Tree mold M	1800cm	70x60cm
Tree mold O	1770cm	150x110cm
Tree mold Q	300cm	70x70cm
Tree mold S	320cm	200x90~74x60cm
Tree mold T	900cm	50x35cm
Tree mold V	500cm	50x50cm

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Recent Discoveries on the Laki Flow Field, S. Iceland

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Speculative expeditions to the 1783/4 Laki flow field (Skaftáreldahraun) in 2000 and 2001 discovered significant caves in the upper part of the eastern arm of the flow field, known as the upper Eldhraun. In an area of approx. 12 km^2, northeast of Miklafell, approx. 12 km of cave passage were located, explored and mapped. Many of the caves were short, but 4 were over 500 m long, and the longest had a survey traverse length of 1.982 km. The caves had impressive volumes, varying forms and a diversity of internal features. Some had isolated locations in remote parts of the flow field, but others were members of complex cave groups. One group located on the eastern side of the flow field appeared to have an origin related to the formation of a large collapse trench. Another, larger and more complex, group of caves, lay on the western side of the flow field adjacent to the seasonal lake, Laufbalavatn. Here approx. 5.0 km of cave passage underlay and had a close association with a range of surface landforms, including short collapse trenches, lava rises and closed depressions. Accurate mapping of the caves and their relationship with the surface landforms in the study area has provided evidence on which to base an interpretation of the morphogenesis and nature of emplacement of the upper Eldhraun.

A Mega-Tube System in the Hallmundarhraun, W. Iceland

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Experimental work to track and map lava tube caves remotely from the surface of a lava flow with geophysical methods was undertaken with great success on the Hallmundarhraun flow field in 2001. Using a caesium magnetometer and a survey method known as area survey, it was possible to accurately map the dimensions and route of an entranceless cave passage lying upflow from the terminal lava seal of Stefánshellir. The work proved the presence of 300m of open cave that trends upflow in an easterly direction. The length of cave discovered simply reflects the dimensions of survey block and it is probable that a future survey will be able to map a further length of this passage.

Farther east and extending over a distance of about 18 km upflow from Stefánshellir is a series of crater-like features, each made of a ring of large blocks of lava crust and sitting like a crown at the summit of a low lava shield. Similar features recently observed on Kilauea have been termed 'shatter rings'. The rings extend across the flow field in the manner of a sinuous necklace. Magnetic survey between three revealed that cavities exist beneath and between them. Interestingly, another shatter ring occurs in the lower part of the flow field, overlying the upflow end of Víðgelmir and demonstrating that shatter rings and lava tubes may be genetically related. A working proposal is that the long necklace of rings formed over the master lava tube that fed lava into the Norðlingafljót valley. It is believed that the newly discovered entranceless cave is also a part of this mega-system.

The Volcanic Landforms and Lava Tube Caves of Jeju Island, S. Korea: Candidates for World Heritage Site Status?

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This paper will be a report-back on a visit to Jeju Island made by the author in mid-August, 2002. The purpose of the visit was to provide some advice to the S. Koreans on technical aspects of a bid to UNESCO seeking nomination of the lava tube caves and other volcanic landforms as a World Heritage Site. The island has over 100 caves, the three longest ranking 8, 10 and 18 on Bob Gulden's list of the world's longest lava tube caves.

2002 SYMPOSIUM PAPERS

Lava Tubes of Harrat Kishb, Saudi Arabia

John J. Pint

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Introduction

Prior to the year 2001, very few reports were made regarding lava caves in Saudi Arabia and no surveys are known to have been carried out. This situation changed in November of 2001 when Dr. John Roobol led an expedition to the vicinity of Jebel Hil Volcano in Harrat Kishb, a lava field located 300 km northeast of Jeddah. The explicit purpose of the expedition was to locate and survey lava caves, as well as to describe them accurately. The location of Harrat Kishb is shown in Figure 1.

The first expedition to Harrat Kishb took place November 10-14, 2001, led by Dr. J. Roobol, J. Pint and M. Al-Shanti. The project took place at the urging of Dr. William Halliday, member and founder of the Commission on Volcanic Caves of the International Union of Speleology (UIS). By coincidence, Dr. Roobol had received, from geologist Faisal Allam, several photographs of cave entrances found some 6 km east of Jebel Hil in Harrat Kishb. Accordingly, the goals of the expedition were to locate the caves shown in the photographs as well as to precisely locate the collapse holes west of Jebel Hil which were observed by Roobol and Camp (1991) and thought to be entrances to a lava tube.

After much searching, the photographed caves were located and one of them, Mut'eb Cave, was surveyed. In addition, the GPS locations of twelve collapse entrances of the Jebel Hil Lava Tube were taken, a difficult undertaking since 12 km of mostly a'a lava had to be traversed on foot.

A second visit to Harrat Kishb was made from February 2-5, 2002, again led by J. Roobol, J. Pint and M. Al-Shanti. Ghostly Cave was surveyed and a new cave, Dahl Faisal, was located and surveyed. The results of the Kishb Surveys were published in Roobol et al., 2002.

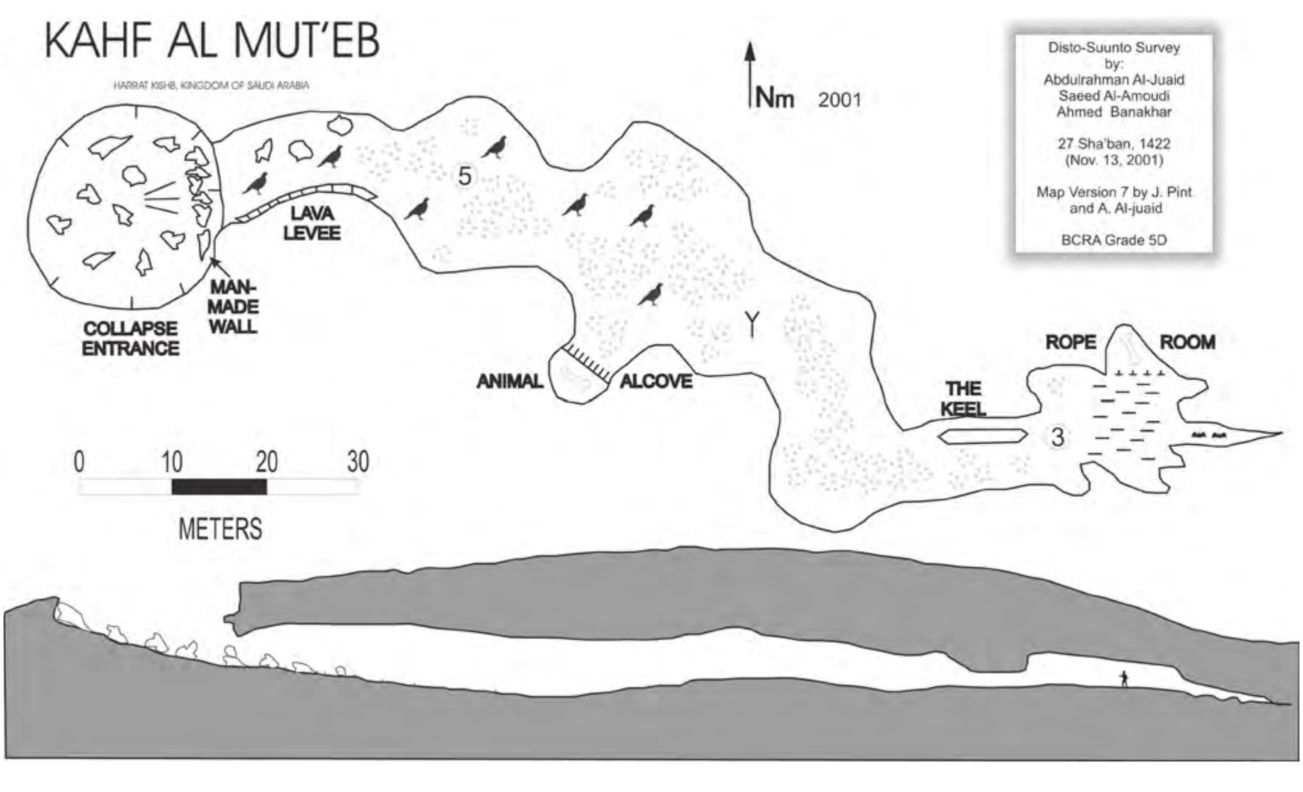

Figure 2. Map of Mut'eb Cave.

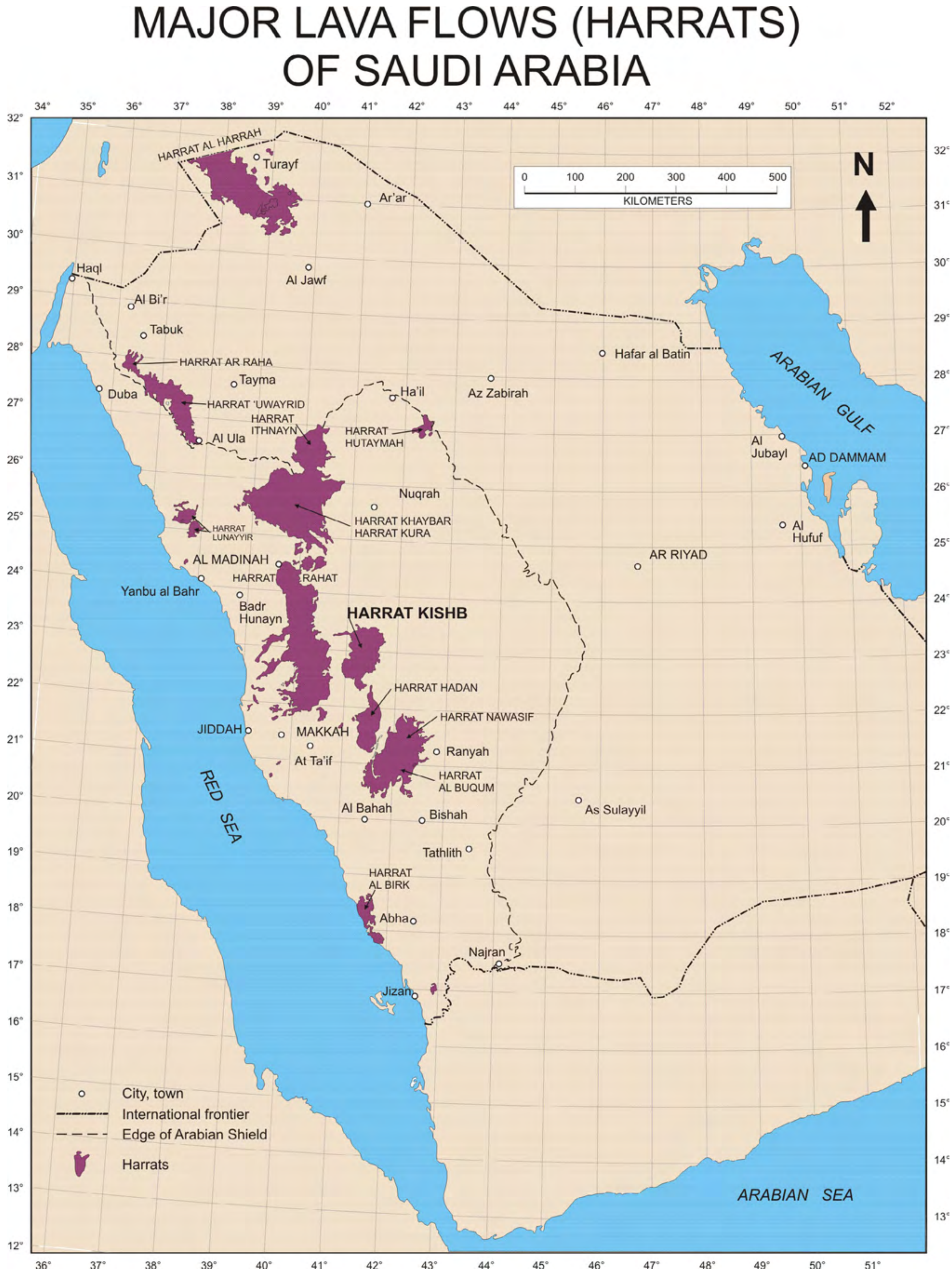

Figure 1. Map showing the location of Harrat Kishb lava field in Saudi Arabia

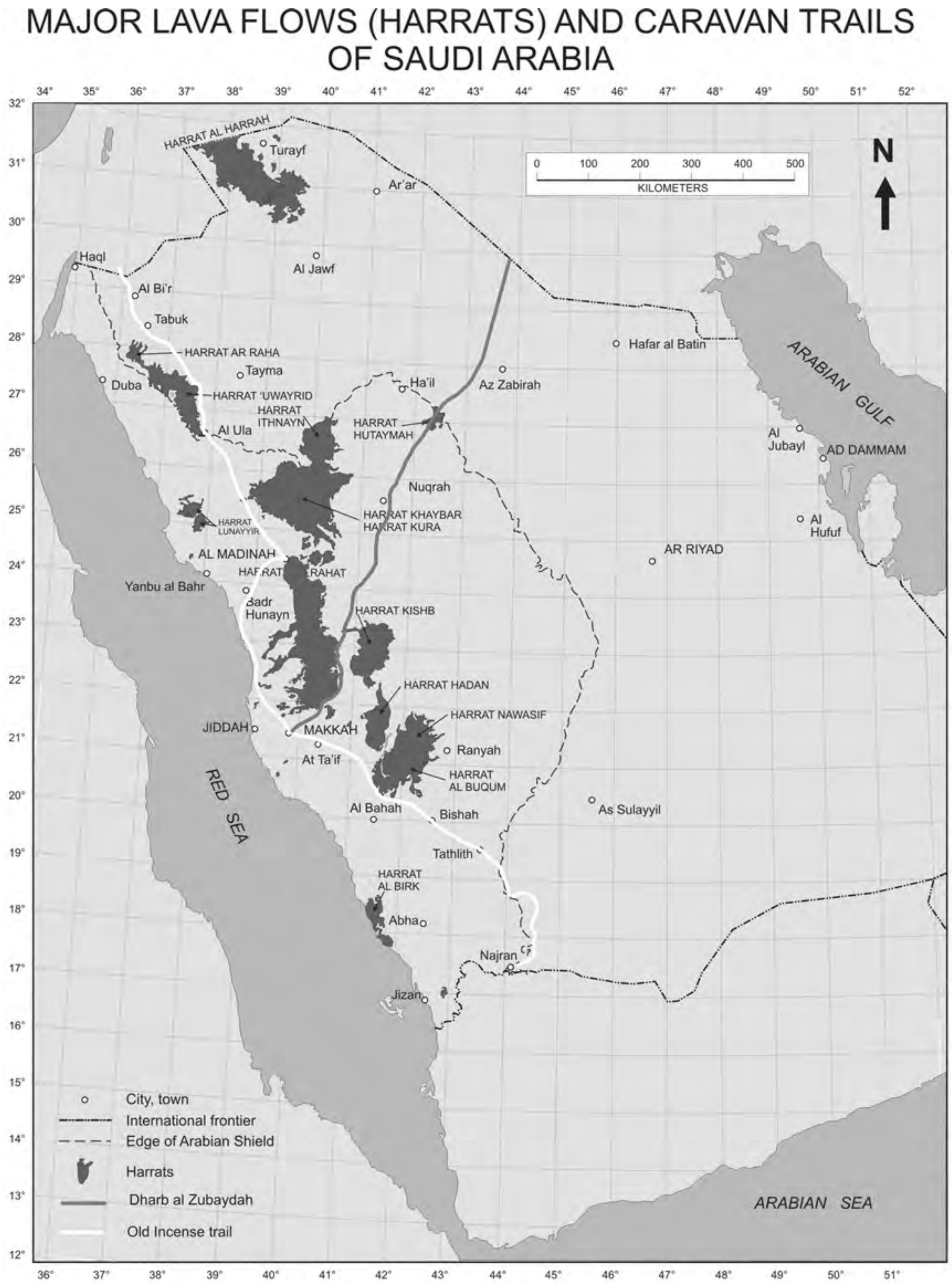

Figure 3. Map of two ancient caravan trails in Saudi Arabia, showing lava fields. After Hussein Sabir, 1991.

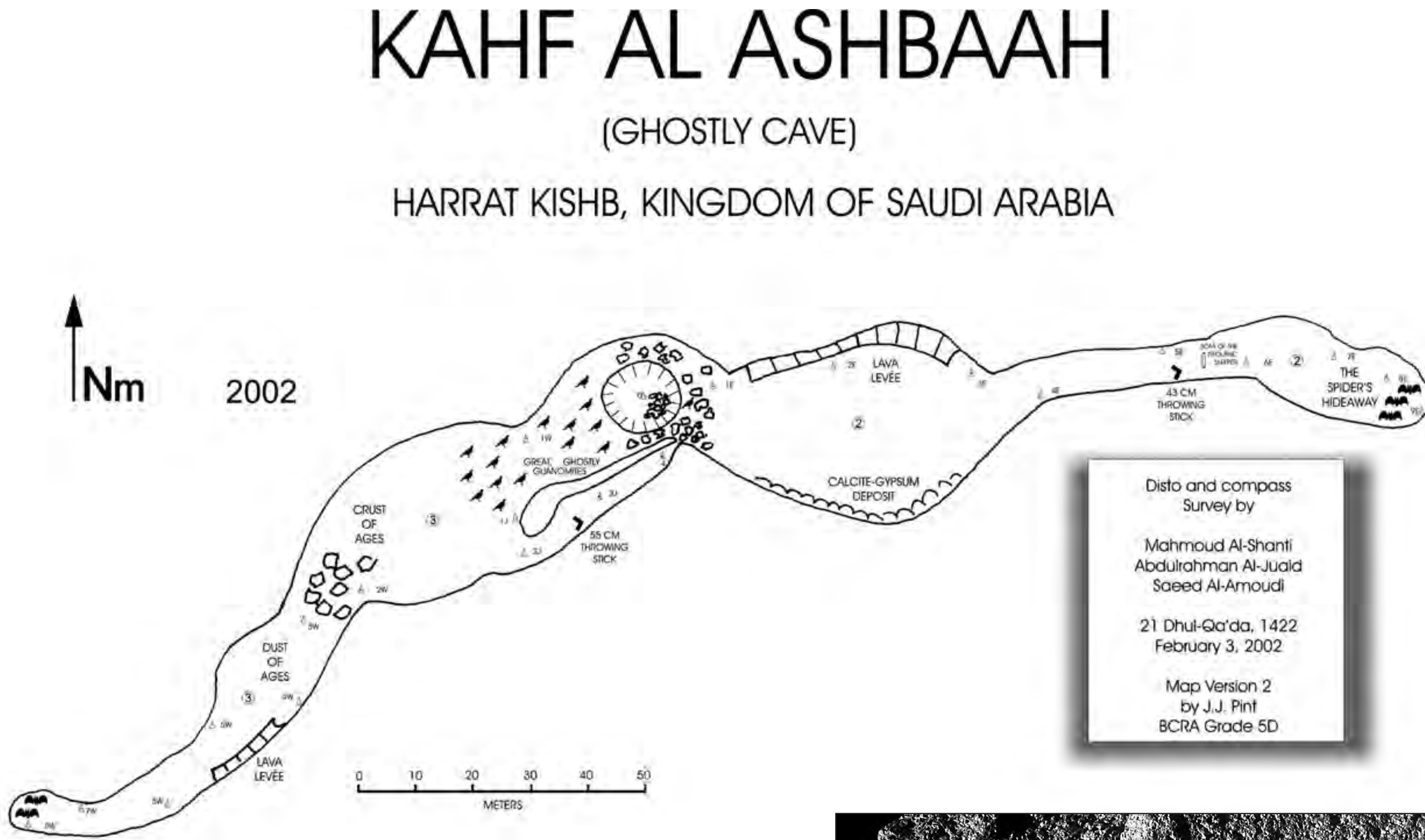

Figure 4. Map of Ghostly Cave.

Figure 5. Throwing sticks found in Ghostly Cave are flat on the bottom and curved on top to provide aerodynamic lift.

Geology of the Hil Basalt

All the surveyed caves found in Harrat Kishb are located in the Hil Basalt, which is a basaltic lava field younger than one million years, with an area of 5,892 km^2, centered about 270 km northeast of Jeddah. These deposits comprise both scoria cones and lava flows which were probably formed during a moist climatic period or pluvial interval and which are distinguished from overlying subunits because they are significantly eroded (Roobol et al., 2002).

Mut'eb Cave

Mut'eb Cave, or Kahf Al Mut'eb is registered as number 124 in Pint, 2002 and is located at 22°55′N,41°24′E. Note: seconds of latitude and longitude have been omitted in this paper in order to help protect these caves from vandalism. The precise location of each cave is given in Pint, 2002.

Geological setting. The cave is found in a sinuous ridge of smooth, hard pahoehoe lava curving around an older, obstructing scoria cone in the volcanic deposits of the Hil Basalt.

Description. A map of this cave is shown in Figure 2. Mut'eb Cave is 150 m long. The entrance to the cave measures 3 x 7 m and is found on the eastern side of a collapse 20 m in diameter. There are remains of an ancient, man-made wall across the front of the cave. A single passage trends east, sometimes reaching a width of 20 m. The passage height varies from 3 to 5 m. Sand or clay-rich sediment cover the floor to an undetermined depth. The cave contains abandoned wasps' nests, mounds of rock-dove guano, animal bones, and bat urine stains on the walls and ceiling. A 40-cm-long cord composed of long plant fibers, with one knot in it, was hidden beneath a flat rock at the eastern end of the cave (Roobol et al., 2002).

Comments. Because a man-made structure is found at the entrance to this cave and because an apparently ancient artifact was found deep inside, it is suggested that the cave be investigated by archeologists. Note that Mut'eb Cave, in Harrat Kishb, is located approximately 55 km east of the celebrated Darb Zubaydah, a well-marked trail complete with shelters, water wells and reservoirs one day's march apart (See Fig. 3). The trail led from Baghdad to

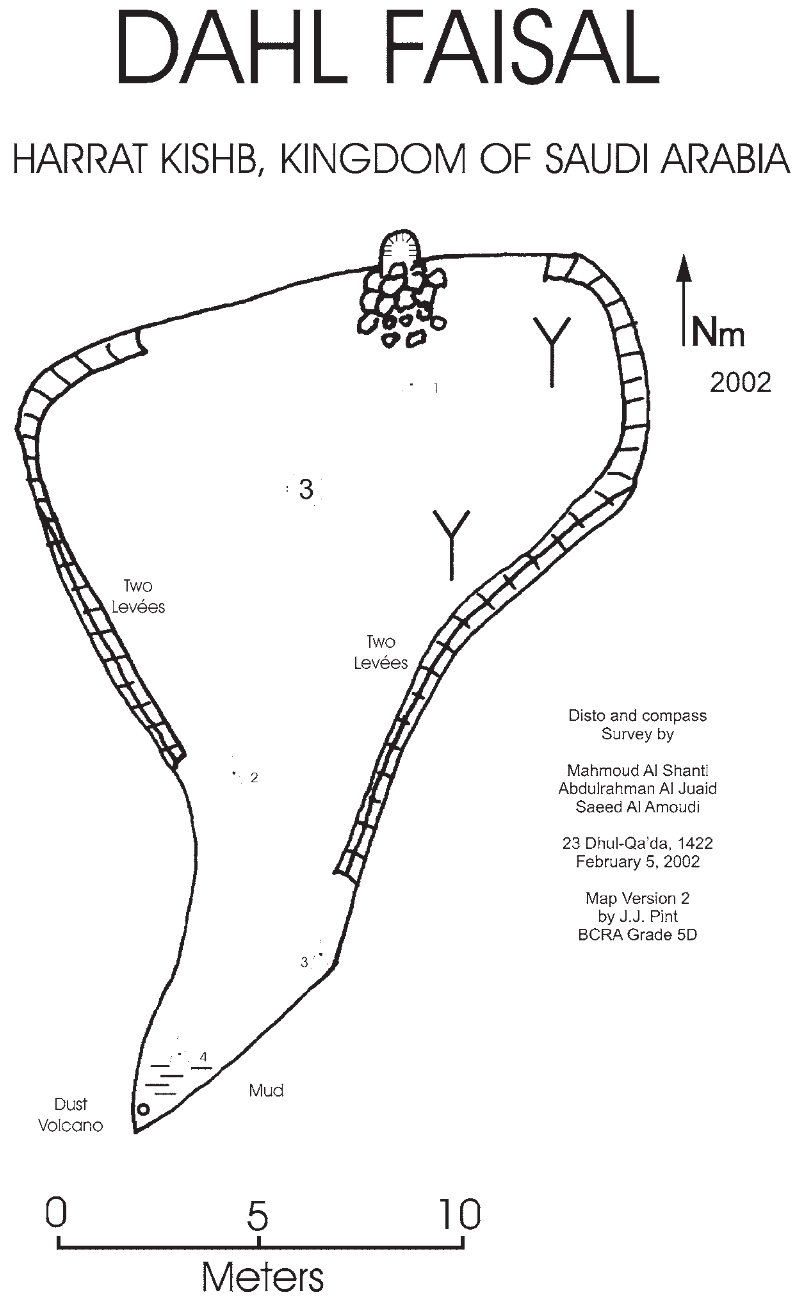

Figure 6. Map of Dahl Faisal.

Mecca and was built by Queen Zubaydah, the enterprising wife of Caliph Harun al-Rashid around the beginning of the ninth century A.D.

Ghostly Cave

Ghostly Cave or Kahf Al Ashbaah is registered as number 123 in Pint, 2002 and is located at 22°55′N,41°25′E.

Geological setting. The cave is found in a flat area of basaltic pahoehoe lava in the volcanic deposits of the Hil Basalt .

Description. The cave is 320 m long. The entrance is a collapse 10 m in diameter with a 7 m drop to a flat floor below. The passage leads off east and west. Up to 50 stalagmite-like mounds of rock-dove guano are found just inside the entrance to the western passage along with the remains of a stone wall partly buried beneath bird guano. The cave passages have a maximum width of 30 m and vary in height from 1 to 3 m. Both passages have white, calcareous patches on the ceiling and a thick layer of powdery dust on the floor. This consists mainly of calcium, potassium and phosphate. Bats are found at both extremes of the cave. Two flat, L-shaped wooden throwing sticks were found in dark areas of the two passages, resembling similar instruments depicted in Neolithic rock art found in Saudi Arabia. See Fig. 3 and 4. (Roobol et al., 2002)

Comments. Man-made constructions and two ancient throwing sticks were found in this isolated and difficult-to-enter cave. Digging in the sediment which completely covers the cave floor may produce historically or archeologically important finds. As noted in the comments on Mut'eb Cave, Ghostly Cave is Cave is located approximately 55 km east of the celebrated Darb Zubaydah (see Fig. 3).

Dahl Faisal

Dahl Faisal is registered as number 162 in Pint, 2002 and is located at 23°11′N,41°27′E.

Geological setting. The cave is found in a nearly flat-lying "whale-back" lava flow of the Jabal Zuwayr volcano. This volcano and its flows consist mainly of basanite and alkali olivine basalt with small volumes of hawaiite, phonotephrite and phonolite and are located in the northern portion of the Hil Basalt.

Description. Dahl Faisal is 22 m long. The cave is entered through a smooth, 3-m-long pipe, 80cm diameter at its narrowest point, oriented at a 60° angle. This appears to have formed when the cave was created. Below the entrance tube lies a heap of rocks apparently piled up by people using the cave in the past. Dahl Faisal consists of one room, 17 x 22 m, with a maximum ceiling height of 3 m. Sediment of unknown depth covers the original floor. The cave contains basaltic stalactites, stalagmites and lava levées. Desiccated animal scat apparently from wolves, hyenas and foxes was also found. See Fig. 5. (Roobol et al., 2002)

Comments. Dahl Faisal is located 60 km east of Darb Zubaydah and about 70 km southeast of Mahad adh Dhahab, an operating gold mine and reputedly the site of one of King Solomon's Mines. See Fig. 3. Carbon-14 dating of wood from fires used for smelting suggests that the mines are 3,000 years old. This information, together with historical studies, indicate that gold, silver and copper were indeed recovered from this region during the period considered by some to be the reign of King Solomon: 961-922 B.C. Evidence of human use and the proximity of the cave to known historical sites, suggest that it could contain artifacts.

Figure 7. Collapse Structure 6 of the Jebel Hil lava tube, looking west, showing the upper part of the lava tube with geologists standing on the roof. Photo courtesy J. Roobol.

Jebel Hil lava tube

This lava tube extends westwards from Jebel Hil. Along its length are aligned small rootless shields, collapse holes, subsided areas and one area of local updoming. Twelve such features were located, one of which is shown in Fig. 6. The lava tube is up to 20 m high and the depth of its floor beneath the surface varies from 28.5 to 42.5 m, measured by Disto Laser Measuring Device at each hole. The surface features of this lava tube were mapped and described, and they suggest that the tube is at least 3 km long. However, the cave itself was not entered. A detailed map and description of these features are given in Roobol et al., 2002.

Other caves located on Harrat Kishb

Two other lava caves, First Cave and Bushy Cave were also located during the Kishb surveys. The entrance to First Cave is a collapse 20 m deep in what appeared to be a lava tube. It was not entered due to apparent instability of the entrance walls. Bushy Cave is a nearly round room 12X13 m, possibly formed by a gas bubble. It was sketched, but not surveyed.

Conclusions

The fact that six caves were located on the first attempt to find and study lava caves in Saudi Arabia should encourage more attempts to carry out vulcanospeleological projects in this country, which has over 80,000 square km of lava fields. The fact that three apparently Neolithic artifacts were found in two of the caves studied suggests that an archeological study of Saudi lava caves may produce interesting results.

The SGS open-file report on the Caves of Harrat Kishb can be downloaded at http://www.saudicaves.com/spspubs. The trip report and photos are at http://www.saudicaves.com/kishb/kishb.htm .

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Small Subcrustal Lava Caves: Examples from Victoria, Australia*

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Introduction

This paper discusses the formation of a type of small lava cave that forms by "Subcrustal drainage" of lava flows. Examples will be drawn from the Western District Volcanic Province of western Victoria, Australia (Figure 1). Caves from that province are numbered in the Australian Karst Index with a "3H" prefix, abbreviated here to just "H" e.g. H-70 (Matthews, 1985).

In a review/study of active volcanoes in Hawaii, Peterson & others (1994) proposed two distinct models for the formation of lava tubes: either by the roofing over of linear surface lava channels (Figure 2); or by the draining of still molten material from beneath the solidified crust of pahoehoe flow lobes (Figure 3). The former process produces relatively large and simple lava tubes. However, this paper will concentrate on the smaller, but commonly complex, caves formed by localisation of flow beneath the crust of thin flow lobes or sheet-flows, and subsequent partial draining - a process that has been progressively recognised and described by Peterson & Swanson (1974), Wood (1977), Greeley (1987), Peterson & others (1994), Hon & others (1994) and Kauahikaua & others (1998) and which is illustrated in Figure 3. Recently, Halliday (1998a & b) has described two types of small lava cave: His "sheet flow caves' and 'hollow volcanic tumulus caves' which he regards as being distinct. I will argue that these are probably just two of several possible members of a continuum of forms which have been referred to as "**Subcrustal lava caves**" (e.g. Stevenson, 1999).

The terminology of surface lava flow features and their caves has become rather complex and confusing in recent years, so I will list here some terms - and my intended usage.

Surface lava features — what is a tumulus? The changing usage of "tumulus" affects the definition of a "tumulus" cave ! Walker (1991) gave the term "tumulus" a genetic definition which both expanded the term to incorporate all lava rises, including elongated ridges, and narrowed its usage to those rises that show evidence of inflation, given by opened axial clefts on the crest, but which have no evidence of lateral compression (if there was, Walker would call them pressure ridges). Unfortunately, on the relatively old (20-40,000 year) flows in Victoria weathering and vegetation growth has reduced much of the surface to a cracked and jumbled rubble. Thus, definitive axial clefts are difficult to identify and the new (genetically-

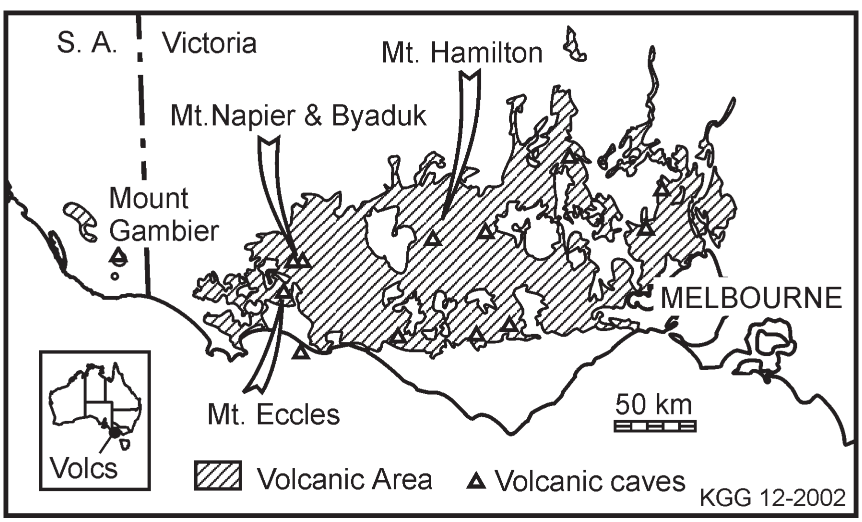

Figure 1. Location map of the Western District Volcanic Province, and its main lava cave areas.

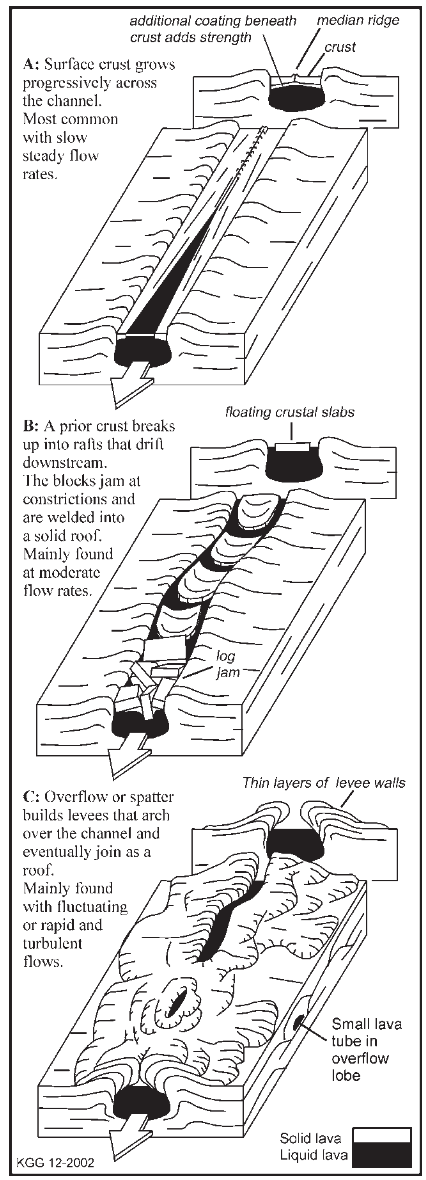

Figure 2. Three ways of forming large lava tubes by roofing a surface channel.

based) usage of the term "tumulus" has limited use. In Victoria the usage of "**tumulus**" has always been restricted to the distinctive, steep-sided, roughly-circular mounds described by Ollier (1964) in the Harman valley (many of which do have obvious large summit clefts) and the more general term "**stony rises**" is used for the chaotic complex of broader hummocks and hollows that occur on many of Victoria's younger lava surfaces. This local usage of "stony rises" would seem to correspond to the "hummocky pahoehoe" of Hon et al (1994) but some have relatively flat surfaces that correspond to their "sheet flows" and there are also transitional forms. In Walker's (1991) terminology the Victorian "stony rises" represent a mix of his "tumuli", "pressure ridges", "lava rises" and "lava rise pits".

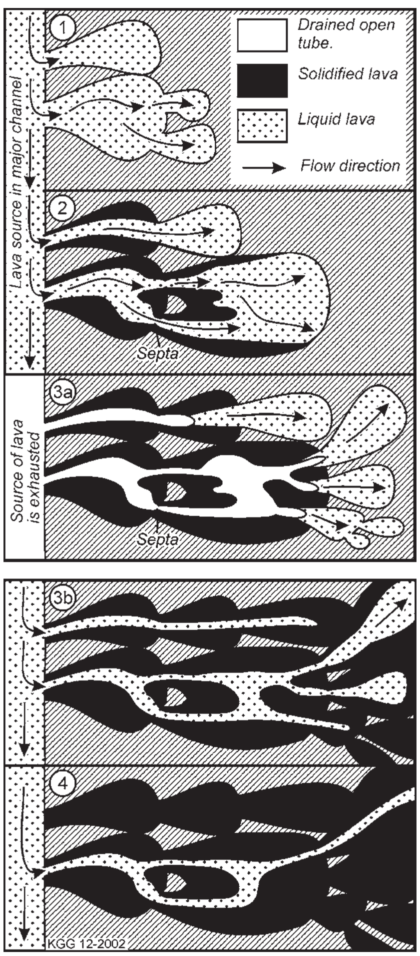

Figure 3. Formation of lava caves by subcrustal drainage of a series of advancing lava lobes. Step 3a is the situation if the source of lava ceases early in the development; irregular caves form. Steps 3b and 4 indicate the further evolution into more linear feeder tubes as lava continues to flow through the system.

For this paper I will use the descriptive, non-genetic, term "lava mound" to describe all high areas within a lava field. Lava mounds are likely places for the formation of small drained subcrustal lava caves, whatever the process of mound formation.

Cave types: In any discussion of lava caves and their genesis it is important to distinguish between active (lava-filled) proto-caves and the drained tubes and chambers (i.e. caves) which appear at the end of the eruption – as discussed by Halliday (2004).

In an earlier paper (Grimes, 1995) I described complex, lateral, levee-breach systems associated with lava channels at Mount Eccles, and distinguished them from smaller, isolated, drained chambers in the surrounding "stony rises" but did not suggest a formal nomenclature. The terminology of Halliday (1998a,b), which is based on the surface lava flow character (after Walker, 1991), is difficult to apply to the Victorian subcrustal caves because of the problem in distinguishing "tumuli" (sensu Walker, 1991) from other lava mounds. I also suspect that rather than two discrete genetic types of small subcrustal cave as proposed by Halliday ("sheet flow caves' and 'hollow volcanic tumulus caves'), we have a broad continuum of forms with a number of distinctive end-members.

I suggest that the cave classification should not be tied to the surface terminology until the processes of cave development are better known. Also, basing the cave nomenclature on the surface lava forms may be confusing cause and effect—rather we should be explaining some surface mounds and tumuli as a result of localised subcrustal flow in tubes, not the cause (see conclusion). The unifying factor in all these caves is that they form by drainage from beneath a broadly-crusted lava flow; hence I will refer to them here collectively as **subcrustal lava caves**.

In this paper my discussion will concentrate on the smaller subcrustal lava caves, those that form originally, rather than the larger more evolved forms which can develop from them over time and which tend to become closer in shape to the tunnels formed by roofing of surface channels. In Victoria, the Mt. Hamilton lava cave (Figure 14) may be an example of the latter type.

In Victoria, speleologists have used the term "**blister cave**" for the small, simple, isolated chambers found under the stony rises (Figure 4). However, care is needed to avoid confusion with another usage of that term for small chambers formed by gas pressure (Gibson, 1974, and Larson, 1993). I suggest usage of **lava blister** for those inflated by liquid lava (and later drained), and **gas blister** for those generated by gas pressure. "Blister" should only be used on its own where the genesis is uncertain.

The basaltic **Western District Volcanic Province** (previously known as the Newer Volcanic Province) of western Victoria has over 400 identified eruptive points and it ranges in age mainly from Pliocene (about 5 Million years) up to very recent times (5ka), though there are some volcanoes as old as 7 Ma (Joyce, 1988, Joyce & Webb, 2003, Price & others, 2003). Lava caves are known across the whole province (Figure 1), but are most common in the younger flows associated with Mount Eccles (20-33 ka, Head, & others, 1991, and P. Kershaw, per comm, 2005) and Mount Napier (about 32 ka, Stone & others, 1997). Recent summaries of both the surface landforms and the volcanic caves of the province appear in Grimes (1995, 1999); and Grimes & Watson (1995). The earlier literature on lava caves of the region by Ollier, Joyce and others is reviewed in Webb & others (1982) and Grimes & Watson (1995) and only some of those papers are referenced here. The younger lava flows have surfaces ranging from strongly undulating ("stony rises") to flat.

At **Mount Eccles** the main volcano is a deep steep-walled elongated crater which contains Lake Surprise. At the north-western end the crater wall has been breached by a lava channel that flows west and then branches into two main channels (referred to locally as 'lava canals') running to the west-northwest and to the south-southwest (Grimes, 1995, 1999). Extending to the southeast from the main crater there is a line of smaller spatter and scoria cones and craters. Several smaller lava channels run out from these. Lava caves occur in a variety of settings.

Beyond this central area of explosive activity, basalt flows form a lava field about 16 km long and 8 km across. From the western end of this lava field a long flow, the Tyrendarra Flow, runs 30 km southwards to the present coast and continues offshore for a further 15 km (sea level was lower at the time of the eruption). This long flow must have had a major feeder tube, but no drained sections have been discovered to date.

Mt Napier and the Harman Valley flow: Mt Napier, about 20 km northeast of Mt. Eccles, is a steep cinder cone capping a broad lava shield 10 km in diameter. Some lava caves occur on the lower slopes of the cone, and on the lava shield, but the main cluster is at the **Byaduk Caves**, at the start of a long lava flow that follows the Harman Valley for at least 20 km to the west. Other lava caves occur further down the valley, as do an excellent set of sharply-defined tumuli (Ollier, 1964). It was at the Byaduk Caves that Ollier & Brown (1965) derived their 'layered lava' model of tube formation - which is still invoked by some authors (e.g. Stephenson, 1999).

Mount Hamilton is a broad lava cone surrounded by "stony rise" lava flows. There is a large lava crater at the summit. The cone contains one group of complex lava tubes (Ollier, 1963).

In the late Quaternary lava flows of Mount Eccles and Mount Napier, in the Western District Volcanic Province, we find both cave types described by of Peterson & others (1994) and also isolated "lava blister" caves - I will draw my examples from those areas. The complex lava cave system at Mount Hamilton appears to be a further-evolved "feeder" system.

Most of the longer caves known at **Mount Eccles** are in or adjacent to the lava channels, but there are a number of small caves scattered throughout the area, and the known distribution may simply reflect the more intensive exploration along the main canals. There are several types of lava cave in the area. Roofed channels include Natural Bridge (H-10; Grimes; 2002b), which has the distinctive "gothic" ceiling of tubes formed by overgrowth of a levee bank (Figure 2c), and also possibly Tunnel Cave (H-9; Grimes, 1998). The remainder are shallow, low-roofed caves that fall into two types: complex, levee-overflow systems on the sides of the major lava channels, e.g. H-51 & H-70

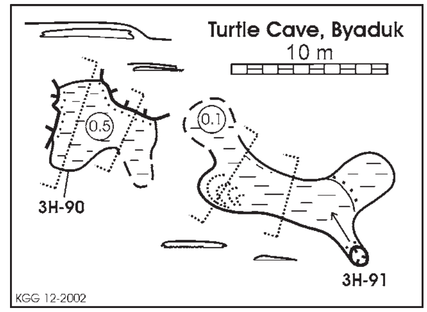

Figure 5. Turtle Cave, H-90, at Byaduk, is an example of a simple "lava blister" cave. The name derives from its resemblance to an empty turtle shell.

(Figure 6); and small, isolated, drained chambers ("lava blisters") within the stony rises (e.g. H-78; Figure 4).

At **Mount Napier**, and in its long flow down the Harman Valley we find both very large tubes (which might be roofed channels, though the evidence is ambiguous) and many small subcrustal caves. Some of the small subcrustal caves are exposed, along with their containing lava flows, at various levels in the walls of collapse dolines formed above the large tubes; for example, the upper of level of Fern cave (H-23, Figure 13) and H-74 and H-108 (Figure 12). Others are shallow isolated caves on the flow surface (H-31, 90, 91 and 106; Figures 4 & 12). One shallow cave has an open feeder from below that connects to a larger 'feeder' tube at depth (H-33, Figure 13).

The shallow lava caves involve a broad array of styles ranging from simple single chambers to multi-level, complexly-interconnecting systems of tubes and chambers. All gradations occur between these extremes, but the group has in common the dominance of shallow, low-roofed, irregular chambers and small-diameter tubes. They also grade (and possibly evolve over time) into larger and more-linear "feeder" tubes. Thus, while we can identify several distinctive types, there are many transitional forms that are hard to classify. Their genesis is discussed in more detail later in this paper.

Simple drained lava mounds and "lava blister" caves: Scattered through the stony rises there are small, shallow, low-roofed chambers; typically only 1m high with a roof 1m or less thick. These can be circular, elongate or irregular in

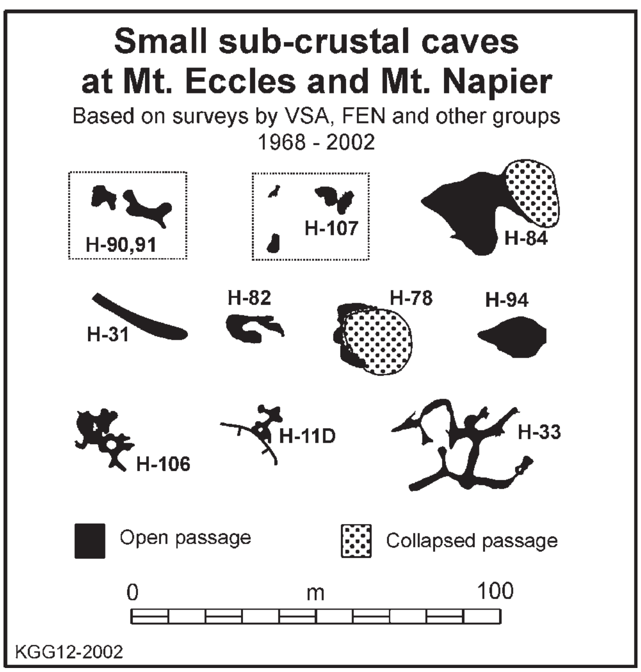

Figure 4. Examples of small, simple, subcrustal caves; mostly associated with low lava mounds. H90, 91 and 107 would be called "lava blisters"; H-78 is a "peripheral remnant" left by the collapse of the roof of shallow chamber; H-31 is approaching a linear "tube" form; H-11, 33 and 106 are grading to the more complex forms.

plan; up to 10m or more across but grading down to small cavities only suitable for rabbits. Some Victorian examples are shown in Figure 4, and include Turtle Cave (which looks like an empty turtle shell) illustrated in Figure 5. In section, the outer edges of the chambers may be smoothly rounded or form a sharp angle with a flat lava floor. The ceiling may be arched or nearly flat, with lava drips, and sometimes has a central "soft" sag that would have formed while the crust was still plastic. Commonly, the thin central part of the roof has collapsed and we find only a peripheral remnant hidden behind rubble at the edge of a shallow collapse doline (e.g. H-78, Figure 4). The more elongate versions grade into small "tube caves"; for example, Shallow Cave (H-31, Figure 4) described by Ollier & Joyce, 1968, p70.

These caves generally are found beneath low lava mounds (with or without the central clefts required to class them as "tumuli"!), though in some cases the surface relief may only rise half a metre! These small simple chambers have been locally called "blister caves" (see discussion in the Terminology section).

A large cluster of well-defined tumuli (*sensu* Walker, 1991) occur in the Harman Valley (Ollier, 1964). One of these is reported to be hollow by G. Christie (pers comm) who entered it as a child, but has not been able to relocate it. There is a 'donut' shaped tumulus which presumably has resulted from collapse of a central hollow. Within its annulus, one can squeeze through the rubble into a small 'peripheral remnant' cave.

More complex **overflow caves** associated with the lava channels at Mt. Eccles are generally shallow systems formed in the levee banks on each side of the channels and would have fed small lateral lava lobes or sheets when the channel overflowed or breached through the levee (Grimes, 1995). Figure 6 shows the lateral caves associated with the South Canal at Mt. Eccles, and Figure 12 shows a group of shallow caves adjacent to a large collapsed feeder tube at Byaduk.

Some of these lateral caves are simple linear tubes (e.g. H-48, 89, and the proximal part of H-53), but mostly they are branching systems with complexes of

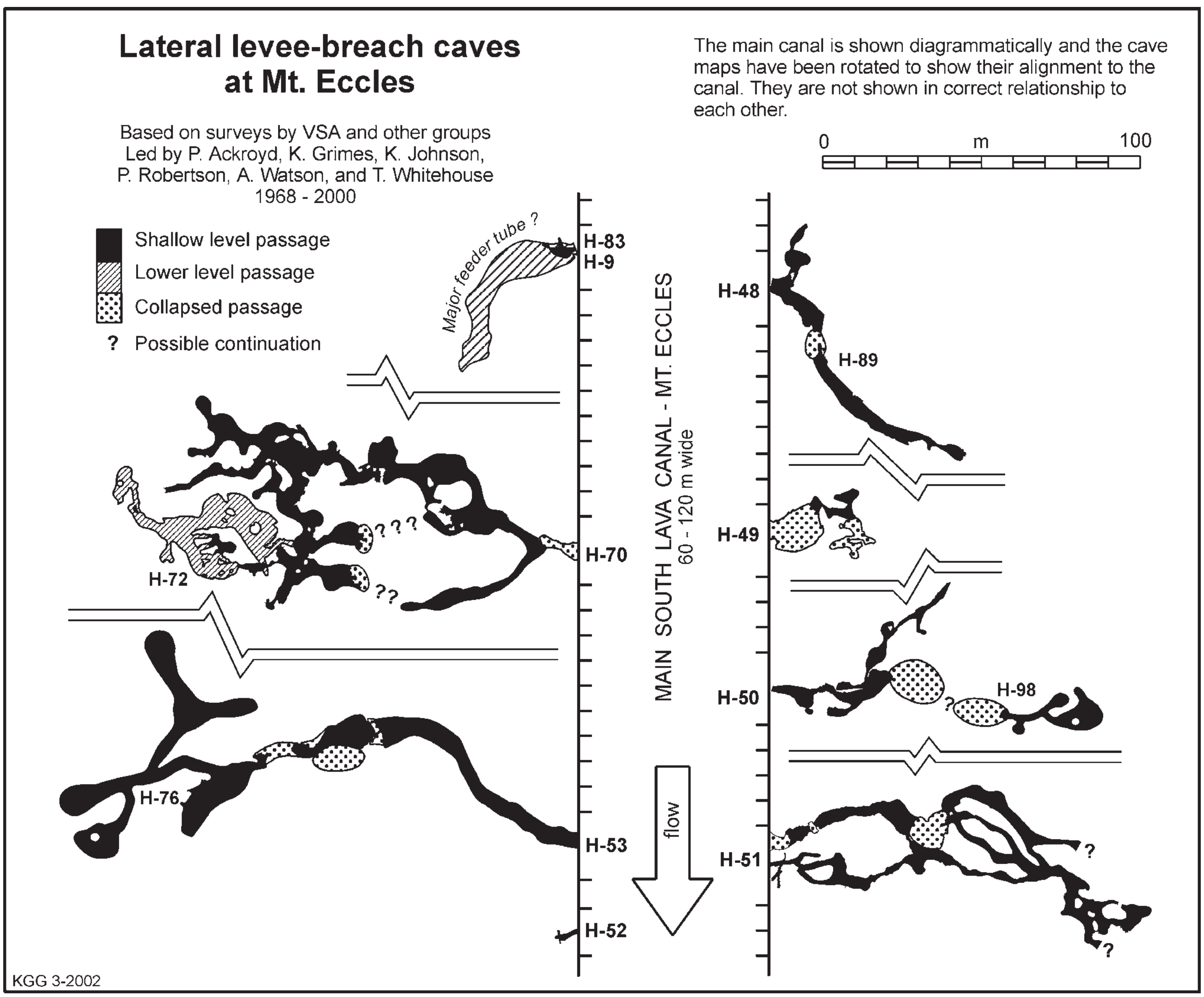

Figure 6. Examples of more complex subcrustal caves formed in thin overflows from a lava channel at Mt. Eccles. See Fig. 7 for detail of H-70/72. A detailed map of H-51 is included in the supplementary material on the CD.

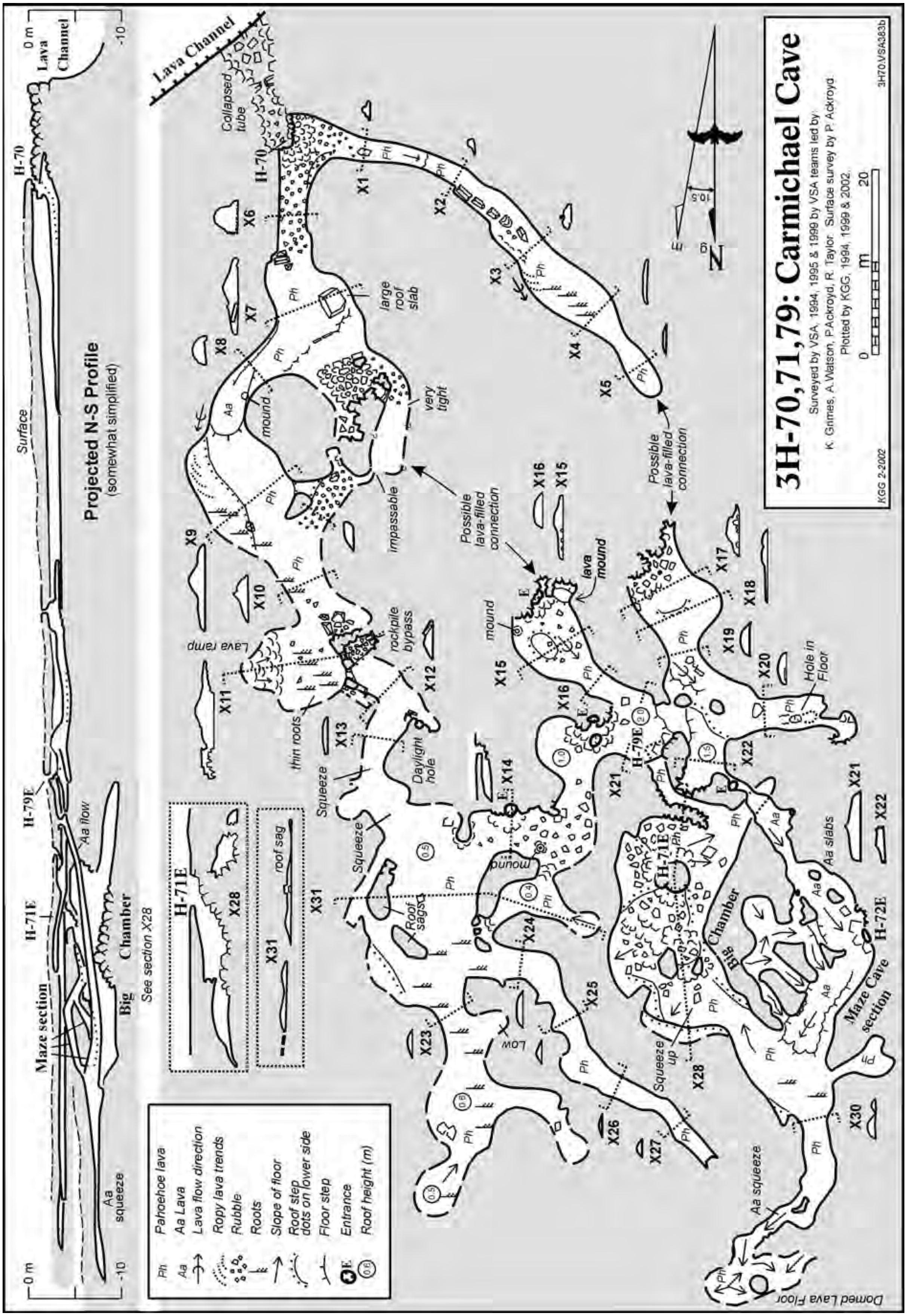

Figure 7. Detailed map of Carmichael Cave (H-70) at Mt. Eccles.

Figure 8. Two-level passage in H-70, looking south from section X22 (Fig. 7). Note the "window" on left which might be the remains of a partition between two lava lobes.

low passages that bifurcate and rejoin, or open out into broad low chambers. The shape suggests draining from beneath the thin solidified roof of a series of coalesced flow lobes. Only a few of the passages are large enough to stand in, typically (but not always) those nearest the proximal end - the channel entrance (e.g. H-48, H-53, H-70). Most passages are crawl-ways about a metre high with low arched roofs and flat lava floors (Figure 8). Some of the smallest passages have smoothly-rounded cross-sections (Figure 9). The ceiling is generally only a metre or so below the present surface, and in places breakdown has exposed the base of overlying pahoehoe flows, indicating that the original roof was less than a metre thick. In some chambers the roof has sagged down in a smooth curve to reach the floor (Figure 10). Where not covered with introduced soil, the floors are generally pahoehoe, with smooth, platy or ropy surfaces; but sharp aa lava floors occur in several places (e.g. H-51 and H-70). Some of these are late-stage additions; running over an earlier pahoehoe floor.

Where not disrupted by breakdown, the walls and roof typically have thin (2 - 20 cm) linings. These conceal the original wall, but in a few places fallen linings have exposed "layered lava" comprising thin sheets with ropy or hackly surfaces (eg the proximal end of H-70). Most caves are at a single level, but some show evidence of several levels (only a metre or so apart vertically) that either have coalesced vertically into a single passage or chamber or are joined by short lava falls (e.g. H-48, H-70 (Figure 7) and H-108).

At Byaduk, three caves occur in a stacked set of thin, 1-3m, lava flows exposed in the wall of a large collapse doline (H-74, 106 & 108; Figure 12). The elongated doline formed over a deeper large feeder tube (up to 25 m wide and 15 m high) and the thin flows may have been fed by overflows from the feeder tube, through roof windows. The three shallow caves comprise low-roofed branching passages and chambers very similar to those found beside the channel at Mount Eccles (Figure 11). In the lowest cave (H-74) there are intrusive lava lobes that may have entered through roof holes from the overlying lava flow. Likewise, in the next highest cave (H-108) a lava fall drops a metre to a short section of lower-level passage that might be in the same flow as H-74.

More complex stacked systems also occur. These can be fed from below, through a skylight in a major feeder tube, or laterally from a remote source. The upper level of **The Theatre** (H-33) is a small subcrustal cave system obviously fed from below as the shallow branching tubes occupy an isolated raised mound and a drain-back tube allows access to lower levels of low-roofed chambers and eventually to a large feeder tube at depth (Figure 13). Lava would have welled up from this lower level and formed the surface rise in several stages (the different "levels"), then drained back to leave the small tubes and chambers. **Fern Cave** (H-23) comprises a large 'feeder' tube at depth, but there is a higher level of low-ceilinged irregular

Figure 9. Small subcrustal tube, H-52 at Mt. Eccles.

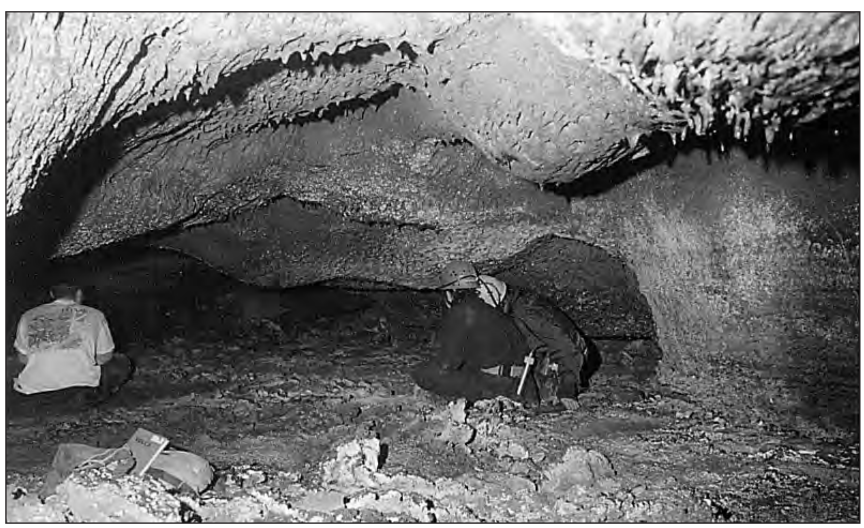

Figure 10. Chamber in H-74, showing sagged parts of roof.

chambers and passages which appears to be in a younger flow that ran over the prior roofed tube (Figure 13). This flow would seem to have been fed from the large collapsed tube to the south, which might have been an open channel at that time. The present connections between the upper and lower levels of Fern cave are later accidents of collapse of the lower tube roof.

The **Mount Hamilton Cave** (H-2) is a complex system of moderately large bifurcating tubes at several levels (Figure 14; Ollier 1963, Webb et al, 1982). It is dominated by linear tubes rather than the broad low chambers typical of most other caves considered in this paper and may indicate a more evolved style of larger subcrustal lava cave (see below).

Genesis

When discussing genesis one must keep in mind the distinction between active tubes (lava-filled) and drained tubes (caves) – as discussed by Halliday (2004). Only some active tubes will be drained and become accessible at the end of an eruption, most will remain filled and solidify. As long as a tube or cavity remains active, its form can evolve by, firstly, mechanical and thermal erosion of its edges; secondly, solidification of its stagnant parts including linings, and thirdly, partial drainage to form an open cave. Collapse of the roof can occur while the tube is active, as well as after it is drained.

Figure 11. Low chamber in H-106, with lava drips and an intrusive lava tongue at left.

Ollier & Brown (1965) used the Victorian lava caves, in particular those at Byaduk, to propose a "layered lava" model of tube development. This is similar to the more recent subcrustal models of Hon & others (1994) but their concept of "layered lava" is confusing as they seem to apply that term to two distinct types of "layer". The lavas exposed in the collapse dolines at Byaduk have flow units from 0.5 to 5m thick that are distinguished by lobate ropy surfaces at top and bottom, with small gaps and partings between them and local areas of rubble. These flow units host small subcrustal lava tubes (e.g. Figure 12) but those had not been mapped at the time of Ollier & Brown's report. However, Ollier & Brown also referred to a still-finer layering within what are now recognised as flow units - marked by sub-horizontal cracks, trains of vesicles, and small flattened cavities which may have stretch structures or small lava drips. They rejected the suggestion that separate flow units were present, and believed that all the layers were "formed by differential movement within one thick lava flow" (not within thinner flow units) and that they were "possibly shearing planes formed during flow just before solidification". They recognised that the flow somehow become differentiated

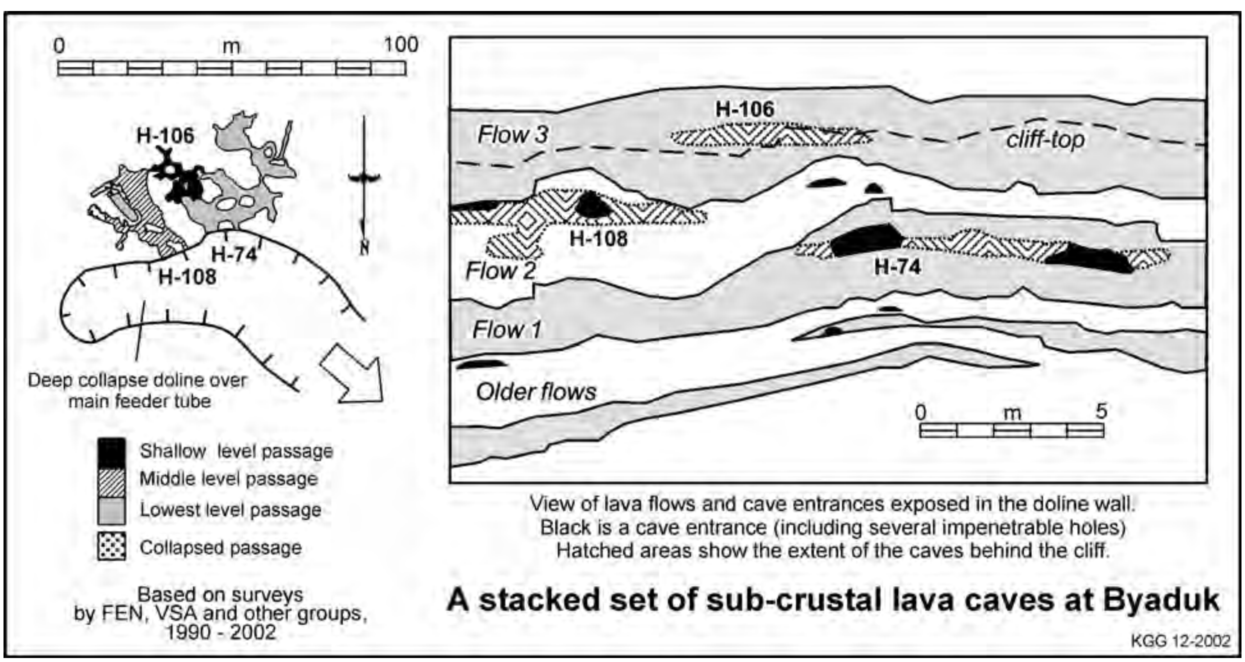

Figure 12. A set of three small subcrustal caves formed in separate stacked lava flows at Byaduk. Detailed reports and maps on H-106 and H-108 are in the supplementary material on the CD.

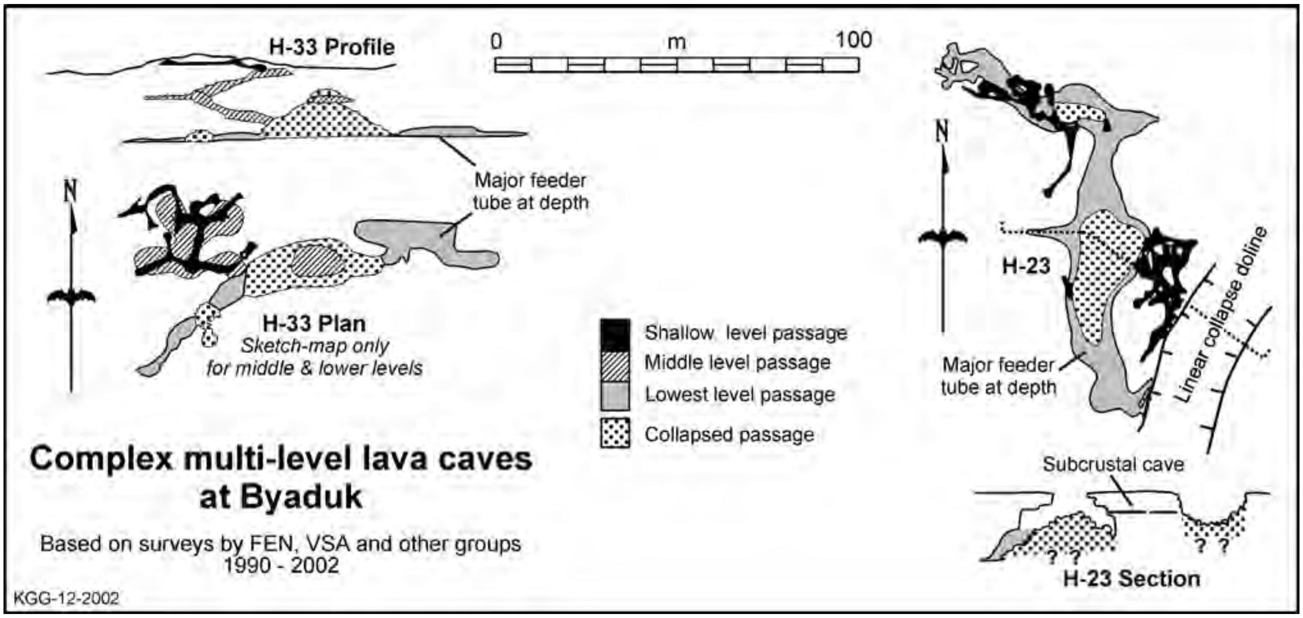

Figure 13. Complex, multi-level lava caves at Byaduk. Shallow subcrustal systems overlie large feeder tubes at depth.

into solid parts and liquid-filled tubes, but a detailed understanding of how this happened had to wait on the observations of active tube-fed lavas by later worker (e.g. Peterson & others,1994 and Hon & others,1994). Ollier & Brown did, however, recognise that the tubes, once formed, could enlarge by eroding the surrounding (layered) lava rock.

For a more detailed description of the observed processes seen in active lava flows, and models deduced from these, see Peterson & Swanson (1974), Wood (1977), Greeley (1987), Peterson & others (1994), Hon & others (1994) and Kauahikaua & others (1998). The model used here is essentially that described in the last three of those papers (Figures 2 & 3).

Isolated small "lava blister" caves found beneath low mounds in the "stony rises" would form by the irregular draining of cavities beneath the thin solidified crust of a broad lava flow. The process is similar to that which forms other subcrustal drainage tubes (see below), but less organised so that only isolated low-roofed chambers appear to result beneath the high points of the undulating surface. Commonly the chamber roof sags (while hot) or later collapses so that only a crescentic 'peripheral remnant' survives, as at H-78 (Figure 4).

Figure 3 illustrates the formation of more complex tubes and cavities by *subcrustal draining* from beneath a crusted flow. The figure shows the case where a channel has overflowed, as along the Southern Canal at Mount Eccles, but similar effects occur at the front of an advancing pahoehoe lava flow where the lava is delivered by a channel or major feeder tube, but then spreads out into a series of lobes. These lobes grow by a process of 'budding' in which a small lobe develops a skin, and is inflated by the lava pressure until the skin ruptures in one or more places. Lava escaping through the rupture develops new lobes and so on (Figure C-1, 2, 3). If the supply of fresh lava is cut off, the still-liquid parts of a lobe may be drained to form a broad but low-roofed chamber (Figure C-3a). However, if fresh hot lava continues to be delivered from the volcano it may become progressively concentrated into linear tubes that feed the advancing lobes, while the remaining stagnant areas solidify (Figure C-3b, 4, 5).

Tubes formed by draining of lava lobes and flows are generally smaller than those formed by the roofing of a channel – although inflation of the flow can provide a thickness of ten metres or more in which larger subcrustal drainage tubes can form. However, if flow continues after they are formed, several small tubes within a lobe complex may coalesce by breakdown of their thin walls or floors (the "partitions" or "septa" of Hon et al, 1994, and Halliday, 1998b) to form a larger feeder tube. Also, a continuing flow of hot lava through a small feeder tube can enlarge it by erosion of the walls or floor (Peterson & Swanson, 1974; Greeley, 1987). Destruction of the crust above the active tube can form skylights or local surface channels, and overflow from these can form secondary flow lobes. Thus, pahoehoe lobes can be stacked vertically as well as advance forwards so that a complex three-dimensional pattern of branching tubes and chambers can form.

H-53 could be regarded as showing a transition from the low branching and chambered systems at the (younger) distal end, to the more linear unbranching tube systems at the proximal end that would develop in time as flow becomes more localised and organised to feed an extensive overflow sheet. The proximal end of this cave approaches the character of a 'roofed channel' tube and determining the origin of simple large lava tubes can be difficult as much of the evidence may have been removed by erosional enlargement of the original tube, or be hidden behind wall linings.

The Mount Hamilton Cave (H-2, Figure 14) may be a further-evolved system in which the original irregular chambers and small passages of subcrustal drainage caves in several stacked flows have combined and evolved into a more linear system of larger "feeder" tubes as lava flow continued through the conduit system on its way to the lava field below. This suggestion is supported by the presence of small ‘proto-tubes’, 20-60 cm in diameter, that are exposed by breakdown in the walls and ceiling of the larger tubes in several parts of the cave (Figure 15).

Conclusion

Small subcrustal lava caves form by drainage of lava from beneath a thin crust developed on a lava surface. In its simplest form, drainage of lava from beneath high areas on the crusted surface will form simple isolated chambers - “lava blisters”. Complex nests of advancing lava lobes create equally complex patterns of active tubes and chambers which can later drain to form open caves. As lava continues to flow through these complex systems they will evolve by erosion and solidification to form larger, more streamlined, linear tube systems that act as “feeder tubes” to carry hot lava to the advancing lava front. If sufficiently evolved, these linear tubes can converge on the form of the, generally larger, linear tubes formed by roofing of surface lava channels. Thus the genesis of many large lava caves remains difficult to deduce.

The “drained tumulus caves” described by Halliday (1998a) & Walker (1991) would be a special case of the small subcrustal type in which the crust was pushed up into a tumulus (sensu lato) before it drained. Halliday’s (1998b) “sheet flow caves” are also a special case tied to a particular surface form. I would expect all gradations between these features and the more extensive systems which can form under both flat-topped “sheet-flows” and undulating “stony rises”.

I suggest that the cave classification should not be tied to the surface terminology until the processes of cave development are better known. Also, basing the cave nomenclature on the surface lava forms may be confusing cause and effect—rather than argue that some types of caves form beneath/in tumuli and others beneath “sheet flows”, it might be better to say that tumuli tend to form above active localised flows within a sheet (i.e. above lava tubes). The hot flowing lava would inhibit thickening of the crust above the tube or chamber so that it would be weaker and more likely to be uplifted by hydraulic pressure in these local areas. A linear lava tube could thus produce a linear ‘tumulus’ or a chain of rounded ones. Wider chambers along the line of the tube would have weaker roofs and hence explain the localised nature of the *sensu stricto* tumuli.

The unifying factor in all these caves is that they form by shallow drainage from beneath a crusted lava flow - hence they can be referred to collectively as **subcrustal lava caves**.

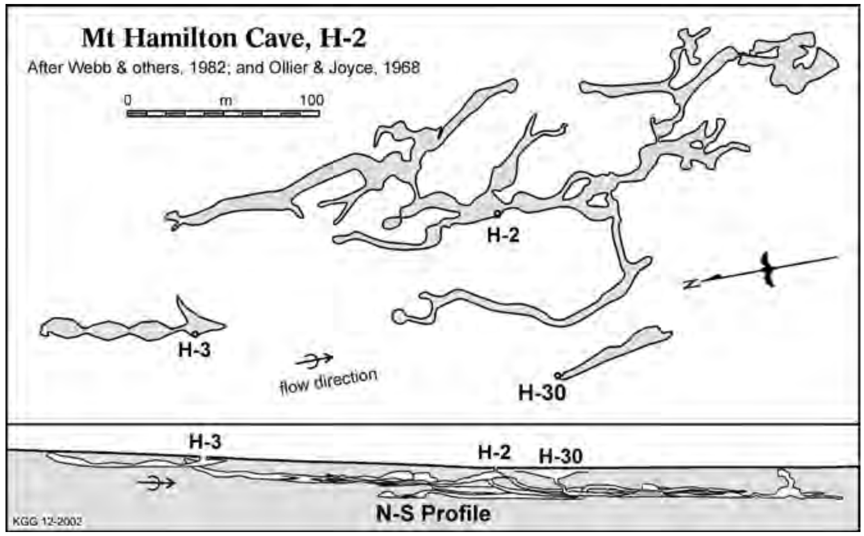

Figure 14. Mt Hamilton lava cave is an evolved system of larger, linear, bifurcating, subcrustal tubes.

Acknowledgements

With acknowledgements to my predecessors who conceived most of the ideas expressed here: In particular Don Peterson, Ken Hon, Bill Halliday, and many other speleo-geologists. This report draws on the exploration and mapping efforts of numerous speleologists from the Victorian Speleological Association and other groups over the last 50 years.

Figure 15. A pair of small ‘proto-tubes’, with 10 cm thick linings, exposed in the wall of a larger, more-evolved, tunnel in the Mt Hamilton lava cave. Scale bar is 10 cm.

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(Note: *Nargun* is the journal of the Victorian Speleological Association)

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*Papers Grimes 1995, Grimes 2002a, and Grimes 2002b are included in the supplementary material on the CD.

A Small Cave in a Basalt Dyke, Mt. Fyans, Victoria, Australia

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Abstract

A small but unusual cave has formed within a large dyke that intrudes a scoria cone at the summit of Mt. Fyans, western Victoria. Draining of a still-liquid area, after most of the dyke had solidified, left an open cavity. Features within the cave mimic those of conventional lava caves, and suggest that the lava levels oscillated within the cave several times.

The volcano

Mount Fyans is a volcano within the Newer Volcanic Province of western Victoria, Australia. The age of the province dates back at least 5 million years, but Mt. Fyans is a relatively youthful eruption, undated, but possibly less than 100,000 years old – judging by the well developed "stony rises" (remnants of the original hummocky lava surface) and minimum soil development. The volcano is a broad shield of basaltic lava with a low scoria cone at the summit and possibly a crater - though an extensive quarry in the scoria makes the original form difficult to deduce!

The scoria at the summit has a thin cap of basaltic lava, and ropy patterns on the underside of this are well-exposed on the southern margin of the quarry. The loose scoria has been intruded by two large basalt dykes up to 12 m across (which would have fed the lava cap) and a number of smaller pipe or finger-like basalt bodies, some of which have been partly drained to leave small cavities. Figure 1 shows the quarry and the main dyke. An inset map in Figure 2 shows the location of the various feaatures described here. The quarry operations have worked around the large dykes, but damaged the smaller intrusive features (which is how we know they are hollow!).

Mt. Fyans Cave

A small horizontal cave occurs within the largest dyke. It lies close to the west edge of the dyke and runs parallel to it (Figure 2). Entry is via a small hole broken into the roof by the quarry operation. The cave is about 17 m long and generally less than one metre high. The roof and walls have numerous lava drips (Figure 3). The floor is a horizontal ropy pahoehoe surface which rises gently towards the northern end – but the ropy structures suggest a final flow direction from south to north. The drainage points for the lava are not obvious; but there is a very small hole in the floor at the southern end. Both roof and floor have common patches of pale-cream coatings over the basalt – possibly fumerolic alteration? There are well-developed rolled benches (10 cm diameter) along the edges of the floor (Figure 4). These suggest that the lava rose and fell several times within the cavity. One small hole in the roof, near the entrance, opened into broken scoriaceous material.

Related features

As well as the cave, the main dyke also has a drained vertical pipe at its southern end – this has been broken into by the quarry operation and we found the upper part lying on its side 20 m to the NE (see inset map, Figure 2). This pipe had spatter and dribble patterns on its inside walls. Elsewhere in the quarry there are intrusive pipes and smaller fingers of basalt that have pushed up through the loose scoria. Several of these have drained back after the outside had solidified so as to leave a hollow core, some with lava drips. Probably the most distinctive are conical "Witch's hat" structures (Figure 5).

The area has other features of both geological and historic interest and warrants preservation. For example, the underside of the lava flow capping the scoria is exposed in several places and shows a wrinkled "belly" with fragments of the loose scoria stuck to it. The surrounding "stony rises" have some particularly elegant and distinctive drystone walls that were constructed by early European settlers.

No other volcanic caves formed in dykes have been reported in Australia, but a larger one has been reported from the Canary Islands (Socorro & Martin, 1992).

Figure 1. View of Mt. Fyans Quarry, looking north towards the large dyke. C = cave, P = Pipe, W = Witch's hats.

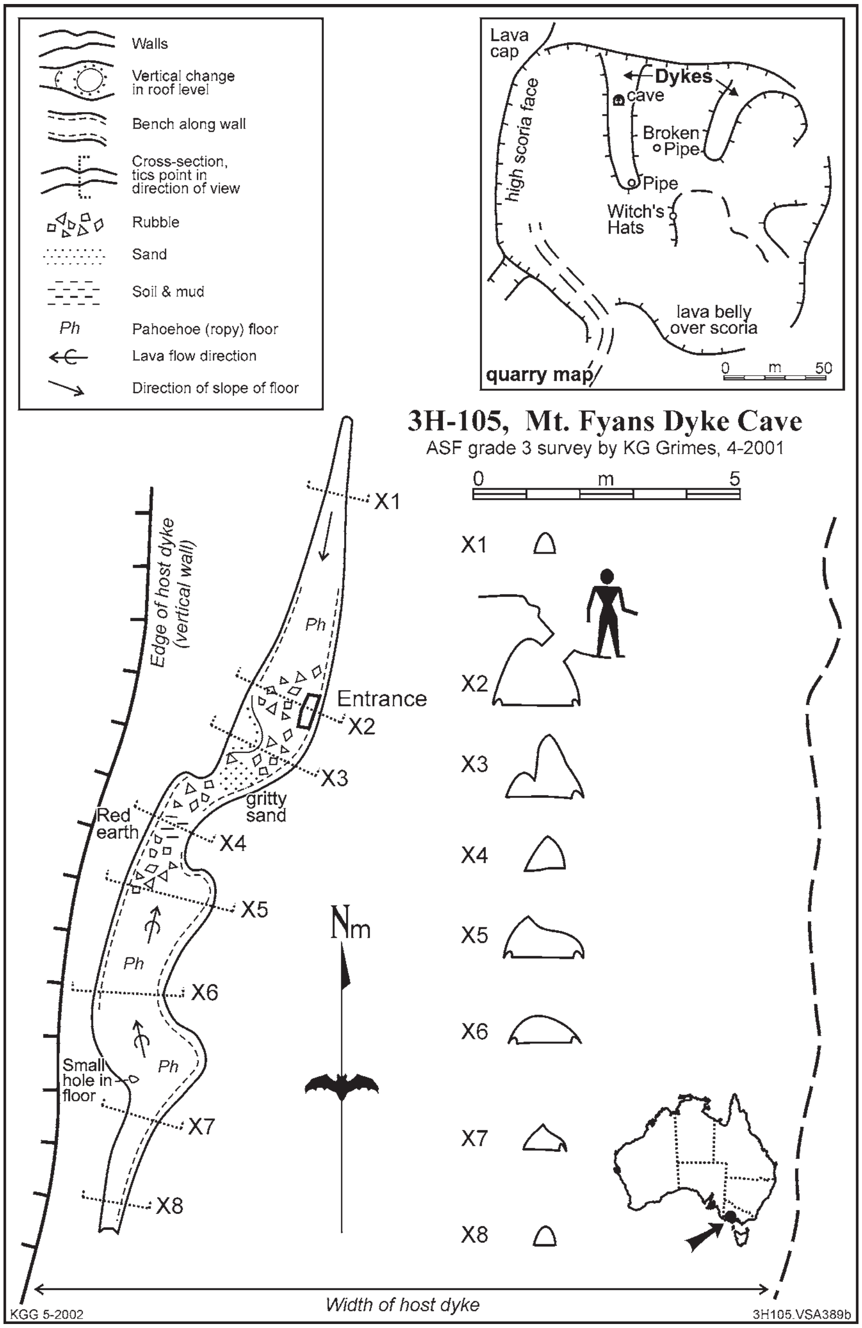

Figure 2 (left). Map of Mt Fyans Cave, 3H-105. The inset map shows the volcanic structures within the quarry.

Figure 3 (below left). View looking north from the cave entrance.

Figure 4 (below right). Looking south from section X5. Note the small rolled bench against the foot of the wall and the pale patches on the wall.

Figure 5. A conical “witch’s Hat” formed by a finger of lava that intruded the loose scoria, then drained back to leave a hollow core. Stereopair.

Genesis

The dykes and other bodies would have been intruded into the loose scoria towards the end of the eruption, would have cooled and partly solidified, and then as pressure was lost those liquid parts that were still connected to the main feeder channels would have drained a little way back to leave the cavities. There may have been some oscillation to form the rolled benches in the dyke cave.

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This paper as published in *Helictite* in 2006 is included in the supplementary material on the CD. That version includes one additional photograph.

What Is a Lava Tube?

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Abstract

Variances and imprecision in defining the term LAVA TUBE have led to its application to a wide range of features, some of them far removed from the ordinary meaning of the word TUBE: "a hollow body, usually cylindrical, and long in proportion to its diameter..." The current American Geological Institute definition helpfully limits the term to roofed conduits and requires that they be formed in one of four accepted mechanisms. However it provides little guidance on whether a variety of injection structures traditionally termed LAVA TUBES actually are undrained or refilled examples or are entirely dfferent phenomena.

Ideally, lava tubes and lava tube caves should be defined as discrete structures with definable parameters which differentiate them from all other volcanic features, e.g., aa cores, lava tongues, tumuli, sills and related injection masses. The defining characteristics should be compatible with:

1) the common meanings of TUBE and CAVE;
2) the presence of solid, liquid, and/or gaseous matter within them;
3) observations of all phases of their complex speleogenesis, e.g., crustal and subcrustal accretion and erosion;
4) their tendency to form braided and distributory complexes, and multlevel structures of at least two types;
5) their propensity to combine with or produce other volcanic structures, e.g., lava trenches, rift crevices, tumuli, drained flow lobes, lava rises, dikes, etc.

The ideal may not be achievable at the present state of knowledge and technology. However, new concepts of flow field emplacement and drainage offer a notable opportunity to shape a clearer definition of this elusive term. I propose that the Commission on Volcanic Caves of the IUS develop such a definition, in collaboration with the AGI and other concerned agencies and organizations, for consideration at the 2005 International Congress of Speleology.

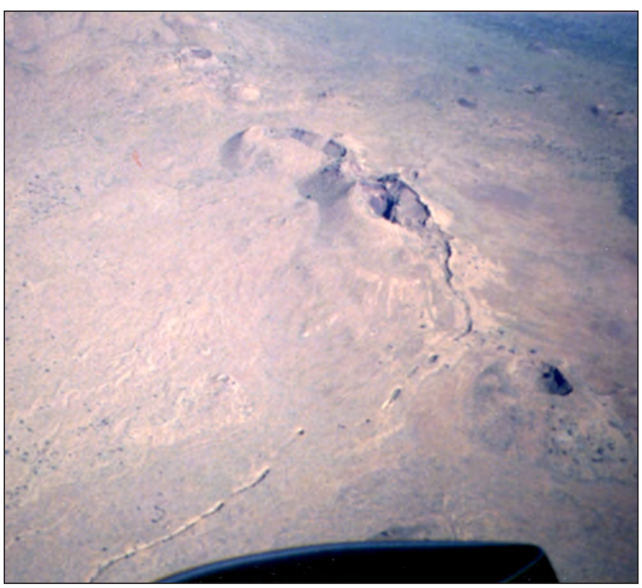


Figure 1. Aerial view of Poikahe Crater and partially collapsed braided lava tube system, Hualalai Volcano, Hawaii Island. Similar patterns have been photographed in several extraterrestrial sites. Photo by the author.

Introduction

Some geologists recently have used the presence or absence of lava tubes or tube-fed lava for important inferences and conclusions. Thus it has become important to have a common understanding of the term. But the term "lava tube" currently is applied to a variety of features which are inconsistent with standard geological and speleological definitions of the term (Jackson, editor, 1997; Larson, 1993), and different observers specify widely different parameters as characteristic of lava tubes.

These inconsistencies are the result of several factors. Uninformed persons commonly confuse tree casts with lava tubes, and vice versa. Indeed, small scale examples lacking bark molds and arborescent branching may be difficult to differentiate; glaze, lava stalactites and accreted linings are sometimes found in tree molds and associated gas cavities (Honda, 2002).

At least in Hawaii, the problem is even more complex. Here and elsewhere, many persons have come to believe that any cave or rockshelter in lava necessarily is a lava tube cave, often simply mistermed a lava tube. Especially misidentified as lava tubes are well-known littoral caves, e.g., Waianapanapa Caves, Maui Island and Kaneana (Makua Cave), Oahu Island (Figure 2). Boatmen on the Na Pali Coast of the island of Kauai commonly refer to spectacular Queen's Bath (Figure 3) as a "vertical lava tube". Actually it is a large littoral cave which has lost most of its roof. Nonlittoral erosional features like Kauai's Fern Grotto are not exempt from this misconception. Such misunderstandings commonly appear in the popular

Figure 2 (top). Entrance of Kaneana (Makua Cave), a littoral cave formed along a dike complex on the northwest tip of the island of Oahu, Hawaii. In the popular literature, it commonly is termed a lava tube. Photo by the author.

Figure 3 (middle). Interior of Queen's Bath, Na Pali Coast of Kauai Island, Hawaii, a large littoral cave which has lost most of its roof. Boatmen commonly refer to it as a vertical lava tube. Photo by the author.

Figure 4 (bottom). Solid invasive structure on the northwest face of Makapuu Point, Oahu, Hawaii. This structure has been termed a solid lava tube. Photo by the author.

press and in a few compilations which unwisely have relied on the supposed accuracy of press accounts.

In the geological literature, various solid features in volcanic terranes have been identified as lava tubes. Palmer (1929) and Wentworth (1925) described caste of lava tubes exposed by erosion on the islands of Oahu and Lanai. Palmer analyzed and depicted features characteristic of these "fossil lava tubes": near-concentric bands of vesicles and "a very slight tendency toward radial jointing" which is not impressive on the accompanying photographs. The example he reported may be considered the prototype of cores of solid lava tubes.

In contrast, Waters (1960) proposed that the elliptical "war bonnet" structures of Columbia River flood basalts are undrained lava tubes 15 to 35 m in diameter. This was not widely accepted. Greeley (1998) pointed that these features lacked linings typical of lava tubes, nor had they the concentric vesicle patterns which he considered "characteristic of lava tubes". Harper (1915) previously had cited and depicted a rosette pattern of smaller radiating features in at least one of several finger-like littoral ridges of dense Permian basalt in Australia, but did not refer to lava tubes as did two recent reports on this locality (Campbell et al, 2001; Carr and Jones, 2001). Others have applied the term to the entire width of cores of flow lobes and lava rises, to intermittent volcanic ridges, to at least one laccolith and a partially hollow dike, and to a variety of inferred structures.

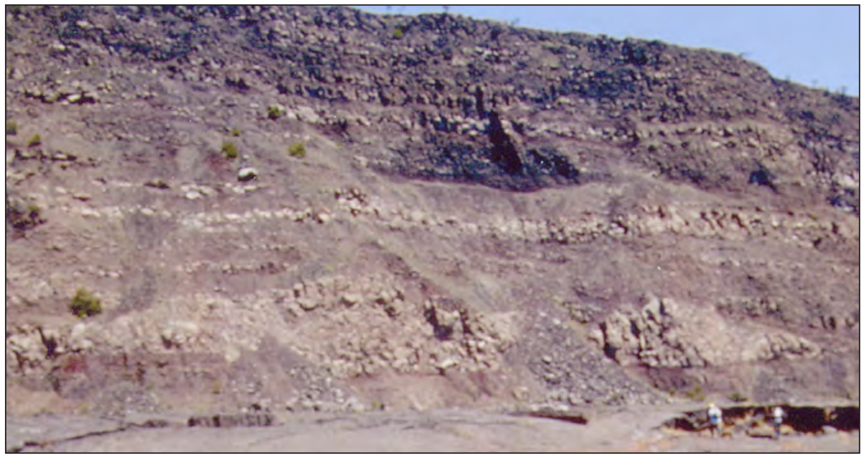
Solid and inferred structures cited as lava tubes

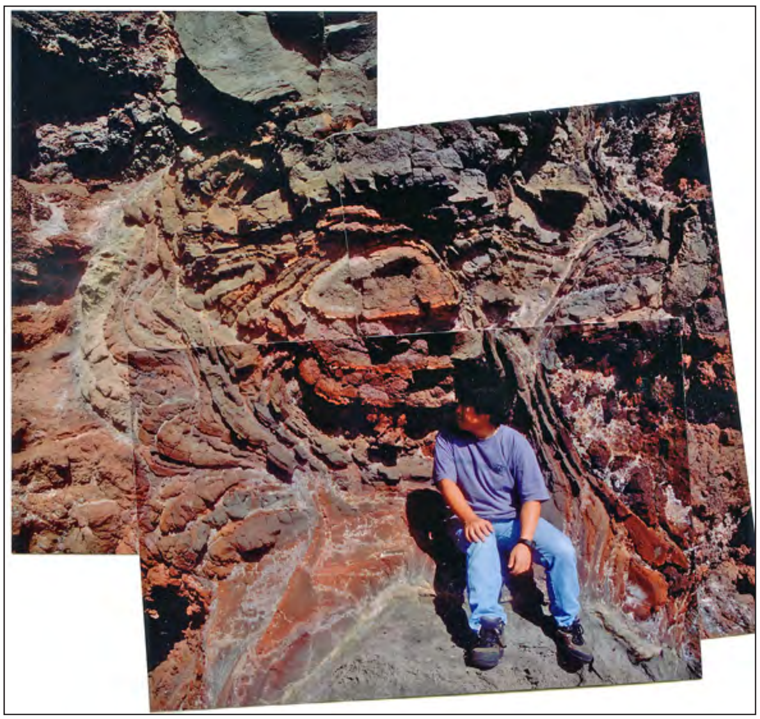
"Radiating columnar jointing" in digitate littoral ridges of Permian basalt were said to be "indicative of filled lava tubes" (Campbell et al, 2001). Imprecise wording has hindered understanding of features at these and other sites. Carr and Jones (2001) asserted that "the larger, more laterally continuous lava masses (at this Australian site) are interpreted as lava tubes while the smaller, less laterally continuous masses are interpreted as lava lobes". The lava fingers at this site "may contain radially arranged columnar joints and less pronounced concentric joints" 5 to 20 m in diameter. An example which they depict appears somewhat similar to an undescribed light-colored

Figure 5 (right). Laccolith exposed in the west wall of Kilauea Caldera. At one time, this was termed a lava tube. Photo by the author.

Figure 6 (below). Detail of central part of structure shown in Figure 7. Note complex of filled tubes and laterally displaced lava filling irregular width of buried crevice. Photos by the author.

Figure 7 (below right). Complex structure on the east fact of Makapuu Point, Oahu, Hawaii. This structure has been termed a solid lava tube. Photo by the author.





feature exposed in the northwest side of Makapuu Point, Hawaii which rests on a narrow outcrop of pyroclastic material (Figure 4) and has "baked" adjacent lava. In local geological circles it is said to be a filled lava tube (C. Okubo, written communication, 1999). A light-colored laccolith exposed prominently in the west wall of Kilauea Caldera, Hawaii (Figure 5) also was proposed as a solid lava tube until its actual structure was determined conclusively (Anonymous, cited by Don Swanson, oral communication 1999).

An especially complex feature termed a filled lava tube by Coombs et al (1990) and by Kesthelyi and Self (1998) is located on the northeast side of Oahu's Makapuu Point It is much lower in the stratigraphic column than the feature discussed above and is not aligned with it The two features have little in common. Contrary to the cited reports, the jaggedness of its lateral margins (Figure 6) indicates that it was a tectonic crevice along which lava flowed turbulently and by discrete injections, much as in the case of the Great Crack of Kilauea Volcano (Halliday, this volume). Present are two cores of dense lava (Figure 7) similar to those reported by Palmer (1926) and several solid tubes of less dense lava (Figure 6) which meet criteria published by the American Geological Institute (Jackson, editor, 1998). A few somewhat similar groups of more or less filled tubes (Figure 9) are exposed in roadcuts on Hawaii Island.

Extraterrestrial and sea floor features identified as lava tubes

Several extraterrestrial and sea floor features have been identified as lava tubes. Fornari (1986) considered that segmentation of a sea floor ridge proved that it is a lava tube. Some lunar rills have been termed collapsed lava tubes, but are many orders of magnitude larger than any terrestrial feature which fits the cited standard definitions of this term. On Kalaupapa Peninsula, Molokai Island,

Figure 8. Detail of top of structure shown in Figure 7. Dense solid cylinder with offset concentric vesicle rings is like that reported by Stearns. Above it is horizontally layered lava filling top of buried crevice. Photo by the author.

Figure 9. Cross sections of small lava tubes in aa exposed in road cut along highway between Kailua and Captain Cook, Hawaii County, Hawaii, USA. Maximum height of open tubes is about 10 cm. Photo by the author.

Figure 10. Lava trench on Kalaupapa Peninsula, Molokai Island, Hawaii said to be a collapsed lava tube extending to small volcanic shield beneath lighthouse in background. Photo by the author.

Hawaii (Figure 10), Kauhako Channel is of similar size and also has been termed a collapsed lava tube (e.g., Coombs et al, 1990). Close field examination of this structure, however, revealed that it is a lava channel complex containing eruptive foci (Halliday, 2001) as reflected on a recent geological map of the peninsula (Okubo, 2001). Coombs et al (1990) considered "three land bridges" (channel-wide accumulations of talus) to be proof of collapse of a lava tube, but such "land bridges" also are present in grabens along the Great Crack of the Southwest Rift Zone of Kilauea Volcano (Okubo and Martel, 1998). Four aligned vents are present downslope from the channel (Okubo, 2001). Coombs et al (1990) asserted that the collapsed tube was the feeder for these vents but no evidence is known that these are tube-fed rather than crevice-fed.

Evidence of a huge, deep-lying tube also was said to be evident in Ka Lua o Kahoalii, a pit crater complex opening downward on a level bench within Kauhako Crater (Figure 11). Coombs et al (1990) interpreted it as a collapse skylight of the tube. The vertical shaft of this pit complex opens downward from the surface of a partially destroyed lava pond within Kauhako Crater and is 8 m from the rim of its funnel-shaped inner pit All of its cavernous extension is beneath the talus-covered slope of the inner pit (Figure 11), and slants downward toward it (Halliday, 2001). The total volume of some thinly glazed cavities in the complex (Figure 11, 12) is >> 1% of the volume of Kauhako Channel. Ka Lua o Kahoalii appears to be part of the vertical conduit system of Kauhako Crater and its pond rather than the beginning of some enormous collapsed lava tube.

Extraterrestrial and ocean floor phenomena which are fully congruent with surface expressions of subaerial lava tube caves (e.g., Figure 13) may be considered to indicate the presence of lava tubes with a high degree of certainty (Halliday, 1966). Others are much less conclusive.

Flow lobes and lava rises as lava tubes

Whitehead and Stephenson (1998) conjectured the existence of even larger undiscovered lava tubes in northeastern Australia. Others have written of cores of lava rises, flow lobes and other seemingly amorphous inflation conduits of lava as being lava tubes. Whitehead and Stephenson emphasized "how much larger these wide, flat lava tubes were... in relation to most known lava tubes... the widths of the Toomba inflation conduits were as great as 500 m. . . ." They explained this seeming dichotomy as the product of a new concept which developed in the decade prior to 1998: "any feeder beneath a lava surface" now may be considered a lava tube. Others (e.g., Fornari, 1986) appear to believe that any subcrustal conduit of lava is a lava tube. While nowhere specifically stated, this presumably extends the concept to include crevices, dikes and sills as well as the cores of lava rises and similar structures. No article specifically proposing this concept has been located, however. It may be that it has moved from theory to partial acceptance without adequate scientific testing.

Conduit tubes and drain tubes

Redefinitions of the term lava tube should consider still other tubular structures in lava. Numerous investigators (e.g., Fornari, 1986; Calvari and Pinkerton, 1998) have written as if lava tubes by definition were conduits of flowing lava. On the other hand, some tubular structures in pahoehoe flow fields have features consistent with subcrustal drainage caves (Grimes, 1999, 2002; Grimes and Watson, 1995; Halliday, 1998 a and b). Lack of downcutting, rheogenic abrasion and accretion all show that such caves have carried little or no flowing lava (other than the small volumes drained from the structures themselves). Most of the shallow, thin-roofed "surface tubes" which formed in profusion on some pahoehoe flows (e.g., the Huehue telephone repeater section of the Kaupulehu flows of Hualalai Volcano, Hawaii), also are drain structures rather than conduits.

In the 1919 flow of Kilauea Caldera, Hawaii, numerous elongate flat-floored depressions are present where still-plastic cave roofs slumped when their feeder halted abruptly. A variety of more or less tubular voids are associated with these closed depressions. Some are shallow, relatively featureless corridors locally split by as many as three subparallel slumps. Others are boundary ridge passages on one or both sides of a wide linear or sinuous depresssion. Nearby, caves

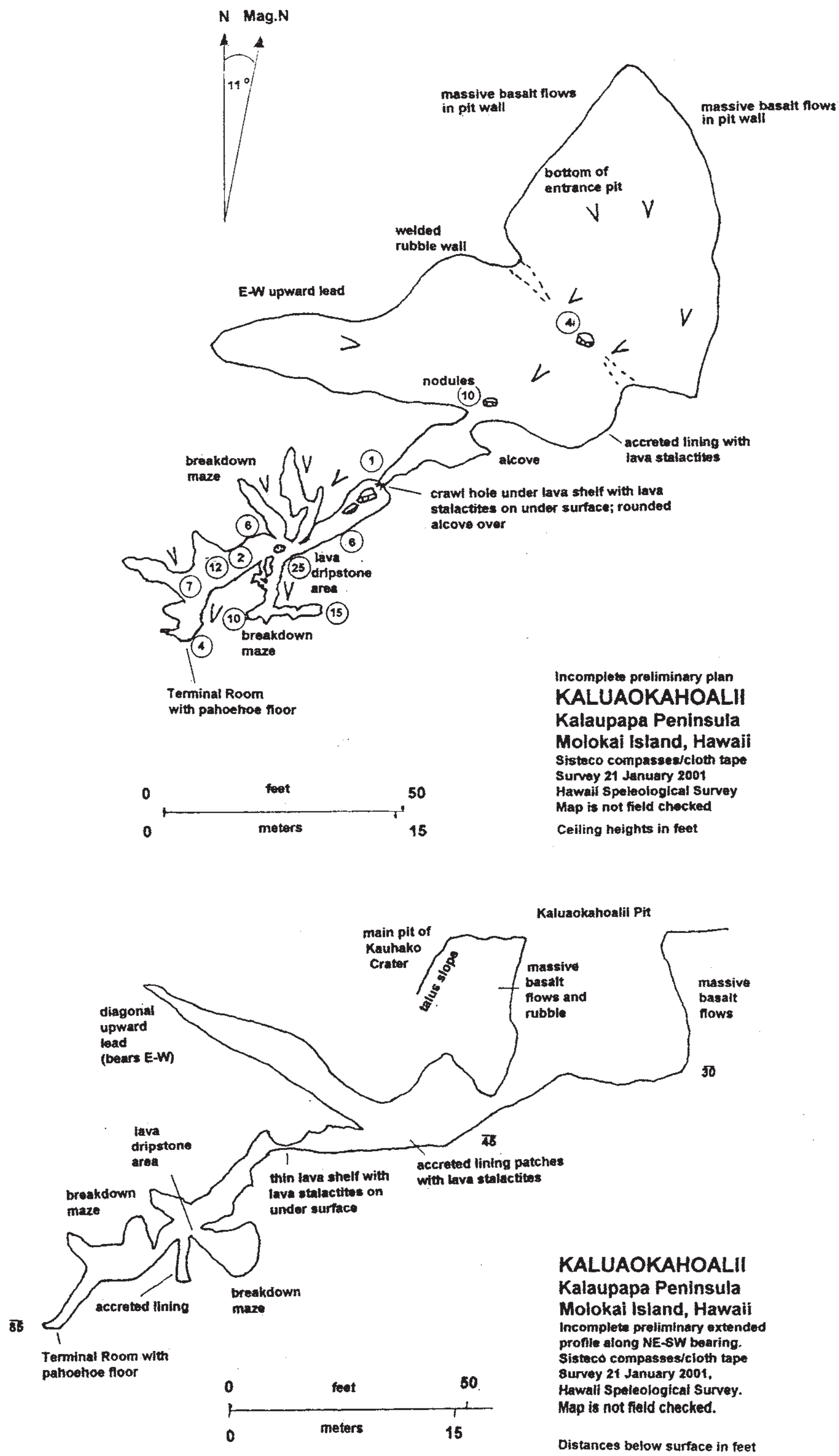


Figure 11. Plan and extended profile of Ka Lua o Kahoalii, Kalaupapa Peninsula, Molokai Island, Hawaii, commonly said to be the start of a lava tube extending from Kauhako Crater to the lighthouse at the tip of the peninsula.

Figure 12. Small lava upwelling at start of breakdown area, Ka Lua o Kahoalii, Kalaupapa Peninsula, Molokai, Island, Hawaii. Photo by the author.

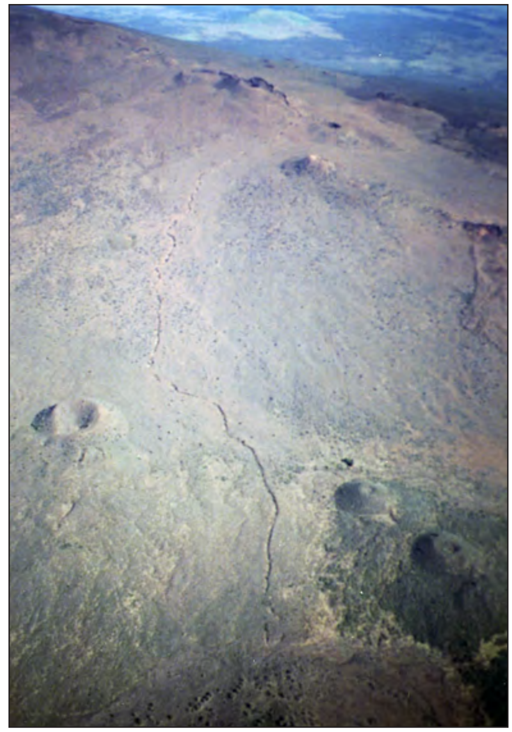


Figure 13. Full length of Poikahe Crater lava tube system, Hualalai Volcano, Hawaii. Poikahe Crater is just below top center. Extraterrestrial and submarine phenomena which are fully congruent with such surface features indicate the presence of lava tubes with a high degree of certainty. Photo by the author.

in sinuous hollow tumuli are essentially featureless but otherwise are much like those of conduit tubes. Cross-sections of donut-shaped boundary ridge caves of lava rises with depressed centers (Figure 14) are similar to those of conduit tubes, and complexes exist combining two or three of these forms. In areas with patent drained flow lobes, some individual cavities are interconnected by essentially featureless drain tubes. Individually, these short tubular segments can easily be accepted as lava tubes, but as a whole, the resulting cave complexes resemble giant ant nests rather than lava tube conduit caves (Figure 16).

At least one basaltic dike (Figure 17) drained and assumed the form of a lava tube cave (Figure 18) where it approached the face of a sea cliff (Socorro and Martin, 1981).

Redefinition of the term "lava tube"

From the above, it is easy to conclude that the term "lava tube" should be redefined in unmistakably specific terms. Ideally, both hollow and solid forms should be included, in terms of specific parameters which differentiate them

Figure 14. Tube-like circumferential boundary ridge passage, Lava Rise C-3 Cave, Kilauea Caldera, Hawaii. Photo by the author.

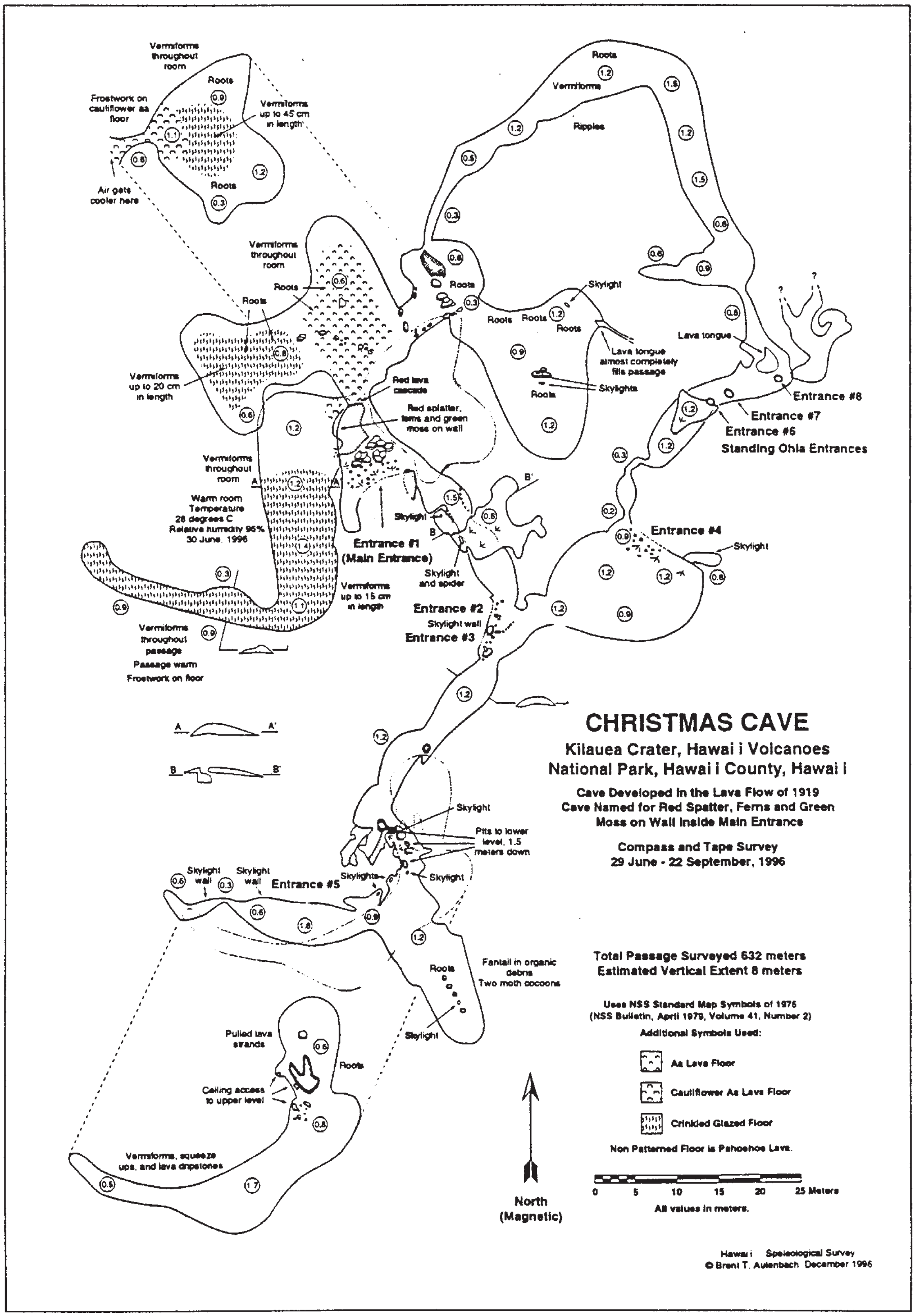


Figure 16. Plan of Christmas Cave, Kilauea Caldera, Hawaii: a nested complex of flow lobe cavities and short tubular connecting passages.

from all other volcanic features (e.g., aa cores, lava tongues, tumuli, sills, self-propagating crevices and related injection masses. But the ideal may not be achievable at the present state of knowledge and technology. However, recent discoveries and new concepts of flow field emplacement and drainage (e.g., Hon et al, 1994) offer a notable opportunity to shape a clearer definition of this elusive term.

In my opinion, the defining characteristics should be compatible with:

1) the common meanings of "tube" and "cave".
2) the presence of solid, gaseous, or liquid matter within them.
3) observations of all phases of their complex speleogenesis, e.g., crustal and subcrustal accretion and erosion.
4) their tendency to form braided and distributory complexes, and multilevel structures of at least two types.
5) their propensity to form within, combine with or produce other volcanic structures, e.g., lava trenches, rift crevices, tumuli, drained flow lobes, lava rises, dikes, etc.

I propose that the Commission on Volcanic Caves of the IUS take the lead in developing such a redefinition, in collaboration with the American Geological Institute and other concerned agencies and organizations, for consideration at the 2005 International Congress of Speleology.

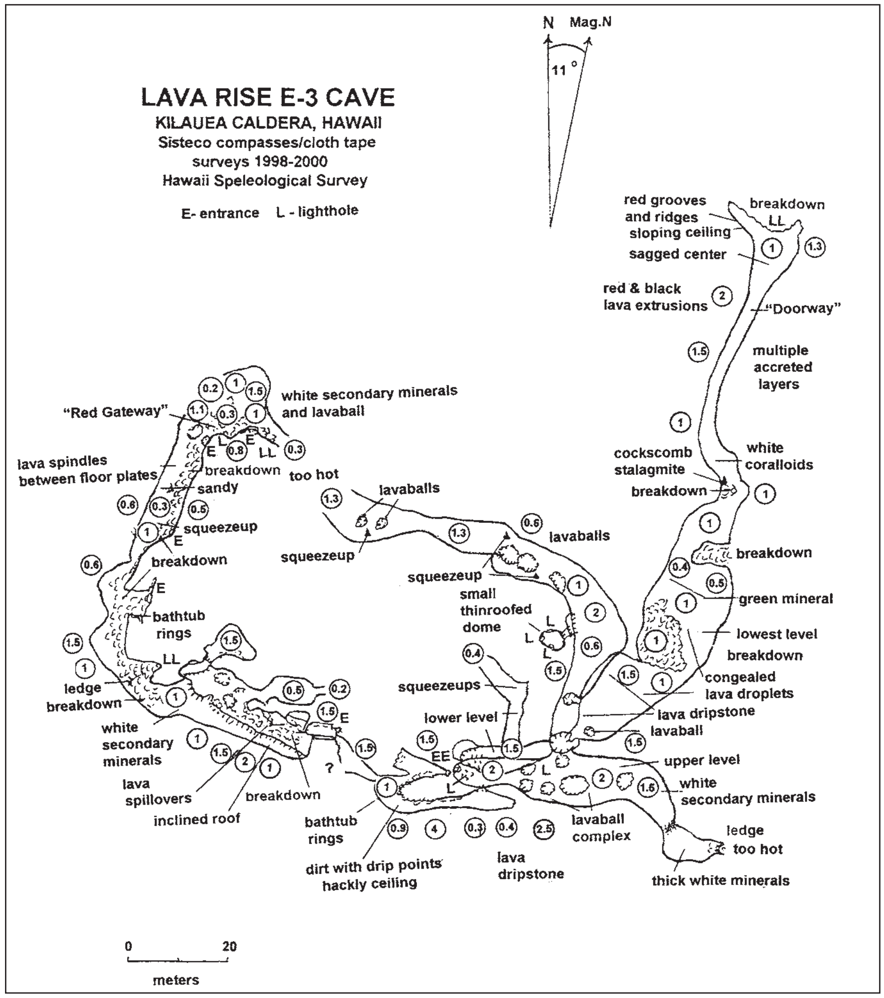


Figure 15. Plan of Lava Rise C-3 Cave, Kilauea Caldera, Hawaii. A typical cross section of the tubular circumferential passsge is depicted in Figure 14.

Figure 17. Dike exposed in ceiling of inner chamber formed in pyroclastics, Cueva de la Fajanita, La Palma Island, Canary Islands. This dike is hollow from a point a few meters behind the photographer to the sea cliff. Photo by the author.

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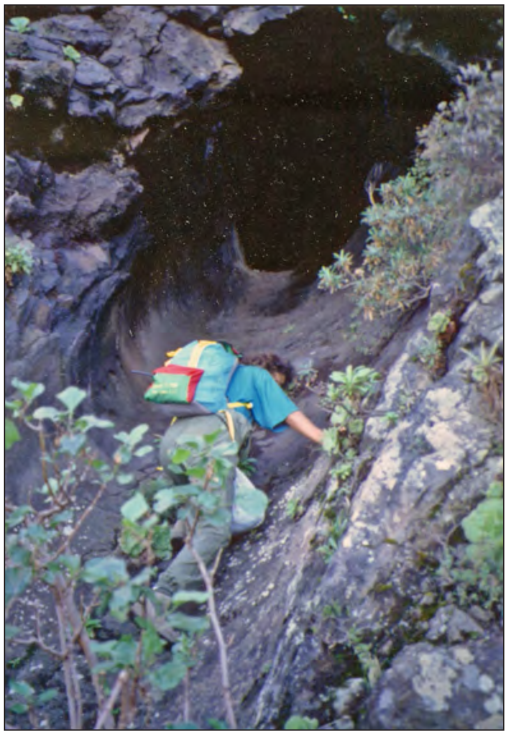

Figure 18. Ascending into the sea cliff entrance of the tubular hollow section of the dike of Cueva de la Fajanita, La Palma Island, Canary Islands. Photo by the author.

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Caves of the Great Crack, Kilauea Volcano, Hawaii

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Abstract

The Great Crack ("17 Mile Crack") is the most prominent feature of Kilauea volcano's Southwest Rift Zone. Rather than consisting of a single crevice, much of the "crack" consists of en echelon crevices of various widths in a strip locally more than 1 km wide. Numerous grabens and collapse pits are present.

Detailed studies of this complex have been begun only in the past decade. Some of the participating geologists have requested support and some leadership by speleologists in investigating cavernous pits at the bottom of steep talus slopes. The Hawaii Speleological Survey of the National Speleological Society subsequently has cooperated with University of Hawaii and U.S. Geological Survey researchers in investigating cavernous pits in the principal axis of the crevice complex. Two pits yielded minimal spelean findings, but the third—labelled Pit H by University of Hawaii geologists—was found to require SRT expertise. In 2001 it was explored and mapped to a depth of 183 m. Despite extensive breakdown, accretion by laterally flowing lava was identified on several levels. A total of 600 m of passage was mapped.

In a similar crevice at the bottom of Wood Valley Pit Crater (which is nearby but off the principal axis of the rift zone), accreted linings and tube segments have been found along the crevice at a depth of almost 90 m. No such tube segments are present in Pit H Cave. These findings indicate that tube formation is not essential to lateral flow of lava in rift crevices, but occurs in some locations. Numerous other pits remain to be investigated along the Great Crack and elsewhere.

Introduction

The Great Crack ("17 Mile Crack") is the most conspicuous feature of the Southwest Rift Zone of Hawaii's Kilauea Volcano (Figure 1,2). The section of this feature discussed in this report is about 2 km long and is located about 2 km north (up-rift) of the historic 1823 Keaiwa lava flow which emerged from its lower end. Okubo and Martel (1998) identified and described 14 collapse pits here, located along two dominant crevices (or paired crevices). The present study reports initial investigations of crevice caves associated with some of these collapse pits, as conducted by members of the Hawaii Speleological

Figure 3. Main (lower) entrance. Cathedral Cave, Pit B of the Great Crack. Photo by the Author.

Figure 4. Looking upward along talus slope to upper entrance of Cathedral Cave located at edge of Pit A. Photo by the Author.

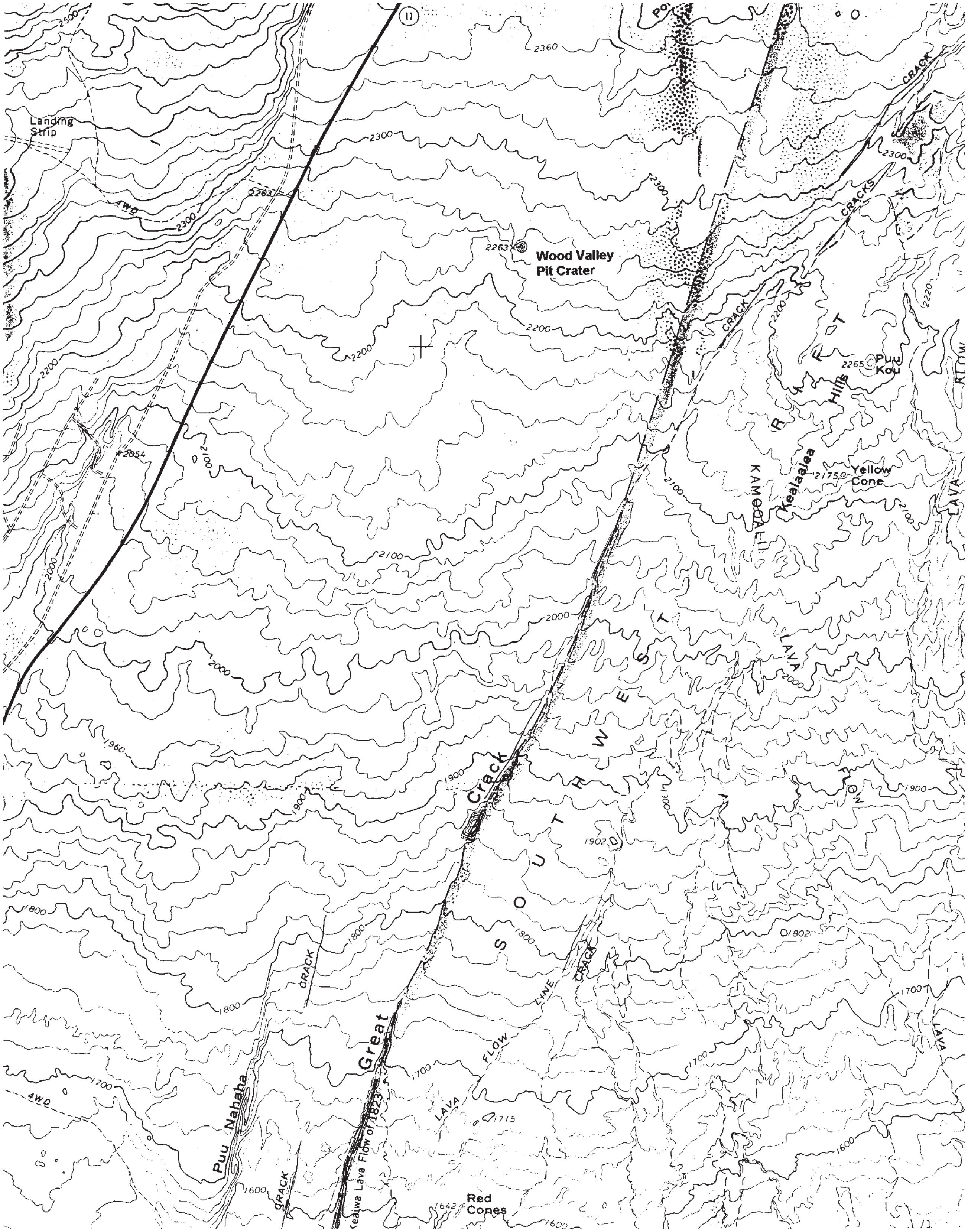


Figure 1. Section of 1981 US Geological Survey 1:24,000 Wood Valley Quadrangle showing the Great Crack and Wood Valley Pit Crater.

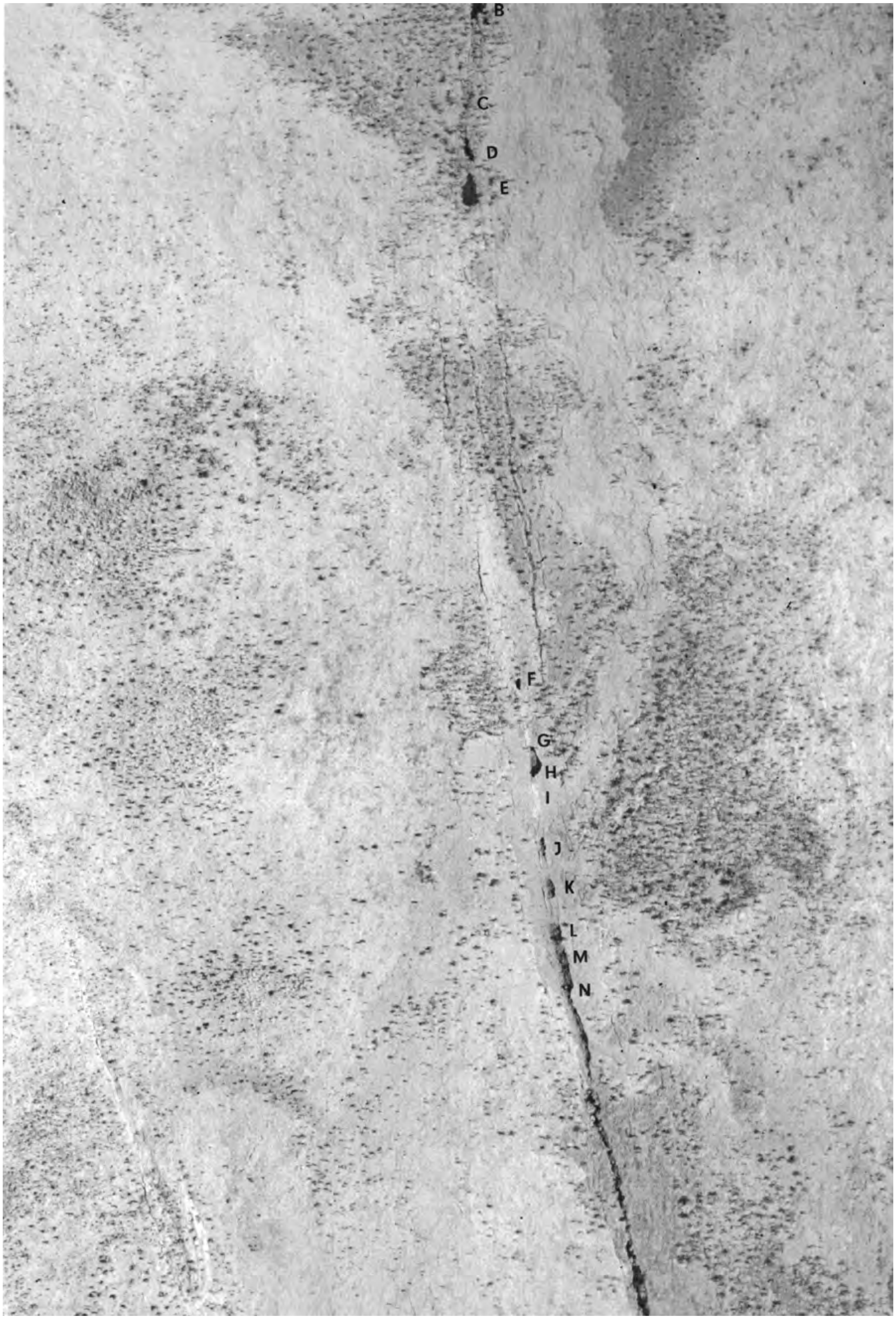
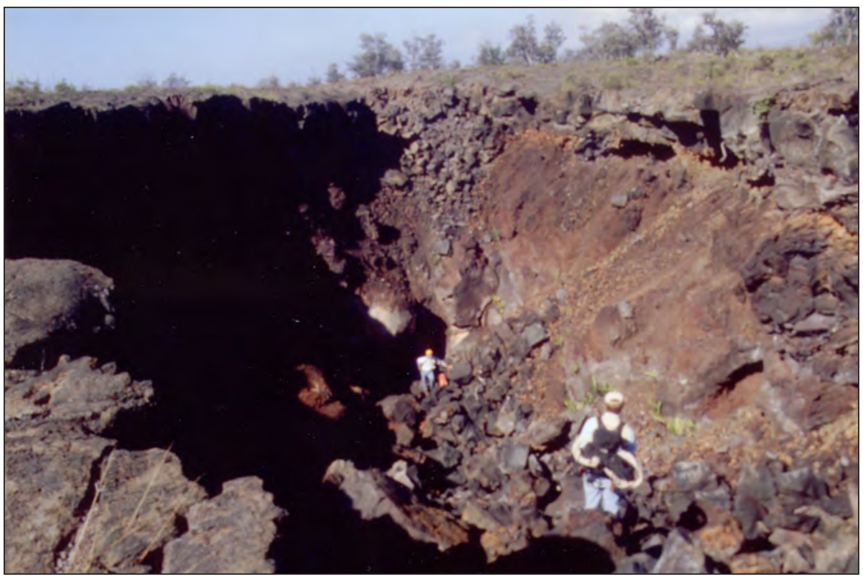


Figure 2. October 1988 NASA aerial photo of study area showing collapse pits B to N. Courtesy Chris Okubo.



Survey of the National Speleological Society in cooperation with Okubo and Martel and with Don Swanson of the U.S. Geological Survey. It compares findings during these explorations with those by Favre et al (Favre, 1993) during exploration of the nearby Wood Valley Pit Crater Complex.

Overview of the study area

The term "Great Crack" implies that the principal rift structure here consists of a single dominant crevice, but this is not the case. Instead, the feature consists of a complex of en echelon crevices of various widths. These are encompassed in a strip locally more than 1 km wide. The area is geologically active, and at least one important collapse pit has developed in the last few years (Okubo and Martel, 1998). As Okubo and Martel have shown, the pits are from 8 to 45 m in diameter and 6 to 28.5 m in depth. They occur in two groups along shallow linear depressions which are not quite aligned with each other. Pairs of deep, near-vertical cracks with apertures of several cm are characteristic of the collapse pits,

Pits A through E (Figure 2) are located along a narrow graben 5 to 7 m wide and 2 to 15 m deep. Locally it is nearly filled with talus and volcanic ash. Individual pits are separated by septae of talus extending almost to ground level. Pits F through N are in a slightly wider depression which is generally shallower but locally contains steep-walled troughs 5 to 7 m wide and 2 to 3 m deep. No tephra is present south of Pit F. Lava exposed in their walls largely consists of pahoehoe and a basaltic lava flows 0.5 to several m thick. Rubble and blocks of talus of similar dimensions mantle pit and cave floors and lower walls. Overhanging pit walls are common; some overhangs initially were mistaken

Figure 5 (top). Hollow dike, Cathedral Cave. Photo by the Author.

Figure 6 (middle). Entrance sink, Pit H Cave of the Great Crack. Photo by the Author.

Figure 7 (bottom). Entrance of Pit H Cave, located beneath dense lava core. Photo by the Author.

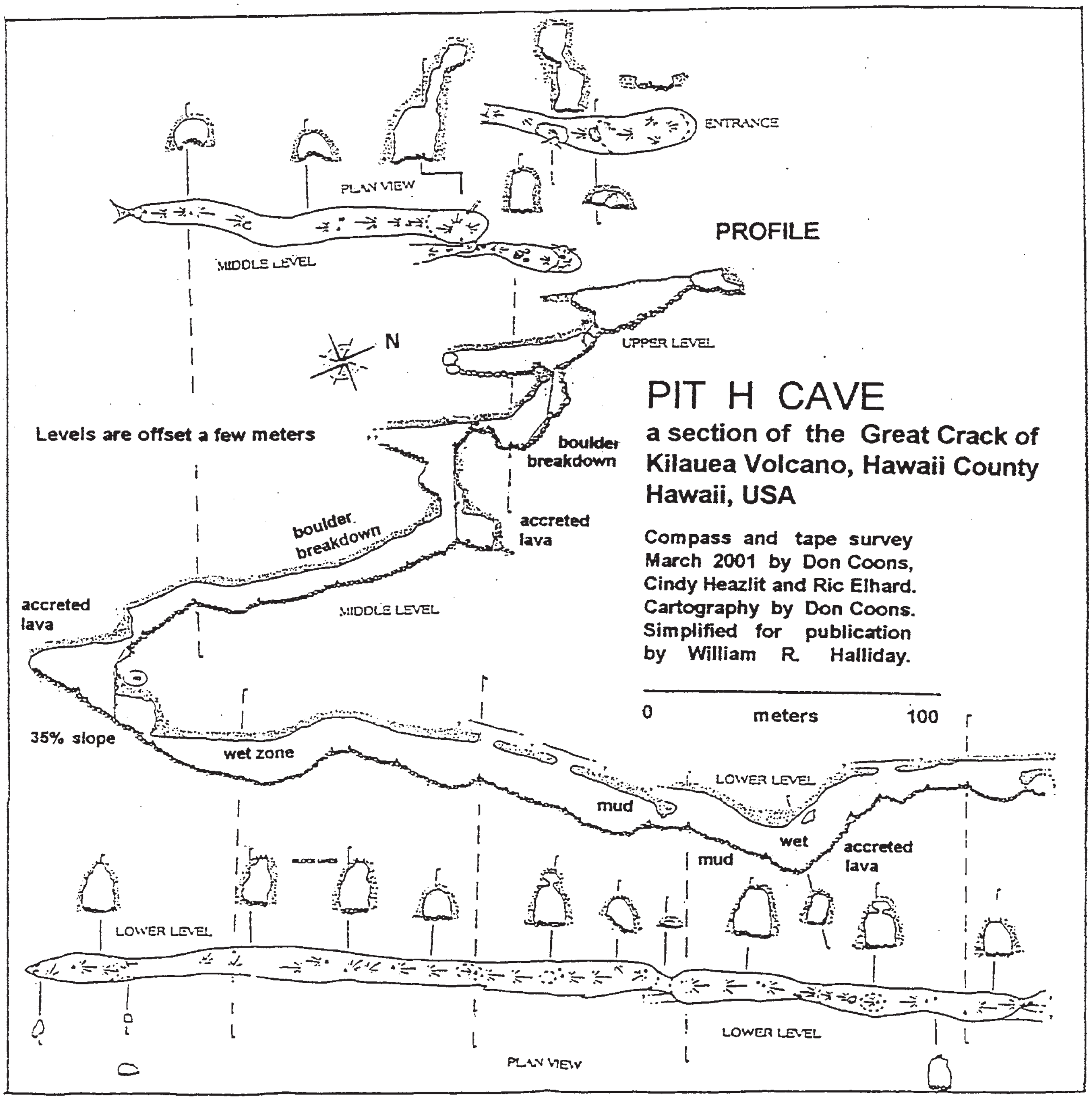


Figure 8, Map of Pit H Cave, redrawn by the author from map courtesy Don Coons.

for cave entrances. Some unusual lava injection features also are seen locally (Figures 5, 10) these are discussed below. Farther downrift are additional collapse pits, then a continuous steep-walled depression from which emerged the historic 1823 flow.

Initial investigations

Based primarily on views from the ground surface, Okubo and Martel (1998) listed all pits from Pit A to Pit I as having known caves. In July 1998 and August 1999, this writer and Chris Okubo investigated cave entrances in the northern group (Pits A - Pit E) which were accessible without special climbing gear. At the north (up-rift) end of Pit B we clambered down into a spacious crevice cavern. Locally almost 10 m wide, its lower portion was both impressive and scientifically significant; its walls contain unusual lava structures which show flow of molten lava into the cavity from within the wall (Figurers 5, 10). The upper portion of this cave extends steeply upward through large talus fragments to a narrow upper entrance which is just within the down-rift margin of Pit A - a vertical extent of nearly 20 m. Because of the spaciousness of its main chamber, we called it Cathedral Cave.

Investigations of Pit H Cave

We planned to return and map Cathedral Cave. On 18 February 2000, however, Okubo and I investigated Pit H Cave in the lower group, Descending a steep entrance slope with large talus blocks at

Figure 9. Mapping the entrance slope of Pit H Cave. Photo by the Author.

Figure 10. Hollow dike in twilight zone of Pit H Cave. Photo by the author.

Figure 11. Composite photograph of upper level of Pit H Cave, looking across pit at end of twilight. Photos by the Author.

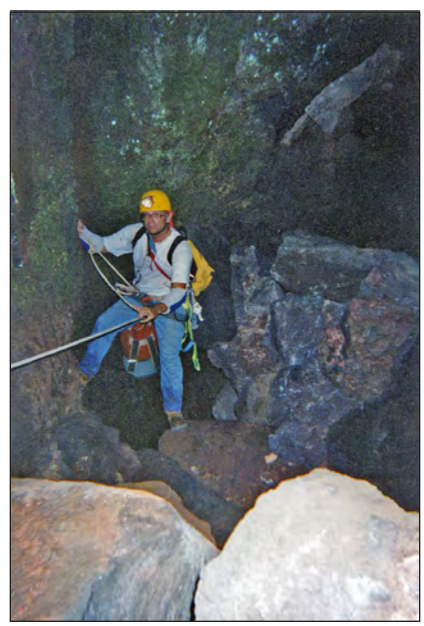


Figure 12. Don Coons at narrows of pit leading to lower levels. Photo by the Author.

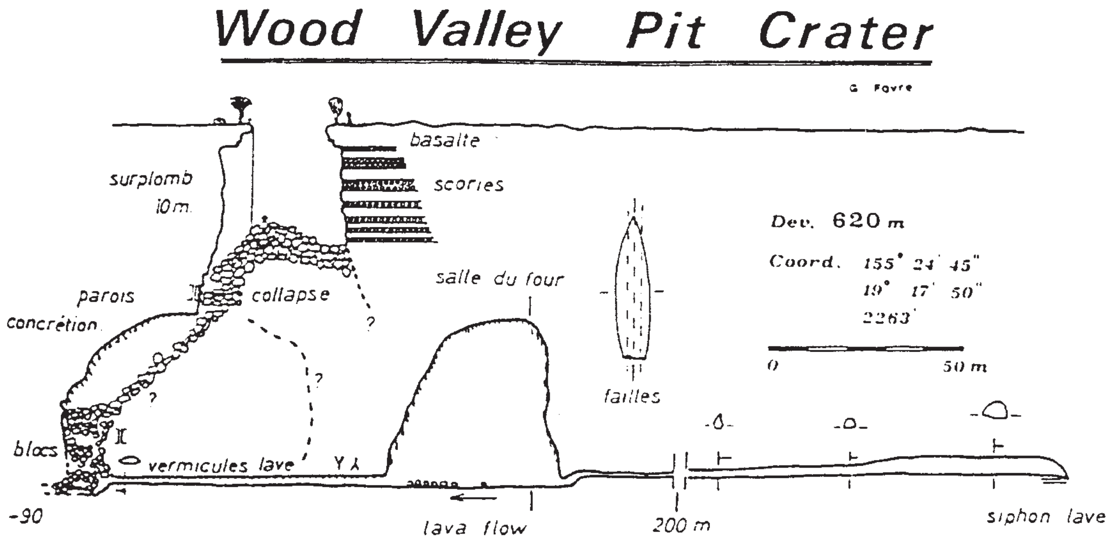


Figure 13. Plan and longitudinal section of Wood Valley Pit Crater Complex. Courtesy Gerald Favre.

the angle of repose, we mapped as far as a funnel-shaped pit in wedged talus, located at the inner margin of twilight This pit extended completely across a near-horizontal passage 5 to 6 m wide, floored by wedged talus. Its depth could not be determined but eventually was found to be 26 m. We photodocumented the accessible area (including a hollow dike exposed in section - Figure 10) but could do no more without specialized climbing gear.

On August 7, 2000 Don Coons accompanied Don Swanson and myself to Pit H Cave. Coons traversed the pit where Okubo and I had stopped, finding about 25 m of additional passage on this level. Then he descended the pit to the next level, 26 m below. After a minor initial ascent here, he encountered an additional pit for which he needed additional rope and a support team (Coons, 2001).

Coons was designated chairman of a formal project of the Hawaii Speleological Survey. On 23 February 2001 he returned to Pit H Cave, accompanied by Rick Elhard and Cindy Heazlitt. In one vigorous day, 30 survey stations yielded 600 m of passages which reached a depth of 183 m. The second vertical pitch was found to be 37 m, with a third pitch of 22 m farther downslope (Figure 8).

Remnants of accreted linings were found at several levels in Pit H Cave. Near the lowest point in the cave, the lining was found to be 25 cm thick and composed of two units: a porous brownish inner layer and a dense black outer layer. Closer to the surface, the accreted lava is increasingly thin and none was found above the second pitch. Nothing suggesting the presence of a lava tube was observed (Coons, 2001).

Comparison with previous observations

Okubo and Martel (1998, page 10) summarized Jaggar's 1947 observations of lava entering the principal Southwest Rift Zone conduit in the wall of Halemaumau. They concluded that Jaggar described "stoping into a previously widened subsurface fracture", rather than a rift tube. This is consistent with findings in Pit H Cave.

On the other hand, Favre (1993) reported dissimilar findings in a crevice passage in the nearby Wood Valley Pit Crater Complex. Wood Valley Pit Crater also is within Kilauea volcano's Southwest Rift Zone, but is off its principal axis (Figure 1). Here, "totally glazed" lava tube segments were found along the crevice, forming most of a cave more than 460 m long at a depth of almost 90 m. Average height of the tube segments is 8 m, average width, 12m. Two large linear chambers also are present. One is directly beneath the shaft of Wood Valley Pit Crater and is nearly filled with talus. The other is 80 m farther along the crevice and is 40 m high, 10m wide and 40 m long. It is intact and is lined with accreted lava ("congealed basalt"). Comparison of these findings with those in Pit H Cave indicates that lava tubes can form in active rift crevices but some lateral flow exists without tube formation.

To confirm and amplify these findings, much more exploration and investigation of volcanic crevice caves and pit craters is needed, along the Great Crack and elsewhere.

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XI International Symposium on Vulcanospeleology

PICO ISLAND

Azores – 2004

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PREFACE

We are honored to welcome everyone to the XIth International Symposium on Vulcanospeleology, held at "Escola Cardeal Costa Nunes", in the town of Madalena (Pico Island). The meeting is hosted by the "Secretaria Regional do Ambiente" (Environmental Department of the Regional Government of the Azores). This is the first time that this international meeting is being held in Azores Archipelago, where volcanoes and volcanic caves are very important features of the natural landscape.

Pico is the second largest island in the Azores. It is about 1000 miles (1600 km) from the Portuguese mainland. Its area is 447 km^2 and the population is 14,804. Its inhabitants are grouped in three municipalities (Lajes, Madalena and São Roque do Pico). The island presents a wide range of volcanic landforms, including approximately 90 known volcanic caves and pits. Most of its lava tube caves are located on the flanks of the impressive Pico Mountain stratovolcano (2,351 m a.s.l.), in the western part of the island, which is the 3rd highest active volcano in the Atlantic Ocean. Among these caves is "Gruta das Torres", the longest in the Azores with about 5,150 m of passages.

This Abstracts Book includes all presentations at the XIth International Symposium on Vulcanospeleology, Azores – 2004, including invited lectures and oral and poster presentations. All underwent advance review by the scientific committee of the symposium.

Pico, May 2004

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2004 SYMPOSIUM ABSTRACTS

Edited by João Carlos Nunes and William Halliday

Invited Lectures

Em Defesa do Património Geológico

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À semelhança de qualquer património construído que, por características de significado, grandiosidade ou outros, é considerado monumento e, portanto, um recurso cultural a preservar, também algumas ocorrências naturais e, em particular, as geológicas têm características que nos levam a classificá-las como **geomonumentos**, entendidos como valores a incluir numa concepção de cultura alargada ao saber científico tradicionalmente subvalorizado na nossa sociedade.

Como resposta ao chamado desenvolvimento e à imparável ocupação do espaço natural pelos múltiplos e variados equipamentos civilizacionais, importa divulgar e impor a ideia de **georrecurso cultural** aplicável a alguns exemplos do património geológico, por natureza não renovável.

A experiência de muitos anos de busca de soluções que salvaguardem e valorizem alguns dos nossos mais importantes geomonumentos tem sido, nas duas últimas décadas, uma tarefa árdua e uma preocupação do Museu Nacional de História Natural da Universidade de Lisboa. A grande resistência à sua classificação, no âmbito da legislação existente, decorre, sobretudo e em última análise, de uma generalizada falta de cultura geológica na sociedade portuguesa, a começar pelos responsáveis da administração.

Genetic Processes of Cave Minerals in Volcanic Environments: An Overview

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Volcanic caves are widespread in the world and are frequently visited by cavers. Therefore it is common to find published descriptions of their exploration, speleogenesis and morphology. But lava tube caves and other volcanic cavities traditionally have been considered of little interest from the standpoint of secondary minerals (Forti, 1994). Thus detailed studies of their speleothems are comparatively new.

Recently, it has become evident that volcanic cavities are very favourable environments for the actions of different processes of mineral development (see Tab. 1). Two of these (sublimation and deposition from aerosols) are largely restricted to volcanic caves. Most known volcanic caves have conditions favourable for development of at least a few small true speleothems (apart from lava stalactites and stalagmites), which normally do not meet the technical definition of the term "speleothem" (Hill and Forti, 1997).

Even from these recent studies of a small number of volcanic caves, 40% of the entire list of cave minerals of the world is known to occur in volcanic caves. Furthermore, 35 of them (about 10% of all known cave minerals) are found only in volcanic caves.

Among the published list of ten caves leading the world in terms of speleothems (Hill and Forti, 1997), two are volcanic: the Alum cave on Vulcano Island, Italy and Skipton Cave, Australia.

Even detailed mineralogical studies have been made just for a few volcanic cavities, the choice of selection criteria for such a list is far from simple. Clearly, the importance of a cave cannot be selected entirely by the number of different minerals which developed within it. Other factors to be considered include the size and beauty of their speleothems, peculiarity of genetic mechanisms, different types of speleogenesis, and the geographical location of the cave.

On the basis of these parameters, it was made a tentative list of the ten most important volcanic caves of the world from the standpoint of mineralogy (Tab. 2).

This overview on the present knowledge on cave minerals in volcanic caves is short and surely not exhaustive. However this presentation and discussion seems sufficient to point out the extreme importance of volcanic cave environments in the development of cave minerals.

Volcanic caves which have been the subject of mineralogical observation to date, are far less than 5% of those presently known around in the world. Thus, it is reasonable to expect that in the near future, broad systematic study of secondary chemical deposits in volcanic caves will significantly increase the number of known cave minerals.

Final remark: This research was performed within the MIUR 2002 Project "*Morphological and Mineralogical Study of Speleothems to Reconstruct Peculiar Karst Environments*", Resp. Prof. Paolo Forti.

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Table 1 (Forti). Temperature range, process, genetic mechanisms, and related chemical deposits in volanic caves (modified after Forti, 1999).

Process			Mechanism	T (°C)	Products
1	Fumarole	A- High temperature	Sublimation	> 100	Elementary sulfur, oxides, hydroxides
		B- Low temperature	Deposition from aerosols and vapors	100 ÷50	Sulphates, halides
2	Solution		Evaporation	100 ÷10	Sulphates, halides
3	Alteration		Oxidation, hydration-dehydration, ionic exchange	100 ÷0	Si-, Al-, Fe oxides-hydroxides, sulphates
4	Karst		Diffusion	40 ÷0	Carbonate
5	Biogenic activity		Digestion, dissolution-precipitation, double exchange	40 ÷0	Phosphates, Nitrates, Sulphates, Halides
6	Phase change		Freezing	< 0	Ice

Table 2 (Forti). The ten most important volcanic caves from the mineralogical point of view.

Cave	Location	Peculiarity	Reference
Algar do Carvão	Terceira Island (Portugal)	Best and largest display of opal speleothems	Hill & Forti 1997
Alum	Vulcano Island (Italy)	Largest number of secondary cave minerals in a volcanic cave	Forti *et al*. 1996
Cutrona	Mt.Etna (Italy)	First cave where several genetic mechanisms have been studied	Forti *et al*. 1994
Kitum	Mt. Elgon (Kenya)	Silicate minerals related to meteoric waters action	Forti *et al*. 1999, in press
Skipton	Mt.Widderin (Australia)	First description of some new cave phosphates	Webb 1997
Grillid	Surtsey (Iceland)	Single cave reference for 5 different new cave minerals	Jacobsson *et al*. 1992
Togawa-Sakaidani-do	Kyushu (Japan)	First description of coralloid made by diatoms	Kashima *el Al*. 1987
Hibashi	(Saudi Arabia)	Noticeable variety of rare organic compounds even related to guano-firing	Forti *et al*. 2003, in press
Dangcheomul	Jeju island (Korea)	Best display of different calcite speleothems within a volcanic cave	Woo *et al*. 2000
Abrigo de el Manzano	Rio Grande (Argentina)	Phosphates and sulphates related to bird guano	Benedetto *et al*. 1998

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An Unusual Lava Tube Cave with an Incipient Hornito

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The 1919 "Postal Rift" lava flow in Hawaii's Kilauea caldera contains a few typical mature lava tube caves and about 200 caves of other types. These include hollow tumuli, drained lava rise and flow lobe caves, immature lava tube caves and complexes. One is a complex cave in a long sequence of subcrustal injection features 2-3 km from the vent. Its main passage is overlain by a small, partially hollow hornito. A puckered cupola is present in the cave ceiling beneath the hornito. The main passage continues as a featureless immature lava tube sloping retrograde to the flowfield, and other unusual features are present. Alternative interpretations of this and other unusual injection structures of Kilauea Volcano will be discussed.

O Papel Estratégico do Centro de Interpretação Subterrâneo da Gruta "Algar do Pena", No Uso Sustentado do Património Espeleológico do Parque Natural das Serras de Aire e Candeeiros

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O Centro de Interpretação Subterrâneo da Gruta Algar do Pena (CISGAP) é uma infraestrutura do PNSAC, vocacionada para a valorização do património espeleológico cársico.

O CISGAP deve a sua existência à descoberta de uma importante cavidade, em 1985, pelo Sr. Joaquim Pena, na sequência do desmonte de uma bancada de calcário para produção de pedra para calçada.

A Gruta Algar do Pena - assim denominada em honra do seu descobridor - é uma cavidade muito interessante do ponto de vista paisagístico, integrando a maior sala subterrânea actualmente conhecida em Portugal. (125 000 m^3 de volume aproximado).

Inaugurado em 1997, o funcionamento do CISGAP assenta em 4 vertentes:

1. Apoio à Investigação Científica e ordenamento do território no domínio da Espeleologia.
2. Divulgação alargada, do meio espeleológico cársico e fenómenos associados, com especial relevo para o público escolar.
3. Apoio às estratégias desenvolvidas pelo Parque, no domínio do turismo e desporto de natureza.
4. e finalmente como estrutura de apoio à formação de espeleólogos.

No decurso dos quatro anos que antecederam a sua abertura ao público, foram desenvolvidos vários estudos prévios destinados a caracterizar a cavidade do ponto de vista biofísico, os quais posteriormente serviram de base ao estabelecimento do regime de visitas e das medidas minimizadoras de impactes provocados pela visitação.

São catorze, as principais medidas minimizadoras de impactes negativos exercidos sobre a Gruta:

1. Estabelecimento da capacidade de carga.
2. Escalonamento de visitas.
3. Posicionamento do Poço do Elevador.
4. Uso de meios de descontaminação.
5. Estanquecidade do acesso artificial à cavidade.
6. Uso de estruturas "transparentes" de apoio à visita, em materiais não oxidáveis e removíveis.
7. Uso de uma área mínima dedicada à circulação de visitantes no interior da gruta.
8. Ausência de fontes de luz branca, exceptuando as autotransportadas.
9. Uso de iluminação fixa de "vapor de sódio".
10. Aplicação de penumbra nas zonas de maior pressão.
11. Uso de um sistema de controle climático e monitorização, das alterações climáticas provocadas pelos visitantes.
12. Limitação do tempo de permanência dos visitantes na gruta.
13. Estabelecimento de períodos de repouso da gruta.
14. Proibições várias de carácter genérico.

Para os grupos mais numerosos, por forma a minimizar o efeito de espera de visita à gruta, dada a sua baixa capacidade de carga – 12 pessoas por sessão de visita – foram criadas, várias actividades pedagógicas e de lazer, desenvolvidas no edifício de apoio e nos espaços exteriores.

Assim, os visitantes poderão optar, por participar em jogos de orientação e simulação de uma exploração espeleológica completa, actividades que permitem a interpretação biofísica dos carsos típicos.

Na visita à gruta, o enquadramento de visitantes è efectuado por "guias", com formação espeleológica de base. O apoio à progressão e interpretação de base científica dos fenómenos observados, está assegurado pelo uso de sistemas automáticos de telecomentário. Os vários programas de visita visam sempre a integração da cavidade no contexto geológico e geográfico regional.

Mas o CISGAP possui outras atribuições no domínio da espeleologia, é a infra estrutura de apoio à equipa de espeleologia do PNSAC, o centro do cadastro espeleológico do PNSAC, funcionando ainda como centro de apoio à rede de medição dos recursos hídricos desta Área Protegida.

O CISGAP, é no seu género, uma estrutura impar e sem precedentes no nosso país, contribuindo também para a inovação futura, participando na edificação de outras estruturas interpretativas singulares nesta Área Protegida, o futuro CARSOESCÒPIO, Centro Ciência Viva do Alviela.

Underground Life in Macaronesia: Geological Age, Environment, and Biodiversity

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The Macaronesian islands (Azores, Madeira, Canary Islands and Cape Verde Islands) are of volcanic origin but are at different stages of eruption and erosion. Their ages and especially those of their surface rocks affect the existence of caves, especially lava tubes.

Availability of caves for hypogean-adapted life is linked to the stage of ecological succession, which in turns depends on the age of terrains and on the local climate. The existence of the Mesovoid Shallow Substratum (MSS) also permits development of adapted fauna in terrains and even islands lacking volcanic caves.

Since all troglobites on islands must have evolved after local epigean species, biogeographical conditions and faunal diversity of each island are important in the final composition of underground faunas. The wellknown disharmony of island faunas provides new and different evolutionary opportunities toward troglomorphism, so animal groups unexpected in these latitudes have colonized the underground.

An outline of known hypogean animal diversity in Macaronesian archipelagos is presented, relating it to their biogeographical and environmental conditions. A comparison with such faunas of distant volcanic archipelagos (e.g. Hawaii or the Galapagos islands) is also made.

Oral Session I— Vulcanospeleology of the Azores Islands

"Gruta do Carvão" (Carvão Cave) in the Island of S. Miguel (Azores) and Environmental Education

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During the first International Meeting on Vulcanospeleology of the Atlantic Islands in 1992, the author presented a pioneer initiative for the Azores: a videotape about "Gruta do Carvão".. Its main objectives were to provide teaching material in the field of volcanology (where there was a lack of such material) and also to promote environmental education.

The present work is intended to provide a brief history of the "Amigos dos Açores" Association in publicizing the value of "Gruta do Carvão" as well as describing its activities since 1992. Main focus has been to demonstrate the importance of that volcanic cave for the purpose of environmental education, namely to create a knowledgeable public with necessary information, ability, mindsets and motivation to work to solve environmental problems.

In addition to environmental workshops in various schools (primarily for grades 5 to 12) and intended to arouse environmental consciousness, between 1998 and 2003 the Association led 41 guided visits to Carvão Cave for 1,441 students.

Ranking Azorean Caves Based on Management Indeces

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The Azorean Speleological Inventory (IPEA) is a data base with information about all known Azorean volcanic caves and pits. 86 caves are known on Pico, 67 on Terceira, 27 on São Miguel, 18 on São Jorge, 11 on Graciosa, 9 on Faial, 5 on Santa Maria, and 2 on Flores (Fig. 1). About 60 of these 225 caves have been mapped, with a total of 41,122 m of passages. About 71% are lava tube caves, 10% are pits, 7% are erosional caves, 4% are crevice caves and the others are multiprocess or undetermined types. To date, about 65% of these caves are unsatisfactorily studied, in particular its biological and geological features.

IPEA includes a classifying system which relies on objective sets of criteria which yield logical, coherent and reliable results. Its multi-criteria sets also can provide complex classifications which can be used as managing tools. IPEA incorporates six major classification topics: scientific value, potential for tourism, access, surrounding threats, available information and conservation status. Each topic is assigned

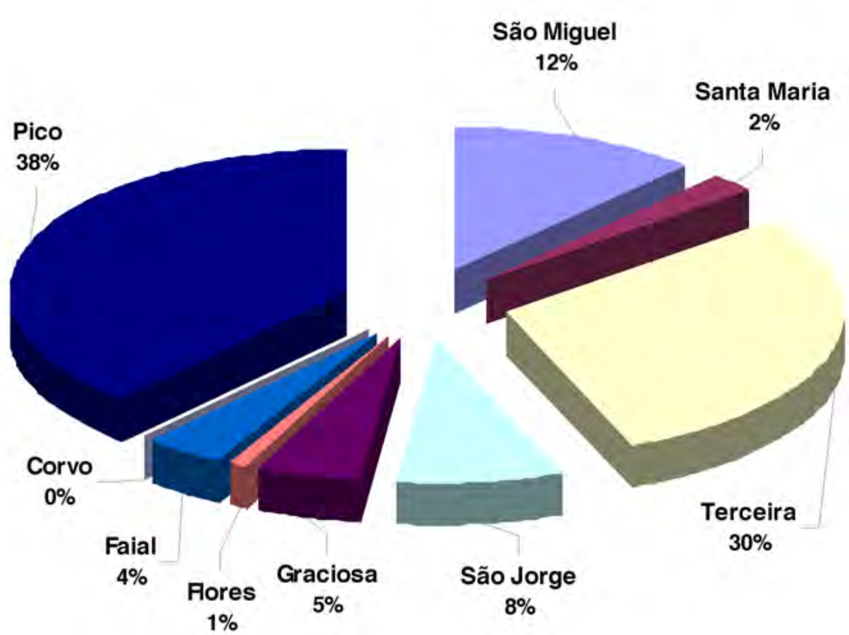

Figure 1 (Constância, et al.). Distribution of volcanic caves in the Azores (total = 225).

Table (Constância, et al.). Ranking most significant Azorean caves, according to three classification issues.

SCIENTIFIC VALUE	TOURISTIC POTENTIAL	CONSERVATION
Água de Pau S. Miguel Island	**Agulhas** Terceira Island	**Água de Pau** S. Miguel Island
Agulhas Terceira Island	**Algar do Carvão** Terceira Island	**Agulhas** Terceira Island
Algar do Carvão Terceira Island	**Branca Opala** Terceira Island	**Algar do Carvão** Terceira Island
Balcões Terceira Island	**Carvão** S. Miguel Island	**Cabras II** Pico Island
Cabras II Pico Island	**D'Água** Terceira Island	**Chocolate** Terceira Island
Canárias Pico Island	**Furna do Enxofre** Graciosa Island	**Furna do Enxofre** Graciosa Island
Chocolate Terceira Island	**João do Rego** S. Miguel Island	**Montanheiros** Pico Island
Frei Matias Pico Island	**Montanheiros** Pico Island	
Furna do Enxofre Graciosa Island	**Natal** Terceira Island	
Henrique Maciel Pico Island	**Ribeira do Fundo** Pico Island	
Montanheiros Pico Island	**Santana** Santa Maria Island	
Natal Terceira Island	**Torres** Pico Island	
Ribeira do Fundo Pico Island	**Túmulos** Pico Island	
Soldão Pico Island		
Torres Pico Island		

by an index (from I to V), based on weighted factors for biological components, geological features, accessibility, singularity and beauty, safety, caving progress, threats, integrity, and available information. Each factor was quantified from 0 (zero) to 5. Lack of information is quantified as zero and the other figures (1 to 5) are objective statements that describe the cave characteristics within the factor.

An initial analysis based on a multi-criterion approach yielded the Table:

1. using positive weighting for geological features, biological components, singularity and beauty, available information, and integrity, 15 caves were found to have especially high scientific values;
2. using positive weighting for geological features, accessibility, singularity and beauty, safety, caving progress, available information, and integrity, and a negative weighting for biological components, 13 caves were found to have great touristic potential;
3. using positive weighting for geological features, biological components, available information, threats, and integrity, 7 caves were found to merit high conservation status.

Algar do Carvão Volcanic Pit, Terceira Island (Azores): Geology and Volcanology

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The Algar do Carvão pit is an impressive volcanic conduit located in the Basaltic Fissural Area, in central Terceira island. Initially it was included in a Geologic Natural Reserve (Regional Legislative Decree nr. 13/87/A, of July 21). Recently it was reclassified as a Regional Natural Monument due to unique volcanic features and additional ecological and conservation importance. Among this features are siliceous speleothems (stalactites and stalagmites of amorphous silica), refusion walls, obsidian dripstones, a lake, vegetation around the vent and along the pit walls, and a troglobitic fauna.

In general terms, the pit had a two-phase genesis. It partially corresponds to the volcanic conduit of a scoria cone previously dated at 2,115 years BP. Also a significant part of Algar do Carvão is developed on older trachytic domes and/or *coulées* related to the silicic polygenetic volcano of Pico Alto.

^{14}C age determinations in charcoal trunks collected near the lake level and on trachytic formations inside the Algar do Carvão gave ages of 3,200 ± 40 years BP. Similar radiometric dating analysis on charcoal found beneath the basaltic lava flow of Algar do Carvão gave ages of 1730 ± 40 years BP for that lava flow. The site of the latter ^{14}C sample was close to the main road and outside the pit. It also should be emphasised that another ^{14}C analysis done on a Pico Alto Volcano pumice deposit, NE of Algar do Carvão's scoria cone gave an age of 2,610 ± 70 years BP.

Together with field studies done in the area and in the pit, these age determinations allowed us to conclude that Algar do Carvão initially formed in trachytic flows about 3,200 years ago. Subsequently, other silicic eruptions occurred on the Pico Alto volcanic centre, with extrusion of lava flows and pumice, one of which occurred about 2,600 years ago. More recently (about 1,700 to 2,100 years ago), several (?) basaltic eruptions occurred in the area with extrusion of flooding lava flows. Along last days of one of these basaltic eruptions, and due to tectonic stress, the very fluid lava retreated inside the conduit of the scoria cone and allowed the formation of Algar do Carvão pit as it exists today.

The Project for the Visitors Center Building of the Gruta das Torres Volcanic Cave, Pico Island, Azores

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Gruta das Torres is a notable volcanic cave in the parish of Criação Velha, municipality of Madalena on the island of Pico in an agricultural landscape.

This paper presents the project for a Visitors Center building for this cave (Table) developed from two primary standpoints: 1) to enclose the access skylight, to control the entrances and provide security; 2) to provide support and information services to the visitor.

To response simultaneously to these two standpoints, a stone wall 1.80 meters high is planned to surround the skylight entrance (Figure) and at the same time to allow the drawing of the building to emerge from it.

Outside the building, will be a small courtyard with a reflecting pool. Visitors will be able to buy entry tickets and wait for the guided tour in a Waiting Room, then proceed to an Auditorium for a briefing. Helmets, electric hand lamps and other necessary equipment will be available in the Auditorium.

Entry into the cave will be by a stairway already built with local pahoehoe slabs. It will continue inside the cave where an overpass 40 m long will allow visitors to avoid existing breakdowns, without the need to remove this debris. Tours will be about 400 m long, 200 m in each direction.

After each tour, visitors will returns to the Waiting Room, through the same stairway and by way of a ramp which bypasses the Auditorium. Thus, several groups of visitors can tour the cave simultaneously without crossing each other.

The building's structure will consist of reinforced concrete, built on a rail, also of reinforced concrete. This solution avoids the use of foundations, believed to cause excessive vibrations in the surrounding area and also being subject to puncture.

The Visitors Center building is continuous with the stone wall protecting the skylight (Figure), not only because both elements were created from a single formal gesture, but because different techniques for emplacement of the local materials will be used. Thus, the wall will consist of stone mortar and the whole south facade of the building will be made in stone and employing the local construction technique known as "currais de figueiras". The latter allows light to enter all along the wall of the building. The remaining facades will be covered by a black waterproof surface that resembles the texture of the glassy lava in the cave.

Vegetation in the area is most impressive on the edge of the skylight and just inside (Figure). Thus, the building and the wall around the skylight just reinforce the whole ensemble, incorporating this vegetation into an architectural unit within an agricultural landscape. Even bearing in mind that the building is itself a constructed architectonic volume.

Oral Session II— Vulcanospeleology of the World

Rare Cave Minerals and Features of Hibashi Cave, Saudi Arabia

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Ghar al Hibashi, located 300 kms SE of Jeddah in the Nawasif-Buqum lava field is the longest lava tube so far mapped in Saudi Arabia (565 m long). Lava levees, stalactites and stalagmites are found throughout the cave and it has a lava channel 13 m long. A bed of loess, up to 1.5 m thick covers the floor and its age is now being determined by OSL. Coprolites from hyenas, sheep, wolves and foxes are found in many parts of the cave and may be very old. Two areas are covered with burnt bat guano and samples taken from one of these areas were found to contain a number of rare cave minerals. A human skull found in the cave has been carbon dated at 450 years BP and shows possible evidence of foul play.

Researchers working with the Field and Space Robotics Lab at MIT to develop microrobots for cave exploration on Mars recently requested permission to use photos of Hibashi Cave to illustrate the possible interior conditions of lava tubes on Mars.

Two large bat guano deposits in this cave caught fire in the past, possibly affecting "bio-stalactities": soft, yellowish concretions thought to be formed of bat urine. Nineteen minerals were detected in samples collected, mostly related to the mineralization of bones and guano deposits.

Hibashi Cave is occasionally visited by local people and is in need of protection from vandalism.

Table. Main characteristics of the project.

Name	Visitors Center of the "Gruta das Torres" volcanic cave
Location	Criação Velha, Madalena, Pico Island, Azores
Client	Direcção Regional do Ambiente - Secretaria Regional do Ambiente
Architects	Inês Vieira da Silva, Miguel Vieira
Structural Engineer	Rui Borges Pereira
Electrical Engineer	Projectangra - Helena Vargas

Figure. Visitors Center building projected for the Gruta das Torres volcanic cave (bottom) and present day surroundings (top).

Illustrations for Vieira da Silva and Vieira.

A Digital List of Non-Karstic Caves in Hungary

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The Volcanspeleological Collective has carried out the study and cataloguing of non-karstic caves in Hungary since 1983. They have compiled descriptions, surveys and photographs from each recorded cave. The cave documentation fills more than twenty volumes, mainly as manuscript notes. However, access to this documentation is restricted. We decided to compile an easily accessible, standard list, of non-karstic caves in Hungary, where changes and updates can be easily made. We decided that a digital list would be the most suitable format.

We began to compile the register in 2002. We have listed each known non-karstic cave and located their positions on a map. Cave surveys and photographs, accompanied by short descriptions were also included in the list . Eighteen regions are represented where non-karstic caves occur. Index Maps were prepared for most of the regions. These are linked to the detailed maps with tabular summaries. The language of the list is Hungarian with an English translation, mainly to facilitate the use of the homepage.

The digital presentation of non-karstic caves was carried out using Arcview GIS as well as available digital map material. Detailed Maps and Index Maps with different scales were developed for specific regions as project files (apr). Layout Maps were then prepared. The layout maps were exported in jpg file format. This enables further utilization and handling. The dbf database was filled with cave data and other data to generate regional data sheets. The digital data from the non-karstic cave list facilitates its use by various presentation software programs and allows transfer of the cave registry to other formats.

The final summary of the non-karstic caves in Hungary is to be found on the Home Page of the cave list. All relevant data has been compiled in htm and html file format.

The Hibashi Lava Tube: The Best Site in Saudi Arabia for Cave Minerals

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Systematic exploration of lava tube caves in Saudi Arabia started only recently, but several large examples have been now explored and mapped in various lava fields around that country.

One of the largest examples in Saudi Arabia is Hibashi Cave, located in Harrat Nawasif-Buqum lava field, 200 km east of Jeddah. It primarily consists of a huge rectilinear gallery (over 400 m long and 15 m wide) accessed down a breakdown slope in a wide collapse which gives entrance to a side corridor. The cave floor consists of uncemented, locally thick loess.

Table (Forti et al.). Identified cave minerals of the Hibashi lava tube (Saudi Arabia).

1 - Anhydrite	$CaSO_4$
2 - Aphthitalite	$(K, Na)_3Na(SO_4)_2$
3 - Arnhemite	$(K,Na)_4Mg_2(P_2O_7) \cdot 5H_2O$
4 - Arcanite	$K_2(SO_4)$
5 - Archerite	$(K, NH_4)H_2PO_4$
6 - Biphosphammite	$(NH_4, K)\ H_2(PO_4)$
7 - Calcite	$CaCO_3$
8 - Carbonate- hydroxylapatite	$Ca_5(PO_4,CO_3)_3(OH)$
9 - Chlorapatite	$Ca_5(PO_4)_3Cl$
10 - Halite	NaCl
11 - Hydroxylapatite	$Ca_5(PO_4)_3(OH)$
12 - Niter	KNO_3
13 - Opal-C	$SiO_2 \cdot nH_2O$
14 - Palygorskite	$(Mg,Al)_2Si_4O_{10}(OH) \cdot 4H_2O$
15 - Pyrocoproite	$(K,Na)_2Mg(P_2O_7)$
16 - Pyrophosphite	$K_2Ca(P_2O_7)$
17 - Quartz	SiO_2
18 - Urea	$CO(NH_2)_2$
19 - Whitlockite	$Ca_9(Mg,Fe)(PO_4)_6[PO_3(OH)]$

The cave was utilized long ago as shelter by wild animals including bats, hyena, wolf and fox. Many bones and coprolites are scattered throughout the floor. Large guano deposits also are present. Some of the guano has caught fire, partially burning overlying bones. The only true speleothems consist of a few small translucent yellow stalactites hanging from the ceiling.

Three different expeditions were conducted in 2003. A few samples of secondary mineral deposits were collected for analysis. Despite the paucity of the samples, 14 different minerals already have been detected (Table). Most are related to biogenic mineralization of bones and guano deposits.

Besides other rare but well understood cave minerals (like arcanite and archerite), pyrocoproite, pyrophosphate, and arnhemite are extremely rare organic compounds strictly related to combustion of guano. Previously these had been observed only in a few caves in Africa. In this paper the SEM images of these minerals are reported for the first time.

As a result of these findings, the Hibashi Cave must be considered the most important volcanic cave in Saudi Arabia and, by far, the richest mineralogical shelter in this Country.

Final remark: This research was made within the MIUR 2002 Project "*Morphological and Mineralogical Study of Speleothems to Reconstruct Peculiar Karst Rnvironments*", resp. Prof. Paolo Forti.

Investigation of the Discharge Mechanism of Hachijo-fuketsu Lava Tube Cave, Hachijo-jima Island, Japan

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Hachijo-fuketsu lava tube cave is located on Hachijo-jima Island south of Tokyo in the Pacific Ocean. This cave is believed to have been formed by the eruption of Hachijo-nishiyama volcano 1100 years BP. Its lava flow is basaltic, with silica content of 50.5%. Hachijo-fuketsu is the second longest lava tube cave in Japan. Despite good accessibility, it is well preserved. Its upper and middle sections have moderate slopes. Its lower end is flat and horizontal.

In modelling the discharge mechanism of this type of lava tube we used an inclined circular tube model for the sloping sections of the cave. For the flat, horizontal section in which the lava flow is driven by hydrodynamic head, we modelled a flattened circular tube. The yield strengths obtained from these two models were similar and comparable to those of other lava flows.

Regarding the inclined circular pipe case, the discharge mechanism of lava tube caves already has been established, based on Bingham characteristics of intratubal lava flow (Honda 2000, 2001a). A simple model of steady state isothermal laminar flow in inclined circular pipes and in flatten circular pipes were used for analyses. Comparison studies were based on the configuration of Hachijo-fuketsu.

Flow characteristics were studied as a function of parameters such as tube radius, viscosity, yield strength of lava and slope inclination. A critical condition was determined for the discharge parameters in which the yield strength plays a dominant role. Existing observational data were introduced to the critical condition. This model was applied to lava tube cave of Mt. Fuji, Mt. Etna, Mount St. Helens, Suchiooc volcano, Kilauea volcano and others. Some deduced yield strengths of lava of the caves in these areas were found to be in good accordance with yield strength as estimated by other methods (Honda 2001b).

General flow equation of Bingham fluid can be shown as

$$f(t)=(t-f_B)/v_B \quad (t>f_B, \text{ or } r>r_B),$$
$$f(t)=0 \quad (t<f_B, \text{ or } r<r_B).$$

Here, f_B is Bingham yield strength, v_B is Bingham viscosity, which takes specific value depending on the materials. t is shearing stress at r.

For laminar flow model in circular tube on the slope, the equation of the distribution of flow speed u of Bingham fluid are shown as follows:

For tw =(d g sin a)R/2>f_B,

$$u=(R-r_B)^2(d\ g\ \sin a)/4v_B \quad (r<r_B),$$
$$u=[R^2-r^2-2r_B(R-r)]\ (d\ g\ \sin a)/4v_B \quad (r>r_B).$$

For tw= (d g sin a)R/2<f_B, u=0.

Here, tw is shearing stress at wall, a is angle of slope or inclination of tube, d: density of the fluid, g: gravity acceleration, R: radius of the tube, r_B :radius of the flowing position where Bingham yield stress takes f_B.

Here, (d g sin a)R/2=f_B is the critical condition to determine if the fluid in the tube can be drained out. For given and known relation between slope angle and diameter (height) of the tube, this critical condition can give the yield strength f_B. This critical condition means that when the yield strength f_B of Bingham fluid is higher than the shear stress at the wall, there is no flow of fluid, as a consequence, no discharge of fluid from the tube. From Table 1, f_B=2.5x10^4dyne/cm^2 can be obtained for Hachijo-fuketsu.

The above model is, however, valid only for flow in inclined tubes. For perfectly flat lava tubes (0 degree), the effect of inertial as driving force due to the head of the flow must be considered, if the flow is continuous together with the inclined

Tables for Honda.

Table 1. Relation between slope angle and height of Hachijo-Fuketsu lava tube cave of sloped configuration

Location of lava cave	Slope angle(a)	Height(2R)
Upper reaches	4.5 degree	~5m
Intermediate reaches	14 degree	~2m
(Lower reaches)	(0 degree)	(~1m)

Table 2. Relation between head and length at horizontal location of Hachijo-Fuketsu lava tube cave of horizontally flat configuration for 2R=1m

Location of lava cave	Head(H)	Length(L)
Upper reaches	25m	33m
Intermediate reaches	85m	80m
Lower reaches	115m	150m

Table 3. Yield strength obtained from the critical condition

Name of volcano	SiO_2 fraction of lava	Obtained yield strength	References
Hachijo-nisiyama	50.4~50.5%*	2-2. 5x10^4dyne/cm^2	*M.Tsukui et al(2002)
Mt. Fuji	49.09~51.3%*	2.5~5x10^4dyne/cm^2	*H.Tsuya(1971)

tube (Honda 2003). Very rough relation between drained tube length and mean head of the flow can be obtained as $(d\,g\,R)H/2L=f_B$ by replacing (sin a) by (H/L). From Table 2, $f_B=2\times10^4$ dyne/cm^2 was obtained for Hachijo-jima.

In summary, obtained basaltic yield stress from slope angle and height of some lava caves (Table 3) are reasonable values as compared with the yield stress obtained for Mt. Fuji.

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Lava Caves of Jordan

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The central section of Jordan is covered by young alkalic olivine basaltic lava flows: the Harrat Al-Jabban volcanics. These are part of the large intracontinental Harrat Al Scham volcanic field. The origin of these lavas may be connected to the existence of a continental intraplate hot spot plume. Its eruptive site should appear to move southward as the Arabian Plate moves northward due to the opening of the Red Sea. The top most and therefore youngest flows, are ca. 400,000 years old (Tarawneh et al., 2000).

In these lavas we explored, surveyed and studied four natural lava tunnels (Abu Al-Kursi, Beer Al-Hamam, Al-Howa Cave and Dabie Cave) and two other lava caves (Azzam Cave and Dahdal Cave) in September 2003 and March 2004 (Table). The two smaller caves are most probably pressure ridge caves formed by the buckling-up of the upper layers

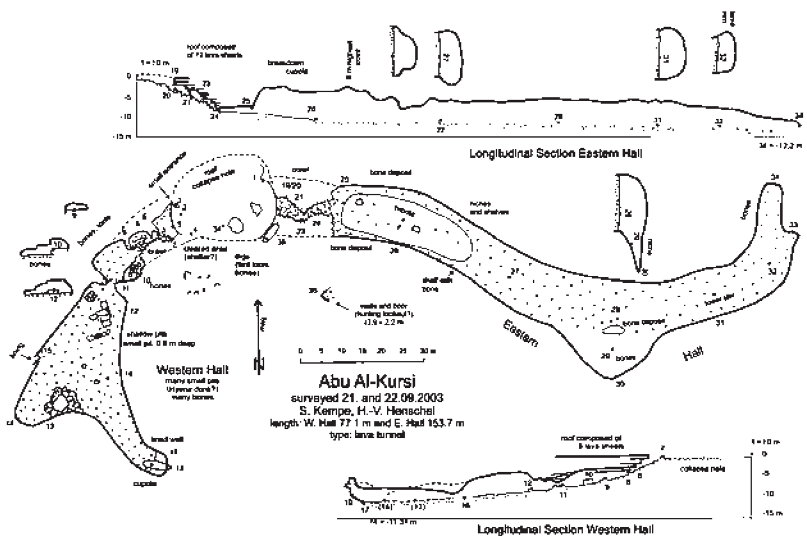

Figure 1 (Kempe et al.). Survey of the Abu Al-Kursi lava tube cave, in Jordan.

Table (Kempe et al.). Data of Jordan lava caves (locations WGS 84).

Name of Cave	Latitude	Longitude	Stations	Length	Stations	Depth	Direction	Type
Abu Al-Kursi W	32°15.401'	36°39.442'	2 to 18	77.1 m	2 to 18	8.1 m	N-S	Lava Tunnel
Abu Al-Kursi E	32°15.401'	36°39.442'	20 to 34	153.7 m	1 to 34	12.2 m	W-E	Lava Tunnel
Azzam Cave	32°17.104'	36°36.594'	13 to 25	44.1 m	1 to 25	4.2 m	NWN-SES	Pressure Ridge
Beer Al-Hamam	32°07.91'	36°49.42'	32 to 23	445.0 m	1 to 23	17.2 m	NW-SE	Lava Tunnel
Dahdal Cave	32°17.344'	36°35.718'	5 to 12	28.9 m	1 t0 12	0.0 m	SW-NE	Pressure Ridge
Al-Howa	32°18.536'	36°37,240'	6-9,6-16	100 m	2-7	11.0 m	NW-SE	Lava Tunnel
Dabié Cave	n.d.	n.d.	0-14	197 m	-	1 m	N-S	Lava Tunnel

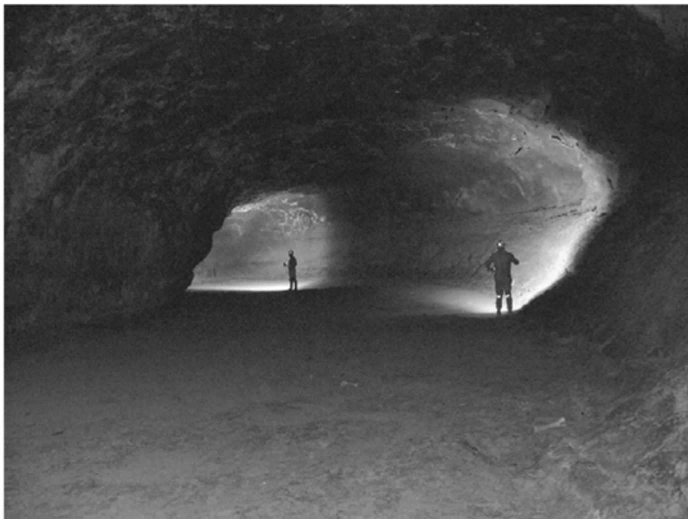

Fig. 2: View of Eastern Hall of Abu Al-Kursi.

Fig. 3: Camel bones, possibly a former hyena den (note bones with missing ends).

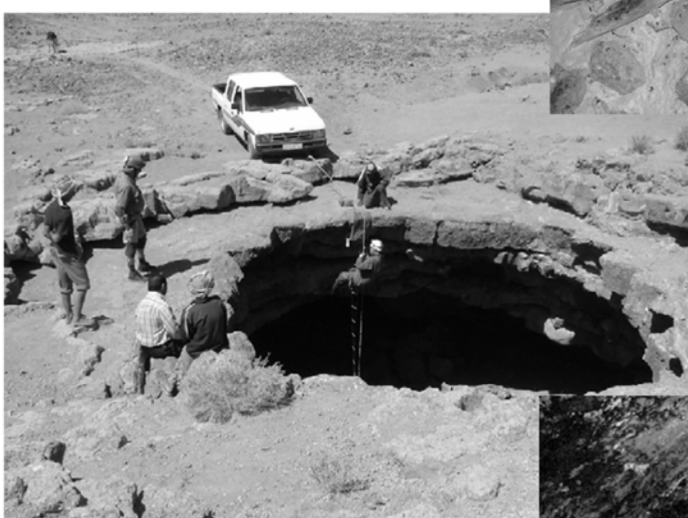

Fig. 4: Entrance to Beer Al-Hamam, a ca. 6 m deep collapse hole in roof of a lava tunnel.

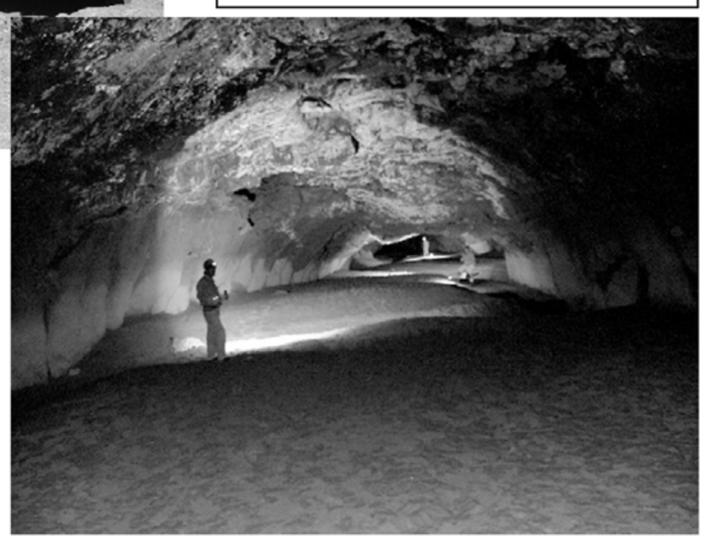

Fig. 5: An upslope view of the lower part of Beer Al Hamam (note sediment floor with channel).

Figures for Kempe et al..

of pahoehoe flowing down from nearby Al-Qu'ays volcano, while they were still hot and plastic. Abu Al-Kursi (Figs. 1, 2, 3) and Beer Al-Hamam (Fig. 4, 5) are large lava tunnels, up to 15 m wide and 8 m high. Al Howa is the section of a medium-sized lava tunnel while Dabie Cave is the smallest of these conduits, less then 4 x 2 m in cross section. These tunnels served to transport lava subterraneously over long distances, i.e. in case of the large caves possibly over several tens of kilometres. Now they are accessible through ceiling collapses, which allow studying the structure of their roofs. These consist of uninterrupted sets of lava sheets which show that these natural tunnels did not form by over-crusting of lava channels, but by repeated under-flowing and inflating of initial lava deltas. In this way lava flows build forward only at the tip, while the rest of the flow is stationary apart from the lava flowing in the tunnel inside. These processes have been studied in Hawaii (e.g., Kempe, 2002) and now can be used to interpret findings elsewhere. The existence of these tunnels shows that the basaltic lava must have been very hot upon eruption, and that it was piped through the tunnels over long distances, thus allowing flow over terrain at slopes at or less than 2°, comparable to the distal slopes of Hawaiian volcanoes. In fact, there should be many subparallel tunnels in these youngest flows.

The age of these flows is much greater than those ages on the Island of Hawai'i. Thus it came as a surprise that such lengths of the tunnels still are accessible. Dahdal Cave, Abu Al-Kursi, Beer Al-Hamam and Dabié Cave contain thick sediment deposits. In the case of the three latter caves, this sediment causes their terminations. During torrential rains, the stream in a wadi washes surface sediment into Beer Al-Hamam. The lower part of the cave ponds during such rains, producing a large reservoir of water. Signs of rapidly flowing water are seen in the sediment surface in the upper part of the cave. The sediments were sampled at a profile. They are mostly silts with some fine sand. Quartz, calcite, plagioclase, illite and koalinite (in decreasing order of amount) compose most of the sediment. That indicates a wind-blown origin, possibly a glacial loess. In the upper centimetres the sediment also contain large concentrations of ammonium nitrate. This is derived from pigeon droppings. In both sections of Abu Al-Kursi, the floor is smooth and covered with a thin layer of fines, laid down by occasional floods that pond at the end of the cave. No sign of flowing water is seen.

All these caves were known locally. Until recently, Azzam Cave was used as a sheep pen. Its entrance was excavated recently, and a nearby sediment pile contains pot shards. Black drippings caused by the use of plastic irrigation pipes as makeshift torches reveal visits by adventurous explorers in Abu Al-Kursi. Visiting Beer Al-Hamam requires climbing down an overhanging pit 5 m deep, but it must have been visited in the past because we found stone cairns inside. Dahdal Cave contains a stone wall so it, too, was visited in the past. Some of these visits, however, may have been in prehistoric times: numerous flint tools (possibly neolithic) were found in the neighbourhood of Dahdal Cave and in two digs in the entrance of Abu Al-Kursi. Dahdal Cave, both sections of Abu-Al-Kursi and Dabié Cave contain camel bones and were used as dens by hyenas (Fig. 3). Shallow circular pits are seen throughout Abu Al-Kursi. They do not appear to be anthropogenic since no excavated material is present. Possibly they are hyena or wolf sleeping pits. The mandible of a wolf or jackal was collected in this cave. A mummified hyena was found in Dabié Cave. Considering the age of these caves, they could contain very valuable deposits of faunal fossils covering a large section of the Pleistocene.

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Caverns in Volcanic Terrains in Costa Rica, Central America

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Costa Rica is located in an evolved volcanic arc (< 30 ma), which is a product of the subduction of the Cocos plate under the Caribbean plate. This country contains many diverse volcanic landforms, developed during the last 200 Ma of its geologic history. This report presents the first classification of caverns and grottos in volcanic areas of Costa Rica, together with a preliminary inventory:

a) volcanic caverns

The majority of its caverns of volcanic origin are small caves or grottos within lava flows (lava fields of Cervantes and Los Angeles). Also included are possible collapsed lava tubes of lava or "jameos", and a grotto which forms part of a crater in Turrialba volcano. All these are less than 11,000 years BP.

b) caverns of marine origin (littoral caves)

These are small caves mostly located in areas frequented by tourists. Thus they are comparatively well known. Most of them are located in cliffs and platforms of marine abrasion developed in oceanic basaltic complexes (ophiolites *s.l.*) These rocks are part of an accreted Cretaceous-Eocene complex located along the Pacific Coast. Comparatively well developed littoral caves also exist at Bajamar-Guacalillo beach in cliffs of Lower Pleistocene epiclastic rocks (debris flows and debris avalanches). These are comparatively large caverns, some of which are interconnected. They are adjacent to sandy beaches, and usually are visited by tourists at the low tide. In addition, submarine and subaerial littoral caverns exist on Cocos Island in the Pacific Ocean. This island is the only subaerial exposure of the submarine Cocos volcanic range.

c) caverns of fluvial erosion

This type of cave is uncommon in Costa Rica and is less known than the others. An example is present in Late Pliocene

Figure (Mora et al.). Grotto that forms part of a volcanic crater in Turrialba volcano.

lava on the left margin of Peñas Blancas River, and a small grotto known as Cave of Death is present on the left bank of the Toro River. It contains lethal concentrations of CO_2. Probably the best known and most spectacular example is a natural bridge formed in Middle Pleistocene ignimbrite called Puente de Piedra (Bridge of Stone). It provides a vehicular crossing of a creek in a town named Tacares of Greece.

d) anthropogenic grottos

The most important of these are pre-Columbian shelters excavated in pyroclastic flows (2.0–0.6 Ma) in the northern part of the country. These include the Indian Cave in Cañas and a cave in Salitral of Bagaces.) Other grottos are present on pumice fall deposits dated of 0.30 ma (the Tibás layer), in the Central Valley of Costa Rica. In general terms, all the caves and grottos are located on Upper Quaternary age formations and were inhabited by humans or were used for rituals.

Because of their small size, those investigated to date have low speleological potential. Some of them, however, have a local tourism potential as well as geoarchaeological value not yet investigated nor exploited. In particular, caves of the spectacular Bajamar-Guacalillo beach have obvious value in geological tourism.

Not yet investigated are a probable natural lava tunnel at Turrialba volcano and a reported erosional tunnel at Liberia River.

The Lava Tubes of Shuwaymis, Saudi Arabia

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Kahf Al Shuwaymis, located 204 km N of Medina in the Ithnayn lava field, is the second longest lava tube (513 m) so far mapped in Saudi Arabia. The lava source is Hazim al Khadra volcano, which is characterized by a series of large collapses terminating with the entrance to Kahf Al Shuwaymis. Several fumaroles are active on the slopes of this volcano, one of which emanates from inside a shelter cave. A small pressure-ridge cave was also noted in the area.

Dahl Romahah is located 168 kms N of Medina in the Khaybar lava field. This lava tube is 202 m long and is well decorated with flowstone and speleothems composed of secondary minerals which have leaked through the ceiling and walls. The cave contains a large cache of bones as well as coprolites from wolves, hyenas and foxes. The radon level in Dahl Romahah is considerably higher than in other Saudi lava tubes. In bygone days, this cave was used as a water reservoir by local people, who built a long wall on the surface to channel water into the cave.

Aerial photographs, maps and other reports suggest that many other lava tubes will be found south of these two caves.

Discovery and Survey of Hulduhellir, a Concealed (Entranceless) Lava Cave in the Hallmundarhraun, W. C. Iceland

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Research undertaken on the Hallmundarhraun in 2000 to ascertain the effectiveness of different geophysical methods in the detection and mapping of cavities in basaltic lava flows revealed the possibility of a concealed continuation of the cave Stefánshellir. The 2000 survey by magnetometer and ground penetrating radar (GPR) indicated that the roof of the main passage of Stefánshellir lifted on other side of the 20m long lava seal that closed the upflow end of the known cave. A further survey in 2001 confirmed this finding and revealed over 350m of cave passage. In 2003 the team were interested in confirming the relationship between the Hallmundarhraun's chain of 20 or more shatter rings (or collapsed tumuli) and the Surtshellir-Stefánshellir lava tube cave system and extended the survey to embrace the three nearest shatter rings.

The results were quite remarkable, showing that the concealed cave - now given the Icelandic name Hulduhellir (Hidden Cave) - passed directly beneath the shatter rings, over a distance of approx. 1.2km from the upflow end of Stefánshellir. The geopysical data infers that Hulduhellir is in places a large diameter passage, although the form that it takes beneath the shatter rings is not clear. In order to better understand the pattern of magnetic anomalies around the cave, a comparable geophysical survey was made over the accessible, large main passage of Surtshellir, while attempts are also being made to replicate anomaly patterns with specialist modelling software.

Oral Session III— Biospeleology of Volcanic Caves

Long-term Study of Population Density of the Troblobitic Azorean Ground-Bettle *Trechus terceiranus* at Algar do Carvão Show Cave: Implications for Cave Management

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Trechus terceiranus Machado (Coleoptera, Carabidae) is the commonest trogobitic insect species in several lava –tube caves and pits and in the Mesovoid Shallow Substratum (MSS) on Terceira (Azores). One of the sites where this ground beetle reaches highest densities is the show cave "Algar do Carvão", an impressive volcanic pit. The troglobitic fauna in this cave is particularly rich, with at least two endemic spider species occurring only in this site.

Cave arthropods were sampled once per month for three years (2001-2003) using baited pitfall traps. All collected specimens were counted and stored for later identification with the exception of the abundant *Trechus terceiranus*, which were counted and returned to their environment.

We found that adults are common all year-round, with some activity-density peaks in months between March and September. The most notable finding was an overall decrease in activity-density of *T. terceiranus* from year to year. The hours of artificial light in this cave also increased during these three years and this could have caused this decrease. We discuss the implications for management of the cave.

Indicators of Conservation Value of Azorean Caves Based on Arthropod Fauna

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All Azorean lava tubes and volcanic pits known to contain hypogean fauna (37 cavities) were evaluated for species diversity and rarity, based on arthropod populations. To produce an unbiased multiple-criteria index (*importance value for conservation,* IV-C) incorporating diversity and rarity based indices and geological and management based indices, an iterative partial multiple regression analysis was performed. In addition, an irreplaceability index and the complementarity method (using heuristic methods) were used to select the most important caves for conservation management.

Most hypogean endemic species have restricted distributions; some are known from only one cave. It was concluded that several well-managed protected caves per island are necessary to preserve an adequate fraction of endemic arthropods. For presence/absence data, suboptimal solutions indicate that protection of at least 50% lava-tubes with known hypogean fauna is needed if the goal is representation of 100% of endemic arthropod species in a minimum set of reserves.

The most diverse arthropod assemblages occur in large (and beautiful) caves; thus cave size plays an important role in explaining the faunal diversity of arthropods in the Azores. Based both on the uniqueness of species composition and/or high species richness, conservation efforts should be focused on the following unmanaged caves: Algar das Bocas do Fogo (S. Jorge); Gruta dos Montanheiros, Gruta da Ribeira do Fundo, Furna de Henrique Maciel, Gruta do Soldão and Furna das Cabras II (terra) (Pico); Gruta das Anelares and Gruta do Parque do Capelo (Faial); Gruta dos Balcões, Gruta das Agulhas and Gruta do Chocolate (Terceira); Água de Pau (S. Miguel).

Indicators of Conservation Value of Azorean Caves Based on Its Bryophyte Flora at Cave Entrances

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Cave entrances in the Azores are particularly humid habitats. These provide opportunities for the colonization of a diverse assemblage of bryophyte species. Using both published data and new field sampling, we evaluated species diversity and rarity of bryophytes at the entrance of all known Azorean lava tubes and volcanic pits with such flora. Most frequent species includes the liverworts *Calypogeia arguta*, *Jubula hutchinsiae*, *Lejeunea lamacerina*, and the mosses *Epipterygium tozeri*, *Eurhynchium praelongum*, *Fissidens serrulatus*, *Fissidens viridulus*, *Isopetrygium elegans*, *Lepidopilum virens*, *Tetrastichium fontanum*.

Several rare Azorean bryophyte species appear with dense populations at some cave entrances (e.g. *Archidium alternifolium*; *Asterella africana*; *Plagiochila longispina*), which highlights the importance of this habitat in terms of conservation of these plants.

To produce an unbiased multiple-criteria index (*importance value for conservation*, IV-C), several indices were calculated (based on bryophyte diversity and rarity, and also on geological and management features) and an iterative partial multiple regression analyses was performed.

Preliminary data sows that three pit caves are particularly diverse in bryophytes (e.g. Algar do Carvão, Bocas do Fogo and Furna do Enxofre). This indicates the importance of shaded and humid openings. Lava tubes with a diverse troglobitic fauna also are diverse in terms of bryophyte species (e.g., Algar do Carvão, Gruta dos Montanheiros, Gruta da Agostinha, Furna do Henrique Maciel). We also evaluate the utility of several cave management indices as surrogates of bryophyte diversity in Azorean volcanic cavities.

On the Nature of Bacterial Communities from Four Windows Cave, El Malpais National Monument, New Mexico, USA

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One of the striking features of some lava tubes is the extensive bacterial mats that cover the walls. Yet, despite their prominence in lava tubes, little is known about the nature of these bacterial communities. To rectify this situation we have investigated the bacterial mats that cover the walls of Four Windows Cave, a lava tube in El Malpais National Monument, New Mexico (see Figure). These bacterial mats, which occur in the twilight zone adjacent to algal mats, and in dark zone of the lava tube, cover from 25-75% of the wall. Their macroscopic and microscopic visual appearance suggests that these bacterial mats are composed of actinomycetes, bacteria that commonly inhabit caves. Actinomycetes are a group of Gram-positive bacteria that break down complex organic matter and thrive in environments where nutrients are sparse and conditions extreme. With a temperature of 0-2°C and seeping organic matter for nourishment, Four Windows provides an excellent habitat for these bacteria. Some types of actinomycetes are medicinally and agriculturally significant because they excrete antibiotic products to repel invaders. Cave bacterial mats may have such antibiotic properties. Vacuuming of the bacterial mats and the adjacent algae, demonstrated the presence of collembola and mites on the algae and no invertebrates on the bacterial mats.

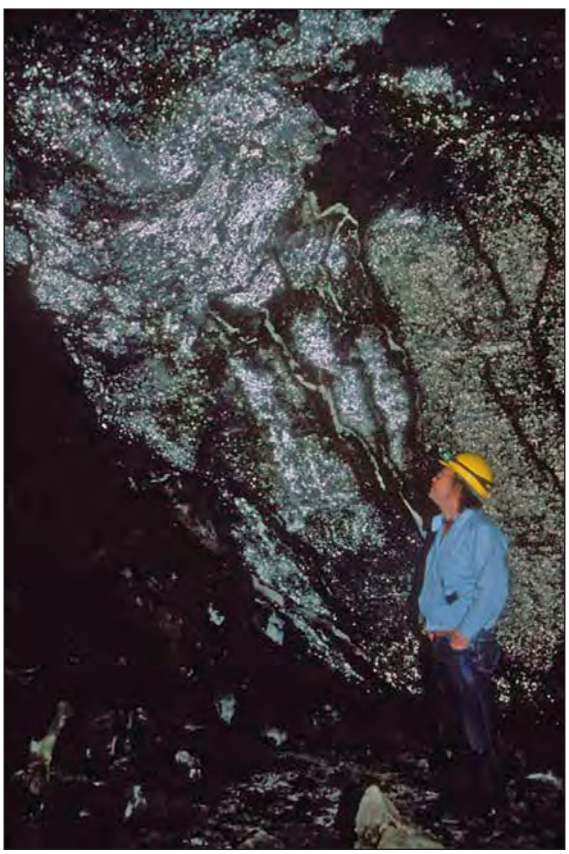

Figure (Northup, et al.). Mats of actinomycete bacteria spread across wall of Four Windows Cave, El Maplais National Monument. During some seasons the bacterial mats are hydrophobic and the walls appear "silvered" when light is shown upon them.

In an effort to phylogenetically characterize bacterial colony members, we extracted DNA from wall rock communities, using a soil DNA extraction technique developed at Los Alamos National Laboratories. The DNA was purified, the 16S rRNA gene was amplified using PCR, amplification products were cloned, and thirty clones were sequenced in their entirety. A restriction fragment length polymorphism (RFLP) analysis of 11 clones exhibited unique banding, an indicator of genetic diversity. Comparison of our sequences with those in the Ribosomal Database II revealed that the Four Windows bacterial sequences are most closely related to actinomycetes, as suspected. Some clones also showed similarities to environmental soil strains. Other clones are related to genera such as *Nocardia* and *Frankia*, although not closely. These results reveal a diverse community of bacteria and the presence of several novel bacterial species.

To investigate the degree to which the actinomycetes had adapted to the lava tube environment, we also investigated the ability of bacteria cultured from these mats to withstand the effects of ultraviolet (UV) radiation. Bacteria from the mats and from the surface rocks above the lava tube were cultured on R2A medium on-site in Four Windows Cave, were allowed to grow for 24-hours in the cave environment, and were then transported to the laboratory where they were grown at 2°C in an incubator. We subjected twelve isolates from the lava tube to one dose (100 seconds) and a half dose (50 seconds) of UV radiation. For controls, we subjected six isolates from the cave surface to the same radiation treatments and also allowed replicates of all the isolates to grow without any radiation. The results showed a general trend in which microbes isolated from the lava tube were much more UV sensitive than the microbes isolated from the surface. However, all of the microbes tested displayed at least slight sensitivity to UV radiation. Based on the results, the bacterial colonies currently inhabiting the Four-Windows lava tube appear to be at least somewhat cave-adapted.

Our studies of the actinomycete communities in Four Windows Cave reveal a diverse community of bacteria that may produce secondary compounds that make them unpalatable to invertebrates. These bacteria appear to have become at least somewhat cave-adapted as evidenced by their loss of UV resistance.

Large Invertebrate Diversity in Four Small Lava Tubes of Madeira Island

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The epigean fauna of Madeira is well known, highly diversified and very rich in endemic species. In contrast, its cave-dwelling fauna was not very well known. Madeira is a comparatively old island (5 My) with few modern lavas and therefore only a comparatively small number of lava tube caves are known: 21 volcanic caves have been reported. Of these, some already have been destroyed and others (e.g. São Vicente caves), have been heavily modified for tourism. To date, only two significant complexes of lava tubes have been studied: São Vicente (Cardais Caves) and Machico (Cavalum Caves). The Machico lava tubes are under serious pressure because of frequent visitation but still represent the best preserved group of lava tubes in Madeira. Yet their cave-dwelling fauna is little known. Although a few reports have been published, they have dealt only with few taxa. Further, these were reported merely from the complex as a whole without indication of which individual species was noted in which cave. At present, its fauna is at special risk because of current plans for construction of a tunnel. The resulting urgent need for detailed information led us to study biodiversity in four of its five small caves.

Invertebrates were sampled by sight and by 32 baited pitfall traps set during a seven months period. Of 8,497 sampled specimens, 14.3% were Phoridae, representing 9 species. This family was excluded from further consideration.

The remaining specimens belong to 69 taxa. Of these, 8 were known endemisms, 5 were new species and 1 was a new record to Madeira. Previously only 18 species were known from these caves, and 8 of these were not found in this study. The estimated number of species in this complex is 79. For a small cave complex with less than 300 m in total length, this is a considerable number. Cavalum II had the greatest number of species. Although many species were present in more than one cave, some were found in only one. For example the endemic spider *Centromerus sexoculatus* was sampled only in Cavalum I, the pseudoescorpion *Microcreagrina madeirensis* in Cavalum III and the carabid *Trechus fulvus maderensis* in Landeiros Cave.

This sampling thus demonstrated that protective measures are urgently needed.for the cave-dwelling fauna of the Machico complex.

Oral Session IV— Theoretical Studies, Conservation, and Management of Caves

Speleothemic Minerals Deposited as Condensates from Vapors, 1919 Lava Flow, Kilauea Caldera, Hawaii, USA

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Few publications acknowledge the existence of cave minerals deposited from fumes and/or steam. The 1919 "Postal Rift" lava flow in Kilauea Caldera contains about 200 caves. Included are lava tube caves, hollow tumulus caves, drained flow lobe caves and others. While a single body of magma is believed to underlie the entire caldera, significant differences in the fumes of different areas are readily detected by human senses, on and beneath the surface. A significant minority of its caves is at least intermittently hyperthermal, with varied patterns of steam and fume emissions and varied mineral deposition along hot cracks and in other locations on ceilings, walls, floors, and lava speleothems.

Working conditions include up to 100% relative humidity and temperatures up to 130 degrees F, but as a result of thermostratification, temperatures as high as about 175 degrees F can be measured in speleothemic areas. Sulfates, chlorides and (rarely) elemental sulfur are believed to be present. An initial project of mineral identification foundered with the termination of the position of Cave Specialist at Hawaii Volcanoes National Park. A new project is strongly indicated.

Climate Modeling for Two Lava Tube Caves at El Malpais National Monument, New Mexico, USA

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Reliable data concerning cave microclimate benefits those who manage caves for human visitation, protection, and the conservation and restoration of bat roosts. Both published and unpublished information about cave climates is limited, however. Mathematical models of cave climate are even more limited, and for lava tube caves, these appear to be totally lacking. Because they are simpler than many limestone caves (thus making the task of modelling tractable) we tested the use of lava tube caves as laboratories in which to do climate modeling.

We present the results of investigating temperature and humidity in two lava tube caves at El Malpais National Monument, New Mexico, USA. One cave was a single-entrance cave with an ice sheet, the other a tube with detectable airflow to/from cracks on the surface. In these two tubes, we collected 1.5 years of temperature and humidity data with Onsett

Hobo™ dataloggers. Using the data, we investigated how temperature and humidity change with season and distance from the entrance, and we now propose mathematical models to predict future temperatures based on heat flow from the surface as well as advection.

Our models show a good fit to the equation

$$T(t) = a1 + a2\cos[(t2\pi)/365.24] + a3\sin[(t2\pi)/365.24] + a4\cos(t2\pi) + a5\sin(t2\pi).$$

This implies that, at least in these lava tube caves, accurate prediction of temperature is possible.

Pa'auhau Civil Defense Cave, Mauna Kea Volcano, Hawai'i: A Lava Tunnel ("Pyroduct") Modified by Water Erosion

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Pa'auhau Civil Defense Cave was surveyed and geologically inspected by the authors in 2001. It is located on the heavily eroded eastern flank of Mauna Kea volcano, in the Hamakua volcanics (200-250 to 65-70 ka). It is the largest lava tunnel ("pyroduct", "lava tube") known on this volcano. Typical morphologic elements of natural lava tunnels are present, including secondary ceilings, linings, base sheets, lava falls, and lava stalactites. The cave has only a moderate width and the cross section of the lava flowing in it did not exceed 1-2 m^2. The cave has a dendritic passage pattern and is only a section of a once longer system (Fig. bottom). The present entrance is situated at the downhill end of the cave. It looks out into a modern canyon (Kahawaili'ili'i Gulch). Upslope, the Alpine Stream Passage of the cave ends in breakdown at the wall of the same gulch. The Main Passage ends at a lava choke, and Mudcrawl and other side passages end in mud and sand chokes. The presence of casts of large trees shows that the cave lava transgressed a forested terrain. Plunge pools expose a diamict which contains large blocks in a fine-grained matrix with a red top layer underlying the cave lava. The Table lists some of the morphometric characteristics of the cave.

Water of the gulch entered the cave upslope and traversed much but not all of the cave modifying it substantially (see Fig. top). It left polished walls and ceilings, large plunge pools, stream potholes, scallops, flutes, gravel, rounded blocks, sand and mud. At high water it partially ponded, flooding high elevation passages which then fed water back to the main gallery. It excavated four large plunge pools, cutting through the dense base sheet of the lava and exposing underlying strata. Polished ceilings show where the water sumped in several places. When in flood the speed of the water was enough to create potholes and to remove blocks of the lava from the cave's margins and grind them to rounded boulders and gravel. Even though dripwater presently collects in the cave and flows along some sections of the floor, no water has flowed out of the cave for a long time. The presence of charcoal shows that nearly all the cave's passages were visited by ancient Hawaiians. They left numerous piles of stones, cairns, and stone rings, and also placed stones on the walls. The purpose of this is unknown. The presence of caves eroded by flowing water in the lavas of Hawai'i offers a new view of deep-seated watercourses in volcanic edifices.

Table (Kempe et al., Civil Defense Cave).
Morphometric characteristics of the cave.

	Stations	Measurements m	Horizontal m
Main survey line	1 to 74	579.6	573.4
Side passages sum:		420.9	415.5
Sum:		1000.5	988.9
End to end (horizontal)			502.6
Sinuosity main passage			1.14
Vertical	1 to 74	48.9	
Slope ($\tan^{-1}$ 48.93/573.3)			4.87°
Slope ($\tan^{-1}$ 48.93/502.62)			5.56°
Main passage/side passage ratio			1.37
Secondary ceiling ratio			0.11

Kuka'iau Cave, Mauna Kea, Hawai'i: A Water-Eroded Cave (A New Type of Lava Cave in Hawai'i)

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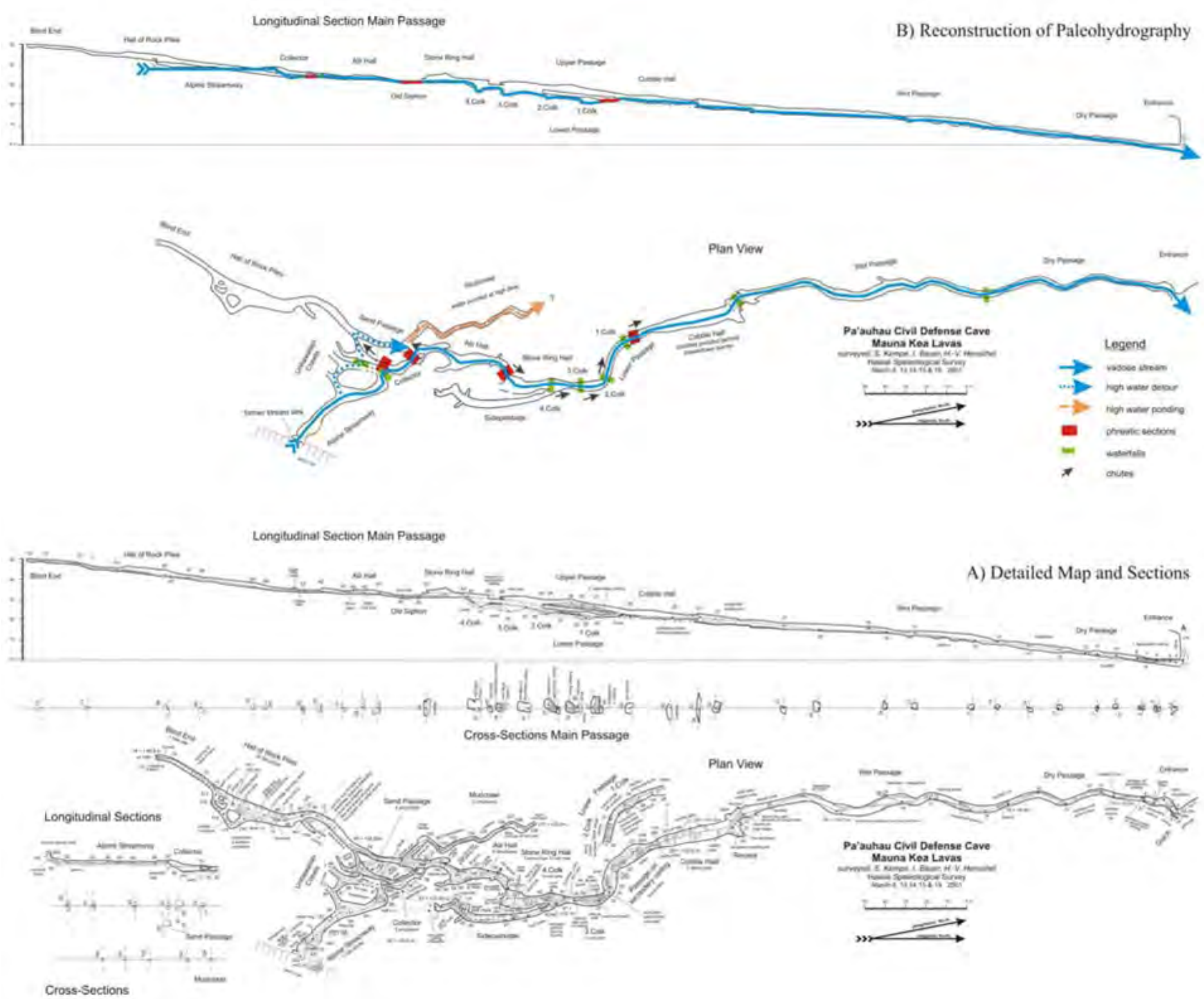
From 2000 to 2002, Kuka'iau Cave (alias ThatCave/ThisCave) was explored, traversed from end to end for the first time, surveyed and inspected geologically. It is located on the heavily eroded eastern flank of Mauna Kea, Hawai'i in the Hamakua volcanics (200-250 to 65-70 ka). Together with Pa'auhau Civil Defense Cave (a natural lava tunnel) it is one of the first substantial caves described in detail in lavas of Mauna Kea volcano. Furthermore, we assert that it is the first cave known in Hawai'i which owes its existence entirely to stream erosion.

Kuka'iau Cave is ca. 1,000 m long. It is used by an episodic river that enters the cave by a series of waterfall pits. The resurgence of the stream is 108 m lower than its insurgence: thus the average slope is 9.8° (Fig. 1). 200 m before the exit the intermittent stream passes through a sump where it flows upward over a series of gravel chutes into a vadose passage which follows the dip of the strata (Fig. 2 a-d).

The cave is essentially erosional in origin. We concluded this from the geology of the strata exposed in the cave, from its morphology and from the lack of typical lava tunnel features (such as pahoehoe sheets of the primary roof, secondary ceilings, lava falls, glazing, etc.). At the upper entrance the cave is located in a thick series of 'aa. The lower section was created by removing 'aa and diamict layers, thus excluding the possibility that the cave developed from a precursor lava tunnel ("pyroduct"; "lava tube"). Also, in its phreatic sump section, the cave makes several right angle turns and moves upward through a series of pahoehoe sheets, unlike any lava tunnel. Furthermore, the major section of the upper cave has



Map for Kempe et al. Civil Defense Cave.

developed along a red paleosoil which forms a base layer. Allophane and halloysite (minerals produced by weathering) helped in sealing the primary porosity of this base layer causing a locally perched water table. Water moved along this base layer on a steep hydraulic gradient through the interstices in ‘aa and through small pahoehoe tubes. This exerted a high pressure on the porous diamict of the lower cave, causing its removal by erosion. These observations of water-eroded caves in lavas in Hawai‘i offer a new perspective on deep-seated water courses in volcanic edifices.

Feasibility of Public Access to Þríhnúkagígur

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Þríhnúkagígur was fully surveyed in two field trips in-Spring 1991. Public access to this tremendous volcanic bottle-shaped chimney subsequently has been proposed and discussed several times.

A tunnel to the bottom of the vault has been considered repeatedly. That proposal is not attractive. Although the vault is impressive from the bottom, the view basically is of bare country rock devoid of its original lava coating and formations, for tens of meters upward. This is not especially exciting, nor is standing on the pile of fallen rock at the bottom. Because of weathering of the uppermost part of the shaft and because of falling snow, ice and other debris, danger from rockfall and shatter exists within a radius of 10m from the center line. The possibility of additional rockfall from the overhanging sides of the shaft has not been investigated.

A spiral stairway down the shaft would damage notable lava formations in the narrow funnel at the top. It also would spoil the view of the impressive crater opening at the top of the cinder cone. For the vault to be enjoyed, a spiral ladder hanging from the top would have to be 65m long. Its construction would not be feasible, nor for most persons to descend and ascend it.

A few months ago, a new idea came to the author. At about -60 m, the shaft could be accessed through a 200 m tunnel. With reflection and study of our maps, the idea became even more attractive. At that level, a grid view balcony under the closed NE vent would be under an overhang of solid rock

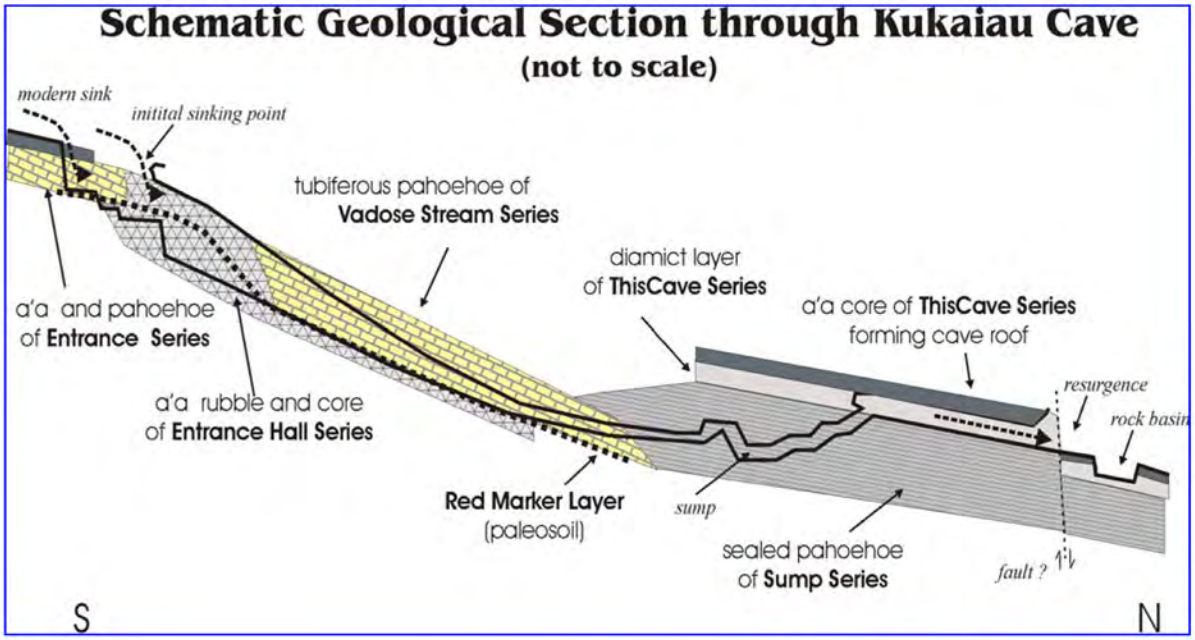

Fig. 1: Schematic geological section through Kuka'iau Cave, showing its complex course through a variety of different rock layers and illustrating the upward movement of water in the sump-section.

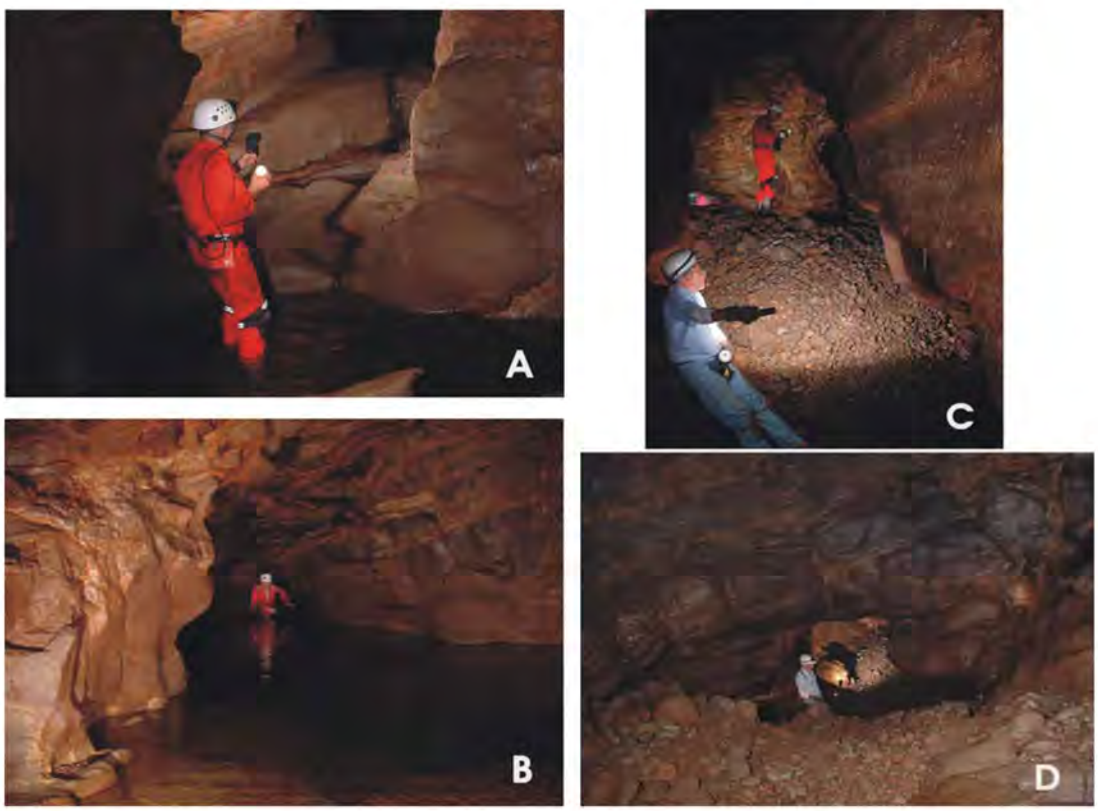

Fig 2: Sump Section: A) Natural rock dam maintaining water level in Echo Lake, a permanent lake even when the sump is empty; B) Echo Lake, which separates the upper and lower parts of the cave. It was first passed in June 2002; C) Chute above Echo Lake. Here, gravel is moved uphill when the cave floods; D) View down the last chute. When the cave floods, the water wells up from this point into the vadose lower section of the cave under a pressure of up to 6 bar.

Figures for Kempe et al. Kuka'iau Cave

where the shaft widens. Thus it would be sheltered from falling rock and snow. Intact lava formations are impressive at this level, and would be in no danger of damage. The sight downward into the widening chamber is as if one were standing on the top of a 20-story building inside a mountain. Two such buildings would fit in this space, side by side. The openings of two tunnels about 4 x 4 m would occupy only about 1:1000 of the wall space. Between such tunnels, a balcony for lighting would do trivial damage to the walls. A light, stable chain fence around the opening at the top would suffice for protective work, thus making the awesome pit accessible and conserving it at the same time.

Whether or not this engineering project can really be done has not been decided, but preliminary work has begun. The author would welcome constructive input.

Volcanic and Pseudokarstic Sites of Jeju Island (Jeju-do), Korea: Potential Features for Inclusion in a Nomination for the World Heritage List

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Scientific research has been conducted on various features of Jeju Island, looking toward a nomination as a World Heritage Site. The Island contains a variety of volcanic landforms and more than 100 lava tube caves of geological and speleological significance. It essentially consists of one major shield volcano, Hallasan (Mt. Halla), with satellite cones around its flanks. Especially notable features include maar (Sangumburi), parasitic cones (Geomunoreum and Seongsan-Ilchubong), giant lava tubes (Bengdwi Cave, Manjang Cave, Gimnyeonsa Cave, Dangcheomul Cave and Susan Cave), an exposure of columnar jointing at Daepodong, a volcanic dome (Mt. Sanbang) and the Suwolbong tuff deposits. Especially notable are the lava tube caves, which show a complete flow system and display perfectly preserved internal structures despite their age of 0.2-0.3 Ma BP. Dangcheomul Cave contains calcareous speleothems of superlative beauty.

Four aspects are identified which demonstrate the congruence of specific features to criteria for World Heritage status:

1) The volcanic exposures of these features provide an accessible sequence of volcanogenic rocks formed in three different eruptive periods between 1 million and a few thousands years BP. The volcanic processes that made Jeju Island were quite different from those for adjacent volcanic terrain;

2) The listed features include a remarkable range of internationally important volcanic landforms that contain and provide significant information on the history of the Earth. The environmental conditions of the eruptions have created diverse volcanic landforms;

3) The largest and most spectacular lava tube caves are located in the western and north eastern parts. With a length of 7.416 km, Manjang Cave is one of the longest and most voluminous. Its single passage contains two (locally three) levels. Other, shorter caves (i.e., 4.481 km Bengdwi Cave) are more complex in form. Susan Cave is a beautifully formed classical lava tube with 4.393 km in length;

4) Of great significance are the abundant carbonate speleothems seen in some low elevation lava tube caves. This phenomenon is very uncommon, and the spectacular caves in which it occurs on Jeju Island are generally acknowledged to be world's leading examples. Dangcheomul Cave can be considered to be the world's most beautiful lava tube cave containing calcareous speleothems.

Closed Depressions on Pahoehoe Lava Flow Fields and Their Relationship with Lava Tube Systems

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Closed depressions have long been recognised as significant features of basaltic pahoehoe lava flows, but their origin has been greatly misinterpreted. Many depressions have been classified as collapse features, while some scientists deny the presence of collapse forms and regard all such features as lava rise pits. In their study of Icelandic pahoehoe lava flow fields the present authors recognise the presence of five different types of closed depressions, which they classify as: open skylights in the roofs of lava caves, conical depressions caused by surface collapse into underlying voids, lava rise pits, shallow sags from the draining of lava rises, shatter rings or collapsed tumuli.

This paper will describe examples of the different types of depressions from the Laki lava flow field (Skaftáreldahraun) and the Hallmundarhraun, and will discuss the role of lava tubes in their formation. It will be seen that an understanding of the forms of closed depressions assists interpretation of the style of emplacement of historic and ancient lava flow fields.

Poster Presentations

GESPEA: Working Group on Volcanic Caves of the Azores

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In 1998, the Regional Government of the Azores established a working group (called GESPEA) to be in charge of studying volcanic caves of the archipelago. This was done because of the rich geological and biological resources and values of the volcanic caves of this region, and their uniqueness. This group is developing a data base and a classification system intended to gather all available information on these caves. It also intends to streamline management of Azorean caves and pits for tourism as well as scientific study.

The various volcanic caves the Azores jointly form a distinct entity. As a whole they provide a diversified geological, biological and aesthetic patrimony that must be publicized and protected in ways consistent with each of these factors. In addition to developing the data base and classification system, the GESPEA is working on policies for overall protection, and on specific legislation where special needs exist.

Analysis of Iron Speciation Microstructures in Lava Samples from Hawaii by Position Sensitive X-Ray Absorption Spectroscopy

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As a result of rapid cooling and solidification of liquid lava after eruption, many volcanic rocks are fine-grained and homogeneous. However, many of them contain fragmented minerals which formed before the eruption and are evident as comparatively large particles within a fine matrix. Also the rock may contain numerous vesicles formed by gases expanding within the melt.

Iron is a common element in volcanic rocks. It may be present in different states of oxidation, depending on the time and speed of oxidation processes during and after cooling. Hematite is specifically noticeable in the form of a thin, shiny bluish-grey layer on surfaces of natural lava tunnels, which have been active for a long time. This shiny layer is commonly called "glaze".

X-ray absorption fine structure spectrometry (XAFS) has become a powerful, widely-used method of speciation analysis. It allows direct, non-destructive determination of chemical bonding forms of selected elements, provided that they are present in sufficiently high concentration and suitable reference data are available. Analysis of the near-edge structure (XANES) of the absorption spectrum provides information about the valence state and coordination geometry. The valence determines the exact location of the absorption edge on the energy axis, called the edge energy (E0). The coordination influences the shape of the absorption edge.

The standard application of XAFS is bulk analysis of homogenized samples. If a sample contains several different species of the selected element, it may be possible to identify all components from the resulting absorption spectrum although without gaining any information on their spatial distribution. Spatial XAFS analyses of metal speciation in solid samples at the micrometer scale have been largely limited to spot analyses, using a microfocussed beam directed at a few pre-elected spots on the sample. The investigation of entire sample areas by this method is not practicable because a spot-by-spot collection of absorption spectra is extremely time-consuming. Only a few attempts have been made to perform XAFS imaging experiments by parallel detection (Kersten and Wroblewski, 1999, Mizusawa and Sakurai, 2004).

Lava glaze samples from Three Fingers Mauka Cave, Mackenzie State Park, Hawaii were analyzed. The rocks which form these lava tubes are known to contain different ratios of FeO / Fe_2O_3, depending on their location (Kempe, 2003). In thin sections, some particles up to 1 mm in diameter were visible within the fine matrix. Details of the analyses will be presented.

The micro XAFS experiments were conducted at HASYLAB Beamline G3. A spatially resolved image of the sample area penetrated by the monochromatic beam (approx. 10 mm wide and 5 mm high) was recorded directly on the X-ray sensitive CCD chip of the camera

(Hamamatsu C-4880, chip dimension 13 x 13 mm, pixel resolution 13 μm, cooled down to 65 °C). The shutter was synchronized with the readout of the CCD and the ionization chambers (I0 in front of the sample, I1 behind it) so the exposure time could be optimized by normalizing it to the I1 reading. The energy range was from 7000 to 7400 eV with incremental steps of 1 eV, so each scan contained a sequence of 401 images along with the readings from the ionization chambers. The monochromator was stabilized electronically.

The image sequences were processed using specific IDL routines and the remote sensing software ENVI. After creating a stack of absorption coefficient images, the Minimum Noise Fraction (MNF) transformation was calculated for an energy range of 100 eV around the absorption edge. Thus the areas on the sample with the most evident differences in the image range around the absorption edge were found. Then classes of different XAFS spectra were identified by selecting specific features from a scatter plot created from two eigenimages. The according spectra were obtained by summarizing the absorption spectra of all pixels which were assigned to the same class. E0 was defined as "halfway up the absorption edge".

The varying shape and height of the absorption edges reflect the inhomogeneous distribution of iron in the sample with a clear resemblance of the map to the visible structures. The E0 values obtained from the average of three scans are 7117.73 eV for class 1 and 7118.15 eV for class 2. These must be interpreted with some caution. A precise calibration of the monochromator was not possible, and since energy steps of 1 eV were used, the difference between the E0 of classes 1 and 2, which is less than 1 eV, may not be significant. However, each scan showed the same E0 with only negligible variation, and the same difference between classes 1 and 2: thus it is believed that the average can be trusted quite well. The edge energy of trivalent iron species is known to be approximately 2 eV above E0 of divalent species.

The results of the present study suggest that the samples contain an inhomogeneous mix of different iron species with slightly different valence states. Pyroxenes and/or olivines are the most likely components, and some hematite particles also may be present, although they could not be seen in the sample. Due to the lack of calibration and the small difference between the absorption edges, a more definite identification of species is not possible at this point. For this purpose, a better signal to noise ratio is needed so that the full EXAFS spectra can be analyzed, not just the XANES region.

With this setup, position sensitive x-ray absorption spectroscopy is possible at about 10μm spatial resolution. By detailed examination of the XANES spectra, information about differences in Fe concentration and oxidation state between areas was obtained. Future efforts will focus on samples with clearly visible hematite glazing while avoiding the presence of holes in the samples. With an improved setup, we will seek to make the full EXAFS range usable for analysis.

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New Data on the Probable Malha Grande Lava Flow Complex Including Malha, Buracos, and Balcões Caves, Terceira, Azores

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Located in the Malha Grande lava field, Gruta dos Balcões is the longest cave on Terceira island. The current length of its mapped passages is 4.421 km.

Recent field surveys have shown that two other nearby lava tube caves are probably isolated segments of the principal tube of Gruta dos Balcões: Gruta dos Buracos and Gruta da Malha Grande. This would make the total length of Gruta dos Balcões system about 5.021 km. Further, other lava tube caves north of Gruta dos Balcões (e.g. Terra Mole, Cascata, Principiantes, Opala Branca and Chocolate) are in the same flow field and probably also belong to the same complex. If this is true, the total length of the Gruta dos Balcões Complex is around 6 km. This would make Gruta dos Balcões the longest lava tube system in the Azores, surpassing the Gruta das Torres lava tube system on Pico island.

The Malha Grande lava tubes are believed to have been formed by the eruption of Pico do Fogo volcano 240 years ago. Its caves are occasionally visited by local people and need protection from vandalism above and below ground. Moreover, the presence of cattle is creating some disturbance in and around entrances to some of the caves. We recommend that this notable area of large and beautiful caves be specifically managed to protect and preserve its extraordinary underground resources.

2004 SYMPOSIUM PAPERS

Rare Cave Minerals and Features of Hibashi Cave, Saudi Arabia

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Abstract

Ghar Al Hibashi is a lava tube situated in a field of vasicular basaltic lava flows located 245 km east of Makkah (Mecca) Saudi Arabia. The cave has 581 m of mainly rectilinear passages containing a bed of loess up to 1.5 m deep, OSL-dated at 5.8±0.5 ka bp at its lowest level, as well as many bones and the desiccated scat of hyenas, wolves, foxes, bats, etc., well preserved due to a temperature of C 20-21° and humidity of 48%. Phytoliths have been found inside plant material preserved in samples of this scat. A human skull, 425 years old and the remains of an old wall indicate a potential for historical or archaeological studies. The loess bed is under study for testing microrobotic designs to navigate inside lava tubes on Mars.

Two large bat guano deposits in this cave caught fire in the past, possibly affecting "bio-stalactites" : soft, yellowish, accretions, c. 4 cm long by 1 cm wide, thought to be formed of bat urine. Nineteen minerals were detected in samples collected, mostly related to the biogenic mineralization of bones and guano deposits. Three of them, pyrocoproite, pyrophosphite and arnhemite are extremely rare organic compounds strictly related to the guano combustion, observed until now only in a few caves in Africa. Hibashi Cave may be one of the richest mineralogical shelters of the Arabian Peninsula, and has been included in the list of the ten minerologically most important lava caves in the world.

Introduction

In the year 2001, the Saudi Geological Survey initiated subproject 4.1.3 "Mapping of underground cavities (caves) in Phanerozoic rocks." Studies of caves located in the Phanerozoic limestone belts of the country demonstrated that some contained artifacts, bones, etc. of historic, environmental and archeological value (Pint, 2003), while others were judged aesthetically and structurally suitable for purposes of tourism (Forti et al, 2003, Cigna, 2004). In light of these studies, the investigation of cavities in Saudi Arabia was broadened to include lava caves in order to determine their possible value for scientific and touristic purposes.

Saudi Arabia has approximately 80,000 kms^2 of lava fields, known as Harrats (Fig.1). In late 2001 and early 2002, a preliminary survey for lava-tube caves was carried out in Harrat Kishb, a young basaltic lava field with an area of 5, 892 kms^2 centered circa 270 km northeast of Jeddah. Six lava caves were located, three of which were mapped. These three caves were found to contain items of historical, geological and archeological interest (Roobol et al, 2002).

From November 2002 to the present writing, other lava caves were located in Harrats Ithnayn, Buqum-Nawasif and northern, central and southern areas of Harrat Khaybar. Two of these caves, Dahl Romahah and Kahf Al Shuwaymis, are briefly described in Pint, 2004 and are still under study.

Hibashi Cave appears to be deserving of special attention due to the wealth of mineralogical data which has come to light from the analyses of speleothems found in it. It has, in fact, recently been included in the list of the ten mineralogically most important lava caves in the world (Forti, 2004). In addition, the floor of Ghar Al Hibashi is covered with a layer of loess or fine silt, up to 1.5 m in depth, of considerable interest to sedimentologists as well as scientists studying the lava tubes of Mars, whose surface is covered with a similarly fine sediment, according to NASA, 2004. Hibashi Cave is also the site of two extensive guano fires, which have rarely been described in speleological publications (Martini, 1994b) and whose effect on secondary cave minerals is of interest to speleo-mineralogists.

The casual discovery of a human skull and a man-made wall inside Hibashi Cave give hope that archeologists and historians could carry out fruitful studies in this cave. In addition, the considerable quantities of bones, guano and animal scat inside the cave may shed light on the past flora and fauna of the Arabian Peninsula. In particular, phytoliths found in plant fibers inside wolf and hyena scat from Hibashi Cave may be of value in studying the desertification of Saudi Arabia.

It is hoped that this publication will confirm the importance of Hibashi Cave and will be of use to government authorities in protecting the cave from vandalism and intrusions.

Geology of Harrat Nawasif-Buqum

Ghar Al Hibashi is located in Harrat Nawasif-Buqum, a group of lava flows encompassing about 11,000 km^2 and roughly situated between the towns of Turubah and Ranyah, E of Makkah, Saudi Arabia. The origin of the basalts in Harrat Nawasif-Buqum is attributable to the period of magmatic eruptions that began in the Miocene and continued until historic times. These basalts can be classified as Upper Tertiary and Quaternary. They are primarily titaniferous olivine basalts, including alkali basalts, basanites and nepheline-basanites, occasionally interlayered with pyroclastics. Hotzl et al (1978) took two samples

Figure 1. Map of Saudi Arabia showing all major laval fields. Hibashi Cave is located in Harrat Nawasif-Boqum.

of Harrat Nawasif-Buqum basalts for potassium-argon age-dating, yielding ages of 3.5±0.3 million years for the older basalts and 1.1±0.3 million years for the younger. Because of the relatively unweathered condition of the basalt in which it is found, it can be assumed that Ghar Al Hibashi lies within one of the younger flows, However, it should be noted that the younger sample dated by Hotzl et al (1978) was taken from the area of Sha'ib Hathag, some 63 kms NE of Ghar Al Hibashi. Arno et al (1980) report ages of 22.8, 15.8, 7.3, 4.4 and 2.8 million years for samples taken from the flows of this harrat, leaving the exact age of the basalt in which Hibashi was formed, very much in question.

Ziab and Ramsay, 1986, state that the Buqum basalt is between 20 and 25 m thick in the Turubah area but much thinner farther north. The depth of Ghar Al Hibashi (about 22 meters from the surface to the cave floor) suggests that the cave may lie within the basalt studied by Ziab and Ramsay, which they describe as gray to dark gray, vesicular, medium grained and prophyritic, containing phenocrysts of olivine, titanaugite, plagioclase and opaque minerals. They further state that it has an SiO_2 content ranging from 42 to 47 percent, high TiO_2 (1.42-2.79 percent), and high P2O5 (0.32-0.67 percent). Almost all the rocks they studied were undersaturated, with 0.3 to 7.8 percent nepheline, 8-21 percent olivine and no quartz in the norm. All the rocks were highly sodic and normative alibite exceeded normative orthoclase, typically by a factor of approximately five.

Figure 2 is an aerial photograph showing the flat-lying undeformed, unmetamorphosed basaltic lava flows and cinder cones in the vicinity of Ghar Al Hibashi. Lava flows from what appear to be at least four different events can be seen within one km distance from the cave entrance. While steep-walled scoria cones less than 200,000 years old lie less than two kms from the cave, the entrance to Ghar Al Hibashi appears to be located in an older flow.

Description of Ghar al Hibashi

The exact location of Hibashi Cave is given in Pint, 2001, where it is registered as Cave number 180. The cave is located approximately in the center of Harrat Nawasif-Buqum inside a vasicular basaltic area, in a slightly raised portion of a major basaltic flow emanating from a large crater to the southeast. The cave lies approximately 22 m below the surface and contains 581 m of passages. The main passage is mainly flat and runs east and west, intersected by a side passage running NW-SE, downsloping from an entrance collapse to the floor of the main passage. Plan and Profile maps of the cave are shown in Figure 3 and the cave entrance in Figure 4.

Secondary Minerals of the Cave. During three different expeditions

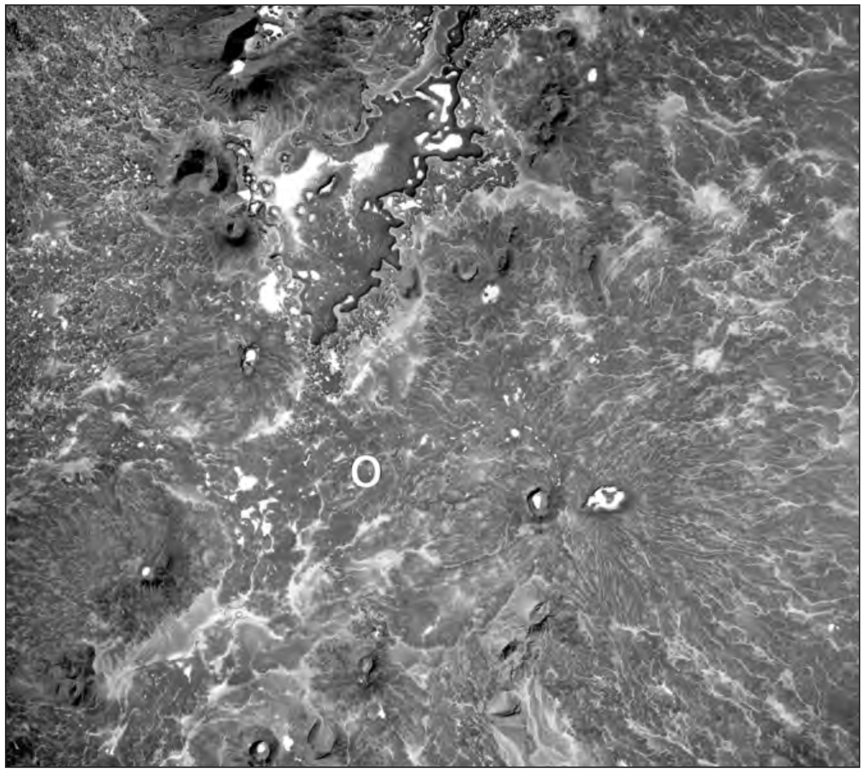

Figure 2. Aerial photograph of the flat-lying undeformed, unmetamorphosed basaltic lava flows and cinder cones in the vicinity of Ghar al Hibashi. located in the circle.

Figure 4. The entrance to Ghar al Hibashi. No rigging is required to visit the cave.

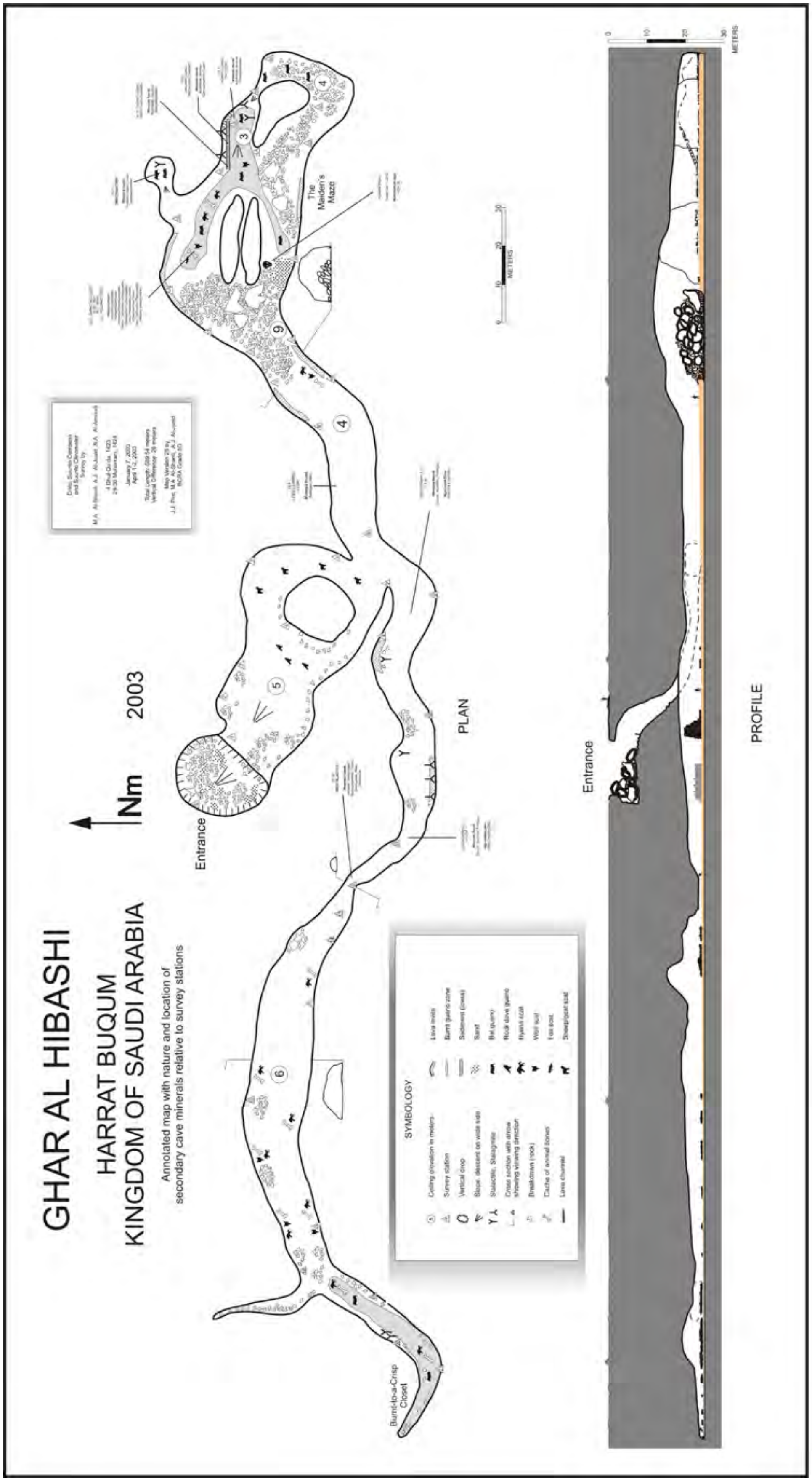

Figure 3. Map of Ghar al Hibashi. A larger version of this map is included in the supplementary material on the CD.

carried out in 2003, a few samples of secondary chemical deposits were collected inside Ghar Al Hibashi to be analysed from the mineralogical point of view. This research was carried out as part of the MIUR 2002 Project "Morphological and Mineralogical Study of speleothems to reconstruct peculiar karst environments" under the direction of Prof. Paolo Forti and is described in detail in Forti et al, 2004. The minerals detected in samples from Hibashi cave are listed in table 1.

Mineralogical importance of Ghar Al Hibashi. A great variety of minerals developed within the cave environment thanks to the peculiar conditions which in time made it possible for different minerogenetic mechanisms to become active. Among these the one related to guano combustion is quite unusual and allows a better description of some very rare cave minerals, which were observed until now only in a few caves of Namibia.

Thanks to these findings, Hibashi lava tube has been referred to as the most important volcanic cave of Saudi Arabia and the richest mineralogical shelter of the country (Forti et al, 2004). For this reason, Hibashi cave has been inserted in the "top ten volcanic caves" for hosted minerals (Forti, 2004). This research is a further confirmation of the recently advanced opinion that amongst the different cavern environments, the volcanic one is the most favourable for the development of minerogenetic mechanisms and consequently of cave minerals.

Loess Floor Cover. To date, six volcanic caves located in Saudi Arabia have been studied and mapped by speleologists. In each of these, sediment covers most, if not all of the original basalt floors. Mud and a phosphate-rich compound were found in lava caves on Harrat Kishb (Roobol et al, 2002) while sand, mud and dust cover the floor of Kahf al Shuwaymis in Harrat Ithnayn and wet and dry mud lies on the floor of Dahl Romahah in Harrat Khaybar. In addition, eight lava caves surveyed in Jordan show similar characteristics (Kempe, 2004). The sediment in Saudi Arabia's Ghar Al Hibashi, however, seems to consist mainly of a thick (up to 1.5 m deep) layer of powdery silt. In order to better understand the nature of the Hibashi sediment, researchers participating in the SGS Loessic Silt Project were invited to visit the cave.

Collection of samples. Two samples of silt were taken on August 31, 2003, in each case from the very lowest level possible, immediately above the original cave floor. Holes were dug by shovel in order to access the bottom of the sediment layer. A pressurized water sprayer

Table 1. Identified cave minerals and their distribution within the cavity: Hi2: burnt wolf scat; Hi6b: ash from burnt zone; Hi7: bone from burnt zone; Hi8: volcanic rock from burnt zone; Hi9: dirt sample from –70 cm below floor; Hi10: nest of insect larvae; Hi12: content of lava channels; Hi13: lower extreme content of lava channel; Hi14: burnt coating on ceiling; Hi15: sticky stalactite between stations 18w-19w; HiZZ: sticky stalactites near station 12w. The following, detrital and/or not cave-related, minerals have been also detected: calcite (Hi2), dolomite (Hi2), feldspar (Hi2, Hi7, Hi8, Hi9, HiZZ), illite (Hi9) and pyroxene (Hi8); no minerals at all have been detected in Hi10.

Sample	Mineral	Formula	Characteristics
Hi7, Hi8	**1** - Anhydrite	$CaSO_4$	Orthorhombic - milky-white small earthy subspherical grains
Hi6b, Hi7, Hi12, Hi13, Hi14	**2** - Aphthitalite	$(K, Na)_3Na(SO_4)_2$	Trigonal Honey yellow to dark brown subspherical grains and/or vitreous fragment mixed with **6** and/or **4**
Hi8	**3** - Arnhemite	$(K,Na)_4Mg_2(P_2O_7) \cdot 5H_2O$	Hexagonal – Soft uncemented white dull material mixed with **13** and **16**.
Hi6b, Hi7, Hi12, Hi13, Hi14, Hi15, Hizz	**4** - Arcanite	$K_2(SO_4)$	Orthorhombic Emi-transparent to lemon yellow vitreous crust, mixed with **9, 13, 15 e 16** or plastic microcrystalline honey yellow small aggregates mixed with **2 e 6**
Hi7, Hi8	**5** - Archerite	$(K, NH_4)H_2PO_4$	Tetragonal – pale gray glassy luster coralloids mixed with **15** and **16**.
Hi12, Hi13, Hi14, Hi15, Hizz	**6** - Biphosphammite	$(NH_4, K) H_2 (PO_4)$	Tetragonal – Honey yellow to transparent subspherical grains and/or vitreous crusts or plastic microcrystalline honey yellow to dark brown and black masses with rare thin elongated prismatical crystals . Often mixed with **2, 4, 6** and **18.**
Hi7	**7** - Calcite	$CaCO_3$	Trigonal- Very rare as insulated crystals or aggregates of elongated crystals
Hi6b, Hi7	**8** - Carbonate-hydroxylapatite	$Ca_5(PO_4,CO_3)_3(OH)$	Hexagonal – honey yellow vitreous semi-transparent hard material
Hi6b, Hi7, Hizz	**9** - Chlorapatite	$Ca_5(PO_4)_3Cl$	Monoclinic – Cream white microcristalline hard material with rare aggregates of small dumpy fibrous prismatic crystals
Hi7	**10** - Halite	NaCl	Cubic – Rare semi-transparent pale blue coralloid grains strictly associated with **9** and **14**.
Hi6b, Hi7	**11** - Hydroxylapatite	$Ca_5(PO_4)_3(OH)$	Hexagonal – Porous to compact fragments within bone partially transformed into **19**.
Hizz	**12** - Niter	KNO_3	Orthorhombic Similar and always strictly mixed to **6**
Hi6b, Hi7, Hi8, Hi15, Hizz	**13** - Opal-C	$SiO_2 \cdot nH_2O$	Tetragonal – Semi-transparent to pale yellow viteous globular or coralloid crusts mixed with **15, 16** and **17**.
Hi7	**14** - Palygorskite	$(Mg,Al)_2Si_4O_{10}(OH) \cdot 4H_2O$	Monoclinic/Orthorhombic – Soft tuft of snow-white thin, bent, fibrous crystals
Hi6b, Hi7, Hi8	**15** - Pyrocoproite	$(K,Na)_2Mg(P_2O_7)$	Monoclinic – Semitransparent to pale grey vitreous globular saccaroidal crusts or pale green elongated pseudo-fibres. Often mixed with **16**.
Hi6b, Hi7, Hi8	**16** - Pyrophosphite	$K_2Ca(P_2O_7)$	Monoclinic colourless to snow-white vitreous saccaroidal crusts. Nearly always mixed with **15**.
Hi6b, Hi7, Hi8, Hi12, Hizz	**17** - Quartz	SiO_2	Trigonal crust or insulated grains without the characteristic prismatic habit often associated with **13, 15** and **16**.
Hi7, Hi8, Hi15, Hizz	**18** - Urea	$CO(NH_2)_2$	Tetragonal – small colourless to pale yellow transparent prismatic tabular crystals or radial aggregates
Hi6b, Hi7, Hi8, Hizz	**19** - Whitlockite	$Ca_9(Mg,Fe)(PO_4)_6[PO_3(OH)]$	Trigonal – Milky white spongy material or small vitreous pinkish crystals over bone fragments

Figure 5. Measuring the depth of the loess bed at the second sampling point.

was used to strengthen the side walls as the holes were dug and also to minimize the amount of dust in the air. Sample number one was taken from a point 4 m SE of station 11W, in the middle of the passage. The sediment was 40 cm deep at this point. The sample was forced into a heavy-duty PVC tube which was then sealed with tight-fitting end caps. Desiccated hyena scat, twigs and fragments of basalt were found lying on the original floor of the cave. The second sample was taken from the bottom of a hole dug halfway between stations 8W and 9W, equidistant from the walls of the passage. At this location, 60 meters closer to the cave entrance than the first sampling point, the sediment was found to be 1.5 m deep (Fig. 5).

Analyses of loess content. The results of analyses carried out on these samples will be reported in Vincent and Kattan, 2005. Below we briefly summarize comments on the Hibashi sediment communicated to the chief author by Dr. Peter Vincent.

A laser granulometer indicates that this sediment is loess with a mean particle size of about 10 microns. It is a fine silt dominated by quartz, feldspar and kaoline, as determined by XRD analysis. The kaoline indicates that it was derived from deep weathering because it is an end-product clay mineral that now only forms in humid tropical conditions. The quartz is almost certainly derived from the deeply weathering laterites which are filled with eroded quartz grains. There is abundant evidence that deep weathering of the Shield took place in Miocene times after the uplift, releasing the quartz silt. Because the silt could not have come from the basalt in the area (which is a basic rock and quartz poor), it is not a local fluvial deposit, but must be related to the weathering underneath the local basalt or must come from further afield. It was almost certainly carried into the cave by air (Vincent, 2004).

Age dating of Hibashi loess. Optically Stimulated Luminescence (OSL) was used to date the two samples from Ghar Al Hibashi. The procedures were carried out during a six-month period in 2003 at Oxford University, U.K., using a Danish instrument from Riso. The age of sample 1 (depth: 40 cm, circa 150 m from the cave entrance) was found to be 4.5±0.2 ka while the age of sample 2 (depth: 150 cm, circa 90 m from the entrance) is 5.8±0.5 ka. Both of these dates are post-Holocene wet-phase (7 ka bp) and presumably relate to the onset of aridity and more frequent windstorms (Vincent, 2004).

Role of Hibashi loess for design of microrobots for Mars. A joint project by the Field and Space Robotics Laboratory of MIT (Massachusetts Institute of Technology) and the Cave and Karst Studies Program at New Mexico Tech. (NM Institute of Mining and Technology) is using Hibashi Cave as a model for lava tubes on Mars. This project, funded by the NASA Institute for Advanced Concepts (NIAC) is looking at microrobotic technology for accessing such systems in extraterrestrial locations (Dubowsky et al., 2003).

Interest in lava tubes on other bodies including Mars and the Moon for future space missions has been suggested by a number of investigators (Boston, 2003, Frederick, 1999, Horz, 1985). A detailed NIAC study over four years has produced a set of enabling technologies that will allow robotic and ultimately human use of Martian lava-tube caves. One of those identified technologies, i.e. the need for highly capable miniature robotics for ground-based detection, reconnaissance, and mapping of lava-tube structures, has led to the most recent project.

Mars has many lava tubes of great size that are quite conspicuous on orbital imaging data from various Mars mission instruments. The NMT team has identified numerous instances of these. Because of the large amount of very fine surface material that is globally distributed on Mars by planet-scale dust storms occurring at fairly regular intervals, the NMT workers have hypothesized (Boston, 2004) that such materials would sift into lava tubes and create a flat floor of such unconsolidated deposits. The Hibashi system is filled with such material and presents a perfect analog for such a situation. According to Boston, 2004, the detailed map of the system, shown in Figure 3, has been invaluable in producing robotic motion simulations created by the MIT team to test the capabilities of the candidate microrobotic designs to navigate into and around such a challenging environment. The project is continuing with a Phase II proposal to be submitted to NASA in the near future.

Animal and avian excreta in Ghar al Hibashi

The arid climate of Saudi Arabia results in relatively low humidity within most of the country's caves and, therefore, the preservation of much of the caves' contents which, under wetter conditions, would be destroyed by decomposition or water movement. The humidity of Hibashi Cave, for example, is typically 48%.

Animal and avian excreta introduced into the cave environment have been remarkably well preserved in Hibashi Cave and merit study, as will be explained below. In contrast, so little evidence of the presence of fauna has been found inside most of the world's caves, that the official List of Cave Symbols of the International Union of Speleology (UIS) has only one symbol for excreta, a v-shaped drawing which represents the guano of bats or birds. Hibashi Cave, however, contains the desiccated excreta of at least six species in such quantity that they are useful not only as landmarks, but also for understanding the history, climate, flora and fauna of the area, both inside and outside the cave.

Figure 6. The three types of animal feces most frequently found in Saudi caves. From left: hyena, fox, and wolf.

Unlike typical coprolites, this dry scat can easily be broken apart and its contents examined.

By far the most frequently found type of scat is tan, sometimes white, in color, less than 4 cm long and less than 2 cms wide, sometimes tapered at one end. Benischke found large quantities of similar scat in B7 (or Murubbeh) Cave, located on Saudi Arabia's Summan Plateau. Toothmarks on bones found near these droppings led experts in Austria to identify them as hyena scat (Benischke et al, 1988). Although hyenas are not normally found in most parts of Saudi Arabia today, they can still be seen in the southwestern part of the kingdom where they are considered unwelcome predators. In 1998, speleologists observed the body of a recently killed hyena hanging in the air near Al Jawah village, approximately 103 kms SSW of Hibashi Cave. The great amount of hyena scat found in caves all over Saudi Arabia (Pint and Pint, 2004; Pint, 2000; Roobol et al., 2002; Al-Shanti et al., 2003) indicates that these animals were more prevalent in the past than they are today. Larger, cylindrically shaped scat, brownish in color, is less frequently found in Hibashi Cave. This is thought to be wolf scat, based on the opinions of local people regarding scat of similar size, shape and color found in other Saudi limestone and lava caves (Al-Shanti et al., 2003). Figure 6 shows the three types of animal feces most frequently found in Saudi caves. Hyena scat is seen on the left and wolf scat on the right. It seems likely that the scat in the middle is from a fox. Similar scat was found in Black Scorpion cave where foxes were observed outside the cave, at night. Live foxes were also seen near and inside Murubbeh/B7 cave where the desiccated body of an Arabian Red Fox (Vulpes vulpes arabica) was found. Carbon dating indicated the remains to be 1890±45 years old, suggesting that foxes have long lived deep inside caves in Saudi Arabia.

Mounds of rock-dove guano are found between stations 3 and 4 and probably once covered a much larger part of the sun-lit portion of the cave, but have been destroyed, probably by human traffic.

Researchers at Oxford University, U.K. have discovered phytoliths in plant fibers found in hyena scat from Hibashi cave. According to Mulder and Ellis (2000), plant opal-phytoliths are of great value for the study of aridification, desertification, wind patterns, etc. Phytoliths are microscopic bodies that occur in the leaves, roots, etc. of plants. They are composed of opaline silica or calcium oxalates and have unique shapes that act as signatures for the plants that produced them.

In Ghar Al Hibashi, the age of phytoliths may be determined from the vertical position of the scat in the bed of loess or by carbon-dating scat samples. Since plant fibers are commonly found in hyena and wolf scat (Fig. 7), caves in Saudi Arabia and Hibashi Cave in particular, may provide a sufficient source of phytoliths for the study of climate change and desertification on the Arabian peninsula.

Observations on a human skull found in Ghar al Hibashi

Parts of a human skull were found in Ghar Al Hibashi by SGS geologist Abdulrahman Al-Jouid on January 7, 2003. The two pieces were lying at the edge of a patch of sand 8 m NE of station 26 near the far eastern end of the cave. Because human skulls previously had been stolen from Murubbeh-B7 cave (see Forti et al, 2003, pp 18-19) and because Hibashi Cave has no gate and is occasionally visited by the general public, as indicated by graffiti at the cave entrance and inside, it was decided to remove the skull parts from the cave for safekeeping.

Photographs of the skull parts (Fig. 8) were shown to Donald A. McFarlane, Associate Professor at the W. M. Keck Science Center, Claremont Colleges, California. He stated (McFarlane, 2003) that both pieces were obviously human and appeared to be in quite good condition, even though the parietal and occipitals of the cranium were missing. He identified the smaller fragment as the back of the cranium, the hole being the magnum foramen into which the spinal column connects. McFarlane noted the cranium had apparently split off along the coronal and squamosal sutures, possibly suggesting a relatively young (adult) individual, since these sutures increasingly fuse with age. He also noted that the skull appeared to have only seven teeth per quadrate. The 3 molar which typically develops between 15 -21 years of age appeared to be un-erupted. Since the second molar

Figure 7. Broken scat showing plant fibers.

Figure 8. The skull found in Ghar al Hibashi. It is approximately 425 years old.

Figure 9. The upper portion of the skull appears to have been removed with the help of a flat blade, such as from a sword or axe, suggesting the possibility of foul play in the death of this individual.

comes through at about 11-12 years, McFarlane was of the opinion that the individual had been about 14-18 years old at the time of death.

Photographs of the teeth were also shown to Dr. Erik Bjurström, dental consultant, who noted (Bjurström, 2003) that in this skull the canines were not fully erupted and baby tooth 5 was still in place. Bjurström estimated that the skull belonged to a person 12 to 14 years old, using norms that apply to modern man.

In 2003, samples were taken from the larger skull piece and sent to the Gliwice Radiocarbon Laboratory at the Institute of Physics of the Silesian University of Technology, Gilwice Poland. Collagen was successfully extracted from the sample and a radiocarbon age of 425±30 years BP was established.

As may be noted in Fig. 9, the upper portion of the skull appears to have been removed with the help of a flat blade, such as from a sword or axe, suggesting the possibility of foul play in the death of this individual.

Conclusions and recommendations

A number of rare and unusual secondary cave minerals were found in Ghar Al Hibashi in a small number of samples taken mainly from one area of the cave. It is recommended that similar studies be carried out on samples from the extreme western end of the cave. In like manner, a thorough study could be made of the cave silt and of the phytoliths contained in fibers found in the animal scat.

To date, no attempts have been made to dig for artifacts nor to study the bones, horns and other primate remains scattered throughout the cave. The subsurface may yield further finds of possible interest to historians, archeologists and perhaps paleontologists.

Although Hibashi Cave as been declared of world-class importance, it is, at present, not protected by a gate or a fence and is occasionally visited by the general public, as indicated by several layers of graffiti on its walls, both near the entrance and deep inside. If the cave cannot be preserved exclusively for scientific studies, it would seem useful to control the spontaneous tourism now going on there. Visitors might be restricted to certain areas of the cave and a walkway might be built (perhaps of native basalt cobbles) to reduce the dispersion of loess into the air. Such a walkway might benefit both tourists and scientists.

Ghar Al Hibashi appears to be an unusual and important cave and it is hoped that studies of this lava tube will continue.

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Biospeleology in Macaronesia

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Geographical and speleological background

In the biogeographical sense Macaronesia is a subregion of the Western Palaearctic which includes southwest continental Portugal, part of the coastal zone of south Morocco, and the Atlantic archipelagos of the Azores, Madeira, Selvagens, Canaries and Cape Verde. Since the establishment of the term in the 19th century by the British botanist P.B. Webb, much has been discussed about the validity of Macaronesia as a biogeographic unit, about its appropriate space and boundaries, and about its different meaning for vegetal and animal organisms. Two continental areas and five volcanic archipelagos have generally been identified within Macaronesia. The islands are of oceanic origin with no surface connection with other land since they emerged from the sea bottom. Independently to other biogeographic considerations, in this text we only pay attention to the strictly volcanic Macaronesian archipelagos, which constitute an insular geographic reality very different to that of the continental Macaronesian enclaves. From a political point of view the Azores, Madeira and Selvagens belong to Portugal, the Canary Islands to Spain, and the Cape Verde form an independent country, though with a strong Portuguese character for obvious historical reasons.

The Macaronesian archipelagos have common geological features mainly derived from their volcanic origin. All the islands have been built up from the sea bottom by successive accumulation of volcanic materials that finally emerged over the marine surface along the Tertiary and Quaternary. Actually the volcanism is still active on the Azores, the Canaries and the Cape Verde islands. Almost all the rocks forming these archipelagos are volcanic. However, in some of the Canary Islands (i.e. La Palma, La Gomera and Fuerteventura) there are plutonic rocks that belonged to their original basements, were uplifted over the sea level and are now exposed on the surface by the effects of erosion. On other islands like Santa Maria (Azores) and Porto Santo (Madeira) some limestone rocks of marine origin have been formed and are actually emerged because of eustatic movements of the sea level. These non volcanic rocks are anyway very scarce, and have developed such a slight karstification that true caves are not found at all inside them. Therefore, in the Macaronesian islands the caves enough developed as to be considered of speleological interest occur only in volcanic terrains.

Such particular cavities have a genesis, morphology and a life span very different than limestone caves. The main types of volcanic caves are lava tubes and volcanic pits, each with their variants depending on the type of speleogenesis (see Montoriol, 1973).

The lava tube caves are formed only in fluid basaltic lavas, never occurring in viscous acidic lava flows of trachytic nature. They originate after more or less permanent lava channels that consolidate by cooling of the peripheral layers, and are finally roofed when significant speed differences are established between the inner and the surface flow. The inner temperature of the tube allows the lava to keep flowing inside until the emission stops, the liquid empties totally and the system becomes a hollow tube. These caves are therefore usually shallow and follow parallel to the surface topography at the moment of being formed. Great accumulation of further new lavas on that containing the cave, and changes on the relief by important erosive effects can alter this parallelism between lava tubes and the actual surface upon them.

A particular type of lava tubes are those originated by the emptying of a dyke. They usually have a different morphology and since their origin are located much deeper below surface than the so called rheogenetic lava tube caves (Socorro & Martín, 1992). These dyke caves do not necessarily follow the surface topography, and normally open to outside at cliffs and other steep terrains due to erosion. Some examples of this kina of caves are Gruta dos Anjos (Santa Maria), Gruta do Inferno (Selvagem Grande) or Cueva de la Fajanita (La Palma).

The volcanic pits often derive from the emptying of volcanic chimneys when the eruption stops and the remaining lava contracts. The spatter cones are hollows with limited dimensions, while other volcanic pits can exceed 100 m deep, like Algar do Montoso, in São Jorge (Azores). They are usually bell-shaped, though they often show more complex structures with connected cavities and multiple vents. The geysers and the vents of gaseous phreatomagmatic eruptions can originate remarkable pits, like that of Sima de Tinguatón in Lanzarote. Some times the retraction cracks originated after cooling trachytic, viscous lavas can also originate remarkable pits, like the 70 m deep Sima Vicky (Tenerife).

Also lava tubes can be combined with volcanic pits in a single but complex cavity with several levels at different depths, like it occurs in Sima de Las Palomas (El Hierro) and Cueva del Sobrado (Tenerife).

Speleogenesis and ecological succession on volcanic terrains

Besides their peculiar speleogenesis when compared to karstic caves, lava tube caves have a geological cycle and an ecological succession also very different (see Howarth, 1996). The formation of a lava tube is very quick, sometimes just a few days, and immediately starts its evolution towards definitive destruction as a cave, which will take place within a period of 100,000 to 500,000 years depending on the local climate and erosion (Howarth, 1973). Volcanic pits, however, can last longer time. The cycle of lava tubes is very short in geological terms, compared to that of limestone caves (millions of years) which needed at least 100,000 years to initiate its formation. On the other hand, lava tube caves usually have much less permanent water than limestone caves (which need it for their formation and is only absent in fossil, inactive caves), and are in general much shallower so that the roots of surface plants often reach and invade the cave.

A recently formed lava tube starts with a juvenile phase characterized by its dependence on the outside climate due to the network of cracks of the lava, easily connecting the cave to the exterior. As ecological succession goes on over the lava, the soil seals the surface, shallower passages retain moisture and the cave enters in a mature phase with the subsequent climatic isolation (temperature and humidity). Thus, there is a simultaneous ecological succession inside and outside the cave, which is very important to determine the living community inhabiting this environment (Ashmole *et al*., 1992). There is a particular way to accelerate this process when a thick layer of small-sized pyroclasts (cinder and lapilli) are deposited upon the recent lavas, which isolate the cave from outside temperatures, keep the moisture and allow many plants to grow up and provide roots to the cave. Many caves in recent or very dry areas of the Canary and the Cape Verde islands have good conditions for troglobites thanks to be covered by ash fields. As time goes by the erosion leads the cave to a senile stage, in which silting of the network of cracks and voids in the surrounding lava isolates the system, the inner space of the cave can be even stuffed up by clay deposits, and internal collapses finally destroy the cavity. Volcanic pits usually have a much longer senile stage due to their larger volume and their vertical shape and more solid architecture. Thus volcanic pits last much longer than lava tube caves, reaching a few million years and being the only caves in the oldest terrains of the islands (Oromí *et al*., 1985).

In the lava tube caves ecological succession typically progresses upwards (Howarth, 1996) in such way that deep levels reach maturity before the upper levels, which need better soil cover on the surface to maintain ideal conditions for troglobites. For example Cueva de Todoque (La Palma, Canary Is.) formed in the lavas of San Juan eruption (1949) some troglobites have been found in the deepest passages, while lavicolous species are the only inhabitants in the rest of the cave (Ashmole et al., 1992; Martín, 1992). In limestone caves instead, the oldest habitats are closer to the surface and ecological succession progresses downwards.

The older is a lava tube, the higher probability to be covered by further lava flows, which keep the cave away from surface. In such conditions the roots do not reach the cave, and provision of organic matter by percolating water is more difficult. Consequently, lava tubes occurring under many lava flows hold a poor fauna or are even abiotic, as it also happens in dyke caves.

Animal communities in volcanic caves

When a lava tube has attained maturity, its environmental conditions are similar to that of limestone caves: absence of light, temperature stability, humidity close to saturation. Scarcity of organic matter is also severe, with lesser provision by water than in limestone caves but frequently compensated by the presence of roots (if there are). In the Macaronesian islands bat colonies are very few inside the caves, therefore the guano is negligible.

Volcanic pits are usually richer in food because they operate as pitfall traps for many organisms; on the contrary, in lava tubes the input of energy through the entrance only affects a few metres inside, and hardly progresses into the cave.

Adaptations to cave life are the same for volcanic and limestone troglobites: depigmentation, eye reduction, elongation of body and appendages, slow metabolism, starving resistance, longer life span, inability to live outside the cave, *k* reproductive strategies (more limited but successful offspring), etc. Higher tolerance to temperature changes has been observed in island troglobites with respect to temperate continental species, both in the nature and in laboratory experiences (Izquierdo, 1997); this could be related to the shallower lava tubes to which they are adapted, and maybe also to the less marked seasonal differences in oceanic islands.

In these volcanic hypogean communities the root-feeding species are particularly abundant with respect to other trophic categories. It is remarkable the richness of sap-sucking plant-hoppers (Cixiidae and Meenoplidae) on three of the archipelagos, while in Europe and North Africa these groups are unknown in the caves. It is also peculiar of these island cave-dwelling communities the presence of troglobitic species belonging to taxonomical groups absent in caves of the nearby mainland, and even very rare all over the world. This is the case for landhoppers (Amphipoda: Talitridae), earwigs (Dermaptera) and thread-legged bugs (Hemiptera: Reduviidae) which have troglomorphic species only in the Canary Islands and in Hawaii. The diversity and abundance of troglobitic cockroaches (Blattaria) in the Canaries contrasts with the absence of these insects in caves of the whole Palaearctic.

Troglobitic species are unable to survive outside their hypogean environment, and therefore they cannot colonize other islands. This implies that all troglobites in Macaronesia are always endemic to a single island. The presence of a troglobite in two islands could only be explained when these islands had been connected in relatively recent past times due to regressions of the sea level (for example Pico and Faial in the Azores; Fuerteventura and Lanzarote in the Canaries).

Types of caves and biological richness

It is very common to find a troglobitic species in different, distant caves formed in separated lava flows within an island. This is due to the existence of the so called Mesovoid Shallow Substratum (MSS: Juberthie, 1983; Culver, 2001), an extensive network of cracks and voids connecting large areas, which is suitable to be occupied by many troglobites. There is a particular type of MSS in volcanic islands made up by the lava clinker covered by a thin soil (Oromí et al., 1986), which has provided a rich adapted fauna in places without caves on the Canary and the Azores islands (Medina & Oromí, 1990 and 1991; Borges, 1993).

Actually troglobites occupy the extensive network of spaces in the appropriate underground, either good caves, crevices or MSS. In general they often prefer small tubes and cracks than proper "caves" that are for us just windows to reach the hypogean habitat. But in

Table I. Types of caves and animal richness.

TYPE OF CAVE	TROGLOBITES	OTHER SPECIES
Lava tubes	rich	moderate
Chimney pits	moderate	rich
Big crevices	poor	poor
Drained dykes	poor	poor
Erosion caves	none	poor

general the abundance of cavities is a good indicator to the richness of well adapted fauna in an area, especially lava tube caves which are found in basaltic terrain, the best for a good network of spaces.

Besides the stage of ecological succession and the geographic situation of a cave, the animal communities occurring in it also depends on its morphology and depth. Mature lava tubes are more isolated from the surface than volcanic pits concerning direct input through the entrance. Thus the pits can hold a richer fauna with many epigean species, while in the tubes the community is poorer but with much higher proportion of troglobites. The dyke caves are usually very poor because of their location very deep underground, where neither roots nor percolating water with organic matter arrive easily. Most of the dyke caves we have studied had a scarce fauna and always close to the entrance. Other pits like big crevices are also poor because they are usually formed in acidic lavas, which are more impermeable and unconnected to the Mesovoid shallow substratum (MSS), an important reservoir of the hypogean fauna in volcanic terrains without lava tubes. The erosion caves generally formed close to the sea shore are very often also dyke caves, and lack an adapted hypogean fauna.

Main features of the terrestrial cave fauna in Macaronesia

Island faunas are always peculiar because of their disharmony, with many absent animal groups that are found in the continent. This is also the same concerning to cave animals, in such way that these lacking species are partially replaced by other species preadapted to hypogean life, very often belonging to unusual taxonomic groups in the continental cave faunas. This is due to the inability for some of these groups to colonize oceanic islands, being their potential hypogean niches occupied by other groups that commonly don't do it in the mainland.

All Macaronesian troglobites have evolved locally, in such way that all species are endemic to a single island with the exceptions above mentioned. This implies allopatric speciation and many independent colonisations of the underground. However, some genera include various related troglobitic species in one island (3 *Trechus* spp. in Pico, 5 *Cixius* spp. in La Palma, 11 *Loboptera* spp. and 8 *Dysdera* spp. in Tenerife, etc.) In some of these cases two or more congeneric species are found together, but they have different epigean sister species, which also implies independent invasions of the underground. Moreover, many of the epigean sister species are actually occurring on the surface in the same area to their corresponding hypogean sister species, what means that the latter have evolved by parapatric speciation. This is a common situation in Macaronesian islands and agrees with the adaptive shift hypothesis for the origin of troglobites (Rouch & Danielopol, 1987; Howarth, 1987). However, there are also troglobites with no epigean relatives at all on their island and even on the whole archipelago. This is the case for the thread-legged bugs *Collartida anophthalma* (from El Hierro) and *Collartida tanausu* (from La Palma), several species of the pseudoscorpion genus *Tyrannochthonius* and the planthopper genus *Meenoplus*. Some of the species belong to endemic genera, like the harvestman *Maiorerus randoi* from Fuerteventura, the ground beetles *Spelaeovulcania canariensis* from Tenerife and *Pseudoplatyderus amblyops* from La Gomera, with no related species elsewhere in the world. It is difficult to say that these species evolved according to the classical climatic relict hypothesis proposed for the troglobites from Europe and North America (Vandel, 1964; Barr, 1968), since glaciations didn't affect these islands of the mid Atlantic. Maybe their relict condition was due to secondary climatic changes derived from glaciations (drought, forest withdrawal).

Azores Islands

This is the western and northernmost archipelago, being located on the Midatlantic ridge. This implies interesting geologic consequences, with predominance of Hawaiian type volcanism and therefore basaltic rocks, very suitable for the formation of lava tubes. Its geographical situation divides the archipelago in two groups of islands, one at west (Flores and Corvo) and the other at east (rest of the islands) of this ridge, in such way that the former shift westwards together with the ocean floor, and the second group move eastwards towards Europe. The age of each island varies depending on the distance to the ridge, the youngest being those of the central group (Faial, Pico and São Jorge) and the oldest one Santa Maria. The greatest abundance on lava tube caves is in general in the youngest islands, though older islands can be also rich in such caves whenever recent volcanism (in geological terms) have took place and have modern terrains, like for instance São Miguel. On the contrary, modern islands like Flores (2.16 Ma) but lacking recent eruptions, are poor in such caves. All the Azores islands are rather rich in lava tube caves except Corvo, Flores and Santa Maria, and at least some troglobitic species are so far known from all the rest except Graciosa (see Table II).

The studies on cave biology had been very sporadic before the 1980's, and only a few freshwater species occurring in pools at the bottom of pits were known. The knowledge on the terrestrial fauna started in 1987, when an expedition by researchers from Edinburgh University (UK) and La Laguna University (Canary Islands) financed by National Geographic Society and with the valuable collaboration of Os Montanheiros members (Angra do Heroísmo) studied the cave fauna from Terceira, Pico, and São Jorge, and discovered the first cave-dwelling species (see Oromí *et al.*, 1990). The same team visited again the archipelago in 1989, also joining the first Azorean biospeleologist (Paulo Borges)

Table II. Islands of the Azorean archipelago. Ages in million years (after França et al., 2004). Presence or absence of volcanic caves with apparent conditions to hold troglobitic fauna. Presence or absence of troglobites.

	Corvo	Flores	Faial	Pico	Graciosa	S.Jorge	Terceira	S.Miguel	S.Maria
age	0.7	2.1	0.7	0.2	2.5	0.5	3.5	4.0	8.1
caves	-	-	+	+	+	+	+	+	-
troglobites	-	-	+	+	+	+	+	+	-

for the study of caves in São Miguel, where they also were helped by the local caver Teófilo Braga (Amigos dos Açores). They also visited Pico, São Jorge, Faial and Graciosa, and found new troglobitic species in all except Graciosa (Oromí *et al*., 1990; Oromí & Borges, 1991; Mahnert, 1990; Merrett & Ashmole, 1989). Since then the biospeleologist team created in Universidade dos Açores at Terceira, has continued the research on cave fauna from the different islands, and now they have an advanced knowledge on the Azorean hypogean fauna, both from caves and from the MSS. The BALA Project carried out in 1998-2001 and directed by Prof. Paulo Borges provided a remarkable improve on the knowledge of the Azorean fauna (Borges *et al*., 2005a, 2005b).

Actually 20 species of troglobites have been found on the archipelago, belonging to eight different orders of arthropods (Borges & Oromí, 1994 and in press). All of them are endemic to a single island, except a few which are found both in Pico and Faial, This is difficult to explain unless a land connection existed between the two islands in the past allowing troglobites to move to each other, separated by less than 50 m depths (see Eason & Ashmole, 1992); however, this hypothesis is controversial since the western part of Pico is extremely recent, probably younger than the descent of sea level during the last glaciation (João C. Nunes, pers. comm.). The hypogean species from the Azores have a moderated degree of troglomorphism, with an obvious reduction of eyes but never reaching the eyeless condition, and never with a very marked lengthening of appendages. The most remarkable case of splitting is found in the genus *Trechus* which includes seven different cave-dwelling species in the archipelago (see Oromí & Borges, 1991; Borges & Oromí, 1991 and in press; Borges *et al*., 2004).

Madeira Islands

The archipelago of Madeira is located at latitude of 33ºN and is formed by two main islands, Madeira and Porto Santo, and the Desertas islets. Porto Santo is an old island (15 Ma), without lava tube caves and troglobitic fauna known so far. Madeira is younger (5.5 Ma) but with scarce recent volcanism, and therefore with few caves. However, the island had often been visited by entomologists which sporadically entered the caves and discovered a few troglobitic species of woodlice (Vandel, 1960), spiders (Wunderlich, 1992) and beetles (Erber, 1990; Serrano & Borges, 1995). In 2000 the GIET team from the University of La Laguna organized a research expedition to Madeira and visited Grutas do Cavalum (Machico) and Grutas de São Vicente, but it has been after 2002 when Dora Aguín and Elvio Nunes, from Universidade da Madeira, who carried about for the first time an accurate study of Machico caves, and discovered several unknown troglobites (Nunes *et al*., 2003).

The cave-dwelling fauna from Madeira is not very rich in species, which have a little marked degree of troglomorphism (Serrano & Borges, in press). This is the only archipelago in Macaronesia where no cave-adapted planthoppers have ever been found. Not a single genus of arthropods includes various troglobitic species, which probable indicates that its limited underground environment has not promoted the radiative evolution in this habitat.

Selvagens Islands

This very small and isolated archipelago is between Madeira and the Canaries, at 30° N. It originated some 24 Ma but it after remained under the sea level for a long time, when new eruptions emerged again the islands between 12 and 8 Ma. They are low islands (less than 150 m) and only Selvagem Grande has one cave, formed in a dyke by marine erosion when it was at the sea level (now the cave is higher up). It was recently visited by a biologist from La Laguna who was looking for cave fauna. The conditions are not good for trogobites, and just a troglophilic spider was collected (*Spermopohorides selvagensis* Wunderlich) (Arechavaleta *et al*., 2001).

Canary Islands

This is the larger archipelago and the closest to the mainland (110 km from Fuerteventura to the Sahara coast), being situated between 27° and 29° N. Their ages rank from 21 Ma (Fuerteventura) to less than 1 Ma (El Hierro), in such way that the age decreases from east to west (see Table III). The origin of the Canaries is not related to the mid-Atlantic ridge like the Azores but to a hotspot model with the peculiarity that the older islands still continue with volcanic activity (Carracedo *et al*., 1998). This has allowed the presence of modern lavas on all the islands except La Gomera where no eruptions have occurred along the last 3 Ma (Cantagrel *et al*., 1984). The islands with more volcanic caves are Lanzarote, Tenerife, La Palma and El Hierro. The lava tube caves in Lanzarote are large and abundant, but the aridity of the climate and the scarce soil covering the lavas prevents the existence of the necessary humidity for the existence of a true troglobitic fauna. The islands containing more troglobites are Tenerife, La Palma and El Hierro. In Fuerteventura they are also rare because of the dry climate, but there are two species. In Gran Canaria there are few caves, but recent research points to the presence of an adapted fauna. A similar situation occurs on La Gomera, where there are no caves at all but a few hypogean species inhabit the MSS in the humid forest.

The studies on the underground fauna in the Canaries early started in 1892 when the crab *Munidopsis polymorpha* was described from the anchialine cave Jameos del Agua (Lanzarote), together with some other adapted species (Koelbel, 1892). The animal community of this cave and the neighbouring Túnel de la Atlántida has been intensively studied along the last century, and as much as 25 species adapted to this particular habitat are so far known (Oromí & Izquierdo, 1994, in press). It is remarkable the existence of *Speleonectes ondinae*, the only Remipede crustacean known from the oriental part of the Atlantic.

The first terrestrial troglobite to be described was *Collartida anophthalma*, discovered in the early 80's by catalan cavers in El Hierro (Español & Ribes, 1983). At this time was created the Grupo de Investigaciones Espeleológicas de Tenerife (GIET) from the University of La Laguna (Tenerife), which has been regularly studying the hypogean fauna with a remarkable success (Oromí & Izquierdo, 1994, in press). In the Museo de Ciencias Naturales de Tenerife also the late J.J. Hernández Pacheco was active on cave research up to his death in 1993 (Hernández Pacheco *et al*., 1995), and in La Palma island members of the G.E. Benisahare caving club also studied many caves with discoveries of many interesting hypogean species (García & Oromí, 1996; Machado, 1998).

The organization in 1992 of the 10th Int. Symposium of Biospeleology in Tenerife by the GIET team, and the 7th Int. Symposium on Vulcanospeleology in 1994 in La Palma by Junonia and GIET groups, show the intense activity and the relevance of their studies. Between 1999 and 2001 this team from La Laguna carried out a research LIFE-Nature project on the cave fauna from the Canary Islands and its conservation.

Table III. The islands of the Canary archipelago set from west to east according to their geographic position. Ages in million years. Presence of caves apparently suitable to hold terrestrial adapted fauna. Number of troglobitic species.

	Hierro	LaPalma	Gomera	Tenerife	G.Canaria	Fuerteventura	Lanzarote
age	0.8	2	12	12	14	21	15.5
caves	+	+	-	+	+	+	-
troglobites	19	31	8	64	4	2	-

The hypogean fauna from the Canaries is the richest in Macaronesia, 132 of terrestrial troglobitic and 57 aquatic stygobiont (either freshwater or anchialine) species having been found so far. This is also the fauna with the most advanced degree of troglomorphism among these Atlantic islands, including some species such as the thread-legged bug *Collartida anophthalma* (Hemiptera, Reduviidae) and the rove-beetle *Domene vulcanica* (Coleoptera, Staphylinidae) easily comparable to the most troglomorphic species from the Palaearctic. The most adapted fauna to the underground occurs in the modern terrains of Tenerife, while the hypogean species from the western islands (La Palma and El Hierro) are usually more ambimorphic with some exceptions.

Various genera having undergone radiative evolution on the Canaries are also represented in the underground fauna, like the spiders *Dysdera* (9 spp.) and *Spermophora* (5 spp.). In other genera such as the cockroaches *Loboptera* (Blattaria), the planthoppers *Meenoplus* (Hemiptera) and the beetles Domene and *Wolltinerfia* (Coleoptera) this radiation has originated only troglobitic species(see Table IV). There are also hypogean species with no relatives on the surface, neither belonging to the same nor to close genera, for which they can be considered as relict species whose epigean ancestors disappeared from the islands after originating the actual hypogean forms. In this sense they are remarkable the cases of *Tyrannochthonius* and *Lagynochthonius* (Pseudoscorpiones

Table IV. Arthropod polyspecific genera with troglobites in the Canary Islands. The islands where each species occurs are indicated (H: El Hierro; P: La Palma; G: La Gomera; T: Tenerife; F: Fuerteventura).

GENERA	TOTAL NO. SPECIES	HYPOGEAN SPECIES	ISLANDS
Dysdera (Araneae)	44	9	P, T
Spermophora (Araneae)	24	5	H, P, T, F
Porcellio (Isopoda)	19	1	T
Dolichoiulus (Diplopoda)	43	4	H, P, T
Lithobius (Chilopoda)	11	4	H, P, G, T
Loboptera (Blattaria)	12	11	H, P, T
Cixius (Hemiptera)	7	6	H, P
Meenoplus (Hemiptera)	3	3	H, P
Trechus (Coleoptera)	12	2	H, P
Wolltinerfia (Coleoptera)	3	3	T
Licinopsis (Coleoptera)	6	2	H, P
Alevonota (Coleoptera)	10	6	P, T
Ocypus (Coleoptera)	7	2	T
Domene (Coleoptera)	5	5	T, G, P
Laparocerus (Coleoptera)	>100	4	H, P, G

Chthoniidae), *Maiorerus* (Opiliones Laniatores), *Collartida* (Hemiptera Reduviidae) or *Spelaeovulcania* and *Canarobius* (Coleoptera Carabidae).

One of the most interesting features of the Canary hypogean fauna is the presence of unexpected groups in such faunas of the neighbouring mainland. The cave-adapted cockroaches are unknown in the whole Palaearctic, while landhoppers (Amphipoda Talitridae), earwigs (Dermaptera) and thread-legged bugs (Hemiptera Reduviidae) have troglobitic species only in the Canary Islands and in Hawaii.

Cape Verde Islands

The Cape Verde Islands are the southernmost in Macaronesia, being located some 500 km west of Dakar, in Senegal. They form a double arch of islands, the windward islands (Ilhas de Barlavento) and the leeward islands (Ilhas de Sotavento) with ages decreasing from east to west. The easternmost islands (Sal, Boavista and Maio) are low and rather flat, with an arid climate and very few caves due to erosion in such old terrains. Santo Antão, São Vicente, São Nicolau, and Santiago are mountainous but with hardly any recent volcanism for which lava tubes are also scarce: only a few unexplored caves in Santo Antão and the clay-silted Gruta do Lázaro in Santiago are known. But in Fogo island there is an active recent volcanism (last eruption in 1995) with abundant basaltic lavas which have originated abundant caves, though never as large as those from the Azores and the Canary Islands. The relatively recent lava tube caves related to the main volcano (both in Chã das Caldeiras and on the eastern slopes of the island) are better preserved than those in older terrains of the rest of the island.

Knowledge and popularization of caves has been scarce in Cape Verde. Besides some popular believes (the so called "grutas de Lázaro" on Santiago, where supposedly this Robin Hood like bandit hid his treasures) and a few references in modern tourist guides (Schleich & Schleich, 1995), very little is published about this subject. The serious surveying of lava tubes started with the Espeleo Clube de Torres Vedras expedition in 1997, and in 1999 the GIET team from La Laguna University carried out a biological study in eight caves, discovering for the first time the presence of an adapted fauna on this archipelago. Troglobites were found only in caves above 2000 m from the sea level, being remarkable for their adaptations the planthopper *Nysia subfogo* (Hemiptera, Meenoplidae), a Cryptopidae centipede and two still undescribed spiders (Hoch *et al*., 1999).

The aridity of Cape Verde prevents most of its caves to be inhabited by troglobites, since the inner environment is highly influenced by the climate outside. Only in Fogo the Chã das Caldeiras caves covered by a thick layer of cinders are isolated and keep humidity enough for the development of true cave-dwelling species. More visits and research are needed to better know this adapted fauna, which is probably richer than the few species so far discovered.

The hypogean fauna from Macaronesia is abundant in spite of being recently studied, it is varied and has a special interest for the peculiarities due to the insular condition. All troglobitic species are endemic to reduced areas, since they are almost always exclusive to a single island. They are the result of local processes of speciation, with the appearance of troglomorphic characters in groups often unexpected in other parts of the world. But they are often threatened species as well, since the fragility of their environment is remarkable. Many caves on the Azores are silting up due to transformation of forest in pastureland, the few caves in Madeira are absolutely spoiled for tourist use without any sensibility by the owners (case of Grutas de São Vicente) or very damaged by uncontrolled visits and vandalism (case of Grutas do Cavalum); and many caves on the Canary Islands are more and more severely polluted by sewage (case of Cueva del Viento and other lava tubes in Icod de los Vinos), stupidly transformed as show-caves in spite of the presence of protected species (case of Cueva del Llano in Fuerteventura and the endangered *Maiorerus randoi*), or spoiled by uncontrolled visits. The troglobitic fauna has a low resistance to environmental changes and they can easily disappear from the caves.

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Investigation of the Discharge Mechanism of Hachijo-Fuketsu Lava Tube Cave, Hachijo-jima Island, Japan

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Abstract

Bingham fluid model by using inclined and flat circular tube are applied for the investigation of Hachijo-fuketsu lava tube cave in Japan. From the size and configuration of Hachijo-fuketsu lava tube cave such as tube length, inclination angle, tube diameter(height), the yield strength of the lava was obtained. The obtained yield strength was compared with other lava which formed lava caves and found to have a reasonable value as basaltic.

Introduction

Hachijo-fuketsu lava tube cave is located on Hachijo-jima island south of Tokyo in the Pacific Ocean. Hachijo-jima island, located on the volcanic front of the izu-Ogasawara(Bonin) arc, consist of two stratovolcanoes: Nisiyama and Higasiyama. Nishiyama is a scarcely dissected cone called "Hachijo-fuji". Nishiyama began its volcanic activities about 10000 years ago. Many lateral volcanoes exist around Nishiyama. Hachijou-fuketsu is believed to have been formed by the eruption of Hachijo-nishiyama volcano 1100 years BP[1]. Its lava flow is basaltic, with silica content of 50.5%[2]. Hachijo-fuketsu is the second longest lava tube in Japan. Despite good accessibility, it is well preserved as shown in Fig. 1. As shown in Fig. 2, its upper and middle sections have moderates slopes and its lower end is flat and horizontal[3].

Modelling, Assumption and Analysis

In modelling the discharge mechanism of this type of lava tube, we used an inclined circular tube model for the sloping section of the cave as shown in Fig. 3. For the flat horizontal section in which the lava flow is driven by hydrodynamic head, we modeled a flat circular tube as shown in Fig. 4. The yield strengths obtained from these two models were similar and comparable to those of other lava flows.

Regarding the inclined circular pipe case, the discharge mechanism of lava tube caves already has been established, based on Bingham characteristics of intratubal lava flow[4,5]. A simple model of steady state isothermal laminar flow in inclined circular pipes and in flatten circular pipes were used for analyses. Comparison studies were based on the configuration of Hachijo-fuketsu.

Flow characteristics were studied as a function of parameters such as tube radius, viscosity, yield strength of lava and slope inclination. A critical condition was determined for the discharge parameters in which the yield strength plays a dominant role. Existing observational data were introduced to the critical condition. This model was applied to lava tube cave of Mt.Fuji, Mt.Etna, Mount St.Helens, Suchiooc volcano, Kilauea volcano and others. Some deduced yield strength of lava of the caves in these areas were found to be in good accordance with yield strength as estimated by other methods[6].

General flow equation of Bingham fluid can be shown as,

$$f(\tau)=(\tau-f_B)/\eta_B \quad (\tau>f_B,\ \text{or}\ r>r_B),$$
$$f(\tau)=0 \quad (\tau<f_B,\ \text{or}\ r<r_B).$$

Here, f_B is Bingham yield stress, η_B is Bingham viscosity, which takes specific value depending on the materials. τ is sharing stress at r.

For laminar flow model in circular tube on the slope, the equation of the distribution of flow speed u of Bingham fluid are shown as follows:

For $\tau_w=(\varrho g \sin\alpha)R/2>f_B$,

$$u=(R-r_B)^2(\varrho g \sin\alpha)/4\eta_B \quad (r<r_B),$$
$$u=[R^2-r^2-2r_B(R-r)]\,(\varrho g \sin\alpha)/4\eta_B \quad (r>r_B).$$

For $\tau_w=(\varrho g \sin\alpha)R/2<f_B$, u=0.

Here, α is angle of slope or inclination of tube, ϱ: density of the fluid, g: gravity acceleration, R: radius of the tube, r_B: radius of the flowing position where Bingham yield stress takes f_B.

Figure 1. Inside of Hachijou-Fuketsu (photo by T. Honda).

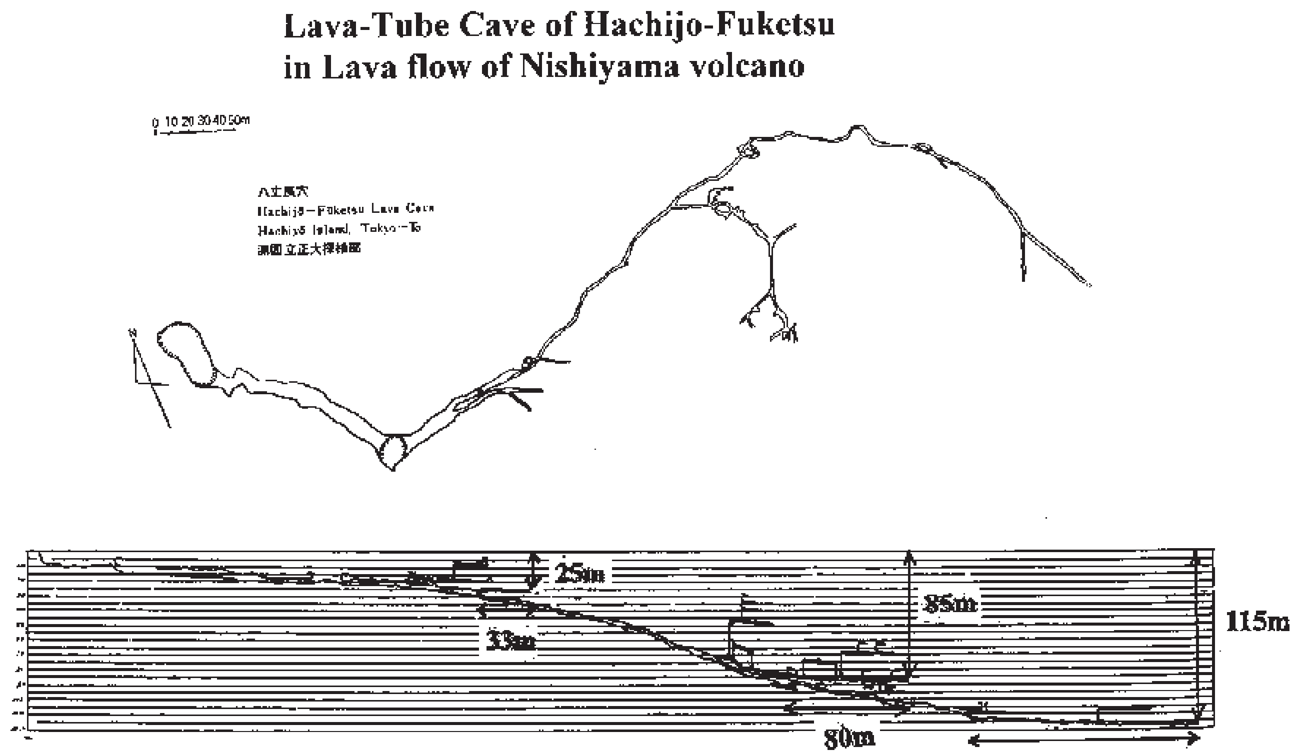


Figure 2. Horizontal and vertical cross section of Hachijo-fuketsu[3].

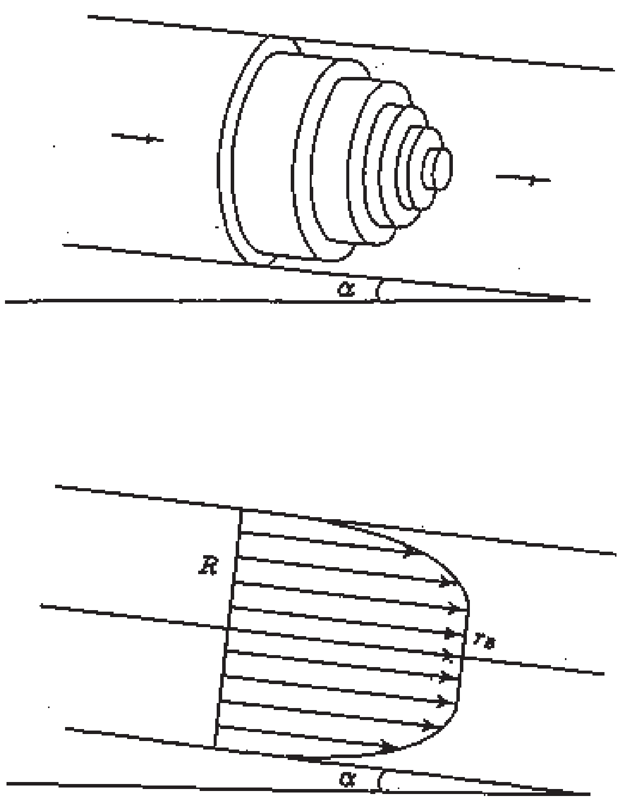
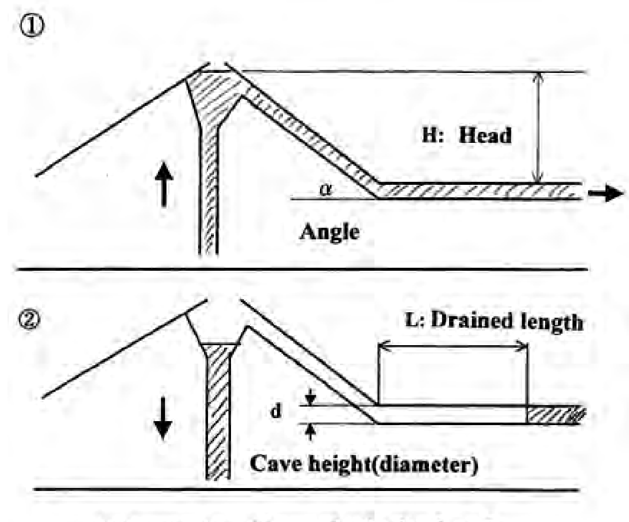


Figure 3. Bingham fluid model of inclined tube.



$$f_B = \frac{\rho gHd}{4L}$$

Figure 4. Simplified model of Hachijo-fuketsu.

Table 1. Relation between slope angle and height of Hachijo-fuketsu lava tube cave of sloped configuration.

Location of lava cave	Slope angle(α)	Height(2R)
Upper reaches	4.5 degree	~5m
Intermediate reaches	14 degree	~2m
(Lower reaches)	(0 degree)	(~1m)

Table 2. Relation between head and length at horizontal location of Hachijo-fuketsu lava tube cave of horizontally flat configuration for 2R=1m.

Location of lava cave	Head(H)	Length(L)
Upper reaches	25m	33m
Intermediate reaches	85m	80m
Lower reaches	115m	150m

Table 3. Yield strength obtained from the critical condition.

Name of volcano	SiO_2 fraction of lava	Obtained yield strength	References
Hachijo-nishiyama	50.4~50.5%*	2.0~2.5x10^4dyne/cm^2	*M.Tsukui et al (2002)[2]
Mt.Fuji	49.09~51.3%*	2.5~5.0x10^4dyne/cm^2[5]	*H.Tsuya(1971)[8]

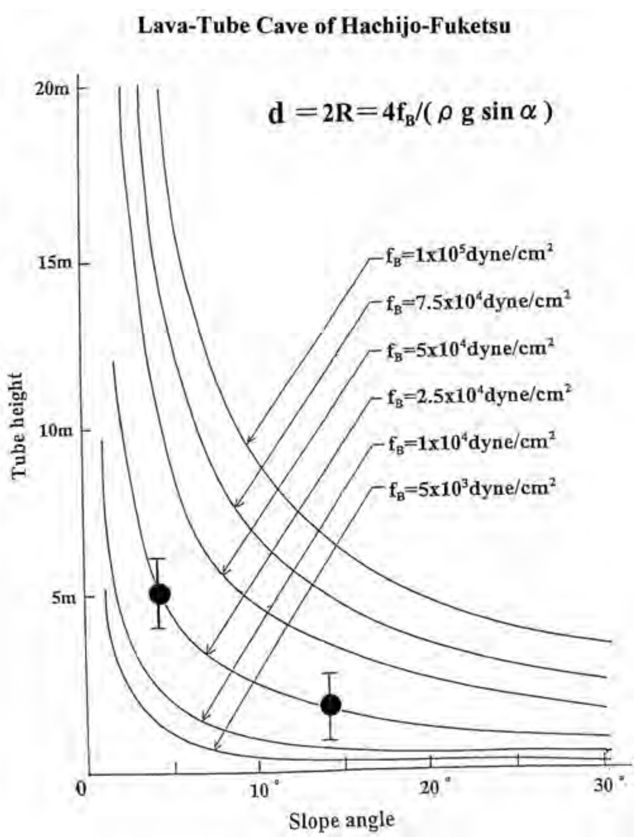


Figure 5. Relation between Slope angle and Tube height in sloped area.

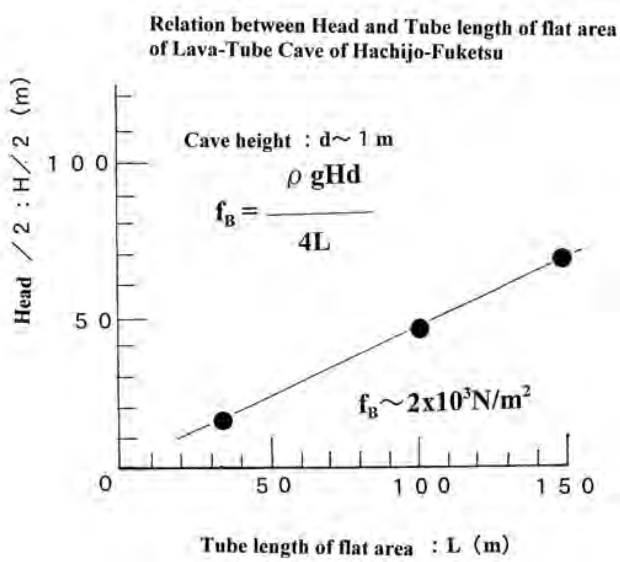


Figure 6. Relation between Head and tube length of flat area.

Here, ($\varrho g \sin\alpha$)R/2=f_B is the limiting condition to determine if the fluid in the tube can be drained out. For given and known relation between slope angle and diameter(height) of the tube, this critical condition can give the yield strength f_B as shown in Fig. 5. This critical condition means that when the yield strength of Bingham fluid is higher than the shear stress at the wall, there is no flow of fluid, as a consequence, no drainage of fluid from the tube. From Table 1, f_B=2.5x10^4dyne/cm^2 can be obtained for Hachijo-fuketsu.

The above model is, however, valid only for flow in inclined tubes. For perfectly flat lava tube(0 degree), the effect of inertial as driving force due to the head of the flow must be considered, if the flow is continuous together with the inclined tube[7]. Very rough relation between drained tube length and mean head of the flow can be obtained as (ϱg R)H/2L=f_B by ($\sin\alpha$) by (H/L). From Table 2, f_B=2x10^4dyne/cm^2 was obtained for Hachijo-jima as shown in Fig. 6.

In summary, obtained basaltic yield stress from slope angle and height of some lava caves(see Table 3)are reasonable values as compared with the yield stress obtained for Mt. Fuji[7].

Conclusions

As a results of this study, Bingham fluid model seems to be well applied for an explanation of formation process of lava tube cave. Further application of this model to other lava tube caves will be necessary and interesting for confirmation. Though the yield strength only plays a main role in this steady state model, for a future study, the analysis by using time dependent transition equation should be performed. In this case, the viscosity of lava will be involved.

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Indicators of Conservation Value of Azorean Caves Based on its Arthropod Fauna

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Abstract

All Azorean lava-tubes and volcanic pits with fauna were evaluated for species diversity and rarity based on arthropods. To produce an unbiased multiple-criteria index (*importance value for conservation*, IV-C) incorporating arthropod species diversity based indices and indices qualifying geological and management features (e.g. diversity of geological structures, threats, accessibility, etc.), an iterative partial multiple regression analysis was performed. In addition, the complementarity method (using heuristic methods) was used for priority-cave analyses. Most hypogean endemic species have restricted distributions, occurring only in one cave. It was concluded that several well-managed protected caves per island are absolutely necessary to have a good fraction of the endemic arthropods preserved. For presence/absence data, suboptimal solutions indicate that at least 50% lava-tubes with known hypogean fauna are needed if we want that 100% of endemic arthropod species are represented in a minimum set of reserves. Based both on the uniqueness of species composition and/or high species richness and geological value of the caves, conservation efforts should be focused on the following caves: Gruta da Beira, Algar das Bocas do Fogo (S. Jorge); Montanheiros, Henrique Maciel, Soldão, Furna das Cabras II and Ribeira do Fundo (Pico); Algar do Carvão, Balcões, Agulhas and Chocolate (Terceira); Água de Pau (S. Miguel); Anelares and Parque do Capelo (Faial).

Introduction

Caves as islands are isolated entities, and, as a consequence, they lack the "rescue effect": only "source" species can be maintained in ecological and evolutionary time (Rosenweig 1995). Thus, cave species could be considered as very restricted in distribution due to their low dispersal abilities and cave isolation. However, cave-adapted species could disperse between cave systems throughout the MSS ("Milieu souterrain siperficiel" or "Mesovoid Shallow Substratum" sensu CULVER, 2001). This is the case of *Trechus terceiranus*, a troglobian species found in many caves from Terceira island (Azores) but also in the MSS (Borges 1993). Than, it is important to investigate how widespread are cavernicolous fauna to better conserve it.

The conservation of the rich Azorean cave-adapted fauna (Borges & Oromí 1994) is urgent but the resources are not enough to protect all caves. Consequently, there is a need to set priorities for conservation. The aim of this study was to examine the faunistic relative value of a set of well sampled lava tubes and volcanic pits in the Azorean islands as a management tool to improve the conservation of Azorean cave-adapted arthropod biodiversity. We examined the following hypotheses:

(a) Using an iterative partial regression analyses to produce a multiple-criteria index incorporating diversity and rarity based indices, at least one cave per island will be highly ranked. This follows the assumption that the dispersal rates of species are low and consequently there is a high level of island-restricted endemism.

(b) The restricted distribution of endemic species will imply that most caves are unique and largely irreplaceable. Consequently, most caves will be needed to ensure each species is included at least one time in a complementary based approach.

Methods

Sites and data. This study was conducted in the Azores, a volcanic Northern Atlantic archipelago that comprises nine islands, as well as several islets and seamounts distributed from Northwest to Southeast, roughly between 37° and 40° N and 24° and 31° W. The Azorean islands extend for about 615 km and are situated across the Mid-Atlantic Ridge, which separates the western group (Flores and Corvo) from the central (Faial, Pico, S. Jorge, Terceira and

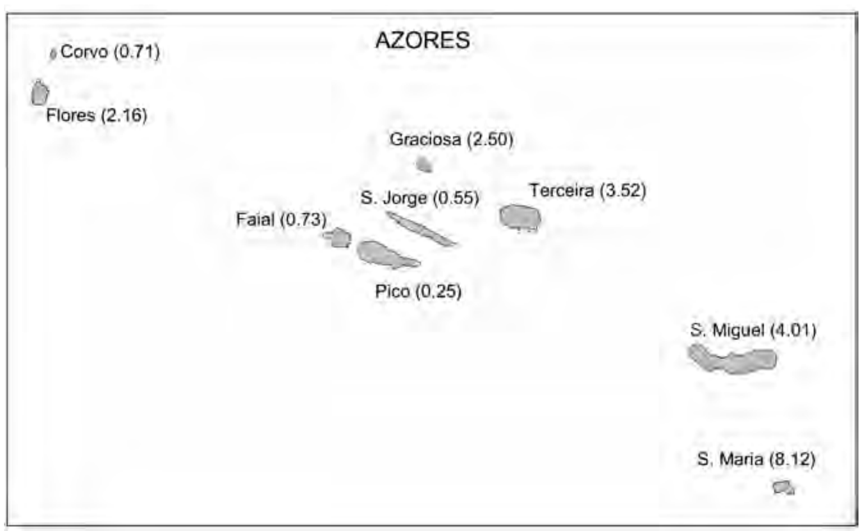

Figure 1. The nine Azorean islands with indication of their geological age based on data from Nunes (1999).

Graciosa) and the eastern (S. Miguel and S. Maria) groups (Figure 1). All these islands have a relatively recent volcanic origin, ranging from 8.12 Myr B.P. (S. Maria) to 250 000 years B.P. (Pico) (Nunes 1999).

In this study a total of 37 volcanic cavities distributed on six of the nine Azorean islands (excluding S. Maria, Flores and Corvo) were surveyed and are listed in Table 1. Some of those caves were surveyed intensively during 1988 and 1990 with two expeditions of "National Geographic" under the supervision of Pedro Oromí (Univ. de La Laguna) and Philippe Ashmole (Univ. de Edinburg) (see Oromí *et al.* 1990). However, many of the caves were also sampled by investigators of the University of the Azores and "Os Montanheiros" (see Borges & Oromí 1994). Part of the arthropod data on the presence/absence in the caves is unpublished and resulted from recent surveys performed by PB and FP. Arthropods were classified to one of three colonization categories: natives, endemics and introduced. In cases of doubt, a species was assumed to be native. Moreover, following information available in Borges & Oromí (1994) all the species were also classified as cave-adapted (troglobites) and non cave-adapted.

Data analysis. For prioritizing the 37 caves two techniques were used: i) indices for scoring conservation priorities based on comparative analyses; ii) the complementarity method.

i) Scoring method. Due to its simplicity a scoring approach was used with 9 different indices, incorporating arthropod species diversity based indices, but also indices qualifying cave geological and management features (data from IPEA database, Constância et al. 2004). (see Table 2). However, as the several indices give quite different ranking of the caves results a multiple criteria index was applied.

Multiple criteria Index: Importance Value for Conservation (IV-C). When different values or criteria are combined in a single index, it is difficult to know what the single value obtained from it represents (see Borges et al. 2005). Moreover, the different indices used to describe a cave value may not be unrelated, thus leading to the possibility of giving a higher weighting to a given feature in the construction of the complex index. To avoid possible problems of collinearity we have used partial regression analysis techniques (Legendre & Legendre 1998, see also Borges et al. 2005), which allow the separation of the variability of a given predictor that is independent (i.e., non related) from the variability of another variable, or set of variables. To do this, we applied generalised linear models (GLM) with natural logarithm link functions, in which the predictor is regressed against this variable, or group of variables, and the resulting residuals are retained as the independent term of the variable. In this particular case, we have developed iterative partial regression analyses, each time extracting the variability of a predictor that is independent of the formerly chosen indices. That is, after selecting a first index (A), which is used without any transformation in the Importance Value for Conservation (IV-C) calculations, we regressed the second one (B) against A, obtaining its residuals (rB). In successive steps, each index (e.g., C) is regressed against the formerly included (in this case, A and rB) in a multiple regression analysis, obtaining its residuals (rC). The first selected index to be used without any transformation was the total number of endemic species ($S_{trogl.}$), since cave-adapted species richness was considered to be of major importance to cave conservation. The other indices entered in the model by decreasing order of their r^2 values of a GLM regression of each index with $S_{trogl.}$. Thus, the final Importance Value for Conservation (IV-C) composite index is as follows:

$$\begin{aligned}\text{IV-C} = [(&S_{trogl.} / S_{trogl.}\,max)\\ &+ (RS_{end.} / RS_{end.}\,max)\\ &+ (RShow / RShow\,max)\\ &+ (RSrare / RSrare\,max)\\ &+ (RGEO / RGEO\,max)\\ &+ (RDif.Expl. / RDif.Expl.\,max)\\ &+ (RIntegrity / RIntegrity\,max)\\ &+ (RThreats / RThreats\,max)\\ &+ (RAccess. / RAccess\,max)] / 9\end{aligned}$$

in which for a reserve the value of the residual variance (R) of each of the additional indices is divided by the maximum value (max) obtained within all reserves. For instance, the residuals of "Show" were obtained after the following polynomial model:

$$Show = a + b\,S_{trogl.} + c\,RS_{end.}$$

This composite index has a maximum value of 1 (see also Borges et al. 2005).

ii) Complementarity. To obtain the minimum set of caves that combined have the highest representation of species we applied the complementarity method (Williams 2001). We used a heuristic suboptimal simple-greedy reserve-selection algorithm in an Excel Spreadsheet Macro. First, the cave with the highest species richness was selected. Then, these species are ignored and the cave with the highest complement of species (that is, the most species not represented in the previous selected cave), and so on, until all species are represented at least once. This method was applied to a dataset comprising only presence-absence data for the cave-adapted arthropods, to have the minimum set of caves to represent all species at least once.

Results

We recorded 35 species of endemic arthropods in the 37 caves (see Appendix 1). From those species, 19 (54%) are

Table 1. List of the lava tubes (LT) and volcanic pits (VP) investigated.

Island	Cave	Type
Faial	Furna Ruim	VP
Faial	Gruta das Anelares	LT
Faial	Gruta do Cabeço do Canto	LT
Faial	Gruta do Parque do Capelo	LT
Graciosa	Furna do Enxofre	VP
Pico	Furna da Baliza	LT
Pico	Furna de Henrique Maciel	LT
Pico	Furna do Frei Matias	LT
Pico	Furna dos Vimes	LT
Pico	Furna Nova I	LT
Pico	Furnas das Cabras II (terra)	LT
Pico	Gruta da Agostinha	LT
Pico	Gruta da Ribeira do Fundo	LT
Pico	Gruta das Canárias	LT
Pico	Gruta das Torres	LT
Pico	Gruta do Mistério da Silveira I	LT
Pico	Gruta do Soldão	LT
Pico	Gruta dos Montanheiros	LT
S. Jorge	Algar das Bocas do Fogo	VP
S. Jorge	Gruta da Beira	LT
S. Miguel	Fenda do Pico Queimado	VP
S. Miguel	Gruta de Água de Pau	LT
S. Miguel	Gruta do Enforcado	LT
S. Miguel	Gruta do Esqueleto	LT
S. Miguel	Gruta do Pico da Cruz	LT
Terceira	Algar do Carvão	VP
Terceira	Furna de Santa Maria	LT
Terceira	Gruta da Achada	LT
Terceira	Gruta da Madre de Deus	LT
Terceira	Gruta da Malha	LT
Terceira	Gruta das Agulhas	LT
Terceira	Gruta do Caldeira	LT
Terceira	Gruta do Chocolate	LT
Terceira	Gruta do Coelho	LT
Terceira	Gruta do Natal	LT
Terceira	Gruta dos Balcões	LT
Terceira	Gruta dos Principiantes	LT

Table 2. The list of indices used to rank the caves.

Code	Index		Explanation
Strogl	**S trogobites**		The number of cave-adapted species
Send	**S endemics**		The number of endemic species
Srare	**S rare**		The number of rare species (those that occur in only one cave)
Show	**Show cave index**	0	No information available
		1	Small cave (less than de 100 x 2 m).
		2	Small and simple cave but with at least 100 m and less than 200m
		3	Size between 200 and 500m but few interesting structures
		4	Large size caves (more than 500m) and with diversity of structures
		5	Large size caves (more than 1000m) and with diversity of structures
GEO	**Geology index**	0	No information available
		1	Relevant geological structures not present
		2	Presence of very common geological structures (e.g. lava stalactites)
		3	Presence of common geological structures (e.g. benches, striated walls)
		4	Presence of rare geological structures (e.g. Secondary deposits, levees, different levels of tunnels, etc.)
		5	Presence of very rare geological structures (e.g. Gas bubbles, stalagmite, columns)
DIF.Expl.	**Difficulty of Exploration Index**	0	No information available
		1	Lava tube or pit of difficult exploration due to difficulty of progression
		2	Lava tube or pit of difficult exploration in some parts due to difficulty of progression
		3	Cavity with some obstacles
		4	Presence of some obstacles but easy to transpose
		5	No obstacles - all people could visit the cave
Integrity	**Integrity index**	0	No information available
		1	More than 50% of the cavity destroyed
		2	some evidences of destruction (< 50% of he length)
		3	More than 90% of the lenght well preserved but presence of Human alterations or disturbance
		4	Well preserved and few signals of Human alterations or disturbance
		5	Very well preserved
Threats	**Treats index**	0	No information available
		1	The cavity has destroyed parts due to epigean land-use changes and disturbance
		2	Well known epigean Human activities are identified and could cause near-future disturbance
		3	Well known epigean Human activities are identified and could cause future disturbance
		4	Well known epigean Human activities are identified but with non potential threat to the cavity
		5	Non occurrence of Human activity or threats in the area of the cave
Acess.	**Acessibility index**	0	No information available
		1	Very difficult to access - no roads or tracks available
		2	Difficult access, far from near locality and more than 45 m walk
		3	Difficult access, far from near locality or need of special permission of the property owner
		4	Easy access, with available public transport
		5	Easy access, easy to locate, near a locality

cave-adapted species. Most hypogean endemic species have restricted distributions, occurring only in one cave (Fig. 2).

Table 3 shows that the first ten caves using the multiple criteria index (IV-C) belong to four out of the six studied islands. No caves from Graciosa and Faial were included in the top ranked list. On the other hand, Pico and Terceira have the highest number of cavities elected in the top ten cavities. The 10 top caves include both large caves (e.g. Montanheiros, Balcões, Henrique Maciel) and small caves. Three currently protected caves, also used as Show-caves, (Algar do Carvão, Torres, Furna do Enxofre), are not listed in the top 10, but Algar do Carvão (Terceira) and Torres (Pico) are 11th and 13th, respectively.

Using presence/absence data, heuristic (suboptimal) solution show that only 9 caves are needed to have all cave-adapted species represented at least once (Table 4). Moreover, five out of the six islands have at least one cave represented in the minimum complementary set of caves (Table 4).

Table 3. Ranking of the 37 caves in terms of the multiple criteria index, Importance Value for Conservation (IV-C).

Cave	Island	IV-C
Gruta dos Montanheiros	**Pico**	**0.63**
Gruta de Água de Pau	**São Miguel**	**0.62**
Gruta das Agulhas	**Terceira**	**0.58**
Gruta do Chocolate	**Terceira**	**0.56**
Algar das Bocas do Fogo	**S. Jorge**	**0.55**
Gruta dos Balcões	**Terceira**	**0.53**
Furna de Henrique Maciel	**Pico**	**0.53**
Gruta do Soldão	**Pico**	**0.51**
Furnas das Cabras II (terra)	**Pico**	**0.51**
Gruta da Ribeira do Fundo	**Pico**	**0.50**
Algar do Carvão	Terceira	0.47
Furna Nova I	Pico	0.46
Gruta das Torres	Pico	0.43
Gruta da Beira	S. Jorge	0.43
Gruta das Anelares	Faial	0.42
Gruta da Achada	Terceira	0.42
Gruta da Madre de Deus	Terceira	0.42
Furna do Frei Matias	Pico	0.42
Gruta do Pico da Cruz	São Miguel	0.42
Gruta do Coelho	Terceira	0.42
Gruta da Malha	Terceira	0.41
Furna do Enxofre	Graciosa	0.41
Gruta das Canárias	Pico	0.41
Furna de Santa Maria	Terceira	0.41
Gruta do Natal	Terceira	0.41
Gruta do Mistério da Silveira I	Pico	0.41
Furna Ruim	Faial	0.41
Gruta do Caldeira	Terceira	0.41
Gruta da Agostinha	Pico	0.39
Gruta do Enforcado	São Miguel	0.39
Gruta do Cabeço do Canto	Faial	0.38
Gruta dos Principiantes	Terceira	0.37
Furna dos Vimes	Pico	0.36
Fenda do Pico Queimado	São Miguel	0.35
Gruta do Esqueleto	São Miguel	0.35
Furna da Baliza	Pico	0.34
Gruta do Parque do Capelo	Faial	0.33

Conclusions

In this study we aimed to quantify the relative value of Azorean caves using both arthropods and cave geological features. Interestingly, data from this study shows that a regional conservation approach, which value at least one cave per island, will be required to conserve arthropod biodiversity in the Azores (see Tables 3 and 4).

Remarkably, Gruta dos Montanheiros was ranked first using two completely different selection approaches, which highlight the importance of this beautiful lava tube located in the island o Pico.

Using a single criterion may not allow us to cover all conservation goals. Therefore, based both on the uniqueness of species composition and/or high species richness and geological value of the caves (Tables 3 and 4), conservation efforts should be focused on the following caves: Gruta da Beira, Algar das Bocas do Fogo (S. Jorge); Montanheiros, Henrique Maciel, Soldão, Furna das Cabras II and Ribeira do Fundo (Pico); Algar do Carvão, Balcões, Agulhas and Chocolate (Terceira); Água de Pau (S. Miguel); Anelares and Parque do Capelo (Faial).

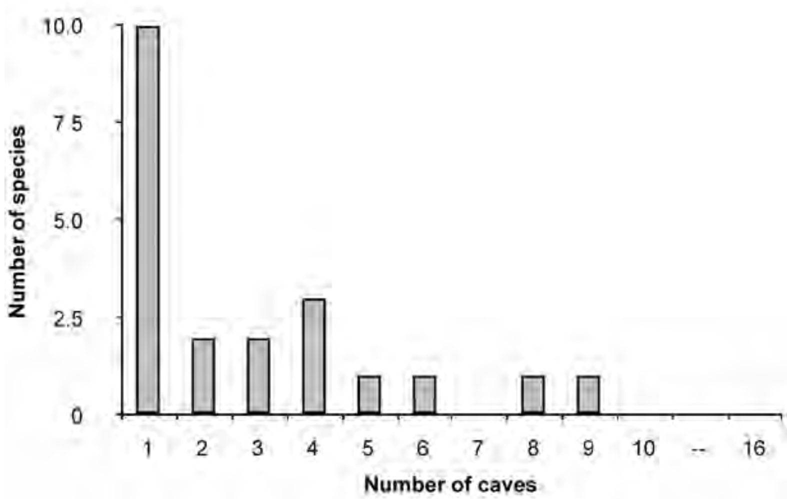

Figure 2. Frequency distribution of Azorean troglobitic species in volcanic caves.

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Table 4. Minimum complementarity set of caves to have all troglobian species represented at least once.

Step	Cave	Island	S	S Accumulated
1	Gruta dos Montanheiros	Pico	5	5
2	Algar do Carvão	Terceira	5	10
3	Gruta da Beira	S. Jorge	2	12
4	Gruta das Agulhas	Terceira	2	14
5	Gruta das Anelares	Faial	1	15
6	Gruta do Parque do Capelo	Faial	1	16
7	Furnas das Cabras II (terra)	Pico	1	17
8	Algar das Bocas do Fogo	S. Jorge	1	18
9	Gruta de Água de Pau	S. Miguel	1	19

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Appendix 1. List of the species endemic species recorded in the Azorean caves. The cave-adapted species are also marked (C).

List of species	Taxonomic group	Troglobian
Calyptophthiracarus maritimus	ACARI-Oribatei	
Damaeus pomboi	ACARI-Oribatei	
Dorycranosus angustatus	ACARI-Oribatei	
Galumna rasilis	ACARI-Oribatei	
Galumna sp. (n sp.)	ACARI-Oribatei	
Hermanniella sp. 1 (n sp.)	ACARI-Oribatei	
Hermanniella sp. 2 (n.sp)	ACARI-Oribatei	
Nothrus palustris azorensis	ACARI-Oribatei	
Phthiracarus falciformis	ACARI-Oribatei	
Tritegeus (n. sp.)	ACARI-Oribatei	
Xenillus discrepans azorensis	ACARI-Oribatei	
Turinyphia cavernicola n. sp.	ARANEAE	C
Lepthyphantes acoreensis	ARANEAE	
Porrhomma n.sp.	ARANEAE	C
Rugathodes acoreensis	ARANEAE	
Rugathodes pico	ARANEAE	C
Lithobius obscurus azoreae	CHILOPODA	C
Lithobius obscurus borgei	CHILOPODA	
Thalassophilus azoricus	COLEOPTERA	C
Trechus jorgensis	COLEOPTERA	C
Trechus montanheirorum	COLEOPTERA	C
Trechus picoensis	COLEOPTERA	C
Trechus terceiranus	COLEOPTERA	C
Trechus oromii	COLEOPTERA	C
Trechus pereirai	COLEOPTERA	C
Onychiurus sp.	COLLEMBOLA	C
Pseudosinella ashmoleorum	COLLEMBOLA	C
Pseudosinella azorica	COLLEMBOLA	
Gen. sp. indeterminado	CRUSTACEA	C
Macarorchestia martini	CRUSTACEA	C
Orchestia chevreuxi	CRUSTACEA	
Cixius azopicavus	HOMOPTERA	C
Cixius cavazoricus	HOMOPTERA	C
Pseudoblothrus oromii	PSEUDOSCORPIONES	C
Pseudoblothrus vulcanus	PSEUDOSCORPIONES	C

Indicators of Conservation Value of Azorean Caves Based on its Byrophyte Flora at the Entrance

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Abstract

Cave entrances in the Azores are particularly humid habitats. These provide opportunities for the colonization of a diverse assemblage of bryophyte species. Using both published data and new field sampling, we evaluated species diversity and rarity of bryophytes at the entrance of all known Azorean lava tubes and volcanic pits with such flora. Frequent species include the liverworts: *Calypogeia arguta*, *Jubula hutchinsiae* or *Lejeunea lamacerina*, and the mosses: *Epipterygium tozeri*, *Eurhynchium praelongum*, *Fissidens serrulatus*, *Isopterygium elegans*, *Lepidopilum virens* and *Tetrastichium fontanum*. Several rare Azorean bryophyte species appear at some cave entrances (e.g. *Archidium alternifolium*; *Asterella africana*; *Plagiochila longispina*), which reinforces the importance of this habitat for the regional conservation of these plants. To produce an unbiased multiple-criteria index (*Importance Value for Conservation*, IV-C), several indices based on bryophyte diversity and rarity, and also geological and management features, were calculated for each cave, and an iterative partial multiple regression analyses was performed. Data sows that three pit caves are particularly diverse in bryophytes (Algar do Carvão, Terceira Island, Bocas do Fogo, S. Jorge and Furna do Enxofre, Graciosa). Lava tubes with a diverse troglobitic fauna also are diverse in terms of bryophyte species (e.g., Algar do Carvão, Gruta dos Montanheiros, Gruta da Agostinha, Furna do Henrique Maciel). We also evaluate the utility of several cave management indices as surrogates of bryophyte diversity in Azorean volcanic cavities.

Table 1. List of the Azorean lava tubes (LT), volcanic pits (VP) and other type (OT) of cavities investigated for bryophytes in this article.

Island	Cave number	Cave	Type
Graciosa	1	Furna do Enxofre	VP
Pico	2	Furna de Henrique Maciel	LT
Pico	3	Furna do Frei Matias	LT
Pico	4	Furna dos Vimes	LT
Pico	5	Gruta da Agostinha	LT
Pico	6	Gruta das Torres	LT
Pico	7	Gruta do Soldão	LT
Pico	8	Gruta dos Montanheiros	LT
S. Jorge	9	Algar das Bocas do Fogo	VP
S. Maria	10	Anjos	OT
S. Miguel	11	Fenda do Pico Queimado	VP
S. Miguel	12	Gruta da Batalha	LT
S. Miguel	13	Gruta do Enforcado	LT
S. Miguel	14	Gruta do Esqueleto	LT
S. Miguel	15	Gruta do Pico da Cruz	LT
S. Miguel	16	Gruta de Ponta Delgada	LT
Terceira	17	Algar do Carvão	VP
Terceira	18	Gruta do Chocolate	LT
Terceira	19	Gruta dos Balcões	LT

Introduction

The study of the Azorean bryophyte flora started with two expeditions of the "National Geographic Foundation" (1988, 1990), under the co-supervision of Pedro Oromí (Univ. de La Laguna) and Philippe Ashmole (Univ. of Edinburgh) and with the support of the speleological Azorean group "Os Montanheiros" (see Oromí et al. 1990, González-Mancebo *et al*. 1991). After those two expeditions, the University of the Azores and "Os Montanheiros" performed most of the bryophyte survey work in the Azores (e.g. Gabriel & Dias 1994, Gabriel & Bates 2005).

Bryophytes include mosses (Class Bryopsida), liverworts (Class Marchantiopsida) and hornworts (Class Anthocerotopsida), all of which are small, non-vascular, primitive plants that occupy a wide variety of habitats and substrates. Bryophytes assume an important functional role in the ecosystems where they occur, performing water interception, accumulation of water and their mineral contents, decomposition of organic matter and physical protection of soils (Longton, 1992). Many bryophyte species are used as bioindicators, and their presence is associated with atmospheric and aquatic purity (e.g. Hylander, Jonsson, & Nilsson 2002).

When air flows into a cave, it carries micro-organisms, leaves, seeds, spores, small arthropods, etc. Some will survive (mainly algae, fungi, ferns and bryophytes), modifying the bare rock. Some will form an important part of the food chain for cave dwelling organisms. In most places, the species found at the caves (either in entrances or areas above) are common species. However, these species add greatly to the diversity of the plant species at the caves and the scenic value of the rocks and rocky outcrops.

Four hundred and thirty eight bryophyte species are given to the Azores (Gabriel *et al*. 2005), but few data are available concerning their relative importance in the Azorean cave environment.

The aims of this manuscript are:

a) To evaluate species diversity and rarity of bryophytes at the entrance of the known Azorean lava tubes and volcanic pits with such flora;

b) To evaluate the utility of several cave management indices as surrogates of bryophyte diversity in Azorean volcanic cavities.

Methods

Sites and data. All main literature for the Azorean cave bryophytes was surveyed, and data was updated using the Herbarium of the University of the Azores

(AZU). Besides, during the summer of the year 2000, 18 Azorean caves were prospected for bryophytes by FP, searching the main substrata available: rock and soil. Only part of this data was identified. However, the quality of the data only allowed to perform statistical analysis for the 19 caves listed on Table 1.

Data analysis. For prioritizing the 19 caves we used a multiple criteria index: Importance Value for Conservation (IV-C) (based on Borges et al. 2005). The multiple criteria index was built using 9 different indices (see Table 2), based on the diversity and rarity of bryophytes, but also on geological and management features of the caves (data from IPEA database, Constância et al. 2004). We also used the total number of cave-adapted arthropods in caves based on information obtained from Borges et al. (2007, this volume).

To avoid problems of collinearity we have used partial regression analysis techniques (Legendre & Legendre 1998, see also Borges et al. 2005), which allow the separation of the variability of a given predictor that is independent (i.e., non related) from the variability of another variable, or set of variables. To do this, we applied generalised linear models (GLM) with natural logarithm link functions, in which the predictor is regressed against this variable, or group of variables, and the resulting residuals are retained as the independent term of the variable. In this particular case, we have developed iterative partial regression analyses, each time extracting the variability of a predictor that is independent of the formerly chosen indices. The first selected index to be used without any transformation was the total number of bryophyte species ($S_{Bryo.}$), since total species richness was considered to be of major importance to cave conservation. The other indices entered in the model by decreasing order of their r^2 values of a GLM regression of each index with $S_{Bryo.}$. Thus, the final Importance Value for Conservation (IV-C) composite index is as follows:

$$
\begin{aligned}
IV\text{-}C = [&(S_{Bryo} / S_{Bryo}\ max) \\
&+ (R\_S_{ECCB} / R\_{}_{ECCB}\ max) \\
&+ (R\_SBryo_{end} / R\_SBryo_{end}\ max) \\
&+ (R\_S_{trogl} / R\_S_{trogl}\ max) \\
&+ (R\_Show / R\_Show\ max) \\
&+ (R\_GEO / R\_GEO\ max) \\
&+ (R\_Integrity / R\_Integrity\ max) \\
&+ (R\_Threats / R\_Threats\ max\ ) \\
&+ (R\_Access / R\_Access\ max\ )] / 9
\end{aligned}
$$

in which for a cave, the value of the residual variance (R) of each of the additional indices is divided by the maximum value (max) obtained within all caves. For instance, the residuals of "$SBryo_{end}$" were obtained after the following polynomial model:

$$SBryo_{end} = a + b\ S_{Bryo} + c\ R\ S_{ECCB}$$

in which "a" is the value of the intercept, "b" is the value of the slope of the first variable and "c" is the value of the slope of the second variable.

This composite index has a maximum value of 1 (see also Borges et al. 2005).

Results and discussion

The majority of bryophytes found at the cave entrances may be found elsewhere in the Azorean islands, and there are no known exclusive cave species. However it is remarkable that 151 species out of the 438 Azorean bryophytes (34.5%) have been recorded for this habitat. For an updated list of bryophytes present at the Azorean caves see Pereira et al. (2006, in press). Among the most frequently recorded moss species are: *Eurhynchium praelongum*, *Fissidens bryoides s. l.*, *F. serrulatus*, *Tetrastichium fontanum* and *T. virens* while among the most recorded liverworts there may be found *Calypogeia arguta*, *Jubula hutchinsiae* ssp. *hutchinsiae*, and

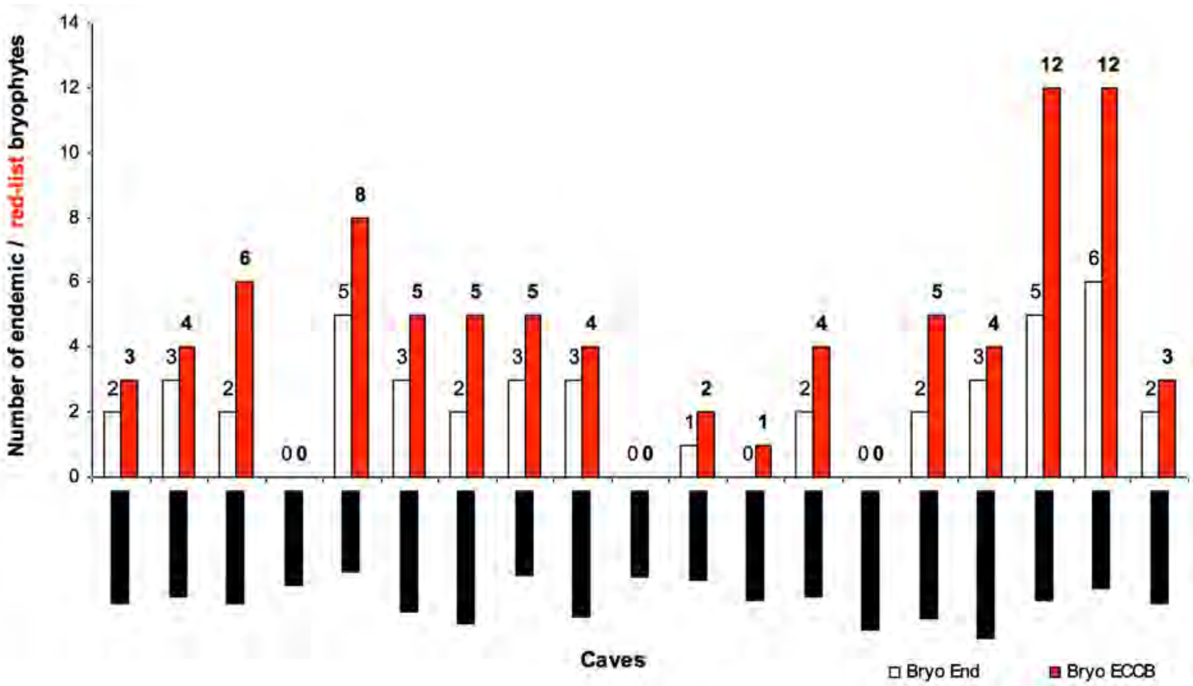

Figure 1. Number of endemic (Azores, Macaronesia) or red-listed (ECCB, 1995) bryophyte species present at the entrances of the studied Azorean caves.

Table 2. Explanation of the list of indices used to rank the Azorean caves.

Code	Index		Explanation
SBryo	S bryophytes		The number of bryophyte species
SECCB	S ECCB		The number of rare bryophyte species based on ECCB, 1995
SBryo.end	S endemic bryophytes		The number of endemic bryophyte species from the Azores and Macaronesia
Strogl	S troglobites		The number of cave-adapted arthropod species
Show	Show cave index	0	No information available
		1	Small cave (less than de 100 x 2 m).
		2	Small and simple cave, at least with 100 m but less than 200m
		3	Size between 200 and 500 m but few interesting structures
		4	Large size cave (more than 500 m) and with a wide diversity of structures
		5	Large size cave (more than 1000 m) and with a wide diversity of structures
GEO	Geology index	0	No information available
		1	Relevant geological structures not present
		2	Presence of very common geological structures (e.g. lava stalactites)
		3	Presence of common geological structures (e.g. benches, striated walls)
		4	Presence of rare geological structures (e.g. secondary deposits, levees, different levels of tunnels, etc.)
		5	Presence of very rare geological structures (e.g. gas bubbles, stalagmite, columns)
Integrity	Integrity index	0	No information available
		1	More than 50% of the cavity destroyed
		2	Some evidence of destruction (< 50% of the length)
		3	More than 90% of the length well preserved but evidence of human alterations or disturbance
		4	Well preserved and few signals of Human alterations or disturbance
		5	Very well preserved
Threats	Threats index	0	No information available
		1	The cavity has destroyed parts due to epigean land-use changes and disturbance
		2	Well known epigean human activities are identified and could cause near-future disturbance
		3	Well known epigean human activities are identified and could cause future disturbance
		4	Well known epigean human activities are identified but with no potential threat to the cavity
		5	Non occurrence of human activity or threats in the area of the cave
Access.	Accessibility index	0	No information available
		1	Very difficult to access, without roads or tracks available
		2	Difficult access, far from near locality and more than 45 min walk
		3	Difficult access, far from near locality or need of special permission of the property owner
		4	Easy access, with available public transport
		5	Easy access, easy to locate, near a locality

Lejeunea lamacerina.

Besides, there are noteworthy occurrences on the Azorean Caves, of either endemic (Azores and Macaronesia) or European red-listed species, and some caves harbour more than 10 classified species according to the ECCB (1995) (see Figure 1). Caves such as "Gruta do Frei Matias" and "Gruta das Torres" (both in Pico) or "Algar do Carvão" and "Gruta dos Balcões" (both in Terceira) contain more than five red-listed bryophytes and only three of the 19 analysed caves ("Furna dos Vimes", "Gruta dos Anjos" e "Gruta de Ponta Delgada") have no classified bryophyte species (see Figure 1, Pereira et al. 2006, in press).

Among the most interesting species that may be found at cave entrances, are the bryophytes *Aphanolejeunea teotonii*, *Asterella africana*, Cephalozia crassifolia, *Echinodium renauldii*, *Plagiochila longispina* and *Radula wichurae*. These European vulnerable species occur at cave entrances at different islands, and for instance *Asterella africana* has not been referred outside that habitat in the Azores, recently. The endemic moss *Echinodium renauldii*, an epilithic species, which is generally found at lower altitudes (below 500 m), has also been referred for at least three caves ("Furna do Henrique Maciel", "Furna da Agostinha" e "Gruta das Torres" – all in Pico Island). Thus, caves may serve as a refuge to some species that otherwise would not be present at that particular altitude and these data highlight the importance of the habitat for the regional conservation of these plants.

A statistical significant relationship was observed between the diversity of cave-adapted arthropods and the species richness of bryophytes in the Azorean cave entrances (r = 0.59; p = 0.008) (Figure 2). In spite of the fact that the relationship is not perfect, there are some caves that are diverse both in troglobitic fauna and bryophyte species (e.g., Algar do Carvão, Gruta dos Montanheiros, Gruta da Agostinha, Furna do Henrique Maciel). Bryophyte richness could, with caution, be used as an indicator of the diverse cave adapted arthropods.

The ranking obtained with the multiple criteria index, Importance Value for Conservation (IV-C) for the 19 caves may be observed in Table 3. Eight caves, have IV-C values equal or above 0.50 (maximum value is 1.00). All of these caves are located in Pico, Terceira and Graciosa Islands.

Considering the present state of speleological and biospeleological knowledge of the Azores, none of the most interesting caves are to be found on S. Miguel Island, the largest and most populated island of the Azorean archipelago. Cave entrances in S. Miguel are highly disturbed, mainly due to land use changes in the surrounding areas.

Also in view of the calculated index, none of the top five caves are show-caves, at the present. This indicates that there are other caves with potential for tourism exploitation, and that their biological value should be highlighted. Care should be taken when developing show-cave projects, in order to preserve their biological and geological features.

Conclusions

Unlike other cave entrances, Azorean caves bear an exquisite and wonderful bryophyte flora. Many species commonly found in this habitat are endemic or red-listed and their populations are important to the survival of the species in the Azores. These species add greatly to diversity of the plant species at the caves and the scenic value of the rocks and rocky outcrops.

In the Azores, the importance of cave entrances to bryophytes is twofold: i) since these are particularly humid, sheltered habitats, they support a diverse assemblage of bryophyte species; in fact circa 35% of the Azorean bryophytes is referred to this habitat and ii) species, either endemic or referred in the European Red List (ECCB 1995) due to their vulnerability or rarity (19 species).

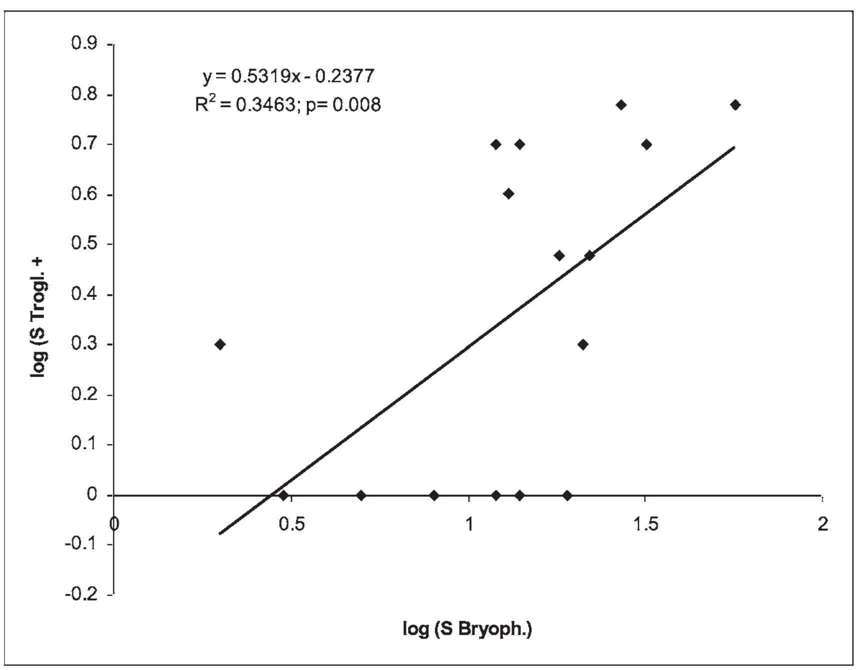

Figure 2. Relationship verified between the logarithm of the number of troglobian arthropod species (S Trogl) and the logarithm of the number of bryophyte species (S Bryoph) found at the entrance of caves.

Table 3. Ranking of the 19 caves using the multiple criteria index, Importance Value for Conservation (IV-C).

Cave	Island	IV-C
Furna de Henrique Maciel	Pico	0.57
Gruta dos Balcões	Terceira	0.55
Gruta dos Montanheiros	Pico	0.54
Gruta da Agostinha	Pico	0.53
Gruta do Chocolate	Terceira	0.52
Gruta das Torres	Pico	0.51
Gruta do Soldão	Pico	0.50
Furna do Enxofre	Graciosa	0.50
Algar do Carvão	Terceira	0.46
Gruta do Pico da Cruz	S. Miguel	0.45
Algar das Bocas do Fogo	S. Jorge	0.44
Furna do Frei Matias	Pico	0.39
Gruta da Batalha	S. Miguel	0.38
Gruta de Ponta Delgada	S. Miguel	0.36
Gruta do Esqueleto	S. Miguel	0.36
Furna dos Vimes	Pico	0.32
Fenda do Pico Queimado	S. Miguel	0.31
Gruta do Enforcado	S. Miguel	0.30
Gruta dos Anjos	S. Maria	0.20

Bryophyte diversity was shown to be a surrogate of cave adapted arthropods, indicating that well preserved caves have a global importance for both the organisms living inside the cave system and to those adapted to cave entrances, hence bryophytes.

In view of the calculated conservation index (IV-C), none of the top five caves are show-caves, at the present. This indicates that there are other caves with potential for tourism exploitation, and that their biological value should be highlighted. Care should be taken when developing show-cave projects, in order to preserve their biological and geological features.

Acknowledgements

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The Nature of Bacterial Communities in Four Windows Cave, El Malpais National Monument, New Mexico, USA

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Abstract

One of the striking features of some lava tube caves is the extensive bacterial mats (a.k.a. lava wall slime) that cover the walls. Despite their prominence little is known about the nature of these bacterial communities. We have investigated the bacterial mats on the walls of Four Windows Cave, a lava tube in El Malpais National Monument, New Mexico, USA. These bacterial mats in the twilight zone adjacent to algal mats, and in the dark zone of the lava tube, cover from 25–75% of the wall. Their macroscopic and microscopic visual appearance suggests that these bacterial mats are composed of actinomycetes, bacteria that commonly inhabit caves. Vacuuming of bacterial mats and the adjacent algae revealed collembola and mites on the algae but no invertebrates were recovered from the bacterial mats. DNA was extracted from wall rock communities, purified, the 16S rRNA gene was amplified using PCR, cloned, and approximately 1000 bases were sequenced from thirty clones. Comparison of Four Windows bacterial sequences with the Ribosomal Database II revealed that some were most closely related to actinomycetes. Others grouped with members of the *Chloroflexi*, the *Verrucomicrobia*, and the *Betaproteobacteria*. Closest relatives of two of the clones were from Mammoth Cave samples. The latter appear to be novel bacterial species. The ability of bacteria cultured from these mats to withstand the effects of ultraviolet (UV) radiation revealed the microbes isolated from the lava tube were much more UV sensitive than the microbes isolated from the surface. However, all of the microbes tested displayed at least slight sensitivity to UV radiation. Based on the results, the bacterial colonies currently inhabiting the Four-Windows lava tube appear to be at least somewhat cave-adapted. Our studies of the actinomycete communities in Four Windows Cave reveal a diverse community of bacteria that appear to be unpalatable to invertebrates.

Introduction

A revolution in microbiology occurred with the introduction of 16S ribosomal methodology to discover the great diversity and distribution of life through genetic sequences. Standard culturing techniques used to cultivate microorganisms from caves, have met with limited success (Amann et al. 1995; Hugenholtz et al. 1998). Culture-independent molecular phylogenetic techniques allow us to reveal the diversity present in many varied environments (Pace 1997). Many novel prokaryotic species have been detected as a result of this new technology. Bacteria have been found in some of the most extreme areas including deep-sea thermal vents, within rock cores, and in caves. These microorganisms are important participants in the precipitation and dissolution of minerals, in caves (Northup and Lavoie 2001) and on the surface (Ehrlich 1999). However, we have barely begun to characterize the microbial diversity of caves and the roles of microorganisms in the subsurface.

Humid lava tube caves contain highly visible mats of bacteria and other microorganisms , nicknamed “lava wall slime,” (Figure 1), but they have received even less attention than limestone caves (Northup and Welbourn 1997). These microbial mats do contain fungi and aerobic bacteria and serve as a habitat for arthropods that feed on nutrients captured in the slimes, e.g. springtails (Insecta: Collembola), mites (Arachnida: Acari), fly larvae (Insecta: Diptera), earthworms (Oligochaeta), a water treader (Insecta: Hemiptera), and carabid beetles (Insecta: Coleoptera) (Howarth, 1973, 1981). Stone and Howarth (Howarth, 1981) also have suggested that the slimes are important sites of nutrient recycling (e.g. nitrogen).

Ashmole et al. (1992) have found slimes present in humid caves in the Canary and Azore Islands, but never in dry caves. In the Northwestern USA (Washington) lava tube slimes consist of different species of bacteria, including actinomycetes in the genus *Streptomyces* (Staley and Crawford 1975). Staley and Crawford (1975) observed two main types: a white slime that is occurs alone, is hydrophobic, and occurs in warmer areas (>6 degrees C), and an orange slime that underlies the white slime and is seen in colder areas. Associated with the slime, Staley and Crawford (1975) found fly larvae (Diptera: Mycetophilidae), overwintering harvestmen (Arachnida: Opiliones), a troglobitic harvestman, *Speleonychia* sp. (Opilionides: Travuniidae), and a millipede (Diplopoda: Polyzoniidae).

We remain almost completely ignorant of the nature of these bacterial mats-due to the lack of culture-independent studies. Thus, this study was undertaken using culture-independent methods to characterize the nature of the lava wall slime in Four Windows Cave. We also investigated the sensitivity of cultured isolates to ultraviolet (UV) radiation to determine whether the bacteria of lava tubes have lost resistance to UV radiation in comparison to their surface bacteria. Previous studies of the sensitivity of deep subsurface bacteria found no differences in sensitivity between deep subsurface and surface bacteria (Arrage et al. 1993a,1993b). Most cave animals lose non-essential traits as they adapt to the subsurface environment, but this has never been investigated in bacteria inhabiting caves.

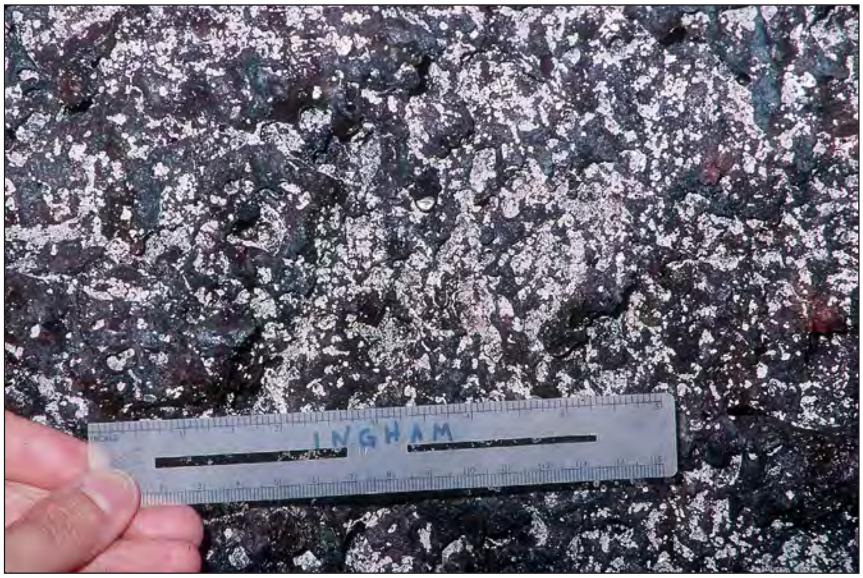


Figure 1. Close-up view of the bacterial colonies on the walls of Four Windows Cave. Photo by Kenneth Ingham.

During a previous investigation of the arthropod community inhabiting Four Windows Cave (Northup and Welbourn 1997), we noted the presence of mites on the algal mats on the walls of the twilight zone, but not on the bacterial mats. A more systematic vacuuming experiment was undertaken to document this anecdotal observation that might suggest that the bacterial mats are distasteful or toxic to invertebrates.

These preliminary studies of the microbial mats present in one lava tube, Four Windows Cave, will allow us to more fully understand the lava tube ecosystem and will lay the groundwork for future studies in other lava tubes.

Experimental Methods

Cave Description

Four Windows Cave, located in El Malpais National Monument, New Mexico, USA is a moderately long lava tube with four skylights that give the cave its name. An extensive invertebrate community exists in the moss garden growing under the skylights. These skylights provide light for the moss garden directly below them and the algal communities on the walls of the twilight zone, both of which support moderately diverse invertebrate communities. Four Windows is cold, ranging from -2 to +2° C with ice stalagmites form in the winter. During the rainy season (July and August), moisture seeps into the cave through cracks and supplies moisture and organic matter for the microbial and invertebrate communities.

The walls and ceiling of Four Windows Cave have extensive deposits of bacterial mats. The distribution of bacterial colonies is patchy (Figure 1), but appears to be most dense in areas of lower light and possibly where moisture enters the cave through cracks. Mat coverage ranges from isolated, individual colonies to dense mats several mm thick (Lavoie and Northup 1994). The visible color of both individual and massed colonies was predominately whitish-tan, but a few gold colored colonies and veins of colonies occur. Observation shows that colonies are hydrophobic, with water or secreted fluids beading up on the surface. This water often reflects light, causing the colonies to appear reflective. Senger and Crawford (1984) associate the hydrophobicity to the presence of spores produced by the bacteria.

Sample Collection for DNA Extraction and Invertebrate Study

Small samples of wall rock covered with bacterial slime were collected from Four Windows Cave in July, 1996 under a National Park Service collecting permit. These samples were chipped from the parent wall rock with an ethanol-dipped, flame-sterilized rock hammer. The samples were then caught in a sterile container, sealed, and placed on dry ice for transport. Upon arriving at the lab, the samples were stored in a -80° C freezer.

Both algae and bacteria were vacuumed with an Insect Vac (BioQuip) to examine the invertebrate communities that inhabit each environment. First, the collection tube of the vacuum was cleaned with ethanol and a sterile filter placed inside. Bacteria patches were vacuumed for one minute, the collection chamber was washed thoroughly with ethanol, and its contents repeatedly transferred to an appropriately labeled, sterile tube. The vacuum filter also was caught in this container and sealed. This procedure was repeated on an algae patch adjacent to the bacterial mats. Bacterial and algal washes were analyzed separately microscopically.

Scanning Electron Microscopy

Samples of the lava tube wall rock covered with microbial colonies were

Figure 2. Cal Welbourn sampling invertebrates from algal colonies on the wall of Four Windows Cave. Photo by Kenneth Ingham.

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

Molecular Characterization of the Bacterial Community

Extraction of DNA. Nucleic acids were extracted and purified from two 0.5 gm aliquots of sample by using the bead-mill homogenization procedure described by Kuske et al. (1997). Following bead-mill disruption and centrifugation, the supernatant was transferred and the bead pellet was washed once with 1 ml of TE buffer (10 mM Tris [pH 8.0], 1 mM EDTA), re-homogenized for 5 sec, and centrifuged again. This supernatant was pooled with the original supernatant. Nucleic acids were precipitated from the solution by using 0.1 volume of 3 M sodium acetate (pH 5.2) and 2.5 volumes of ethanol, incubated on ice, and centrifuged for 30 min at 12,000 x g. Precipitated nucleic acids were suspended in TE. DNA was purified using Sephadex G-200 spin columns equilibrated in TE, as described previously (Kuske et al. 1997). The clear column eluate containing DNA was precipitated and suspended in TE buffer. Negative control samples were prepared with TENS buffer alone containing no sample addition and were subjected to the same procedures as used with the samples.

PCR amplification of small subunit rRNA genes from environmental DNAs. The forward primer used was 533F and the reverse primer used was the 1492R primer (Lane 1991). Amplification reaction mixtures contained 30 mM Tris-HCL (pH8.3), 50 mM KCl, 1.5 mM $MgCl_2$, 5 μg bovine serum albumin (Boehringer-Mannheim), 200 μM (each) deoxynucleoside triphosphates, 100 pmol of each primer, and 5 U of Taq polymerase (AmpliTaq LD; Perkin-Elmer, Foster City, Calif.) in a final reaction volume of 100 μl. PCR was conducted with a Perkin-Elmer 9600 thermal cycler as follows: 2 min at 94 °C (denaturation), followed by 35 cycles of 60 sec annealing at 48 °C (annealing), 60 sec at 72 °C (extension), and 5 sec at 94 °C (denaturation), with a final 60 sec at 48 °C (annealing) and 5-min at 72 °C (extension) step after cycling was complete. Five microliters of each reaction mixture was analyzed on 1% SeaKem agarose gels and the desired PCR amplification products were ferified by ethidium bromide staining and UV illumination of the gels.

Small-subunit rDNA libraries. A clone library of small subunit rRNA gene copies was generated from the Four Windows sample. PCR products from 533F-1492R amplification reactions were ligated into pGEM-T plasmid vectors (Promega, Madison, Wis.) using T4 DNA ligase and overnight incubation at 4 ºC, according to the manufacturer's protocols. Recombinant plasmids were transformed into *Escherichia coli* JM109 competent cells (Promega), and colonies containing plasmids with inserts were identified by blue/white color selection on LB/ampicillin/IPTG/XGal agar plates.

RFLP. To assist in determining the genetic diversity of the bacterial colony, the 16S ribosomal DNA of seventeen clones were cut with enzymes to produce RFLPs (restriction fragment length polymorphisms): one μl of plasmid DNA, two μl of React Buffer 3, sixteen μl of double distilled water, and one μl of enzyme were used to digest the DNA. Enzymes used were *EcoR1*, *Bstu 1* and *RSA1*, with one enzyme per reaction. Sheared DNA patterns were visualized using a 4% Metaphor (FMC Rockland, Maine) electrophoresis gel in TAE, stained with 1 μl of ethidium bromide and exposed to UV light.

DNA Sequencing. PCR products from 32 clones with inserts of the correct size (approximately 1.0 kb) were purified with a QIAprep plasmid miniprep kit (Qiagen, Inc., Chatsworth, Calif.). 125-300 ng of purified DNA was used as a template in cycle sequencing reactions with thermo sequenase dye terminator cycle sequencing pre-mix kit (Amersham Life Science, Inc., Cleveland, Ohio) and ABI PRISM dye terminator cycle sequencing kit (Perkin-Elmer, Foster City, Calif.) on an ABI 377. Primers used for sequencing were T7 and SP6. Full-length insert sequences were obtained for a subset of clones by using primers for internal sequencing (906F, 907R, and 765F) of the rRNA gene.

Phylogenetic analysis. Each sequence was submitted to the CHIMERA_CHECK program of the Ribosomal Database Project (RDP; Maidak et al. 2001; (http://rdp8.cme.msu.edu/html/)) to detect the presence of possible chimeric artifacts. All sequences were initially analyzed using BLAST (NCBI; Altschul et al. 1997) and SIMILARITY_MATCH (RDPII; Maidak et al. 2001) to identify related sequences available in public databases and to determine phylogenetic groupings of clone sequences. Clone insert representatives of each phylogenetic group identified were sequenced in their entirety. Alignment of the final dataset was accomplished using the RDP II alignment software and manually using the BioEdit editor (http://www.mbio.ncsu.edu/BioEdit/bioedit.html), guided by 16S primary and secondary structure considerations. Identity values were generated by the similarity identity matrix program in BioEdit (http://www.mbio.ncsu.edu/BioEdit/bioedit.html). Distance analyses were performed using PAUP (version 4.0b10, distributed by Sinauer; http://paup.csit.fsu.edu/) with the Jukes-Cantor model. The tree of highest likelihood was found by repeated tree building using random sequence input orders. Bootstrap analyses were conducted on 1000 resampled datasets using PAUP.

UV Sensitivity Experiments

Bacterial inoculation, isolation and growth. To obtain bacterial isolates from the rock walls and surface rocks, we swiped polyester fiber-tipped swabs across the rock and inoculated thirty R2A medium (low-nutrient) plates using the standard streak isolation method. We obtained water samples with sterile 5 ml syringes from a pool of water that had accumulated inside the cave and dispensed 0.2ml of the water onto ten R2A plates, which were spread with a flame-sterilized glass spreader onsite in the cave. Inoculated plates were incubated in the cave for 16 hours before transport to a 3°C incubator in the laboratory where they remained in the dark for two weeks. Surface inoculates were stored for just under three weeks at 37°C. Morphologically unique colonies from both sets of plates were sub-cultured to provide pure cultures for UV experiments. In addition, we sub-cultured the surface colonies onto nutrient-rich LB plates.

UV Radiation Treatment. Once the subcultures were grown, we chose twelve of the most interesting cave colonies and six of the surface colonies to expose to UV light. Interesting was defined as the most morphologically different and slowly growing (likely to be more cave-adapted) colonies. Three replicate plates of colonies per R2A plate were inoculated for each of two treatments plus the control. Immediately after inoculating the plates, we placed the plates, with lids off, under the sterile hood and exposed the plates to a UV light from a germicidal lamp for 100 seconds (1 Dose) or 50 seconds (½-dose plates). After the treatment, we covered the plates, wrapped them in foil to prevent photoreactivation and placed them in the appropriate incubators. The control replicates that were not exposed to UV light were also wrapped in foil and incubated. We monitored the growth of the cultures with visual checks of colony growth for six days, and documented them with a digital camera.

Results

Invertebrate Vacuuming

Visual observation of the bacterial colonies in Four Windows Cave revealed no macroscopically visual invertebrates. Therefore, bacterial and algal mats were vacuumed as described above to more thoroughly investigate the presence of invertebrates. No invertebrates were found within the bacterial mat collection tube. The algal mat collection tube contained fourteen collembola. Eleven of these belonged to the family Hypogasturidae and three belonged to the family Entomobryidae. Previous vacuuming had also yielded Acari (mites) in the Nanorchestidae, and undetermined Oribatida and insects in family Chironomidae (Diptera) were also found.

Scanning Electron Microscopy

Examination by Scanning Electron Microscopy (SEM) of samples of white bacterial mat samples from Four Windows Cave revealed a dense mat of bacteria (Figure 3), some of which were tentatively identified as actinomycetes from their visual appearance. Additional morphologies observed with SEM (not shown) resembled planctomycete-like or *Verrucomicrobium*-like bacteria.

RFLP Analysis and Nucleotide sequences

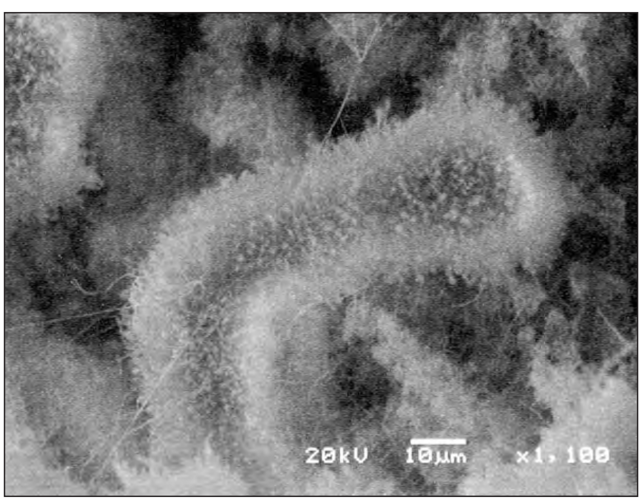
All eleven RFLP clones examined exhibited unique banding. Several clone sequences appeared to be chimeras and were removed from the analysis. Comparison of our sequences with those in the Ribosomal Database II and Blast revealed that some Four Windows bacterial sequences are most closely related to *Actinobacteria*, as suspected. Other clones grouped with members of the *Chloroflexi*, the *Verrucomicrobia*, and the *Betaproteobacteria*. Two of the closest relatives to our clones were sequenced from Mammoth Cave samples. The latter appear to be novel bacterial species. Figure 4 shows a phylogenetic tree of representative clone sequences and their closest relatives.

UV Sensitivity

Six days after the UV treatments, we scored the UV sensitivity of the different strains based on comparisons with the control strains. Each replicate was rated from one to three, with three being the most sensitive. Overall, every strain showed at least some sensitivity to the 1 dose (100 sec) of UV radiation and all but four strains (all surface) showed some sensitivity to ½ dose (50 sec) of UV. All of the cave strains showed significantly more sensitivity than the surface strains and seven of the cave replicates showed no growth at all with both 1 and ½ doses. All cave bacteria replicates were scored a three. Figures 5 and 6 show the dramatic differences in growth after UV exposure in surface and cave isolates respectively.

Discussion

The lack of invertebrates on the bacterial mats while invertebrates were found on adjacent algal mats suggests that the bacterial mats may contain toxic or distasteful compounds. Scanning electron microscopy and molecular phylogenetic analysis suggest the presence of actinomycete (*Actinobacteria*) bacteria in the bacterial mats. Actinomycetes are a highly varied group of Gram-positive bacteria that have the unusual characteristics of filamentous growth and exospore production. They may make up 10–33% of total soil microbes,



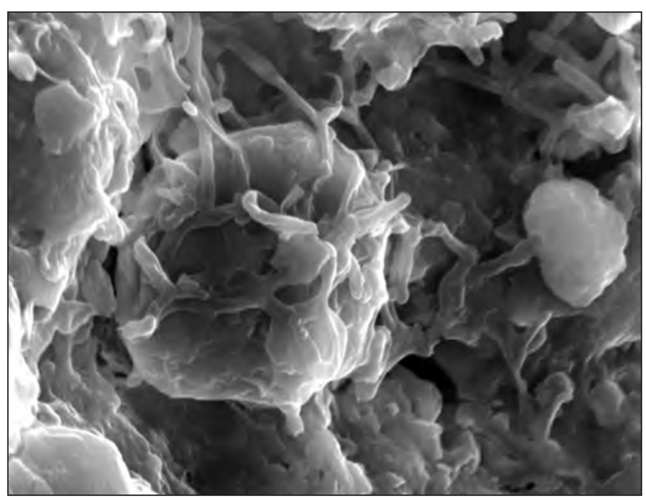


Figure 3. Scanning electron micrographs of sampled white bacterial colonies showing the presence of unusual morphologies (left) and filamentous (right). Photomicrographs by M. Spilde.

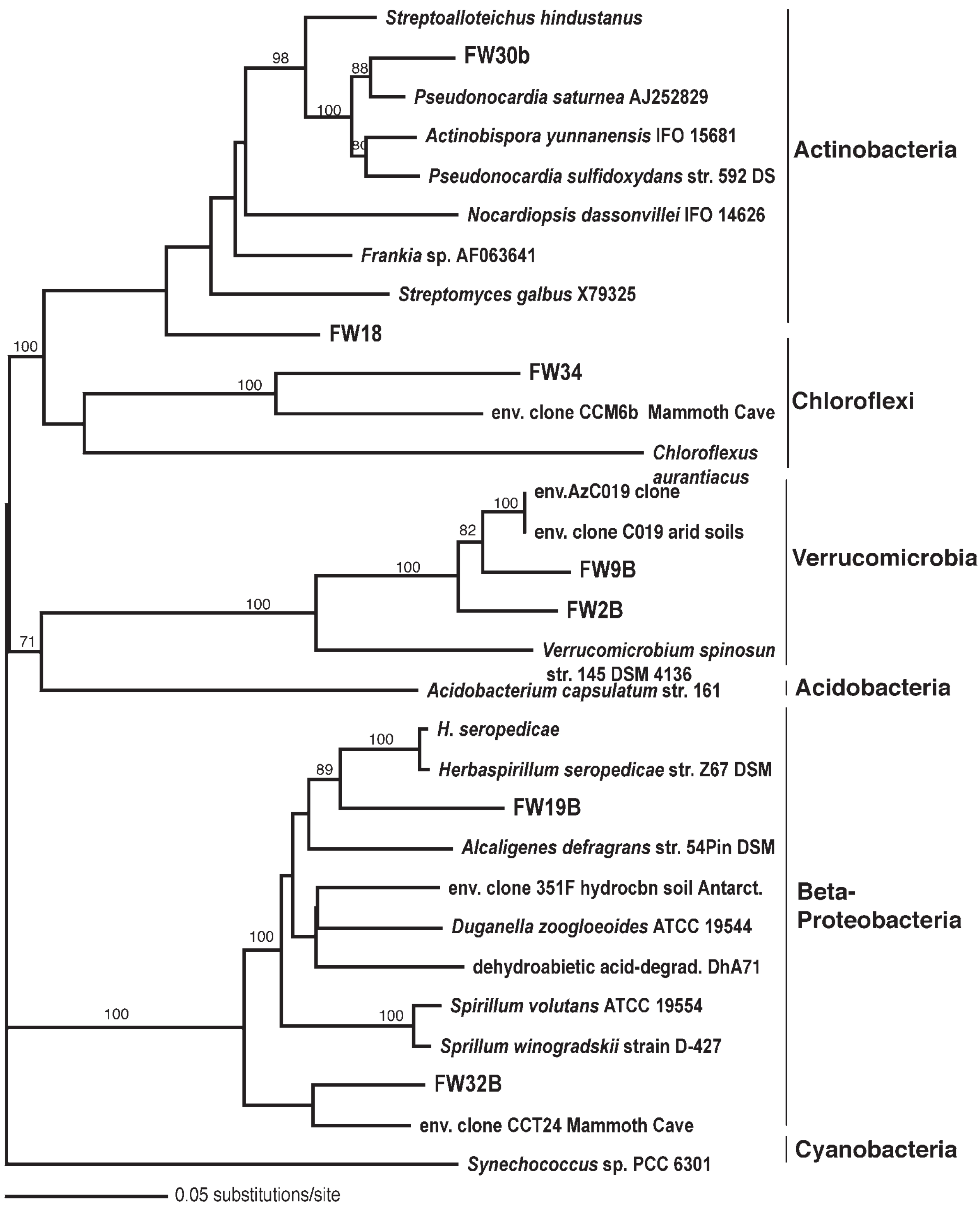


Figure 4. Phylogenetic tree of bacterial rDNA clone sequences from Four Windows Cave lava wall microbial mats. Partial rRNA gene sequences (ca. 1000 nucleotides) from clones (designated "FW" in bold type) were analyzed with most closely related sequences obtained from the databases, as well as other representatives of major bacterial groups. *Synechococcus* sp. PCC 6301 was used as the outgroup. The tree was inferred by maximum likelihood analysis of homologous nucleotide positions of sequence from each organism or clone. Numbers indicate percentages of bootstrap resamplings that support branches in maximum likelihood (above branch) and maximum parsimony (below branch) analyses. Bootstrap results are reported only for those branches that attained >70% support with at least one of the methods used.

with *Streptomyces* and *Norcardia* being the most abundant genera. They are relatively resistant to desiccation, and prefer alkaline or neutral pH environments. Metabolically, their main role in nature is in decomposition of organic matter and they thrive in environments where nutrients are sparse and conditions extreme. Many actinomycetes are known to fix atmospheric nitrogen either in association with some plant roots or as free-living cells. The role of Actinomycetes in nitrogen fixation in caves has not been explored (Lavoie per. comm. 1993). With a temperature of -2 to +2°C and seeping organic matter for nourishment, Four Windows Cave provides an excellent habitat for these bacteria. Some types of actinomycetes are medicinally and agriculturally significant because they excrete antibiotic products to repel invaders. The antibiotic properties of many bacteria species make them interesting to the medicinal industry. The lack of invertebrate life on the bacterial slime communities could be an indicator that the environment may be excreting antibiotic compounds toxic or distasteful to these small animals.

The molecular phylogenetic analysis of bacteria adhered to the rock walls of Four Windows Cave revealed that the community is not merely actinomycetes, but contains organisms from three other major bacterial groups: *Chloroflexi*, *Verrucomicrobia*, and the *Betaproteobacteria*. None of these relationships are especially close as evidenced by the long branch length for many of the Four Windows Cave clones. The closest relatives are those from Mammoth Cave environmental isolates and other soil environmental isolates, indicating the novel nature of these isolates. Clone FW34 grouped with the *Chloroflexi*, a group of generally phototrophic, filamentous organisms. However, other studies have shown cave bacteria grouping with the *Chloroflexi* (Engel, personal communication 2005), and in this case, the association is not a close one. The closer relative of clone FW34 is an isolate from the soils of Mammoth Cave in Kentucky. The lack of a close relationship to a cultivated bacterial species and the fact that close relatives can have different physiologies does not allow us to draw any conclusions concerning this clone. Several clones, as represented by FW2b and FW9b, group with the *Verrucomicrobia*, a recently proposed division that has been elevated to phylum status within the Bacterial Domain (Schlesner et al. 2001). The genera *Verrucomicrobium* and *Prosthecobacter* within the *Verrucomicrobia* are prosthecate with fimbriae (finger or hair-like appendages) extensions from their tips. Their morphology is similar to some of the morphologies seen in the SEM photomicrographs of Four Windows samples. The *Verrucomicrobia* have been found in a variety of aquatic and terrestrial habitats worldwide. While most cultivated members are heterotrophic, we are just beginning to learn about their physiology. Thus, little can be said about the physiology of the Four Windows clones based on their association with the *Verrucomicrobia*.

The grouping of isolate FW19B with *Herbaspirillum seropedicae* in the *Betaproteobacteria*, probably reveals an isolate from the surface rhizosphere. Bacteria in the *Herbaspirillum* are usually associated with plant roots, often as nitrogen-fixers. Isolate FW32B groups with another Mammoth Cave environmental isolate within the *Betaproteobacteria*.

Overall, the molecular phylogenetic analysis of a small clone library from Four Windows Cave points to the novel nature of the isolates and the need to learn more about their physiology through enrichment culture studies. Of note is the observation that the closest relatives come from another cave, Mammoth Cave in Kentucky. It is tempting to speculate that this is a small bit of evidence for the existence of an indigenous cave microbial community, but much remains to be learned about the microbial diversity of caves.

Our UV sensitivity experiments with cultured isolates from Four Windows Cave showed a marked sensitivity to UV radiation in comparison to surface cultured isolates, showing a different trend than that seen by Arrage et al. (1993b).

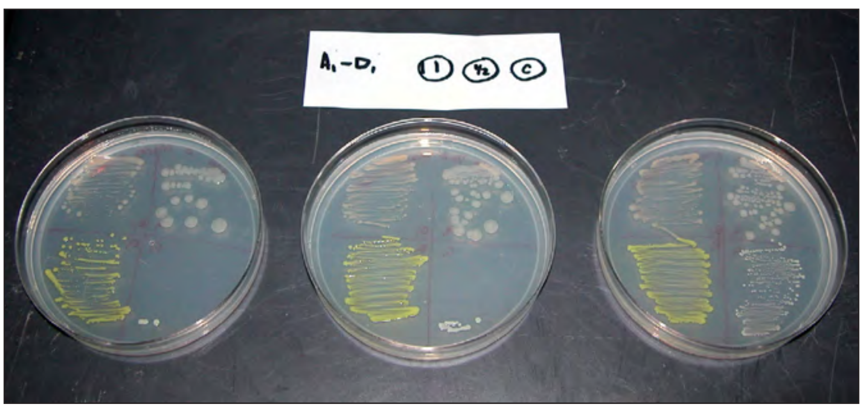


Figure 5. Comparison of replicate 1 surface strains A – D. 1= full UV dose, ½= half UV dose, C= no UV. Replicates 2 and 3 showed similar UV sensitivity (data not shown).

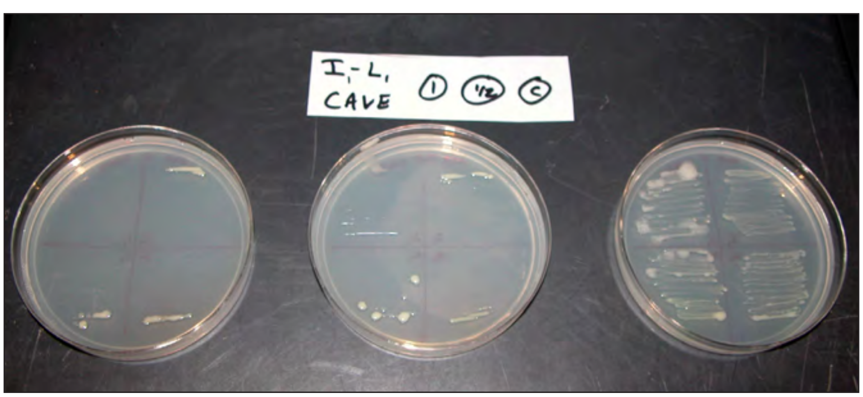


Figure 6. Comparison of replicate 1 cave strains I – L. 1= full UV dose, ½= half UV dose, C= no UV. Replicates 2 and 3 showed similar UV sensitivity (data not shown).

To further test these findings in a more rigorous manner, we are repeating the experiments with isolates from other caves with quantification of the starting inoculum and final growth amounts. If the finding is confirmed, the loss of UV sensitivity may represent an adaptation to the cave environment by bacteria that have no need of UV radiation resistance in the dark environment of the cave. Many of the same genes (*recA*) that control for UV resistance/repair also control repair for other environmental stresses such as desiccation.

This study represents some small steps in adding to our understanding of the bacterial mats that coat the walls of many lava tubes worldwide. We have established that there is a morphologically and genetically diverse community in these mats, that the culturable bacteria are UV sensitive, and that these mats are distasteful to invertebrates who preferentially feed on adjacent algal mats. These studies will hopefully spark interest in these interesting and novel communities, allowing us to further investigate their nature.

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Climate Modeling for Two Lava Tube Caves at El Malpais National Monument, New Mexico USA

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Abstract

Reliable data on cave microclimate benefits those who manage caves for human visitation, protection, and the conservation and restoration of bat roosts. Information, both published and unpublished, on cave climates is limited. Mathematical models of cave climate are even more limited, and for lava tube caves, these appear to be totally lacking. Because lava tube caves are simpler than many limestone caves (thus making the task of modeling tractable) we tested the use of lava tube caves as laboratories for climate modeling.

We present the results of investigating temperature and humidity in two lava tube caves at El Malpais National Monument, New Mexico, USA. One cave was a single-entrance cave with an ice sheet, the other a tube with detectable airflow to/from cracks on the surface. One and one-half years of data were collected in these two tubes using data loggers. Using these data, we investigated temperature and humidity changes with seasons and distance from the entrance, and propose mathematical models to predict future temperatures based on heat flow from the surface as well as advection.

Our models show a good fit to the equation

$$T(t) = a_1 + a_2 \cos[(t2\pi)/365.24] + a_3 \sin[(t2\pi)/365.24] + a_4 \cos(t2\pi) + a_5 \sin(t2\pi)$$

This implies that, at least in these lava tube caves, accurate prediction of temperature is possible.

Introduction

Cave managers need temperature and humidity data to assess the impact of visitors, conservation and restoration of bat roosts, etc. For example, in an ice cave, the question might arise, "Is human visitation melting the ice?" We show that for some caves, a manager could start by collecting data during a time without visitation. Once the baseline data exists, the predictions can allow the manager to know if the visitation is affecting the cave climate.

This paper presents the results of a cave climate study from October 1993 through August 1995 of two lava tubes at El Malpais National Monument, New Mexico, USA. The original goal was to study the impact of prescribed fire on lava tube caves; however, for political reasons the prescribed fire never occurred. If we had planned to do a cave climate study, we would have placed data loggers differently.

Description of the caves

Both of the lava tubes are located in an open Ponderosa pine forest on El Malpais National Monument, in west-central New Mexico, USA (Figure 1).

Lava Wall cave (also known as Peel Bark cave) is the smaller of the two lava tubes. It has a large wide entrance (Figure 2) approximately 6.5m x 1.5m, and it gets progressively narrower and lower. Within 6m, it turns into a muddy crawl which continues for at least 24m. The crawl shows evidence of repeated flooding and organic input, and a commonly-felt breeze implies that it connects to cracks in a nearby (30m distant) sink. Figure 3 shows an approximate cross-section of the cave. Note that this cave is

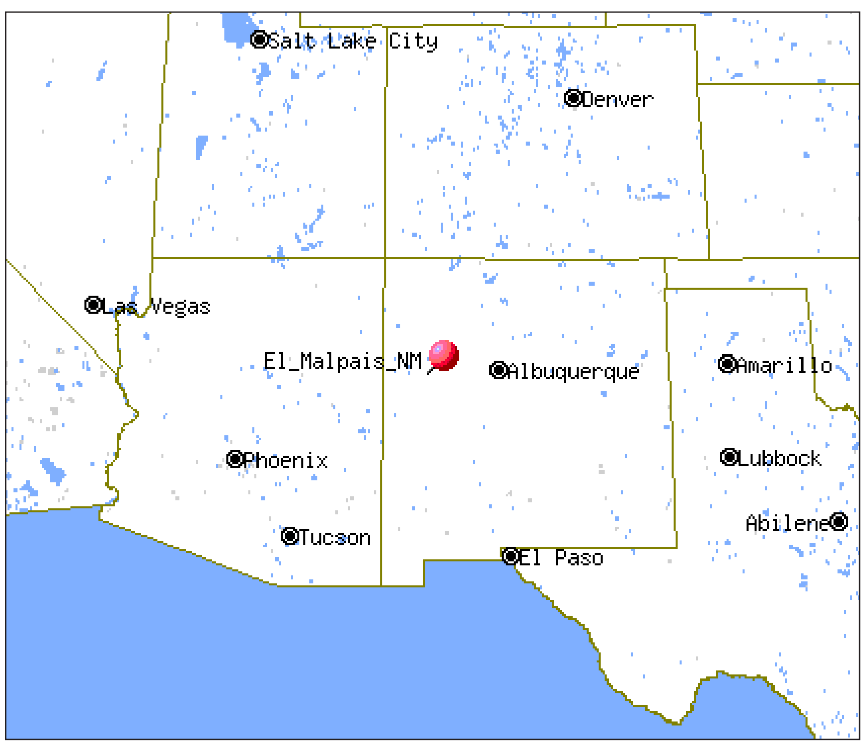

Figure 1. Approximate location of El Malpais National Monument, where the two lava tubes are located.

Figure 2. Entrance of Lava Wall cave.

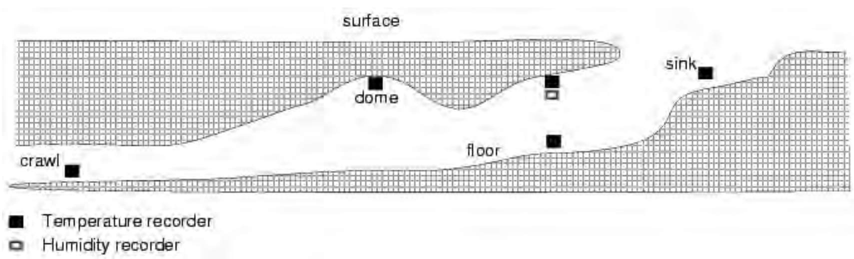

Figure 3. Cross section of Lava Wall cave.

relatively level once you are inside.

Frozen Mat cave is larger, with two rooms and a passage. The small (less than 1 meter square) entrance leads into a breakdown room (about 4m x 9m). Over a breakdown pile is a second room (about 5m x 20m) containing a 5m x 6m ice sheet (Figure 4), covered with up to 2.5cm of water in the summer. The ice is about 3m-4.5m below the entrance and about 20m from the entrance. The ice sheet varies in extent and depth throughout the year and year-to-year. The room extends no more than about 7.5m beyond the ice. Figure 5 shows an approximate cross-section of the cave.

On the left side of the entrance room in Frozen Mat is a low passage that proceeds for at least 13m and appears to pinch out. No airflow was detected through this passage.

Literature Review

Heat drives much of the airflow, and airflow can move heat around. As a result, we review previous work by looking at what is known about heat flow and caves, and then looking at previous studies of airflow.

Heat

Heat is important for two reasons. First, to predict the temperatures inside caves, we need to know from where the heat comes. Second, heat is sometimes responsible for airflow.

Heat in caves comes from three sources:

- the radioactive decay of elements in the Earth's core (geothermal heating).
- surface heat generated by the sun and transported by conduction through the soil and rock.
- surface heat generated by the sun and carried into the cave by air movement (advection).
- heat moved by a stream running through a cave (which does not apply to the caves we studied).

Figure 4. The ice sheet in Frozen Mat cave.

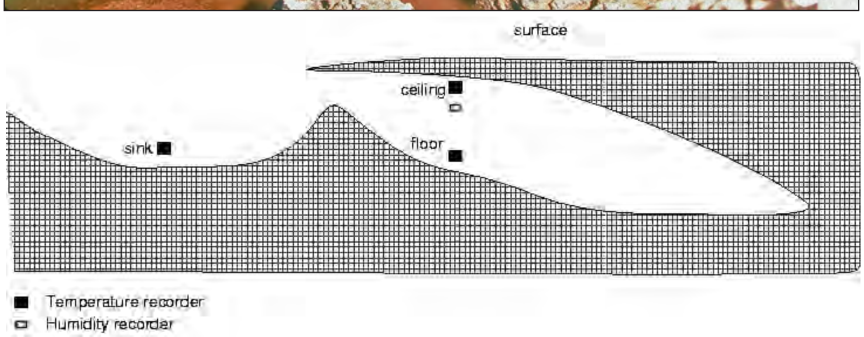

Figure 5. Cross section of Frozen Mat cave.

Geothermal heating. Atkinson, Smart, and Wigley [2] used geothermal heating to explain the difference between the mean annual temperature and the actual measured temperature deep in Castleguard cave in Alberta Canada. Most likely, geothermal heat is omitted from studies because most caves (especially the lava tubes we were studying) are close to the surface, and the other factors dominate their temperature.

Solar heat transported by conduction. Daily variations in temperature in the soil and rock die out about 1m deep [16]. Annual variations in temperature may be observed as deep as 20-24m [16] depending on the rock and soil types. At depths below below where the surface influence is felt, the temperature of a cave should be stable at the mean annual surface temperature [4, 8, 14, 16].

Heat transferred by advection. Advection is the transfer of heat by air movement. In this case, rather than the heat which is being moved causing the movement (as in convection), some other factor is causing the air movement.

Airflow

To know about airflow, we must look at the factors that can cause air to move in caves:

- density differences in air caused by temperature variations,
- the number of entrances a cave has and their relative elevation, and
- differences in air pressure from various factors considered below.

The single most important factor affecting airflow is the number of entrances a cave has and the relative height of these entrances. A cave with multiple entrances where those entrances are not at the same level will nearly always have a breeze blowing through it. When the temperature inside is lower than the temperature outside (as it is in summer), the cool (and therefore denser) air will exit the lower entrance, and the outside, warmer air will enter at the upper entrance. Conditions reverse when the temperature inside is higher than the temperature outside (as it is in winter). During times when the inside and outside temperatures are nearly the same, no breeze may blow or other factors may dominate the airflow. The velocity of the air movement in this chimney effect is directly related to the temperature (and to some extent the humidity) differences between the air inside and outside of the cave. Airflow velocities will also be affected by the volume of the cave as well as the sizes of the entrances.

Wigley and Brown [19] and Atkinson, Smart, and Wigley [2], note that a cave may have extra "entrances" in terms of fractures leading to the surface which may be too small for humans to travel but are large enough to allow air to flow. These airflow routes will cause the chimney effect to occur even in what appear to be single entrance caves. This effect probably occurs in Lava Wall cave.

For caves with a single entrance, airflow is controlled by a complex collection of factors including:

- convection,
- the current barometric pressure and how it is changing, and
- wind blowing across or into an entrance.

Additionally, surface roughness, and the sinuosity of passage affect the airflow by making it more turbulent and hence slowing it down.

Since warm air is less dense that cool air, it will tend to rise or flow along the upper part of the cave. Similarly, cool air will flow along the bottoms of the passages. The slope of the cave and orientation of the entrance will determine if or how convection will cause air exchange with the interior portions of the cave [19]. This convection was the primary air movement discovered at Altimira Cave in Spain by Villar et al. [17]. It also is a part of the airflow at Glowworm Cave in New Zealand [6]. Another example where convection is a major cause of the airflow was investigated by Smithson [15]. He looked at vertical variations of temperature in Poole's Cavern U.K. and saw the effects of convective airflow.

Convection explains why single-entrance caves which slope downward are cold traps. In the winter cold air flows into the cave. In the summer it becomes stagnant, and hence remains cool and in some cases collects ice [3, 8]. In upward-trending caves, the reverse would happen and cooler air would fall out the entrance when it was cooler in the cave than outside [19].

Other than convection, airflow also results whenever the barometric pressure outside is different from the pressure inside. When this difference occurs, the cave will inhale or exhale to equalize the pressure. Lewis [12] and Wigley and Brown [19] noted many factors which affect the atmospheric pressure outside and hence the breathing of a cave:

- weather patterns as high and low pressure systems move across, the cave lags the outside by a small amount as air flows to equalize the pressure.
- atmospheric tides are caused by the atmosphere absorbing heat directly from the sun and from the heat reflected from the earth's surface. A typical tidal curve has two maxima and two minima in 24 hours.
- gravity waves are the atmospheric equivalent of the waves we commonly associate with the ocean. They have periods from about three minutes to three hours.
- infrasound from sources such as the aurora, nuclear blasts, distant storms, waterfalls, the jet stream, volcanic explosions, earthquakes, waves on the ocean, large meteorites, supersonic aircraft.
- cave resonance from wind blowing across an entrance, much like a bottle resonates when blown across its opening.

Wigley and Brown [19] noted that a cave with widely separated entrances which has a strong storm (such as a summer thunderstorm) over one entrance may have a notable difference of pressure between the entrances which causes airflow.

Wind blowing into an entrance can cause airflow as noted by Smithson [15]. In multi-entrance caves, the wind may blow in one entrance and out another. Wind blowing across an entrance will lower the pressure at that entrance which will affect the airflow.

Any of the above mechanisms for airflow can act simultaneously to result in airflow which may be barely detectable (as in the flickering of a candle) all the way up to wind which moves gravel [19].

Temperatures in the cave

When the temperatures are different from the mean annual temperature, it is due to one of the causes mentioned above. First, we note that rock stores heat, and it will release that heat to cooler air or will absorb heat from warmer air [18].

Second, adding humidity to air cools it [7, 18] because of the heat needed to change liquid water to water vapor (about 540 calories/gram, depending on temperature). Therefore unsaturated air (from the surface) moving across a source of water (such as water percolating in from the surface) will cool as the water evaporates into it.

Taking these two factors into consideration, Wigley and Brown [18] develop the following formula to describe the temperature in the cave:

$$T = T_a + (T_0 - T_a)e^{-X} + \frac{L_v}{c_p}w(q_0 - q_a)Xe^{-X}$$

where T_a is the deep cave rock temperature, T_0 is the temperature of the air entering the cave, X is the ratio of the distance from the entrance (x) and the relaxation length (x_0), L_v is the latent heat of vaporization, c_p is the specific heat of air, w is cave wetness which indicates the fraction of the cave wall which is wet, q_0 is specific humidity of the air entering the cave, q_a is the specific humidity of the outside air when it is cooled to T_a.

The relaxation length, $x_0 = 36.44\ a^{1.2}V^{0.2}$, where a is the radius of the cave in cm and V is the velocity of the air moving into the cave in cm/sec. It is the distance it takes the temperature T_a to decay to $T_a e^{-1}$. In some caves it may be easier to calculate this distance rather than measure the airflow [5]. Wigley and Brown [19] found relaxation lengths in the range of 10 to 500m.

Given the equation of Wigley and Brown along with data obtained from monitoring the cave, we can predict the temperatures in the cave based on temperature and humidity outside the cave, current airflow, and amount of moisture on the wall of the caves. Preceding a prescribed fire, the cave should be monitored, a plan suggested by Smithson and Wigley and Brown [13, 19]. These predictions then should be compared with actual conditions observed to determine how the cave varies from predicted. During the prescribed fire, the cave can be monitored and any effects of the fire can be noted as divergence from the predicted values.

Humidity

Humidity is of interest because when water evaporates, it absorbs heat. Conversely, when it condenses, heat is released. So humidity is tied together with heat. Additionally, Howarth [1, 10, 11] states that the key environmental factor that determines the distribution of troglobites is the degree to which the atmosphere is saturated.

As you travel deeper into a lava tube (provided there are not additional entrances), evaporation decreases. Howarth [9] found that the rate of potential evaporation in the deep cave zone was only 8% of that of the twilight zone and hypothesized that the rate within the mesocaverns was much lower still. Cave organisms further take advantage of areas with low evaporation by moving into the small voids, which are often sites of accumulation of organic matter [1].

The degree of saturation of air in lava tubes is dependent on several surface factors and is a dynamic phenomenon. Climate on the surface influences the movement of air in lava tubes. When the temperature is lower outside than inside, as often happens at night in the winter, the vapor pressure of water is higher inside the cave than outside causing moist air to diffuse out of the cave. If the daytime water vapor pressure is still less than that in the cave, the water vapor will continue to diffuse out of the cave in the daytime, resulting in a winter drying of the cave known as the "wintering effect" [1]. When conditions reverse, the cave will gain moisture from the surface air.

The "wintering effect" does not seem to apply to the blind tubes at El Malpais. Frequent snowpacks that remain for days or weeks provide moisture for the lava tubes both in the form of atmospheric moisture and as melting water percolating through cracks. Ice in the lava tubes accumulates over winter, reaching a peak in early spring.

The deeper in to the cave you go, the longer the lag between changes in the surface conditions and the corresponding changes in the cave environment. Similarly, the amount of change becomes less with increasing distance from the entrance [1].

Materials and methods

Onset Hobo (Onset Computer, 470 MacArthur Blvd., Bourne, MA 02532, +1-508-759-9500, http://www.onsetcomp.com/) temperature and humidity data loggers capable of storing 1800 observations were used to collect the data. The recording interval varied from 5.6 minutes to 96 minutes, and was based on our expected return date to download data. During the winter, access to the caves was often impossible. The data loggers themselves were stored in plastic containers to shield them from the elements, with the temperature sensor outside of the container.

Unfortunately, animals destroyed some of the remote sensors. To protect the sensor, we moved the sensor for two data loggers inside the plastic container. This changed the reaction time from two to 40 minutes.

Results

Plotting raw data from the data loggers results in a graph such as the one from Frozen Mat cave (Figure 6). The data from the other data loggers were similar, and all exhibit a diurnal cycle.

A Fast Fourier Transform requires data with equal intervals, a requirement we could not meet due to the varied data collection intervals. We tried a traditional Fourier Analysis, but the resulting spectrums were not helpful in predicting temperatures.

We used a least-squares algorithm to fit sine and cosine to the daily and annual data, specifically:

$$T(t) = a_1 + a_2\cos(\frac{t2\pi}{365.24}) + a_3\sin(\frac{t2\pi}{365.24}) + a_4\cos(t2\pi) + a_4\sin(t2\pi)$$

By using both the sine and cosine, we are able to represent the annual/diurnal cycles, as well phase information.

The resulting equations for Lava Wall are in Table 1, and for Frozen Mat are in Table 2.

Discussion

Not surprisingly, diurnal cycles are strongly evident in all temperature data. Both caves are small, and have an interaction coupled to the surface temperature. The oscillations diminish as you go deeper in the cave. In Frozen

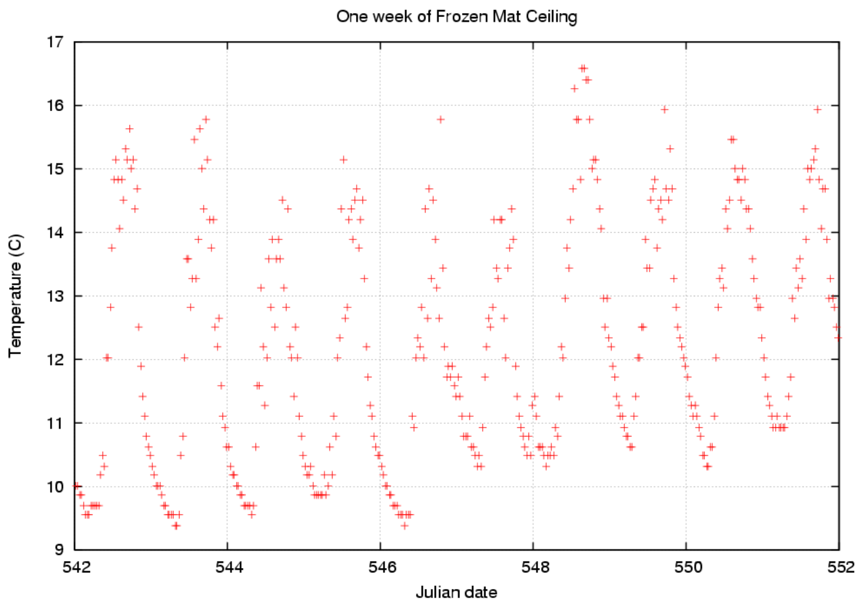

Figure 6. A week of data from the ceiling data logger in Frozen mat cave.

Table 1. Equations fitting the data for the data loggers in Lava Wall cave.

ceiling	$T(t) = 0.0(\pm 0.0) + -10.843922(\pm 0.016795)\cos(\frac{t2\pi}{365.24}) + -14.900744(\pm 0.015138)\sin(\frac{t2\pi}{365.24}) + -0.147362(\pm 0.015631)\cos(t2\pi) + -0.261526(\pm 0.015624)\sin(t2\pi)$
floor	$T(t) = 0.0(\pm 0.0) + -7.237748(\pm 0.016262)\cos(\frac{t2\pi}{365.24}) + -15.836785(\pm 0.013960)\sin(\frac{t2\pi}{365.24}) + -0.129653(\pm 0.014451)\cos(t2\pi) + -0.361877(\pm 0.014440)\sin(t2\pi)$
crawl	$T(t) = 0.0(\pm 0.0) + -1.427401(\pm 0.033754)\cos(\frac{t2\pi}{365.24}) + -10.884780(\pm 0.025210)\sin(\frac{t2\pi}{365.24}) + -0.261690(\pm 0.020269)\cos(t2\pi) + -0.531103(\pm 0.020291)\sin(t2\pi)$
sink	$T(t) = 0.0(\pm 0.0) + -19.417273(\pm 0.016925)\cos(\frac{t2\pi}{365.24}) + -13.317093(\pm 0.016707)\sin(\frac{t2\pi}{365.24}) + 0.625014(\pm 0.016633)\cos(t2\pi) + 0.546246(\pm 0.016627)\sin(t2\pi)$
dome	$T(t) = 0.0(\pm 0.0) + 31.512697(\pm 0.054709)\cos(\frac{t2\pi}{365.24}) + -25.051178(\pm 0.054308)\sin(\frac{t2\pi}{365.24}) + -0.198811(\pm 0.052696)\cos(t2\pi) + -0.744981(\pm 0.052707)\sin(t2\pi)$
relative humidity	$T(t) = 0.0(\pm 0.0) + -16.574255(\pm 0.016254)\cos(\frac{t2\pi}{365.24}) + -36.632496(\pm 0.013953)\sin(\frac{t2\pi}{365.24}) + -1.820918(\pm 0.014438)\cos(t2\pi) + -0.763961(\pm 0.014441)\sin(t2\pi)$

Table 2. Equations fitting the data for the data loggers in Frozen Mat cave.

ceiling	$T(t) = 0.0(\pm 0.0) + -8.430573(\pm 0.012779)\cos(\frac{t2\pi}{365.24}) + -20.716593(\pm 0.011610)\sin(\frac{t2\pi}{365.24}) + -0.368887(\pm 0.012041)\cos(t2\pi) + 0.136714(\pm 0.012025)\sin(t2\pi)$
sink	$T(t) = 0.0(\pm 0.0) + -23.819973(\pm 0.015790)\cos(\frac{t2\pi}{365.24}) + -22.008461(\pm 0.013915)\sin(\frac{t2\pi}{365.24}) + -3.382733(\pm 0.014441)\cos(t2\pi) + -0.264057(\pm 0.014429)\sin(t2\pi)$
floor	$T(t) = 0.0(\pm 0.0) + -8.482291(\pm 0.015796)\cos(\frac{t2\pi}{365.24}) + -17.615507(\pm 0.013921)\sin(\frac{t2\pi}{365.24}) + 0.014079(\pm 0.014441)\cos(t2\pi) + -0.054044(\pm 0.014440)\sin(t2\pi)$
relative humidity	$T(t) = 0.0(\pm 0.0) + -5.646605(\pm 0.015349)\cos(\frac{t2\pi}{365.24}) + -38.756611(\pm 0.013631)\sin(\frac{t2\pi}{365.24}) + 0.471688(\pm 0.014182)\cos(t2\pi) + 0.210453(\pm 0.014171)\sin(t2\pi)$

Mat cave, the ice sheet melting produces nearly constant temperatures until the ice retreats far enough from the data logger. The humidity is lowest mid-afternoon, which corresponds to the high point in the diurnal temperature cycle.

The error values show that the daily plus annual sine and cosine functions fit the data well. This good fit implies that the temperatures in these caves are predictable. Other, simple caves should be as predictable. More complex caves, e.g., those with multiple entrances, may be more difficult to model due to more factors affecting the temperature and/or humidity. Because each cave has a different geometry, airflow, etc., the optimal placement for climate sensors will vary.

Since our data loggers were placed for observing effects of fire, we were unable to test the prediction by Wigley and Brown [18]. To confirm their prediction would have required airflow data and/or additional temperature data in order to determine the relaxation length.

Conclusion

Cave managers can use temperature and humidity predictions for guiding their decisions for cave management. For example, bats require temperature and humidity within certain tolerances in order to use the cave. Ice formations in lava tubes may melt from the heat produced by humans visiting the cave. We have shown that for simple caves, accurate prediction of temperature and humidity is possible.

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vulcAnospeleology

XII INTERNATIONAL SYMPOSIUM

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The XII International Symposium on Vulcanospeleology is sponsored by the Sociedad Mexicana de Exploraciones Subterráneas (SMES), the Commission on Volcanic Caves of the International Union of Speleology (UIS), Grupo Espeleológico ZOTZ, Club de Exploraciones de México A.C., Veracruz Section (CEMAC), the Association for Mexican Cave Studies (AMCS), and the State of Morelos Section of the National Institute of Anthropology and History (INAH).

A total of 37 abstracts were presented, of which 24 will be oral presentations, 10 will be posters, and there will be three papers *in absentia*. Eleven are about México, the host country. There are papers about Jeju island in Korea, the Azores islands of Portugal and Iceland in the Atlantic Ocean, Arabia, Jordan and Israel in the Middle East, and of course, several papers on Hawaii and one on Japán in the Pacific Ocean. Besides, there are several biospeleology papers, and several miscelaneous or theoretical papers.

All these information has been arranged into four different Sessions: México, Rest of the world, Biology and Theoretical.

<u>México Session, Chairman C. Lloyd:</u> Several papers give information about the Sierra Chichinautzin, where México's most important lava tubes discovered to date are located. Other papers will be about lava tubes in other regions of México. Of special interest are erosional (or solutional) caves hosted in volcanic deposits, and two papers on the role of volcanic sulfur in the development of caves in limestone.

<u>Rest of the World Session, Chairmen K. S. Woo, João C. Nunes and J. Pint:</u> Most papers in this session are special studies on numerous caves distributed around the world. We will get a glimpse of recent advances in the exploration of lava tubes and other volcanic caves in various geological settings (Continental, Island Arch, and Midoceanic).

<u>Biospeleology Session, Chairman Luis Espinasa:</u> Several papers will introduce recent advances in the knowledge of microorganisms in lava tubes, while the studies of bat population and other species in the Sierra Chichinautzin provide information on biospeleological aspects of caves discussed in the México Session.

<u>Theoretical Session, Chairman J. P. Bernal:</u> A paper on the possible uses of Uranium dating and paleoenvironmental studies, several proposals for cave data bases, and a very welcome review of lava tube morphogenesis round up the discussions of the symposium.

2006 SYMPOSIUM ABSTRACTS

Edited by Ramón Espinasa-Pereña and John Pint

México Session

Inaugural Address

Importance of Lava-Tube Flow Emplacement in the Sierra Chichinautzin Volcanic Field, Mexico

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The Sierra Chichinautzin Volcanic Field (SCVF), located in the central portion of the Transmexican Volcanic Belt, is a volcanic highland elongated in an E-W direction, extending from the flanks of Popocatépetl stratovolcano (presently active) to the east to the flanks of Xinantécatl (Nevado Toluca) stratovolcano to the west. It is made up by over 220 scoria cones and associated block, A'a or pahoehoe lava flows (Martin del Pozzo, 1982). This volcanic field is on the continental drainage divide that separates the closed basin of México, which artificially drains to the north, from the valleys of Cuernavaca and Cuautla, which drain south and the Lerma river basin which flows west. Large cities, including Cuernavaca, Toluca and especially México City, together with several other populated locations, are located nearby, so renewed activity might represent a serious risk for them.

Lava flows in the SCVF vary considerably in their morphology. Some are compound andesite or basaltic andesite A'a flows, some of the thicker blocky lava flows are dacitic and others are basaltic tube-fed pahoehoe flows. Lavas belong to the calc-alkaline suit, and are genetically linked to the subduction of the Cocos plate (Martin del Pozzo, 1982). The tephra cones, lava shields, associated lava flows, tephra sequences and intercalated alluvial sediments that make up the Sierra Chichinautzin cover an area of approximately 2,500 km^2. Paleomagnetic measurements indicate that most exposed rocks were produced during the normal Brunhes Chron and are therefore younger than 0.73-0.79 Ma (Urrutia and Martin del Pozzo, 1993), which is not surprising in view of the very young morphological features of most tephra cones and lava flows.

Recent studies by Siebe (2000) and Siebe *et al*. (2004, 2005) have published dates for 10 of the youngest volcanoes in the SCVF, several of which were emplaced by lava tubes. These and other previously published dates imply a recurrence interval during the Holocene for monogenetic eruptions in the SCVF of <1,250 years (Siebe et al., 2005). Siebe et al. (2004) conclude erroneously that very long lava flows must have necessarily been emplaced by high-effusion rate eruptions, and do not consider that tube-fed pahoehoe flows can reach very far in low to moderate-effusion rates (Peterson *et al*., 1994).

In this paper an attempt is made to quantify the importance of lava tube flow emplacement in the SCVF. All known locations of lava tubes have been plotted on the topographic maps and their source volcano identified. Maps of distribution of tube-emplaced lava flows have shown that almost a third of the surface area of the SCVF is covered by these kind of lava flows, including all those over 10 kilometers in length. The four youngest eruptions known in the area were emplaced through lava tubes. We conclude that lava-tube flow emplacement is very common in the SCVF, a fact that should be taken into account when performing risk assesments.

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Oral Presentation

Lava Tubes of the Suchiooc Volcano, Sierra Chichinautzin, México

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Suchiooc volcano is the youngest of a cluster of tephra cones collectively known as Los Otates, roughly aligned in a WNW-ESE direction, and located at the crest of the Sierra Chichinautzin. The tephra cone is 200 m high and culminates at 3,100 m.a.s.l. Its tube-fed pahoehoe lavas (SiO_2<52%, Figure 4) flowed south along very steep slopes (up to 12°) until reaching the Sierra de Tepoztlán, a range of mountains made of Miocene vulcanosedimentary deposits which have been heavily eroded, creating large pinnacles with very steep to vertical sides, often separated by very narrow, vertical-sided ravines and gorges. This Tepoztlán Formation consists of alternating layers of lahars, tuffs, fluvial sediments and volcanic breccias, in layers that have a variable dip of 0° to 6° to the north. Numerous E-W and N-S fractures and small faults cut these rocks. They are considered the erosional remnant of the middle portion of a volcaniclastic fan, possibly originating from the Zempoala volcanic center to the northwest.

The Suchiooc lava flow separated into several branches among the Tepoztlán pinnacles, before continuing south towards the Oaxtepec plains, where it stopped at 1,280 m.a.s.l., having covered over 1,800 m in height at an average slope of 5.7°. With over 18 km in length, it is one of the longest lava flows recognized in the Sierra Chichinautzin. Considering an average thickness of 20 m and an area of 25 km^2 covered by the flow, a volume of 0.5 km^3 for the lava flow, plus 0.076 km^3 for the tephra cone was calculated, giving a total of almost 0.6 km^3 for the entire Suchiooc products.

Although the existence of large caves in the lava flows surrounding Tepoztlán was known for many years, no systematic surveys had been done until the SMES started the survey of Cueva del Ferrocarril in 1990. Since then, nearly 30 kilometres of lava tubes have been surveyed in detail in the lava flows of Suchiooc volcano, including the two longest lava-tube caves in continental America, Cuevas de la Iglesia-Mina Superior and Ferrocarril-Mina Inferior, 5 and 6 kilometers in surveyed length respectively, separated only by a small collapse, and also the deepest lava tube in the same continent, Sistema Chimalacatepec, with 201 meters of vertical extent.

Lava tubes have been found in the vent or proximal area, and also in the middle and distal portions of the lava flow, and in widely variable slope conditions. Morphology of the lava tubes is correspondingly very variable and include very complex anastomosing tubes, simple and unbranched unitary tubes, and also large multilevel master tubes, reflecting the variable conditions, history of lava flow emplacement, and evolution of the lava tube during activity.

Thanks to the detailed survey and the study of the numerous primary and secondary features present inside these caves, a model was developed for the evolution of lava tubes through time, and the downslope growth of feeder conduits (master tubes) through coalescence and thermal erosion of the original simple or anastomosing tubes.

Poster Presentation

Sistema Tlacotenco, Sierra Chichinautzin, México: Maps and Profiles

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The Suchiooc lava flow separated into several branches among the Tepoztlán pinnacles, before continuing south towards the Oaxtepec plains, where it stopped at 1,280 m.a.s.l., having covered over 1,800 m in height at an average slope of 5.7°. With over 18 km in length, it is one of the longest lava flows recognized in the Sierra Chichinautzin.

To date over 25 kilometers of lava tubes have been surveyed in the Suchiooc flow. Of these, the most striking are the caves that together form Sistema Tlacotenco, a group of 14 anastomosing caves with a total surveyed length of 16 kilometers along a 301 meter diference in height, developed under the town of San Juan Tlacotenco.

These caves include Cueva del Ferrocarril-Mina Inferior, which at 6,538 m is the longest surveyed lava tube in continental America, and which is only separated from Cueva de la Iglesia-Mina Superior, 5,278 m long, by a collapsed trench less than 20 meters in length. Other important caves in the group include Cueva de Marcelo, 1,268 meters long; Cueva del Capulín, 820 meters long and separated from Ferrocarril by the artificial trench cut during construction of the México-Cuernavaca railroad; Cueva de Tepetomatitla, 554 meters; recently discovered Cueva del Castillo, 455 meters, and Cueva de la Tubería, 428 meters long but 116 meters in vertical extent.

The complex relations among these caves, and their control by the underlying topography is presented through a series of maps in plan, profile and three-dimensional views, which help dilucidate the evolution of this complex lava-tube system, and is also illustrated with several photographs that exemplify the different types of primary and secondary structures and features that decorate these amazing caves.

Aditionally, evidence was found which allowed the development of a model for the evolution of lava tubes through time, and the downslope growth of feeder conduits (master tubes) through coalescence and thermal erosion of the original anastomosing tubes.

Poster Presentation

Palaeoenvironmental Reconstruction of the Miocene Tepoztlán Formation Using Palynology

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To date, palaeobotany in volcanic settings has dealt with intercalated sediments namely paleosols, fluvial volcaniclastic sandstones, peat or lignites. Even when authors worked on tuffaceous material, they focussed on either the macroflora or charcoals. Publications on palynology in pyroclastic rocks and their reworked deposits (lahars) are rare.

In this study we investigated a volcaniclastic section of the Mid-Miocene Tepoztlán Formation with respect to palaeoenvironment using palynology. The Tepoztlán Formation crops out in the States of Morelos and Estado de Mexico and consists of pyroclastic flows, volcanic debris-flows (lahars), dacitic lava flows, and intercalated fluvial or lacustrine sediments, attaining a total thickness of several hundred meters. K/Ar geochronology on some lava flows has revealed an age of about Early to Mid-Miocene.

For palynological analyses we investigated the fine-grained matrix of lahars, ash-flow deposits, and clayey layers on top of those deposits. The samples reveal a diverse pollen and spore assemblage, enabling a first palaeoenvironmental interpretation of the Tepoztlán Formation. Pollen assemblages dominated by Caryophyllaceae, Chenopodiaceae, Asteraceae and Cupressaceae indicate dry conditions, whereas spore dominated associations accompanied by Cyperaceae pollen types indicate wet to aquatic conditions. Characteristic stratigraphical vegetation patterns are interpreted in terms of short-term destruction-recolonization cycles which are controlled by volcanic eruptions and intermittent quiescence.

Present day vegetation of Central Europe is very similar to that recorded in the Tepoztlán section. Thus, a rather temperate climate is appropriate for the depositional environment of the Tepoztlán Formation.

Poster Presentation

Comparison between the Texcal Lava Flow and the Chichinautzin Volcano Lava Flows, Sierra Chichinautzin, México

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The Texcal lava flow is located to the south of the Sierra Chichinautzin Volcanic Field near the city of Cuernavaca. With 24 kilometers in length, it is the longest lava flow known in the area. Recent work by Siebe *et al.*(2004) dated this volcano at between 2,835±75 and 4,690±90 years before present (ybP), and made morphological comparisons between it and the nearby Chichinautzin volcano, dated at 1,835±55 ybP. They also conclude that the Texcal lava flow must have been emplaced at a very high effusion rate to have reached such a tremendous length with a relatively low total volume, while they consider that Chichinautzin volcano was of low effusion rate, created lava tubes, and therefore had a much shorter lava flow despite a similar volume.

The Chichinautzin flows are compound A'a and toothpaste lavas. Flow channels limited by prominent levees are easily identified both in the field and in aerial photos. Although many inflation structures are noticeable on the Chichinautzin flows, no evidence has been found of emplacement through lava tubes. Meanwhile, the whole Texcal lava flow is made up of pahoehoe, as can be seen on most surface outcrops which show the typical ropy texture. Five large lava tubes have been recently surveyed in the Texcal lava flow, all of them representing a huge master tube, in places over 10 meters wide and 20 meters high, and with evidence of continuous and sustained activity which caused thermal erosion of the underlying lithology. In the downflow direction they are Cueva Grande, Cueva Pelona, Cueva Redonda, Cueva de la Herradura and Cueva del Naranjo Rojo, for a total of nearly 4 kilometers of tubes mapped in this flow.

We therefore conclude that Chichinautzin volcano lavas were emplaced at a high effusion rate, which prevented the formation of large lava tubes and caused the A'a or toothpaste morphology, while the Texcal lava flow was emplaced at low to moderate effusion rates, which favored the formation of lava tubes.

As has been well documented previously, lava tubes isolate the lava from the air and prevent cooling of the flow, favoring the development of extensive and very long lava flows. This was the case of the Texcal lava flow. Risk assessment for the cities of Cuernavaca and México, which could easily be affected in case of renewed activity at the Sierra Chichinautzin, should take this into account, since lava tube emplacement has not been considered by any of the authors who have studied this volcanic field before.

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Siebe, C., Rodríguez-Lara, V., Schaaf, P., and Abrams, M., 2004, Radiocarbon ages of Holocene Pelado, Guespalapa, and Chichinautzin scoria cones, south of Mexico-City: implications for archaeology and future hazards; Bull. Volcanol. 66, pags. 203-225.

Oral Presentation

Surveyed Lava Tubes of Jalisco, Mexico

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La Cueva Cuata, also known as La Cueva de Tequilizinta, was the first lava tube surveyed in the Mexican state of Jalisco. The cave is situated 52 kms northwest of Guadalajara in a canyon wall overlooking the Santiago River and appears to be in the Rio Santiago alkali basalts, which are from 1.3 to 0.4 million years old. The cave is 280.79 m long with passages varying in height from 1.9 m to .25 m and ranging in width from 15 m to 1 m. Dry, powdery sediment covers the floor of the entrance room while the rest of the cave contains a thick layer of mud or clay. The cave has lava stalactites less than 4 cm long and a pool of water measuring 15 x 20 m and less than 60 cm deep, contaminated by the droppings of vampire bats which roost above it. Two other species of bats have been observed in the cave. Cuata Cave was surveyed by Grupo Espeleológico Zotz in 1990.

In 2006, La Madriguera de los Lobos, a cave located directly beneath La Cueva Cuata, was also surveyed by Zotz. The passages in this cave total approximately 100 m in length, ranging in width from 25 m to 1 m. The average passage height is 1 m. The floor of the cave is covered with powdery sediment, bat guano and, in places, what appears to be the dry scat of wolves. Calcite stalactites less than 10 cm long were observed on the ceiling. Bats were found in several parts of the cave and an air current was noted among breakdown at the back of the cave.

Oral Presentation

Cueva Chinacamoztoc, Puebla

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The Los Humeros Caldera was formed by the collapse of a pre-existing stratovolcano due to the eruption of very large pyroclastic flows, which formed the Xaltipan Ignimbrite 0.56±0.21 Ma (Ferriz and Mahood, 1984), distributed mostly to the north of the Caldera. Much later activity generated extensive basaltic lava flows emitted through the rim fractures on the southern side of the Caldera. These lava flows are known from east to west as the El Limón, Tepeyahualco and Tenextepec lava flows. One of them at least, the Tenextepec flow, was emplaced through lava tubes. It is possible that the other lava flows extruded from the caldera rim fractures were also emplaced through lava tubes, explaining their lengths of up to 16 kilometers.

Chinacamoztoc means Cave of the Bats. It was first mentioned in the scientific literature by Virlet d'Aoust (1865). Later, in a study specifically dedicated to the cave, Haarmann (1910) calculated its length at about 500 meters. Finding stream deposits in the cave floor, he proposed that the cave had formed when the lava flow covered a flowing stream, which evaporated and the gas pressure pushed the lava flow upwards leaving a void underneath. The portion of the cave visited by Haarmann is no longer accessible. Wittich (1921) in a study of the geology of the entire area, describes the cave as being almost two kilometers long, and suggests that the stream deposits seen by Haarmann entered the cave after it solidified. He concludes that the cave formed by the solidification of the flow crust, but with liquid lava remaining inside. After the lava broke the crusted front, it flowed onwards, leaving a void behind.

No other references have been found about this cave. In may 2006, members of Sociedad Mexicana de Exploraciones Subterráneas (SMES) and Veracruz section of the Club Exploraciones de México A.C. (CEMAC), visited and surveyed the lava tube. Chinacamoztoc cave is a large master tube 10 to 30 meters wide and >10 meters high in most places. The original entrance, as described by Haarmann, is now completely filled by stream deposits originated on the fields which partially cover the upper end of the lava flow. Haarmann describes the passage, now inaccessible, as being of similar dimensions. He also mentions that the upper portion of the cave ends at an artificial wall built to prevent soil loss. The lower side of the wall was accessible through a lower entrance. Sometime in the last ten years, somebody dug a hole through the artificial wall, probably believing it hid a treasure, and the completely sediment-filled passage beyond is accessible through the dug tunnel for about 15 meters.

A total of eight skylights break up the lava tube, of which three actually segment the 1,577 meters long tube into 4 caves 413, 248, 597 and 164 meters long (in a downflow direction). The skylight areas are used by large white owls as nesting sites, so please try to avoid disturbing them. On some of the skylights, the entrances to small anastomosing tubelets are visible high up the wall, near the ceiling level, and probably represent the original braided tubes from which the master tube evolved through thermal erosion.

Separation of the canyon passage into superposed levels is only visible in two sections close to skylights that might have been open during activity, but other skylights are probably post-activity collapses. The ceiling and walls of one of the lower levels is decorated with many small tubular stalactites. The segregates were extruded straight from the wall, which does not show lining breaks. In two other places, evidence of thermal erosion is seen where collapse of a lava lining exposes tephras and the Xaltipan ignimbrite. This is on a ledge still >10 meters above the lowermost cave floor.

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Poster Presentation

Lava Tubes of the Naolinco Lava Flow, El Volcancillo, Veracruz, México

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Antecedents: The Speleology Commission of the Club de Exploraciones de México Sección Veracruz, A.C., has been prospecting and exploring caves since 2005 on the Río Naolinco lava flow, originating from El Volcancillo around 800 years ago. When we noticed the vulcanospeleological potential we decided to create this project with the aim of locating caves of volcanic origin. To date we have explored the following caves in the Municipio of Jilotepec, although we believe many more caves are to be found.

Cueva de la Virgen N 19°38′1.77″ W 96°56′26.752″ 1388 m.a.s.l.
Cueva de los Cochinos N 19°38′1.77″ W 96°56′26.752″ 1388 m.a.s.l.
Cueva de la Envidia N 19°38′1.77″ W 96°56′34.987″ 1379 m.a.s.l.
Sistema del Falso N19°38′13.099″ W96°56′10.890″ 1358 m.a.s.l.
Cueva del Tirantes N 19°38′17″, W 96°56′31″ 1384 m.a.s.l.
Hoyo del Becerro N 19°36′13″, W 96° 58′22″ 1667 m.a.s.l.

Purpose: To develop a vulcanospeleological investigation in order to obtain specific data on the subterranean systems of the Municipio of Jilotepec, originated on the Río Naolinco lava flow.

Specific Projects: Obtain a photographical and topographical documentation of the caves and pits already found. Analyze the microbiological characteristics of the water found in the caves. Give alternatives to diminish the contamination of the caves due to bad management of residual waters in the towns of La Virgen and Piedra de Agua, Mpio. De Jilotepec. Generate a data base for future geomorphology and biospeleology studies.

Aims: Involve the competent institutions and local authorities in the research. Edit and publish a report with all the results.

Conclusions: Making local inhabitants aware of the underground richness and importance of their area is vital if we want to preserve the caves as geological vestiges of other times.

Oral Presentation

The Lithic Tuff Hosted Cueva Chapuzon, Jalico, México

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Chapuzon Cave is hosted in a rhyolite lithic tuff about 25km west of Guadalajara, Jalisco, Mexico. The host formation appears to be part of the Acatlan pyroclastic flow which was produced by a caldera eruption of about 400 cubic km in size about 1 million years ago. The cave is hosted in a section with about 50% heterolithic lithic fragments varying in size from 1 to 15cm and located about 30km from the likely source caldera. The cave was mapped by Grupo Zotz in 1988 to 623m in length with a vertical range of about 30m.The cave development appears to be typical dissolution of more soluble material originally taking advantage of a clay filled bedding plane. Initial development from the controlling bedding plane was phreatic in the upper part of the cave eroding both above and below the bedding plane, while in the lower part of the cave, there appears more vadose development with deep incised trenches below the same bedding plane. The cave still has an active stream for 6 months of the year which helped maintain a short swim in the lower entrance until it was mainly filled with sand a couple of years ago. The cave is also a significant bat hibernacula with a population estimated roughly of at least 10,000 individuals from at least 7 different species. This cave was featured in a television movie produced for National Geographic about bat phobias that has yet to be aired.

Poster Presentation

Cueva Tecolotlán, Morelos, México: An Unusual Erosional Cave in Volcanic Aglomerates

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Tecolotlán cave, located near the town of Cuentepec, Morelos, with a suveyed length of 870 meters and a vertical extent of 105 meters, is one of the longest erosional caves known in non-calacareous conglomerates. It is contained in volcaniclastic deposits, mainly lahars and fluvial conglomerates and a few intercalated ash layers belonging to the Cuernavaca formation, which constitute the Buenavista volcaniclastic fan, which has its apex at the Sierra Zempoala volcanic complex and extends south to the limits with the state of Guerrero.

This volcaniclastic fan has been eroded by numerous streams running almost paralel to the south, which have excavated deep "barrancas" or gullies. In particular the "barranca" of the Río Tembembe is over 100 meters deep near the location of the cave.

The cave captures the drainage of a surface "arroyo", and is developed along a single passage which for almost 600 meters follows a single fracture, oriented almost east-west. This passage is a subterranean canyon, typically vadose in its configuration, with several cascades along its length. These are developed along lithological changes, and deep plunge pools have developed at their bases. The only chamber is located under a collapse which formed a skylight almost 40 meters high, but no collapse debris remain, as they have been flushed out by the torrential floods that sweep the cave during the rainy season.

The final portion of the cave changes completely in morphology when the passage abandons the main fracture to develop along the contact between two different lahar deposits, marked by a small ash layer. The huge canyon turns into a small round tube, slightly incised in its floor, which mimics a phreatic passage in karstic caves. The cave resurges at the wall of a small tributary of the Río Tembembe canyon, almost 45 meters above the river level.

The lithology in which the cave is developed prevents solution from playing an important role in the generation of the cave, which owes its origin entirely to mechanical erosion, probably aided in the beginning by a process similar to piping in unconsolidated deposits. The morphology of the final portion would seem to indicate that the cave started its development when the Río Tembembe was at its level or just above it.

Oral Presentation

Limestone Dissolution Driven by Volcanic Activitiy, Sistema Zacatón, México

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Volcanically formed caves are typically considered to be those formed in volcanic terrain, such as lava tubes or other voids in basaltic flows. However, extreme dissolution of limestone as a result of volcanic activity is hypothesized to have developed the deepest phreatic sinkhole in the world, El Zacatón. Sistema Zacatón in northeastern Mexican state of Tamaulipas is an isolated karst area juxtaposed to the Pleistocene volcanic field near Villa Aldama, and is characterized by unique hydrothermal cenotes. The volcanic activity in the area is characterized by the presence of effusive products and explosive deposits. Their compositions range from alkali basalts to trachytes, and the structures developed in the area are flows, sheets, scoria cones, tuff rings and phreatic craters. Shallow level syenitic and granitic plutons crop out northwestern of the volcanic field. The volcanism belongs to the younger magmatic activity in the Eastern Mexican Alkaline Province. This igneous activity introduced elevated levels of CO_2 and H_2S to the groundwater within the Upper Cretaceous limestone. Pre-existing fractures focused circulation of this hyper-acidic groundwater in the localized area of Sistema Zacatón, thus radically accelerating dissolution rates of the carbonate rocks. The source of acidity in this model of karst development is originated at depth and has little influence from surface geochemical processes. This pattern of deep phreatic karst development is also observed in Pozzo del Merro, the deepest underwater cave in the world. Pozzo del Merro lies in Mesozoic limestone adjacent to the Pleistocene volcanic region near Rome, Italy.

Poster Presentation

Possible Structural Connection between Chichonal Volcano and the Sulfur-Rich Springs of Villa Luz Cave (a.k.a. Cueva de las Sardinas), Southern México

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Regional strike-slip faults may serve as groundwater flowpaths from the active Chichonal Volcano to the Villa Luz Cave (a.k.a. Cueva de Las Sardinas, CLS). In this cave, located near Tapijulapa, Tabasco, several springs carry hydrogen sulfide. Previous studies have linked the CLS spring sulfur source to basinal water and an alkaline active magma volcano, but the groundwater flow paths still needed to be reviewed. The understanding of the sulfur origin will provide insights into the possible sources, the extreme microbial environment, the sulfuric acid speleogenetic mechanism (i.e. creation of caves by strong acid dissolution), the subsurface water-rock interactions and groundwater flow paths in the area. The Volcano and CLS location in the Chiapas Strike-Slip structural Province, suggests a left-strike slip fault may be serving as a groundwater flow path, allowing deep-source magmatic water to carry the sulfur-rich water that is dissolving the limestone at CLS. Detailed geological mapping of the surface and the caves in between, coupled with chemical analyses of the water may help to prove this connection. Specifically the springs in the area will be sampled as part of the surface expression of groundwater interaction with the subsurface rock.

Rest of the World Session

In Absentia Presentation

Investigation of a Lava-Tube Cave Located under the Hornito of Mihara-Yama in Izu-Oshima Island, Japan

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A lava-tube cave recently found under the hornito of Mihara-yama in Izu-Oshima island, located in the Pacific Ocean at 120 km south of Tokyo, was surveyed and investigated by the Vulcano-Speleological Society. This lava cave was formed inside of the 1951 eruption lava flow deposited at the edge of the inner crater of Mihara-yama. The lava tube cave consists of a flat region and a sloped region whose total length is about 40 m. Inside of the lava-tube cave, general characteristics such as lava stalactites and lava benches can be found. Two important lava characteristics, yield strength and surface tension, were obtained from the observation of this lava tube cave. By using a simple model of steady state flow in a circular pipe for analysis based on Bingham characteristics of lava flow in the tube (T.Honda,2001) and from the height and slope angle of the lava tube on the sloped region, the yield strength of the lava can be obtained as 50000 dyne/cm^2. This value is very near to the value calculated as 43000 dyne/cm^2 by G.Hulme (1974) for the 1951 eruption lava flow configuration observed by T.Minakami (1951). From the pitch of lava stalactites on the roof surface (3 to 4 cm), the surface tension of lava was determined as 600 to 1000 dyne/cm. This value agrees well with the extrapolated value obtained by I.Yokoyama (1970) in the melting lava surface tension measurement experiments carried out in the laboratory.

Oral Presentation

Jeju Volcanic Island and Lava Tubes: Potential Sites for World Heritage Inscription

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Mt. Halla, Seongsan Ilchulbong Tuff Cone and Geomunorem Lava Tube System were proposed to be included in the World Heritage Sites by the Korean government in February, 2006. Jeju Island contains a variety of volcanic landforms and more than 120 lava tubes of geological and speleological significance. It essentially consists of one major shield volcano, Mt. Halla, with satellite cones around its flanks. Also notable features include the parasitic cone (Seongsan Ilchubong Tuff Cone), which shows a Surtseyan-type underwater volcanic eruption. Most notable is a variety of lava tubes (Bengdwi Cave, Manjang Cave, Gimnyeonsa Cave, Yongcheon Cave and Dangcheomul), which show a complete flow system and display perfectly preserved internal structures despite their old age. Dangcheomul and Yongcheon Caves contain calcareous speleothems of superlative beauty.

Five aspects are identified which demonstrate the congruence of specific features to criteria for World Heritage status. 1) The volcanic exposures of these features provide an accessible sequence of volcanogenic rocks formed by at least three different eruptive stages between one million and a few thousand years BP. The volcanic processes that made Jeju Island were quite different from those for adjacent volcanic terrains, in that Jeju Island was formed by huge plume activity (hot spot) at the edge of the continent. 2) The nominated features include a remarkable range of internationally important volcanic landforms that contain and provide significant information on the history of the Earth. The environmental conditions of the eruptions have created diverse volcanic landforms. 3) Eroded by the sea, Seongsan Ilchulbong Tuff Cone discloses the inner structure of the volcano of the Surtseyan-type eruption, which provides immense scientific value illustrating a large variety of sedimentary and volcanic characteristics of phreatomagmatic eruption, in addition to its magnificent natural beauty. 4) Geomunoreum Lava Tube System contains a parasitic cone and five significant lava tubes with various dimensions, shapes, internal morphology and speleothems. 5) Perhaps the significance lies in the abundant secondary carbonate mineralization to be found in two of the low-elevation lava tubes, Yongcheon and Dangcheomul Lava Tubes, which can be considered to be the most beautiful lava tubes filled with wonderous calcareous speleothems. They are acknowledged to be the best of this type of lava tubes in the world.

Oral Presentation

New Discovery of a Lime-Decorated Lava Tube (Yongcheon Cave) in Jeju Island, Korea: Its Potential for the World Heritage Nomination

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Jeju Island in Korea is essentially made of one shield volcano with more than two hundred parasitic cones around it. Among more than 120 lava tubes can be found a series of lava tubes formed by several lava flows erupted from the Geomun Oreum (parasitic tuff cone), called the Geomun Oreum Lava Tube System. The system includes several lava tubes such as Seonheul Vertical Cave, Bendwi Cave, Bukoreum Cave, Daerim Cave, Manjang Cave, Gimnyeong Cave, Yongcheon Cave and Dangcheomul Cave. All these caves are estimated to be developed between about 300 and 100 ka BP. Two lava tubes (Yongcheon and Dangcheomul Caves) in low elevation areas contain calcareous speleothems.

Yongcheon Cave was recently discovered accidentally in May, 2006, during the installation of a telephone pole. Yongchoen Cave became especially famous for its superlative beauty from magnificent carbonate speleothems together with Dangcheomul Cave, and has become a potential site for the World Heritage Nomination. The cave is about 3 km long, and lies across the gentle northeastern slope of Mt. Halla, where there is a large area of basalt lava plains, largely in alkaline olivine basalt. This lava tube is situated between Gimnyeong and Dangcheomul Lava Tubes. Inside, a majestic arched ceiling is met by vertical walls, mostly creating a dome-shaped cross section. The cave includes a typical lava tube configuration and shows diverse morphology and micro-topography such as lava shelves, lave benches, lava stalactites, lava stalagmites, extensive lava rolls, lava falls and a spring-water lake. In addition, the cave contains a variety of carbonate speleothems such as soda straws, stalactites, stalagmites, columns, cave corals, curtains, flowstone, rimstone, and cave pearls. Windblown sediments, forming carbonate sand dunes, transported from beaches nearby, are present over the tube. Calcium and carbonate ions responsible for the formation of carbonate speleothems are supplied by dissolution of the carbonate sediments by meteoric water and transportation through plant roots and cracks. Animal skeletons, abalone shells, wooden torches and historical earthenware make Yongcheon Cave even more valuable scientifically.

Oral Presentation

Structural Characteristics of Natural Caves and Yongchon Cave on Jeju Island

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Jeju Island is a volcanic island which was formed after having experienced volcanic reactions over five times on a large scale and over a hundred times on a small scale. This island is located at a latitude of 33° 11′ 27″ - 33° 33′ 50″ north and a longitude of 126° 08′ 43″ - 126° 58′ 20″ west. The island covers an area of 1,845.92 km^2. The island runs approximately 73 kilometers from west and east and 31 kilometers from north to south. Volcanic caves and sea caves are distributed widely on this small island. The total number of natural caves which have been discovered and/or confirmed to exist on Jeju Island according to the studies conducted by the author from the year of 1975 through June of the year of 2006 amounts to 172 which include 137 volcanic caves and 35 sea caves. The purpose of this paper is to present the results of the fundamental academic research which was undertaken for the purpose of having volcanic caves such as Manjang Cave, Beungdwi cave, Dangcheomul Cave and Yongchon Cave be recognized as World Natural Heritages. Further, this research centers on examining Yongchon Cave, which was discovered on May 2005, as a Non-Limestone Cave (also known as Lava cave, Pseudo Limestone Cave, Lime-decorating Lava cave).

The summary of this paper is as follows:

1. The total length of the part of the Yongchon cave that is measured to date is 2470.8m +αm. This length will be greater after a survey of the lake and its vicinity is complete.
2. The height of the cave to the ceiling is between 1.5 meters and 20 meters and the width is between 7 and 15 meters. The cave runs mainly west and southward and north and eastward.
3. The cave has her marvelous features, such as a gigantic lava roll which is approximately 140 meters long, a lava terrace, a lava fall, a lava shelf and other formations.
4. Those carbonate sediments that are distributed variously inside the Yongchon Cave include stalactites, soda straws, columns, stalagmites, cave pearls, cave corals, flow stones and rimstones along with other sediments in eccentrical shape. A cave that reminds people of a chandelier is very rare anywhere in the world.
5. Those materials that were considered to have been brought inside the cave include earthenware allegedly from an ancient period, animal bones, burnt wood and metal ware including a poker. The earthenware which has been subject to archeological study has been determined to belong to the period of between eight and nine centuries.
6. The animal bones which are found inside the cave will be employed as important material to study the ecosystem both inside and outside the cave. These types of bones are various and determined to have been brought in by humans and still being under study.
7. The survey and research has been currently on hold on a temporary basis due to safety and hazard concern after a large scale lake had been found. Once further and closer examination is carried out, the determinations regarding Yongchon Cave will become clearer and her significance will be greater.

Oral Presentation

Recent Contributions to Icelandic Cave Exploration by the Shepton Mallet Caving Club (UK)

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The Shepton Mallet Caving Club has a connection with Icelandic cave exploration going back 35 years to 1971. The interest in caving in this country was re-awakened by participation in the Laki Underground Expeditions in 2000 & 2001 (in association with Bournemouth University). Since these visits, members of the club have carried out further work in 2003 and 2005 on the Reykjanes Peninsula and the Ódáðahraun lava fields in the central part of the country.

This work has been a mixture of original exploration and surveying of previously known sites, in conjunction with Hellarannsóknafélgs Íslands. Major sites surveyed on Reykjanes include Flóki, a 1-km-long maze cave, and Búri, just under 1 km of huge trunk passage recently found by locals. In the Ódáðahraun, the first descent was made of a shaft called Hellingur, which revealed over 500 m of large well decorated passage. This is now the longest cave known in this part of the country.

In Absentia Presentation

Basalt Caves in Harrat Ash Shaam, Middle East

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The Harrat Ash Shaam is one of the largest volcanic fields in the Middle East, ranging across the north-western Arabian plateau, from Saudi Arabia through Jordan and Syria to Israel. The present study deals with voids in Pleistocene basalts, mostly of the last 500,000 years. Circular voids, probably associated with large volcanic gas bubbles, commonly appear on the surface as circular depressions, with vertical or sloped walls.

Lava tubes and pressure ridge caves are common around Jebel Druze plateau. The pressure ridge caves are commonly some tens m long, located very close to the surface, within the last local lava flows. The longest lava tube was found within a porphyritic and vesicular olivine basalt flow. The cave is entered through central skylights, has one level with tributary and distributary systems. Several stages of internal lava flow are distinguished, with a final aa basalt filling the lower reaches of the tube, covering a former pahoehoe surface.

Oral Presentation

Prospects for Lava-Cave Studies in Harrat Khaybar, Saudi Arabia

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To date one lava tube, Dahl Rumahah, 208 m long, has been surveyed in Harrat Khaybar, a lava field of approximately 12,000 square km, located north of Medina in western Saudi Arabia. However, lava-cave entrances have been observed and/or photographed in the northern, central and southern parts of the same lava field, suggesting that many other caves may be found in this area. Strings of collapses up to 25 km long, observed by helicopter, indicate the possibility that some of these caves may prove to be of significant length.

The lava caves of Harrat Khaybar may have been frequented and used by ancient peoples, but no archeological study has ever been conducted in Saudi lava tubes, whose floors are typically covered by a meter or more of sediment. One of the routes used by the first human beings to leave Africa 50,000 to 70,000 years would have brought early Man close to the edge of Harrat Khaybar. Lava caves in this area would have provided much needed water and shelter to these people. In later years, these caves lay within reach of the Nabatean spice trail between Yemen and Petra. In addition, one of the richest sites of petroglyphs in Saudi Arabia is situated at the edge of Harrat Khaybar.

This paper suggests that Harrat Khaybar is an ideal place to search for unexplored lava tubes in Saudi Arabia and recommends the undertaking of a vulcanospeleological survey of this lava field. In addition, it urges the commencement of an archeological study of lava tubes in Harrat Khaybar.

Oral Presentation

Al-Fahde Cave, Jordan, the Longest Lava Cave Yet Reported from the Arabian Peninsula

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The northeastern region of Jordan is volcanic terrain, part of a vast intercontinental lava plateau, called the Harrat Al Shaam. The centre is formed by young alkali olivine basaltic lava flows, the Harrat Al-Jabban volcanics or the Jordanian Harrat (Al-Malabeh, 2005). The top most and therefore youngest flows are ca. 400 000 years old (Tarawneh et al., 2000). There we explored, surveyed and studied a total of twelve lava caves since September2003, among them six lava tunnels (one has two caves) and five pressure ridges caves. This includes the 923.5 m long Al-Fahda Cave (Lioness Cave), which was surveyed September 16th and 19th 2005 by the authors. It is currently the longest reported from the Arabian Peninsular (J. Pint, pers. comm.).

Two entrances exist. The main entrance is a roof collapse at the apex of a 15 m wide hall, dating much later than the activity of the cave. This entrance gives access to the cave stretching for almost 490 m downslope and almost 190 m upslope. The tunnel is on the one hand amazingly wide (average > 7m!) but also very low (average 1.2 m). The slope measured apparently is less than one degree (8.6 m altitude change on 755 m). This is very low, even compared to the lower levels of Hawaiian lava tunnels and an important observation since it shows why the Harrat lavas could spread so far: They were tube-fed pahoehoe lavas.

Oral Presentation

State of Lava Cave Research in Jordan

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The northeastern region of Jordan is volcanic terrain, part of a vast intercontinental lava plateau, called the Harrat Al-Shaam. The centre is formed by young alkali olivine basaltic lava flows, the Harrat Al-Jabban volcanics or Jordanian Harrat (Al-Malabeh, 2005). The top most and therefore youngest flows are ca. 400 000 years old (Tarawneh et al., 2000). In these lavas we explored, surveyed and studied a total of twelve lava caves since September 2003. 2,525 m of passages were surveyed as of September 2005 (Table 1).

The discovery of so many lava tunnels in the Harrat Al-Shaam lava field by Al-Malabeh in the period between 1986 and 2006 came as a surprise, considering the old age of these volcanics. It also is surprising considering the fact that the Harrat is covered by loess that can be easily washed into caves filling them eventually. Al-Fahda Cave, Beer Al-Hamam, Dabie and the two Abu Al-Kursi Caves are all terminated by sediments. Only Al-Howa Cave is terminated on both ends by roof collapse due to the loading of a later a‘a lava flow. It is interesting to note also that branching of the caves is noted only at both ends of Al-Fahda Cave, but not in the others. Other features, so typical for Hawaiian lava tunnels,

Table 1 (Kempe et al.). List of currently known and surveyed lava caves in Jordan, arranged by total passage length.

Name of Cave	Latitude	Longitude	Stations	Length m	Stations	Depth m	Direction	Altitude m	Type
Al-Fahda Cave	32°18'	37°07'	Complex*	**923.5**	2 to 54	6.7	SW-NE	832	Lava Tunnel
Beer Al-Hamam	32°07'	36°49'	32 to 23	**445.0**	1 to 23	17.2	NW-SE		Lava Tunnel
Abu Ras Cave			21 to 35	**231.1**	1 to 23	10.0	NW-SE		Lava Tunnel
Al-Ameed Cave			Complex*	**208.0**	2 to 31	4.0	SW-NE		Pressure Ridge
Dabie Cave	32°10'	36°55'	0 to 14	**193.6**	0 1to 13	1.8	NW-SE	893	Lava Tunnel
Abu Al-Cursi Makai	32°15'	36°39'	20 to 34	**153.7**	1 to 34	12.2	W-E		Lava Tunnel
Al-Howa	32°18'	36°37'	Complex*	**97.1**	2 to 6	10.8	SW-NE		Lava Tunnel
Al-Haya Cave	32°17'	36°34'	1 to 11	**81.3**	1to 9	4.2	NW-SE	911	Pressure Ridge
Abu Al-Cursi Mauka	32°15'	36°39'	2 to 18	**77.1**	2 to 18	8.1	N-S		Lava Tunnel
Azzam Cave	32°17'	36°36'	13 to 25	**44.1**	1 to 25	4.2	NNW-SSE		Pressure Ridge
Al-Ra'ee Cave	32°17'	36°34'	1 to 6	**42.0**	1 to 34	3.5	NW-SE	911	Pressure Ridge
Dahdal Cave	32°17'	36°35'	5 to 12	**28.9**	1 to 12	0.0	SW-NE		Pressure Ridge
Total				**2525.4**					

* calculated from station networks.

like lava falls, plunge pools, and secondary ceilings seem to be absent. Shelves are prominent only in Dabie Cave. The presence of the lava tunnels underscores the fact that the Harrat consists of tube-fed pahoehoe.

Oral Presentation

Gruta das Torres—Visitor Center

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Located in Pico Island, at 285 m altitude, Gruta das Torres is a volcanic cave originated from *pahoehoe*-type lava flows, extruded from Cabeço Bravo. It is the longest lava tube known on the Azorean Islands: it is around 5 150 m in total length and 15 m in maximum height. It is composed of one main, large-sized tunnel and several secondary lateral and upper tunnels. Gruta das Torres, because of its size, beauty, cave fauna and geological formations, was therefore designated a Regional Natural Monument by regional decree nr. 6/2004/A of March, 18th.

In the year 2000, the Azorean Environmental Services initiated the process to transform part of Gruta das Torres into a "show cave" creating a visitors' center, improving accessibilities, and attributing the tourist exploration to the NGO "Os Montanheiros".

The visits will take place in small groups of 15 visitors, for a 45 minutes guided tour, along 450 meters, with individual lightening system which will also work as an emergency device.

After the opening of Gruta das Torres Visitor Center to the public on the 24th of May, 2005, large numbers of tourists have visited this volcanic cave, reaching the number of 3525 visitors in the period of June to December 2005.

Poster Presentation

GESPEA - Field Work (2003–2006)

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In 1998, the Regional Government of the Azores established the GESPEA - Working Group on Volcanic Caves of Azores, with the aim of studying the volcanic caves of the archipelago. That decision was taken because of the geological and biological interest and diversity of the volcanic caves, their importance in terms of Natural Heritage, educational purposes and also their uniqueness and importance in terms of tourism.

In the last three years, GESPEA promoted four scientific expeditions in three different islands: Picospel 2003 (Pico island), Beira 2003 (São Jorge island), Pico 2004 (Pico island) and Graciosa 2005 (Graciosa island).

On those expeditions, 76 caves were visited, 22 new caves were discovered, and geological and biological information were collected to update the Azorean Speleological Inventory and Classifying System (IPEA). Also new topographies, schemes, videos and photos were performed for some of those caves. New records of animals and plants were obtained for many of the caves. A new species of beetle was discovered in a volcanic pit from S. Jorge during the pre-symposium activities of the XI International Symposium on Vulcanospeleology (Pico Island, Azores, 2004).

Poster Presentation

Catalogue of the Azorean Caves (Lava Tubes, Volcanic Pits, and Sea-Erosion Caves)

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In this contribution we present the first catalogue of the currently known Azorean caves, namely lava tubes, volcanic pits and sea-erosion caves. This was possible due to: i) the wealth of information compiled by several Azorean environmental associations (e.g. "Os Montanheiros", "Amigos dos Açores" and Speleological group of CAIP – Circulo dos Amigos da ilha do Pico) and ii) to the development of the IPEA Database and classification system by GESPEA Working Group, created by the Regional Government of the Azores in 1998. A total of 250 structures (185 lava tubes, 23 volcanic pits, 8 pit-caves, 18 sea-erosion caves, and 6 other type of structures) are described in the Catalogue, and for each of them is included information about: name, name synonyms, location (island, locality), length/depth, general description, main geological features, biological interest, main references and a map with the location of the cave/pit in the island. When available, a detailed topography or sketch is also provided. The catalogue also includes comprehensive lists of the fauna and flora known for each cave and the main speleological and biospeleological literature from the Azores. Several of these volcanic caves harbour great geological and biological diversity. Together, they provide a diversified geological, biological and aesthetic patrimony that must be protected and promoted according to the specificities of each structure. It is hoped that the present catalogue may help to achieve a better management of the Azorean caves.

Oral Presentation

Thurston Lava Tube, the Most Visited Tube in the World. What Do We Know about It?

Stephan Kempe[1] and Horst-Volker Henschel[2]
Survey by Stephan Kempe, Matthias Oberwinder, Holger Buchas, Klaus Wolniewicz
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Thurston Lava Tube, discovered in 1913, is a celebrated tourist attraction in the Hawaii Volcanoes National Park. It is visited daily by hundreds, if not thousands. Hardly any other lava tube in the world can match its popularity. In spite of its many references in literature, not much is known about its speleogenesis and previously published maps have not been very detailed (Powers, 1920; Wood, 1979; Halliday, 1982). To get a more detailed view we surveyed it on March 9th, 1996 in high precision, using digital compass and level mounted on antimagnetic tripods (Table 1).

Vulcanologically the cave is important since it is situated very near to the original vent of the Ai-la‘au Shield at 1195 m a.s.l., the site of the last massive summit eruption of Kilauea (Holcomb, 1987) ending about 350 years ago and producing Kazumura Cave. When inspecting the cave, a series of questions arise. For the casual observer the cave appears strangely dull, without many detailed features. Also the typical smooth, continuous glazing found in lava tubes is missing throughout. And finally the cave ends at a lava sump, which poses quite a puzzle. These questions will be discussed in light of what is currently known about the cave.

Oral Presentatiion

Geology and Genesis of the Kamakalepo Cave System in Mauna Loa Lavas, Na‘alehu, Hawaii

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The Kamakalepo Cave system south of Na‘alehu, Hawaii, consists of four larger sections of a once much longer tunnel in Mauna Loa lavas. It formed in very olivine phenocryst-rich, picritic lavas of high density and moderate vessicularity. Similar flows, belonging to the same age group crop out further to the west, from which one ^{14}C age is available, dating the flows to 7360±60 a BP.

Table 1 (Kempe, et al. Thurston Lava Tube). Survey data for Thurston Lava Tube.

Length (from the beginning of cave roof - which is 13.5 m mauka of St. 18 above entrance bridge- to lava sump end at St. 0)	inclined	horizontal
total cave (m)	490.84	490.08 (St 0 to St.18= 476.58 m)
wild section (m)	357.43	356.76
tourist section (m)	133.41	133.32
total survey length (m)	531.75	(total of 19 Stations)
as the crow flies (m)	-	432.5
sinuosity (490.076/432.5)	1.133	
vertical extension (m) (St. 0 at lava sump to floor at St. 18 at makai end of bridge)	-20.08	
width (m)	max. 10.5	min. 3.5
height (m)	max. 11.5	min. 1.6
total lava fall height (m)	1.8	8.96% of total vertical
slope (°) (tan^{-1} (20.08/476.576)	2.413	

The system is entered through two pukas (holes): Lua Nunu o Kamakalepo (Pigeon Hole of the Common People) and Waipouli (Dark Waters). Both give accesses to uphill (mauka) and downhill (makai) caves totalling almost 1 km in length (Table 1). In addition Waipouli is filled with an underground brackish tidal lake 200 m. Two further pukas belong to the system, "Pork Pen Puka" (mauka of Lua Nunu) and "Stonehenge Puka" (makai of Waipouli). Pork Pen Puka is a depression set into the roof of Lua Nunu Mauka, the bottom of which is a secondary ceiling to the cave below. Stonehenge Puka is a 60 * 40 m large and up to 20 m deep crater, which not only issued lava as a rootless vent but from which large blocks were swept out, that today mark its rim (giving it a certain resemblance with the real Stonehenge). Using stratigraphic profiles of Lua Nunu and Waipouli and detailed geological maps we discuss the genesis of the system and its fate due to later lava intrusions.

Oral Presentation

Archeology of the Kamakalepo/Waipouli/Stonehenge Area, Underground Fortresses, Living Quarters, and Petrogylph Fields

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South of Na'alehu, Hawaii, near the coast, the Kamakalepo area contains unique archaeological features both above and below ground (Bonk, 1967; Kempe, 1999). A large cave system consisting of four sections of a once much longer tunnel in Mauna Loa lavas was used extensively by the native Hawaiians. The system is entered through two pukas: Lua Nunu o Kamakalepo (Pigeon Hole of the Common People) and Waipouli (Dark Waters). Both of these pukas give accesses to uphill (mauka) and downhill (makai) caves, totalling together 1 km in length.

Table 1 (Kempe et al. Kamakalepo Cave). Length of Kamakalepo Cave System (north to south).

Lua Nunu o Kamakalepo Mauka (of this mauka of crawl)	416.8 m 111.5 m
Lua Nunu Central Cave	26 m
Lua Nunu o Kamakalepo Makai	169.6 m
Waipouli Mauka	125.5 m
Waipouli Makai	260 m
Total	997.9 m

Underground, the caves of the Lua Nunu are the ones used primarily. Retaining walls are found at both entrances providing for dwelling platforms. The main features are two large defence walls across the cave erected by stacking breakdown blocks. The wall in the Makai Cave collapsed mostly, but the one in the Mauka Cave, ca. 60 m into the cave, is well preserved. It has all the characteristics of a medieval defence wall 25 m long and reaching up to 5.5 m above the floor.

Both of the Waipouli Caves show little signs of Hawaiian presence. In the mauka sections just a few places with charcoal are found and a few bits of seafood shells. The makai part is filled with a brackish tidal lake which is caped by freshwater at times of high groundwater flow. We found one large beach stone on the steep entrance slope and a whale vertebra in the water (^{14}C dating in progress).

Above ground the area shows many signs of usage: beach-stone covered paths, platforms (heiaus), lava dug up for agricultural purposes, animal pens, and areas with petroglyphs, some of them post-contact.

In Absentia Presentation

Cave Detection on Mars

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Exploration of the Martian subterranean environment offers a unique avenue for: (1) investigating promising localities to search for extinct and/ or extant life; (2) identifying areas likely to contain subterranean water ice; (3) evaluating the suitability of caves for the establishment of human habitation areas; and, (4) investigating subsurface geological materials. Use of remote sensing offers efficient means of cave detection. Due to the long and widespread volcanic history of Mars, the low gravity, possible low seismicity, and low rates of processes that could collapse or fill in caves, lava tubes are expected to be common and widespread. Detection of these features on Mars involves: (a) development and interpretation of thermal dynamic models of caves to identify the thermal sensor requirements for detection; (b) evaluation of available imagery of both Earth and Mars for their utility in cave detection; and, (c) collection, analysis and interpretation of ground-based measurements of thermal dynamics of terrestrial caves (and then relating these data to detection of Martian caves).

Our models suggest detectability will be influenced by both time of day and geological substrate. We have also determined that certain bands in THEMIS IR are best for cave detection and have examined cave size in relation to thermal detectability. Thermal data from terrestrial caves supports model results indicating imagery capture at the appropriate time of day is critical to detection. These data also reveal numerous interesting thermal characteristics of caves, which will improve our understanding of thermal properties of caves on both Earth and Mars.

Biospeleology Session

Oral Presentation

A Comparison of Microbial Mats in Pahoehoe and Four Windows Caves, El Malpais National Monument, NM, USA

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Colorful microbial mats exist in lava tubes in many areas of the world, yet little is known about the composition of these microbial communities. Earlier studies of white microbial mats in Four Windows Caves revealed the presence of members of the *Actinobacteria*, *Betaproteobacteria*, *Chloroflexi*, and *Verrucomicrobia*. We have expanded our research to determine whether microbial mats of yellow/ gold coloration, and located in another lava tube, Pahoehoe Cave, have different or similar community compositions. We also wished to ascertain whether novel microbial species are present. Scanning electron microscopy of white and yellow/ gold colonies showed the presence of a variety of cellular morphologies including filaments (textured and smooth), planctomycete-like shapes, and rods. To avoid the pitfalls of culture-based studies, we extracted DNA from colonies adhered to rock samples collected aseptically. The DNA was cleaned, amplified with polymerase chain reactions, cloned, and sequenced. We compared the resultant 16S rDNA sequences against the BLAST and RDPII databases to determine closest relatives, which we aligned and used to generate a phylogenetic tree of evolutionary relationships. This analysis revealed that (1) the only overlap between the two caves occurred in the *Actinobacteria*, but even here the sequences were not closely related; (2) samples from the white colonies in Pahoehoe Cave were most closely related to *Enterobacteriaceae*, such as *E. coli* and *Shigella* spp., possibly originating from surface contamination; (3) additional groups found in Pahoehoe Cave included *Alphaproteobacteria* and other *Gammaproteobacteria*; (4) several novel species were identified based on genetic sequences.

Oral Presentation

Use of ATLANTIS Tierra 2.0 in Mapping the Biodiversity (Invertebrates and Bryophytes) of Caves in the Azorean Archipelago

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In this contribution the software ATLANTIS Tierra 2.0 is described as a promising tool to be used in the conservation management of the animal and plant biodiversity of caves in Macaronesia. In the Azores, the importance of cave entrances to bryophytes is twofold: i) since these are particularly humid, sheltered habitats, they support a diverse assemblage of bryophyte species and circa 25% of the Azorean brioflora is referred to this habitat and ii) species, either endemic or referred in the European red list due to their vulnerability (19 species) or rarity (13) find refuge there. Cave adapted arthropods are also diverse in the Azores and 21 endemic obligate cave species were recorded. Generally these species have restricted distributions and some are known from only one cave. ATLANTIS Tierra 2.0 allows the mapping of the distribution of all species in a 500 x 500 m grid in a GIS interface. This allows an easy detection of species rich caves (hotspots) and facilitates the interpretation of spatial patterns of species distribution. For instance, predictive models of species distribution could be constructed using the distribution of lava flows or other environmental variables. Using this new tool we will be better equipped to answer the following questions: a) Where are the current "hotspot caves" of biodiversity in the Azores? b) How many new caves need to be selected as specially protected areas in order to conserve the rarest endemic taxa? c) Is there congruence between the patterns of richness and distribution of invertebrates and bryophytes? d) Are environmental variables good surrogates of species distributions?

Poster Presentation

Bryophytes of Lava Tubes and Volcanic Pits from Graciosa Island (Azores, Portugal)

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Mainly due to historical reasons, Graciosa Island is the poorest island of the Azores regarding the number of bryophytes (119), especially of rare and endemic species. However, Lava Tubes (Furna da Maria Encantada, Furna do Abel, Galeria Forninho) and Volcanic Pits (Furna do Enxofre) seem to offer refuge to some interesting plants. Previous studies have recorded, among others, the European endemic moss, *Homalia webbiana*, present only in four of the nine Azorean Islands and with less than 10 localities recorded in the archipelago. The main purposes of the fieldwork were: i) to update with field work, the bibliographic records of bryophytes that may be observed in the volcanic formations of Graciosa; ii) to identify in those formations, endemic bryophyte species (from the Azores, Macaronesia and Europe) and species with a conservation risk associated, according to the European Committee for the Conservation of Bryophytes (ECCB). The results show that although no Endemic plants from the Azores were found at this point, six European endemic species and four Macaronesian endemic species were confirmed in the entrances of these volcanic formations, including one Vulnerable species and three rare species, according to ECCB criteria. In conclusion, besides the rich geological interest of the caves in Graciosa, their entrances continue to harbour rare or endemic bryophytes, not commonly found on other parts of the island, possibly due to the greater stability of these habitats. This is an additional reason to preserve the caves and a further possible motive of interest to all that visit them.

Poster Presentation

First Approach to the Comparison of the Bacterial Flora of Two Visited Caves in Terceira Island, Azores, Portugal

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"Algar do Carvão" and "Gruta do Natal" are two interesting volcanic show caves in Terceira Island. The purposes of this work were: i) to characterize the main groups of bacteria observed on their walls and ceiling in four different illumination conditions: darkness, artificial light, half-light and under natural light; ii) to look for *Actinomycetales*, mainly from the family *Streptomyceteae*, due to their ability to produce high-value biochemical products; iii) to investigate if the human activities associated with the economic exploitation of the caves (artificial illumination, visiting activities, cattle raising in their vicinities) had ecological impacts on the composition of the local microbial flora. Although it was not possible to isolate *Actinomycetales* at this point, the preliminary results show that the bacterial flora of both caves was diverse; 52 different isolates were obtained, and these are mostly the result of water infiltration from the overlying fields. In "Algar do Carvão", the half-light area supported the highest diversity of bacterial flora, with 26 isolates, including mostly bacteria associated with the grazing activity that occurs above the Algar. The most interesting species isolated was *Sphingobacterium multivorum*, which has the natural ability to accumulate zeaxanthin, a molecule used as a food pigment and which recently has been considered important in eye-health, reducing the risk for age-related macular degeneration. The darkness microhabitat of "Gruta do Natal" was the most diverse of the sampled areas of that cave, producing 13 isolates, the majority of which not associated with faecal contaminations. The microbial flora of the two studied formations shows that human activities, mainly cow and goat grazing, are affecting their composition. It is hoped that a management plan could incorporate this information, in order to ensure that only the natural bacterial flora of these caves develop.

Oral Presentation

Cueva del Diablo: A Batcave in Tepoztlan

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In Mexico, almost half of the 138 species of bats use caves as alternative or primary roosts. One volcanic cave that houses important colonies of these animals is Cueva del Diablo in Tepoztlan, Morelos, central Mexico. At least three bat species have been reported in this cave. One of them, the Mexican long-nosed bat (*Leptonycteris nivalis*), is of particular importance in economical and ecological terms. This species migrates from central to northern Mexico and southern United States in mid spring and come back in mid autumn. In Mexico, *L. nivalis* is classified as a threatened species, and in the U.S. as an endangered one.

Owing to the fact that Cueva del Diablo is the only known roost in which this species mates, the cave was proposed by us as a sanctuary to the CONANP (National Commission of Natural Protected Areas) in 2004. In addition to this proposal, the PCMM (Program for Conservation of Mexican Bats) has conducted environmental education efforts in the region as an attempt to modify the negative ideas about bats and to share the information concerning their importance and that of caves for them.

Other PCMM studies conducted in this cave focus on the diet of the species and understanding its mating system, among the first studies on those subjects for this species. This document represents a compilation of those works in Cueva del Diablo with emphasis in their importance for the general conservation of bats and caves.

Oral Presentation

Troglobites from the Lava Tubes in the Sierra de Chichinautzin, México, Challenge the Competitive Exclusion Principle

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In ecology, the Competitive Exclusion Principle establishes that no two species in the same ecosystem can occupy the same niche indefinitely. Two species which make their living in identical ways, eat the same food, and compete for the same limited resources, are unable to coexist in a stable fashion. If two species try to occupy the same niche, one will out-compete and drive to extinction the other.

Multiple lava tubes from the Sierra de Chichinautzin, Mexico, are inhabited by a troglobitic silverfish (*Anelpistina* sp.: Nicoletiidae: Zygentoma: Insecta). At first glance, individuals appear morphologically uniform as expected when they belong to a single species, but when DNA analyses were performed, it was established that despite their morphological similarity, individuals within these caves belonged to at least two distinct species. As individuals of these different species live side by side, most likely occupying the same niche, the Competitive Exclusion Principle is challenged.

The lava tubes inhabited by these troglobites were formed by lava flows emitted by different volcanoes. This implies that Nicoletiid troglobites cannot only cross the boundary between lava tubes, but even between adjacent lava flows. Since some of the lava flows have been dated, one of them even to recent historical time, their efficient dispersal capabilities can be tracked and roughly dated.

Theoretical Session

Oral Presentation

Uranium in Caves

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Uranium is ubiquitous, it is found everywhere, caves and spelean formations and minerals are no exception. However, its presence represents no harm, as it is only present at concentration levels rarely exceeding 10 μg/g. Radioactive decay of U produces minute amounts of several isotopes, radioactive themselves, with half-lives ranging from seconds to several thousand years. This provides the basis for one of the most widely used geo-chronometers which, only until recently, has been applied to the understanding of cave processes and evolution.

The abundance of short- and long-lived U daughter isotopes in different spelean formations and minerals allows us to establish geochronological constrains on their evolution. Furthermore, such information has allowed an increasing number of scientists to use spelean formations as indicators of past climatic and hydrologic conditions. For example calcite stalactites, stalagmites and flowstones are "routinely" used as archives of climate change as they can be dated relatively easy measuring the relative abundance of ^{238}U-^{234}U-^{230}Th. On the other hand opal and silica varnishes in lava tuffs 500 m below the surface, have been used to track paleohydrological activity during the last 500,000 years.

The basic principles for dating such mineral phases will be presented, along with more detailed information on the above examples and the potential to apply U-dating methods to spelean formations in lava tubes.

Oral Presentation

Development of a Karst Information Portal (KIP) to Advance Research and Education in Global Karst Science

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The University of New Mexico, the National Cave and Karst Research Institute, and the University of South Florida are developing the Karst Information Portal (KIP) to promote open access to karst, cave, and aquifer information and linkages among karst scientists. The resulting connectivity and collaboration will drive innovative solutions to the critical human and environmental challenges of karst. Our purpose is to advance karst knowledge by: (1) facilitating access to and preservation of karst information both published and unpublished, (2) developing linkages and communication amongst the karst community, (3) promoting knowledge-discovery to help develop solutions to problems in karst, (4) developing interactive databases of information of ongoing karst research in different disciplines, (5) enriching fundamental multidisciplinary and interdisciplinary science, and (6) facilitating collection of new data about karst. The KIP project is currently (1) transforming *A Guide to Speleological Literature of the English Language 1794-1996* into the portal's first searchable on-line product and (2) creating an institutional repository of scanning electron micrographs from research in caves that includes social software to promote linkages among karst scientists. In the future, thematic areas, such as cave sediments, conduit flow models, sinkholes, geo-engineering, and speleothem records of climate change, are among the many topics to be included in the portal. A key project focus is the gathering of lesser-known materials, such as masters' theses, technical reports, agency file reports, maps, images, and newsletters. Thus, this project responds to disciplinary needs by integrating individual scientists into a global network through the karst information portal.

Oral Presentation

A Data Base for the Most Outstanding Volcanic Caves of the World: A First Proposal

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During the XI International Symposium on Vulcanospeleology (Pico Island, Azores, 2004), the Commission on Volcanic Caves (CVC) of the UIS recognized the interest of a database for the most important volcanic caves of the world. At that time it was suggested that the Azorean speleological group GESPEA ought to present a proposal to accomplish this task. Following the challenge of the CVC, the GESPEA designed a proposal, as follows:

Aim: Assemble in a database the world most relevant volcanic caves, grouped into 3 major classes, and selected by dimensions, geological exceptionality and biological exclusivity.

Methodology: *Main Tool:* A database (the "WoMOVoC—World Most Outstanding Volcanic Caves" database) will be available in the Internet, having a non complex structure, but comprising a set of fields that enable an accurate characterisation of the volcanic cave, namely: the cave's name, location (e.g. country/region), geographic coordinates, length/depth, main geological features, biological singularity, general description, main references, location map, topography and photos.

New Proposals: Each proposal must be submitted using an electronic form, available in the web site, and comply with the instructions and the criteria for acceptance. To be accepted, the cave must obey the criteria for each main class of relevance:

Class "Relevant Dimensions": caves more than 3 km long and pits more than 100 m depth.

Class "Geological Exceptionality": one or more rare speleothem.

Class "Biological Singularity": one or more troglobian, endemic species.

Selection: The proposal evaluation will be done by a scientific committee, composed by 5 or 7 individuals, assign by the CVC-UIS. The selection of the volcanic caves will be according to the accepting criteria and having in mind other important aspects, as the information accuracy and conservation status. The committee might accept other geological and biological features, if very well documented and if it is a relevant and unambiguous case of uniqueness.

Data Incorporation: After approval by the scientific committee, the new cave will be added to the database by an executive committee, which can be the GESPEA group.

With this paper we fulfil the CVC desideratum, hoping that the proposed methodology might be a first step to gather worldwide information of the most significant volcanic caves, and, by that, a broader recognition of the value of this geological heritage.

Oral Presentation

Morphogenesis of Lava Tube Caves: A Review

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It is now many years since there was a published scientific review of the formation of lava tube systems and lava tube caves. Possibly the last was this writer's chapter on volcanic caves in the BCRA's 1976 *The Science of Speleology*, although entries in the more recent encyclopedias of caves and karst update some of this information. Yet there have been significant and substantial discoveries in the last 30 years, including exploration of new cave areas (for example, in Iceland, Rwanda, Saudi Arabia, Jordon, Hawaii and Mexico), a more comprehensive appreciation of the extent of the world's vulcanospeleological resource, creation of regional cave databases (eg, Azores, Iceland, Jeju Island), an increasingly higher standard of mapping of cave forms revealing new details of both labyrinthine complexes and long axial systems, acquisition of improved data on the position of caves and cave groups within their parent lava flows or lava flow fields, and better knowledge of associated cavities in lavas.

The contribution made by cavers in cold lava flows has been supplemented by highly revealing observations of active tube-forming processes, principally from the 1969-74 Mauna Ulu and 1983-present Pu'u 'O'o-Kupaianaha flank eruptions of Kilauea volcano, Hawaii, and the recent activity of Mount Etna, Sicily. These observations have contributed substantially to the formulation of new concepts of flow emplacement. The period is also one in which there has been growing realization that the formation of long lava flows, the building of Hawaiian-type shield volcanoes and, possibly, the emplacement of flood basalts, may be products of tube-fed lava flow. Furthermore, there has been increasing evidence of active and ancient lava tube systems on planetary bodies of the solar system, for example, most recently on Jupiter's innermost moon, Io.

Trying to piece this information together to provide one or more coherent theories of cave formation is challenging. For one thing, despite all the observations of active systems, we still do not observe the most important process of all—the method by which principal feeder conduits, or master tubes, grow (extend) downslope. Another shortfall has been analysis of the evidence internal cave forms may provide of fluid activity within an active tube system and subsequent post-activity modifications. This paper reviews the last 30 years of observation of cave data and active tube-fed flow as an attempt to draw together evidence and ideas on the morphogenesis of lava tube caves, in particular to identify areas of uncertainty that would benefit from further investigation.

2006 SYMPOSIUM PAPERS

Cueva Tecolotlán, Morelos, México; An Unusual Erosional Cave in Volcanic Agglomerates

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Abstract

Tecolotlán cave, located near the town of Cuentepec, Morelos, with a surveyed length of 870 meters and a vertical extent of 105 meters, is one of the longest erosional caves known in non-calcareous conglomerates. It is contained in volcaniclastic deposits, mainly lahars and fluvial conglomerates and a few intercalated ash layers belonging to the Cuernavaca formation, which constitute the Buenavista volcaniclastic fan, which has its apex at the Sierra Zempoala volcanic complex and extends south to the limits with the state of Guerrero.

This volcaniclastic fan has been eroded by numerous streams running almost parallel to the south, which have excavated deep "barrancas" or gullies. In particular the "barranca" of the Río Tembembe is over 100 meters deep near the location of the cave.

The cave captures the drainage of a surface stream, and is developed along a single passage which for almost 600 meters follows a single fracture, oriented almost east-west. This passage is a subterranean canyon, two to five meters wide and three to over 20 meters high, typically vadose in its configuration, with several vertical pits or cascades along its length. Deep plunge pools have developed at their bases. The only chamber is located under a collapse which formed a skylight almost 40 meters high, but no collapse debris remain, as they have been flushed out by the torrential floods that sweep the cave during the rainy season.

The final portion of the cave changes completely in morphology when the passage abandons the main fracture to develop along the contact between two different debris flow deposits. The huge canyon turns into a small round tube, slightly incised in its floor, which mimics a phreatic passage in karstic caves. The cave resurges 12 meters up the wall of a small tributary of the Río Tembembe canyon, and almost 45 meters above the river level.

The lithology in which the cave is developed prevents solution from playing an important role in the generation of the cave, which owes its origin entirely to mechanical erosion, probably aided in the beginning by a process similar to piping in unconsolidated deposits. The morphology of the final portion would seem to indicate that the cave started its development when the Río Tembembe was at its level or just above it.

Introduction

Although karstic phenomena in conglomerates is relatively common, in almost all cases described, either the matrix or the blocks are calcareous in nature, and few if any described caves are developed in volcanic aglomerates of andesitic nature. A recently mapped cave, developed in the Buenavista volcaniclastic fan to the south of the Zempoala volcano, in central Mexico (Figure 1), seems to have developed by erosion, possibly aided by a process similar to piping, along a fracture, but its morphology perfectly mimics an active stream cave in a karstic environment.

The Buenavista volcaniclastic fan

The Buenavista volcaniclastic fan (BVF) is a conspicuous geomorphologic unit to the south of the Zempoala volcano, in central México (Figure 2). It was first mapped by Fries (1960), who described the Cuernavaca Formation as a series of thickly bedded conglomerates with sub rounded andesitic blocks up to metric in size, interbedded with fluvial sands and mud, and occasional thin ash layers.

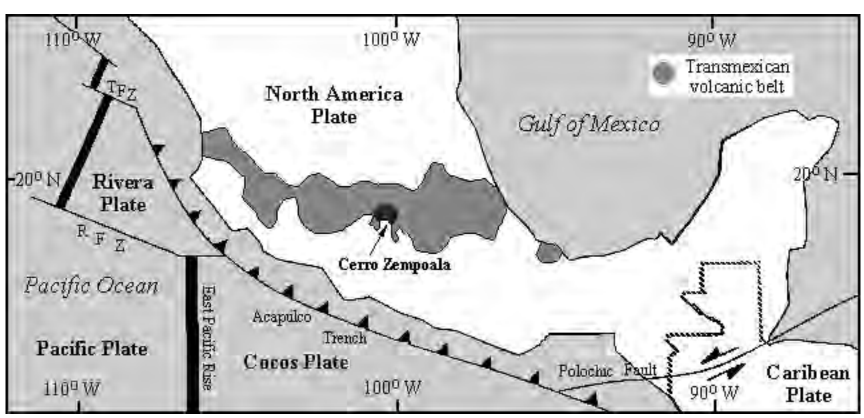

Figure 1. Map showing the tectonic setting and location of Volcan Zempoala, in the central portion of the Transmexican Volcanic Belt.

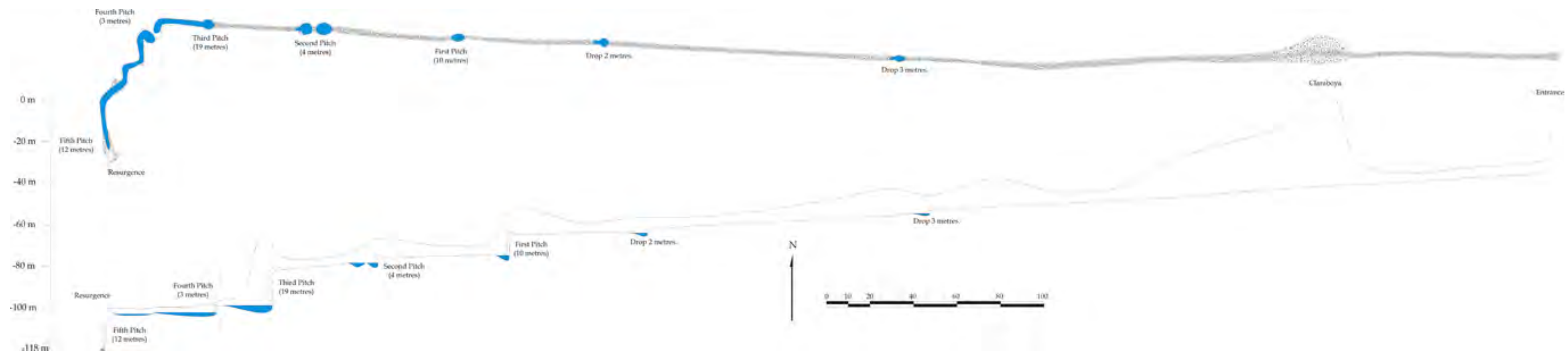

Figure 2. Plan and profile views of Cueva de Tecolotlán. A larger version of this map appears in the supplemental material on the CD.

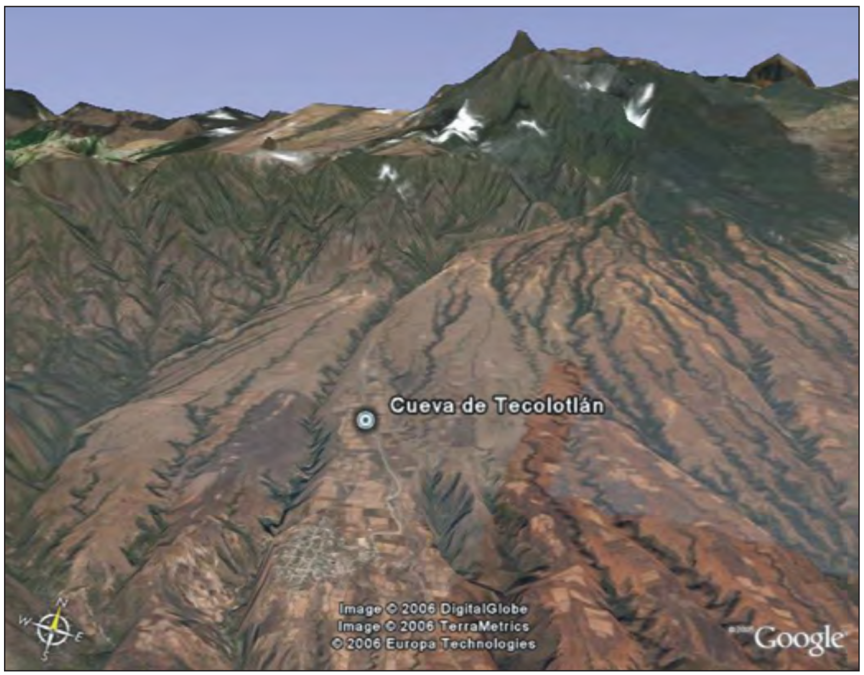

Figure 3. Upper portion of the Buenavista volcaniclastic fan, with the location of Cueva Tecolotlán. The Cerro Zempoala volcano can be seen at the apex of the fan. The canyon which drains its west slopes and then cuts through the fan is the Río Tembembe

Figure 4. Location of the three entrances of Cueva Tecolotlán.

Figure 5. Entrance sink of Cueva Tecolotlán. Two cavers can be seen on the left slope. The average dip of the fan can be seen from the slope of the road behind the cave entrance.

Ortiz-Pérez (1977) believes that the fan was formed in response to climate changes during the Pleistocene deglaciation of Zempoala volcano, although no proof of such a glaciation is given.

Recent studies show that this volcano collapsed to the southwest sometime during the Pliocene (Capra et al., 2002). The resulting horseshoe-shaped crater probably directed Pleistocene eruptive products (pyroclastic and debris flows) towards the south, creating the huge volcaniclastic fan. Since the end of activity at Zempoala volcano, fluvial erosion has excavated numerous deep ravines on the surface of the Buenavista fan, the largest of which, Cañón del Río Tembembe, drains the southern flank of the Cerro Zempoala and then cuts south through the entire fan (Figure 3). The cross section of the valley is V-shaped, with a rim to rim distance of about 200 meters on average, and about 100 meters deep, but at the bottom of the V is a vertical walled gorge 20 to 70 meters deep.

Cueva Tecolotlán

The entrance to the cave is at the end of a small ravine whose headwaters are barely a kilometer away (Figure 4), and which has carved into the conglomerates to a depth of 30 meters at the cave entrance (Figure 5), which is a 2 meters wide and 5 meters high tunnel that heads almost west following prominent fractures, almost vertical, which are clearly visible in the cliff above the entrance (Figure 6). After nearly 100 meters, the passage reaches the bottom of a 40 meter high skylight formed by ceiling collapse in a widening of the passage to almost 20 meters in width. No collapse blocks remain in the floor, so all the material emptied from this room has been carried away by the seasonal stream. The controlling fractures are again visible in the walls of the skylight chamber (Figure 7).

The passage continues perfectly straight, shaped like an underground

Figure 6. The actual entrance is triangular in shape and follows a near vertical fracture.

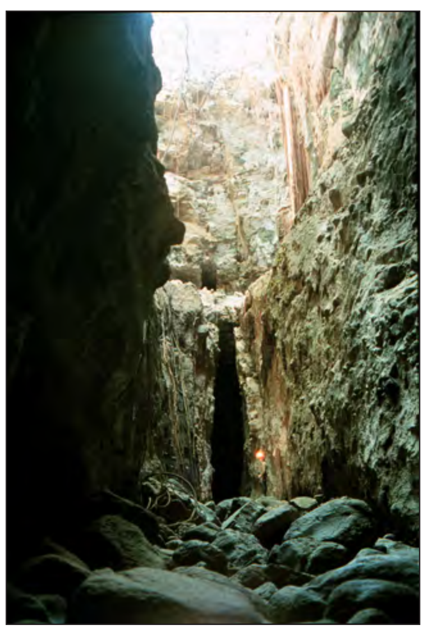

Figure 7. On the skylight walls the vertical fractures that control the cave development are clearly visible.

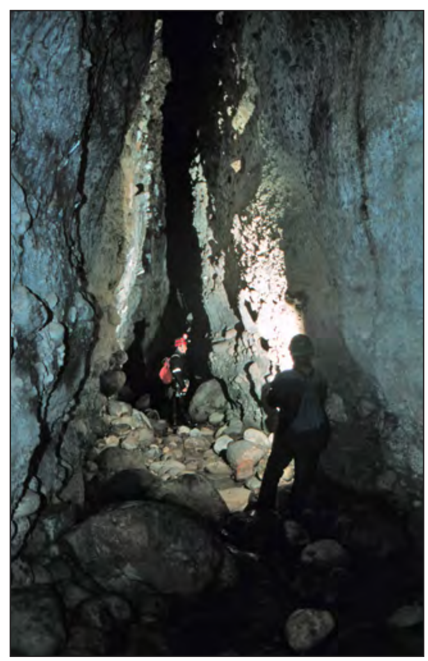

Figure 8. Most of the passage is a tall, canyon-shaped passage. The large andesitic subrounded blocks on the walls form part of the debris flow deposits in which the cave is excavated.

Figure 9. Plunge pool at bottom of third drop. The large andesitic subrounded boulders that form the host rock are perfectly visible.

Figure 10. Rounded cross-section of the lower passage of the cave. Notice the change in lithology which is the stratigraphic contact which controlled the development of this portion of the cave.

Figure 11. Hourglass cross-section of the lower passage of the cave. Notice the entrenchment of the floor below the phreatic original passage.

canyon (Figure 8); two hundred meters beyond the skylight, a three meter climbable drop is found, followed a hundred meters later by another two meter climbable drop. Sixty meters later, a deep 10 meter pitch is found (Figure 9). Fifty meters later a second pitch, four meters deep, is found. All drops and pitches are followed by deep, round plunge pools where swimming is necessary.

A third pitch of 9 meters follows after another 50 meters. The plunge pool at the bottom is followed by a narrow canal, and suddenly the passage turns left, quitting the fractures that controlled its development to this point, and meandering instead along an ill-defined bedding plane between two conglomerate deposits, marked by a <1 centimeter thick ash layer. The passage consequently diminishes in size, turning into an almost round tunnel which perfectly mimics a phreatic tube in karstic caves (Figure 10), 1 to 2 meters wide and 1 meter high. As the passage aproaches the exit, a small trench is developed in the floor (Figure 11). This ends at the resurgence, which is a hole hanging 12 meters above the

Figure 12. Resurgence hanging 12 meters above the floor of a small tributary of the Río Tembembe. Notice the lithology of the Cuernavaca Fm, in which the cave is hosted, is a sequence of volcanic debris-flow deposits of probable *laharic* origin, interstratified with fluvial conglomerates, ash-flow deposits and thin air fall ash layers.

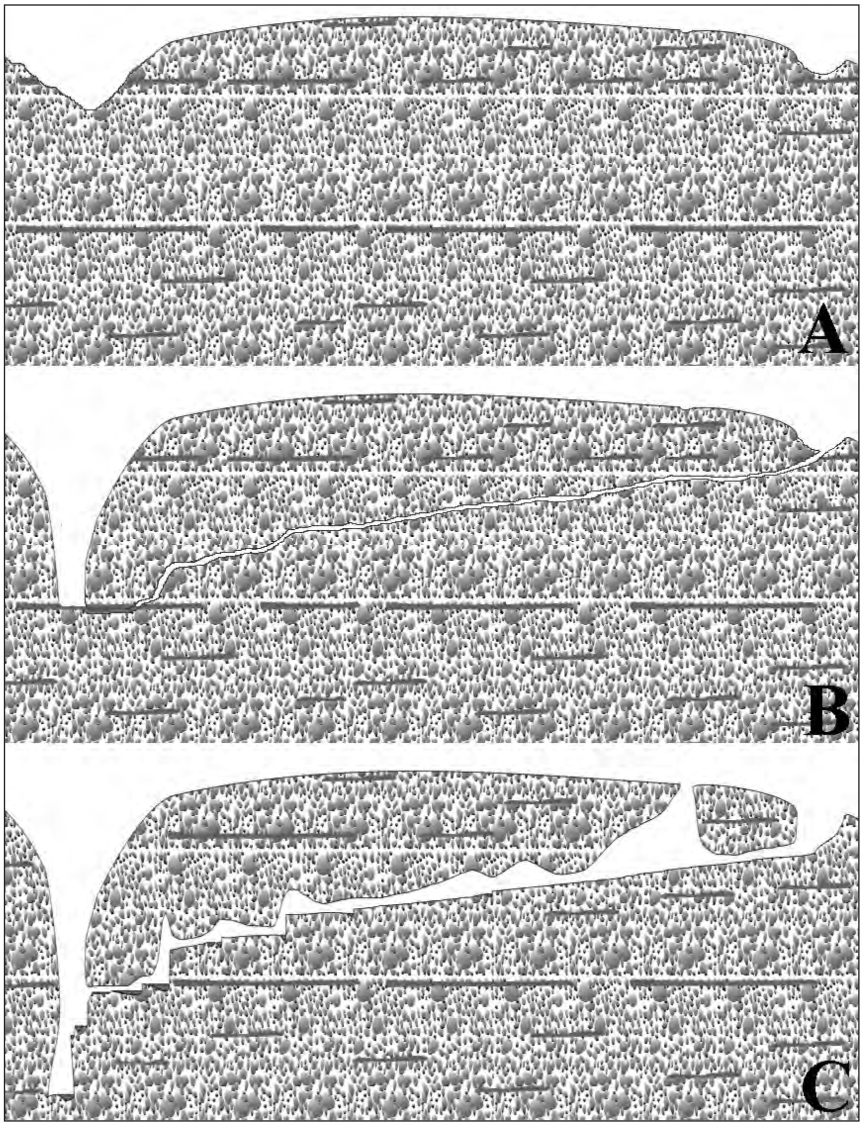

Figure 13. Geological cross-sections showing the development of Cueva Tecolotlán. The first stage would be the formation of the Tembembe valley almost to the level of the cave. When erosion first breached the ash layer between conglomerate deposits, it allowed water filling the fractures to start flowing through the contact that marks the bottom portion of the cave, probably aided by some sort of piping, at least at the beginning, but soon fluvial erosion took over, excavating the upper canyons and cascades along the fractures (second stage). Finally, as the Tembembe river eroded the deep gorge below the resurgence, the cave drained its "phreatic" portion, but stream erosion continues to be active every rainy season.

floor of a surface tributary of the Rio Tembembe, and still 45 meters above the present level of the river (Figure 12).

The lithology in which the cave is developed prevents solution from playing an important role in the generation of the cave. The morphology of the final portion would seem to indicate that the cave initiated its development when the Rio Tembembe was essentially at its level, which coincides with the change in slope of the valley flanks. The excavation of the cave might have been aided, at least in the beginning, by a process similar to piping in unconsolidated deposits. Above the cave the morphology of the cave is essentially that of a vadose canyon.

Since the inception of the cave, the Tembembe has excavated a vertical-walled canyon at least 45 meters deeper. The slope change in the valley walls probably reflects rejuvenation of the relief, and the deepening of the valley drained the cave (Figure 13).

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Palaeoenvironmental Reconstruction of the Miocene Tepoztlán Formation (Central Mexico): Preliminary Results of Palynological Investigations

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Introduction

In Miocene times, a major volcano-tectonic change took place due to a re-organization of the tectonic plates in the western Pacific region. Since the Mid-Miocene, the Transmexican Volcanic Belt (TMVB, Fig. 1) began to form (Delgado-Granados et al. 2000). However, there is still a controversial scientific debate on its development. The aim of our study is to establish a stratigraphic framework and a palaeoenvironmental interpretation of the Mid-Miocene Tepoztlán Formation.

To date, palaeobotany in volcanic settings has dealt with intercalated sediments namely paleosoils, fluvial volcaniclastic sandstones, peat or lignites (e.g., Lund 1988, Hilton et al. 2004). Even authors working on tuffaceous material focussed on either the macroflora (e.g., Pole 1994) or charcoals (Scott and Glasspool, in press). Publications on palynology in pyroclastic rocks and their reworked deposits (lahars and fluvial deposits) are rare (Satchel 1982, Taggert & Cross 1990, Jolley 1997, Bell & Jolley 1997). In this study we investigated a volcaniclastic section of the Mid-Miocene Tepoztlán Formation with respect to palaeoenvironment using palynology. This method has not been applied to this formation previously.

Geological setting

The study area is situated along the southern edge of the TMVB in the state of Morelos, where Tertiary volcaniclastic series emerge underneath Quaternary volcanics (Fig.1). In spite of the spectacular outcrops of these up to 800 m thick volcaniclastic successions around the towns of Malinalco, Tepoztlán and Tlayacapan, the so called Tepoztlán Formation belongs to the least studied rocks of the TMVB. The Tepoztlán Formation is underlain by the Balsas Formation, a terrestrial-lacustrine sedimentary succession also rich in volcaniclastics. It is probably representing the earliest volcanic phase of the region (Fig. 2).

The Tepoztlán Formation consists of a characteristic succession of lahars (debris-flow and hyperconcentrated-flow deposits), pyroclastic-flows, occasional andesitic to dacitic lavaflows and intercalated fluvial or lacustrine sediments, attaining thicknesses of several hundred meters. K/Ar geochronology on a dacitic lava flow in the lower part of the Tepoztlán Formation and a younger dike reveals an age of the formation of between 21.85 ± 0.21 Ma and 15.83 ± 1.31 Ma. Thus, a deposition between Early to Mid-Miocene is proposed (Lenhardt et al. 2006).

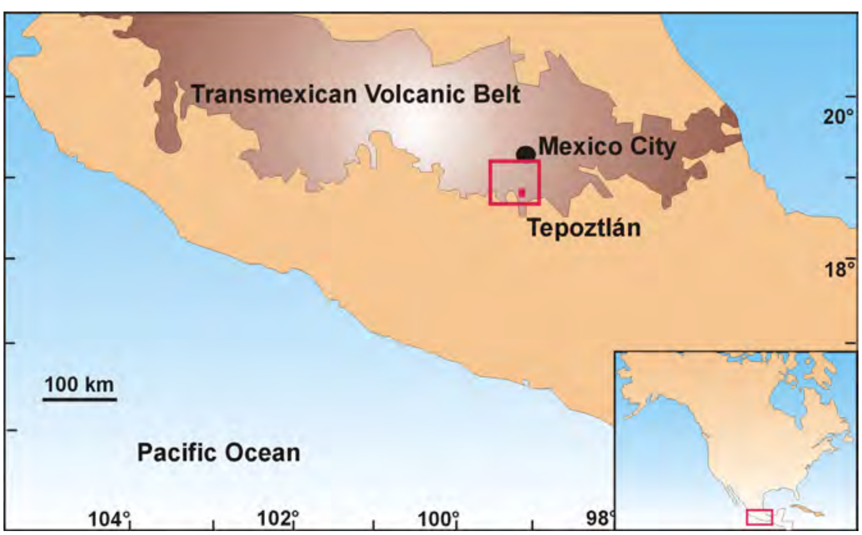

Figure 1. Extend of the Transmexican Volcanic Belt in Central Mexico. The position of the study area is indicated.

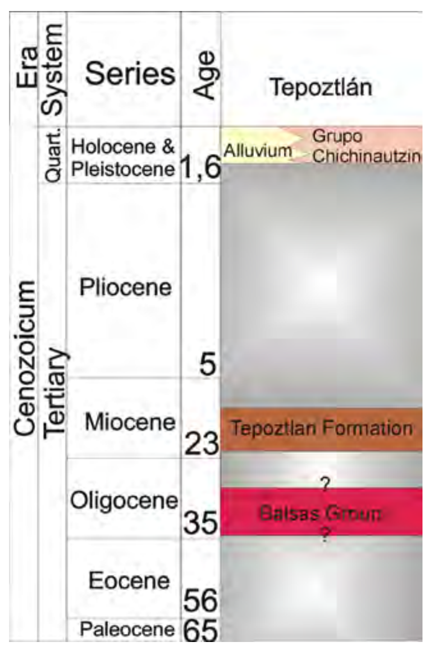

Figure 2. Stratigraphic succession in the study area.

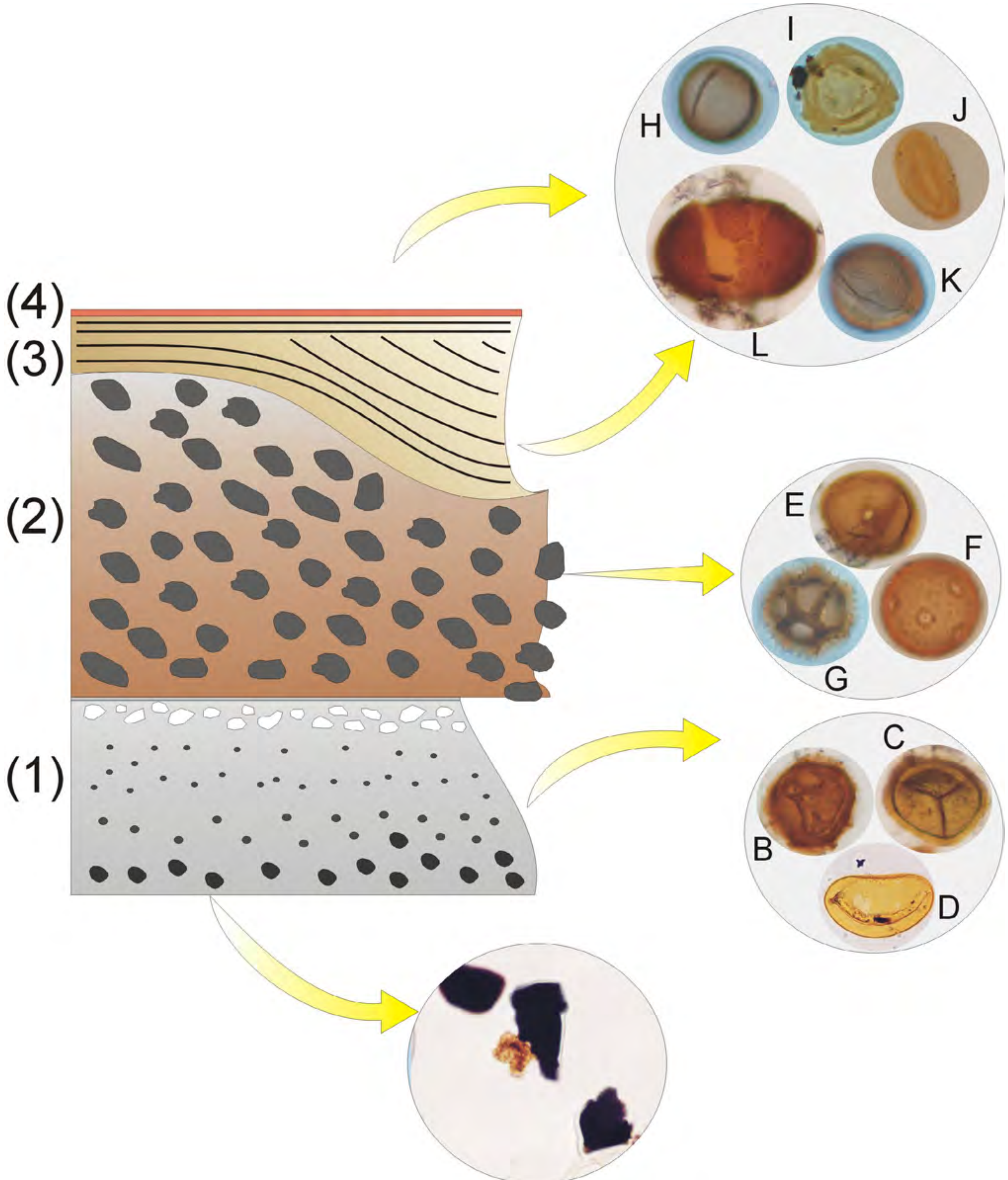

Figure 3. Ideal sedimentary succession of volcaniclastic sediments and characteristic sedimentary organic particles: (1) pyroclastic flow deposit, (2) lahar, (3) fluvial deposit, (4) lacustrine or waning-flood deposit.
A charcoal, B *Lycopodium* sp. (51 μm), C *Selaginella* sp. (42 μm), D Polypodiaceae (45 μm), E Graminae (38 μm), F Compositae (16 μm), G Caryophyllaceae (17 μm), H *Quercus* sp. (18 μm), I *Betula* sp. (22 μm), J *Salix* sp. (18 μm), K *Acer* sp. (20 μm), L *Pinus* sp. (61 μm).

Materials and methods

For palynological analyses we investigated samples of 150 g each representing the fine-grained matrix of fluvially reworked deposits, lahars, ash-flow deposits, and clayey layers on top of these deposits.

All samples were processed following the standard palynological processing techniques, which include the treatment with HCl (30%), HF (73%) and heavy liquid separation with $ZnCl_2$ solution. All samples were centrifuged and washed with distilled water after each step. The residue was cleaned by sieving using an 11 μm mesh. For strew mounts we used Eukitt, a commercial mounting medium on the base of resin. The counting is based on 50 pollen grains and spores per slide. All samples reveal a well preserved and diverse pollen and spore assemblage, enabling a preliminary palaeoenvironmental interpretation of the Tepoztlán Formation.

Preliminary palaeoenvironmental reconstruction

As far as we can conclude from first analyses, the pyroclastic and volcaniclastic sediments show characteristic stratigraphical vegetation patterns (Fig. 3). The base of pyroclastic-flow deposits is marked by a high amount of charcoal particles (unit 1 in Fig. 3), wood material that was burned due to the heat during a volcanic eruption, whereas the top is rich in fern spores, the first colonizers after an eruption (Spicer et al. 1985). This points to the development of thin palaeosoil layers although a sedimentary record is lacking.

The lahars (unit 2 in Fig. 3), representing reworked deposits that were formed within days to tens of years after the initial eruption, show the development of the first higher plant communities. These are dominated by the plant families Graminae, Compositae and Caryophyllaceae. Finally, fluvial and lacustrine sediments (units 3 and 4 in Fig. 3) show the tree population of a mature mixed forest that is dominated by oaks and pines.

The above described stratigraphic vegetation patterns are interpreted in terms of short-term destruction-recolonization cycles that are controlled by eruptions and intermittent quiescence (Fig. 4). After an initial eruption (Fig. 4a), the volcanic deposit is settled quickly by ferns and other opportunists, colonizing open and disturbed ground (Collinson 1996). The aftermath of the eruption is characterized by the deposition of lahars (Fig. 4b). The second stage of re-colonization involves herbaceous plants, mostly Compositae, and grass as the first higher evolved pioneer plants, followed by pines as the first trees. Later a mature mixed forest develops (Fig. 4c and 4d). Modern botanic studies on the Canary Islands (Dale et al. 2005) show that the pioneer phases on volcanic ash take about 20 to 30 years, trees appear first after 200 to 300 years. As a modern analogue of the Tepoztlán Formation, Fig. 5 shows volcaniclastic deposits of the eruption of the Cotopaxi volcano (Ecuador) in 1877 with four sedimentation phases recognized. After the initial deposition of pyroclastic flows (Fig. 5a), the following years were characterized by debris flows (Fig. 5b) caused by rain storms. After tens of years, the lack of further sediment supply caused the change from debris flows to fluvial deposition (Fig. 5c, d). Today´s development of the vegetation of this area (130 years after the eruption) is characterized by the transition from grass- and scrub-land to the appearance of the first trees.

Present day vegetation of Central Europe is very similar to that recorded in the Tepoztlán section. Thus, the depositional environment of the Tepoztlán Formation displayed a rather temperate climate. These palaeoclimatic signatures, indicating moderate temperatures in Miocene low latitudes may be caused by a high palaeoaltitude. This in turn may point to an early uplift of Central Mexico. Further studies and statistical methods based on modern analogues have to clarify this hypothesis.

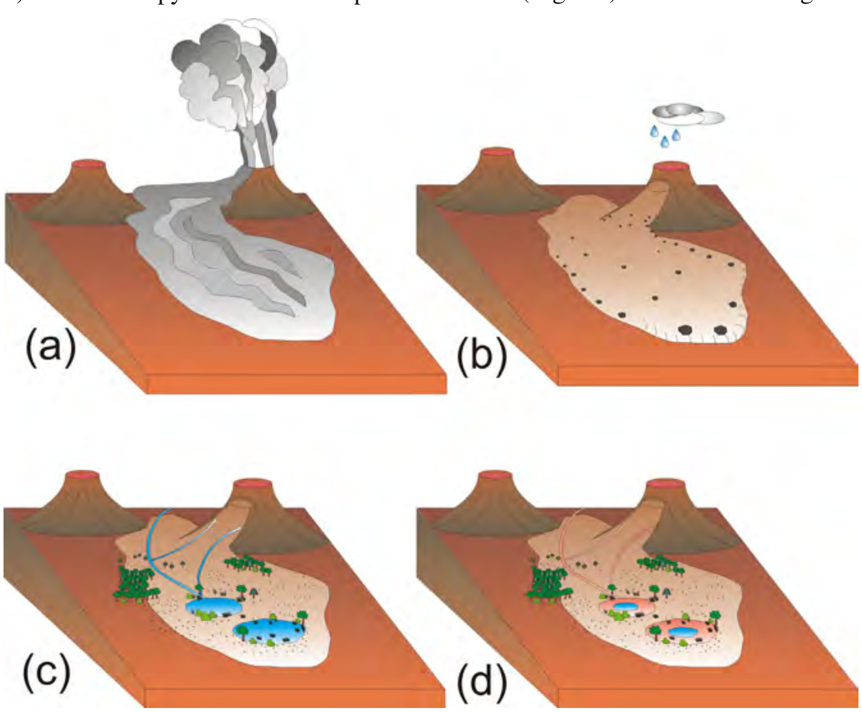

Figure 4. Changes in palaeoenvironment within time: a) ash flow, b) debris flow (lahar), c) fluvial reworking, d) waning stage.

Acknowledgements

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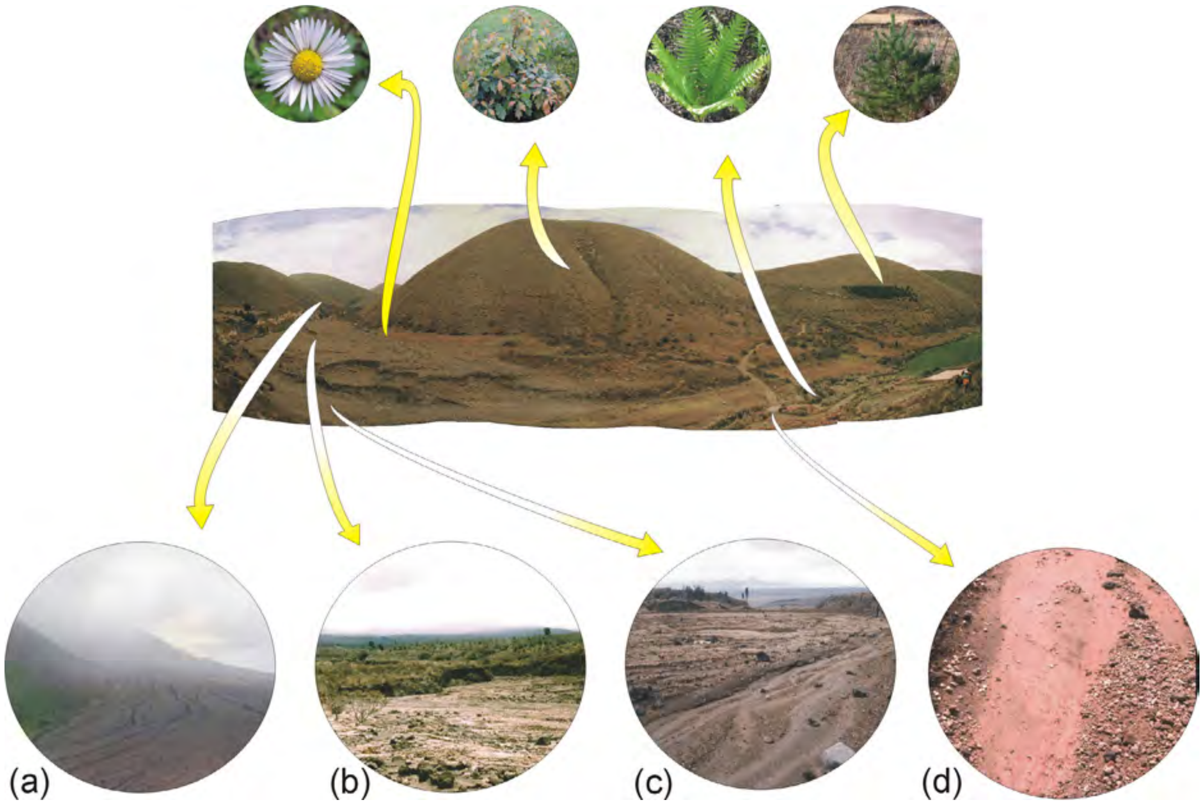

Figure 5. Modern analogue of the Tepoztlán Fm. (here with volcaniclastic deposits and their vegetation from the recent eruption of Cotopaxi, Ecuador, in 1877): a) pyroclastic-flow deposit, b) lahar, c) fluvial reworked deposits, d) waning-flood deposits.

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Lava Tubes of the Texcal Lava Flow, Sierra Chichinautzin, México

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Abstract

The Texcal lava flow is located to the south of the Sierra Chichinautzin Volcanic Field, near the City of Cuernavaca. With 24 km in length, it is the longest lava flow known in the entire field. Recent work by Siebe et al. (2004) showed that it originates from the Guespalapa group of volcanic cones, and dated the lava flow at between 2,835±75 and 4,690±90 y.b.P. They conclude that the Texcal lava flow is A'a and must have been emplaced at a very high effusion rate to have reached such a length with a low total volume.

Recent field work has demonstrated that the entire lava flow is actually tube-emplaced pahoehoe lava, as evidenced by surface structures such as ropy lava, hornitos, tumuli and lava-rise structures. Field work has also resulted in the discovery, exploration and survey of 5 lava-tube caves, known in a down-flow direction as Cueva Grande, Cueva Pelona, Cueva Redonda, Cueva de la Herradura and Cueva del Naranjo Rojo, for a total of nearly 3 kilometers of lava tubes mapped in this flow. The first three caves (Grande, Pelona and Redonda) are basically sections of a large, multilevel master tube over 10 meters wide and 20 meters high, with evidence of continuous and sustained activity which caused thermal and/or mechanical erosion of the underlying lithology, made up of volcaniclastic agglomerates belonging to the Cuernavaca Formation, which can be seen in at least one section of Cueva Pelona behind a collapsed lava lining. Cueva Grande contains a section with numerous tubular stalactites and drip stalagmites of segregates and several curling A'a levees. The lowermost caves (Herradura and Naranjo Rojo), in reduced slopes, also contain a master tube of similar dimensions, but are further complicated by the presence of upper level braided side passages which mark the originally emplaced lava tubes, one of which pirated the lava from the others as it eroded a canyon tube downwards. The superposed levels on the master tube represent growth of successive crusts as the lava level gradually lowered.

These finds lead us to believe that the Texcal lava flow was emplaced at low to moderate effusion rates, which favored the formation of a large master lava tube which fed the entire lava field. As has been well documented previously, lava tubes isolate the lava from the air and prevent cooling of the flow, favoring the development of very long lava flows with relatively low total volumes. Risk assessment for the cities of Cuernavaca and México, which could easily be affected in case of renewed activity at the Sierra Chichinautzin, should take this into account, since lava tube emplacement has not been considered by most authors who have studied this volcanic field before.

Introduction: The Sierra Chichinautzin Volcanic Field

The Sierra Chichinautzin Volcanic Field (SCVF) is a volcanic highland elongated in an E-W direction (Figure 1), extending from the flanks of the Sierra Nevada, including Popocatepetl stratovolcano (presently active) in the east to the flanks of Xinantecatl (Nevado Toluca) stratovolcano in the west, in the central portion of the Transmexican Volcanic Belt (Martin del Pozzo, 1982).

This volcanic field is made up by over 220 scoria cones and associated block, A'a or pahoehoe lava flows. SCVF forms the continental drainage divide that separates the closed basin of México, which artificially drains to the north, from the valleys of Cuernavaca and Cuautla which drain south, and from the Lerma River basin which flows west. According to Fries (1966), the Basin of México drained to the south before the Pleistocene. Since then, formation of the SCVF sealed the basin to the south (Mooser, 1963).

Lava flows in the SCVF vary considerably in their morphology. Most are compound andesite or basaltic andesite A'a flows, some of the thicker blocky lava flows are dacitic and a few are basaltic tube-fed pahoehoe flows. Lavas belong to the calc-alkaline suit, and are genetically linked to the subduction of the Cocos plate (Martin del Pozzo, 1982). The tephra cones, lava shields, associated lava flows, tephra sequences and intercalated alluvial sediments that make up the Sierra Chichinautzin cover an area of approximately 2,500 km^2 (Bloomfield, 1975; Martin del Pozzo, 1982; Lugo-Hubp, 1984). Paleomagnetic measurements indicate that most exposed rocks were produced during the normal Brunhes Chron and are therefore younger than 0.73-0.79 Ma (Urrutia and Martin del Pozzo, 1993), which is not

Figure 1. Location map of the Sierra Chichinautzin, showing the tectonic setting.

surprising in view of the very young morphological features of most tephra cones and lava flows.

Recent studies by Siebe (2000) and Siebe et al. (2004, 2005) have published dates for some of the youngest volcanoes in the SCVF, several of which were emplaced at least partially by lava tubes: Teuhtli (>14,000 years B.P.), Pelado (9,620±160 to 10,900±280 years B.P.), Guespalapa (2,835±75 to 4,690±90 years B.P.), Chichinautzin (1,835±55 years B.P.), and Xitle (1,670±35 years B.P.). Other undated volcanoes whose lava flows were tube-emplaced, and which are morphologically very young include Yololica and Suchiooc. These and other previously published dates imply a recurrence interval during the Holocene for monogenetic eruptions in the SCVF of <1,250 years (Siebe et al., 2005).

Guespalapa Volcano and the Texcal lava flow

Guespalapa volcano (3,270 m.a.s.l.) is a group of four small (80-150 m high) overlapping cinder cones, known locally as El Caballito, El Palomito, Manteca and El Hoyo (from West to East), located just south of the drainage divide. The first three are obviously contemporaneous, but El Hoyo is probably the remnant of an older volcano. Lava issued from the southeast side of El Caballito and from a subsidiary vent to the southeast of Manteca, producing the Texcal basalt lava flow, first mentioned by Ordoñez (1937), which is the most extensive lava flow in the SCVF with 24 km in length (Figure 2). It traveled south far into the Cuernavaca plain, where it stands out due to its relative lack of vegetation (Texcal means "badland" in Náhuatl).

Siebe et al. (2004) conclude that this very long lava flow, which they consider to be A'a, must have necessarily been emplaced by a high-effusion rate eruption, and do not consider that tube-fed pahoehoe flows can reach very far in low to moderate-effusion rates (Peterson et al., 1994).

Nevertheless, recent field work has uncovered five large lava tube caves, suggesting that the lava flow is mostly tube-fed pahoehoe. Near the vent area, hornitos or rootless vents produced short lava flows which also developed small tubes.

Los Cuescomates *hornitos*

These rootless vents developed when the Guespalapa lava flow encountered a flat area, called "Llano de los Conejos",

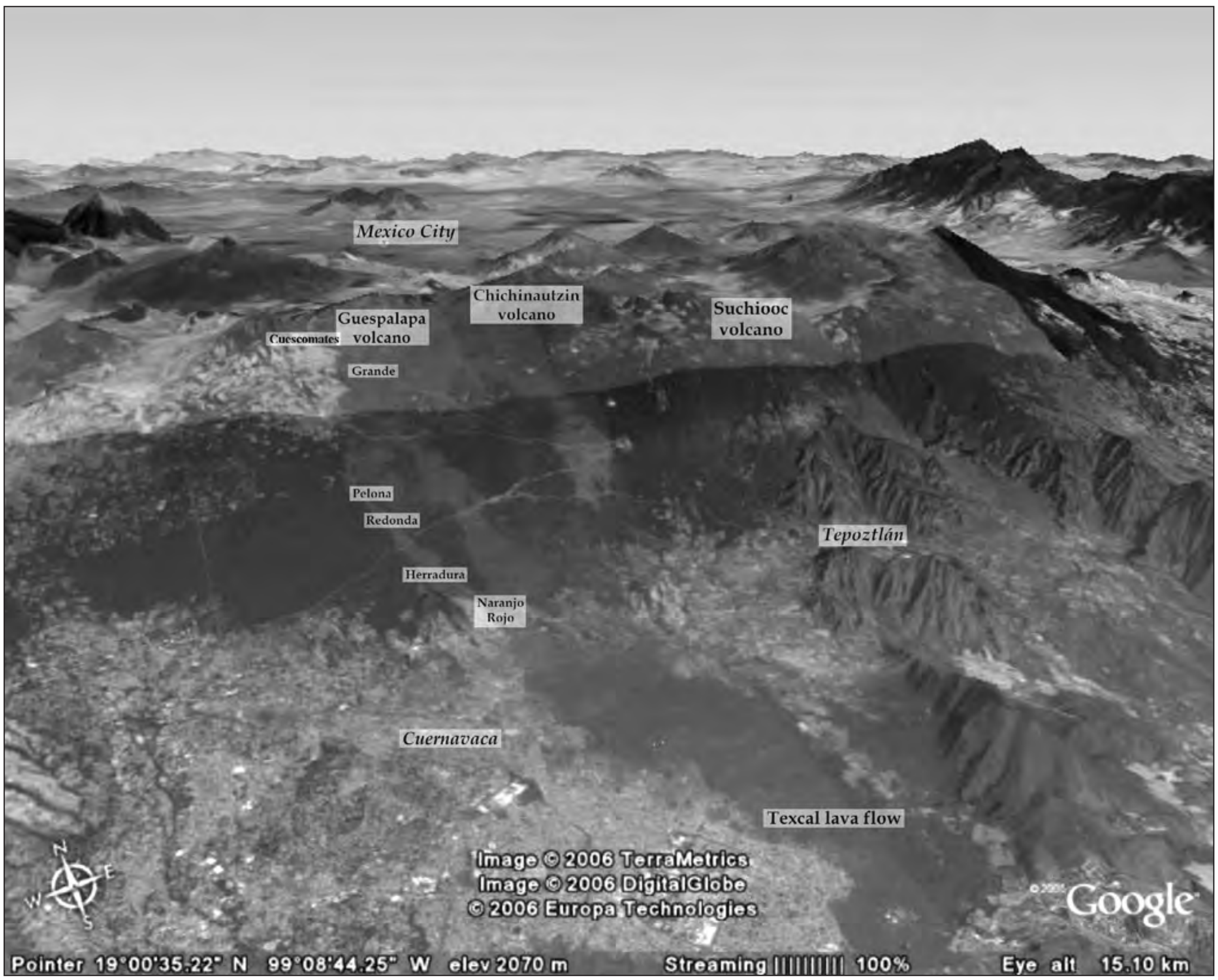

Figure 2. Image of the southern slopes of the Sierra Chichinautzin, with the location of the caves known along the upper slopes of the Texcal laval flow.

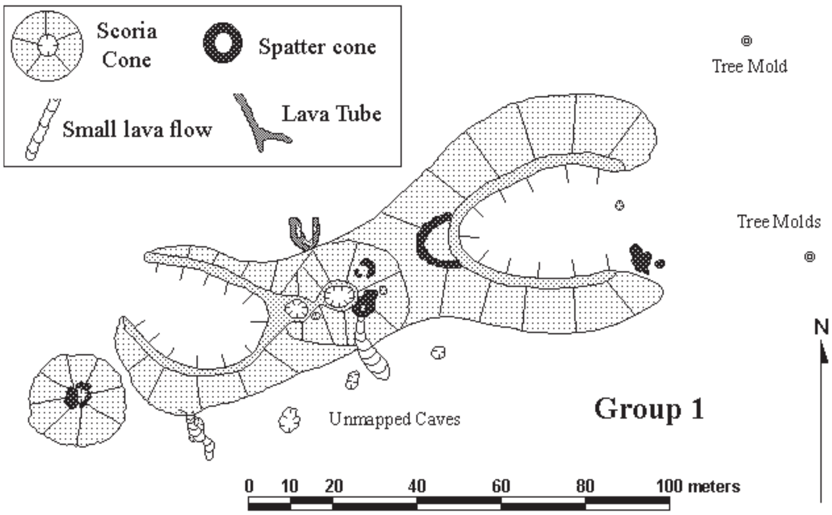

Figure 3. Plan of Cuescomates (Group 1).

just north of the Tres Cumbres volcanic edifice. Thick ash and soil deposits, probably saturated with water, fill this ponded area and probably were in part responsible for the formation of the *hornitos*. In Nahuatl, Cuescomate means conical gourd or container.

Group 1 consists of 8 different rootless vents aligned along a single ENE-WSW fracture (Figure 3). Four of them created small scoria cones, while the other four built spatter cones in which individual spatter blobs can be identified. The three middle vents have vertical-walled craters which can be entered with caving equipment and are connected through very tight fissures. Accreted lava lining covers the inner reaches of these rootless vents.

Small lava flows, issued by this group of "*hornitos*", formed several small lava tubes located to the NW and SE of the central vents. The area must have been covered by pine trees similar to the ones growing there today, as evidenced by several lava tree molds, up to 5 meters long, preserved to the east of the cones.

Group 2 is a group of 5 vents, three of which are tephra cones and the other two spatter cones (Figure 4). Only one of the vents, the easternmost, has a vertical-walled crater, which is connected through a tight fissure with a small hole on the northern base of the cone. A lava lining covers most of the inner walls of this vent, which is also lined with a large inner *levee* marking a former lava level inside the crater. Since this small cone is used as a quarry, its structure made of scoria fragments is easily seen. Lavas issued from this cone to the south generated well formed *levee*-bounded channels, and growth of the *levees* formed small caves. A collapsed cave to the north is used as an animal enclosure ("Potrero").

Less than 100 meters away is Group 3, which includes the largest of these small "*hornitos*" (Figure 4). El Cuescomate Mayor is 20 meters high and almost entirely made up of spatter (Figure 5). The crater is easily enterable, and still preserves part of a lava lining. At its southern base, a very interesting vent-channel structure is found, from which several different small lava flows were emitted, developing small lava tubes. One of them contains Cueva de la Laguna, with 62 meters of small passage and a little lake which gave it its name.

Further west, three other small vents produced small lava flows but no tephra or spatter, and are only recognizable by surface flow structures and the presence of small lava tubes. One of the vents has

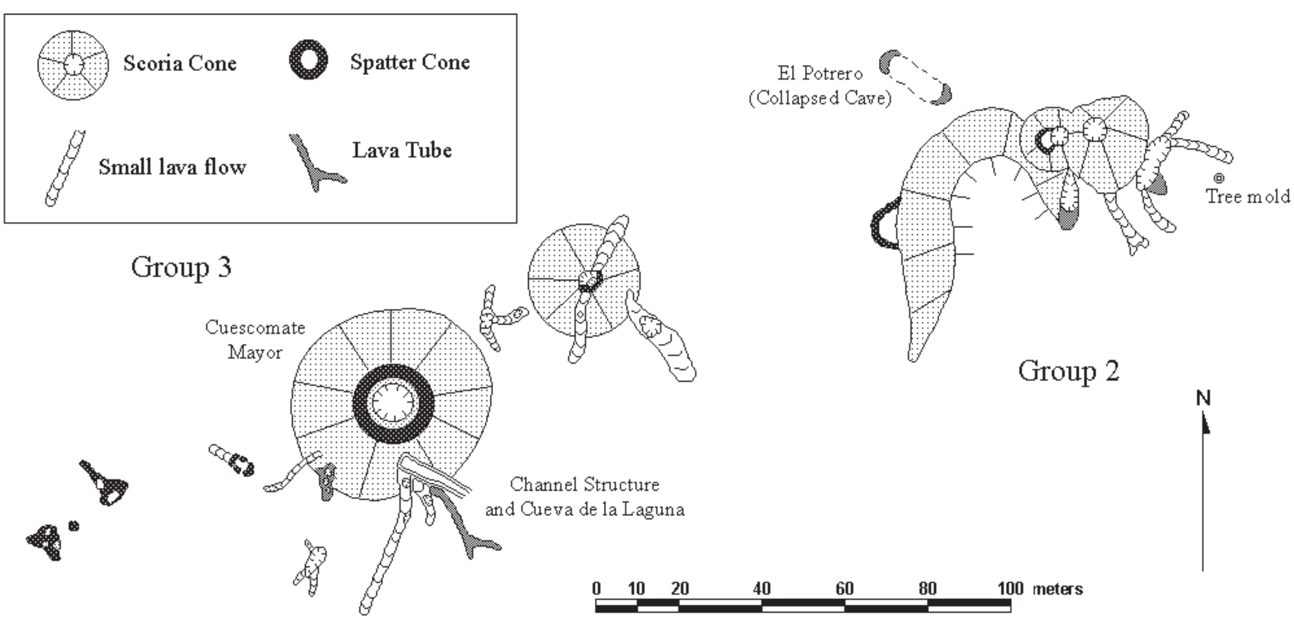

Figure 4. Plan of Cuescomates (Groups 2 & 3).

Figure 5. Los Cuescomates rootless vents are dwarfed by the surrounding 20 meters tall pine trees. Cuescomate Mayor is the one on the right.

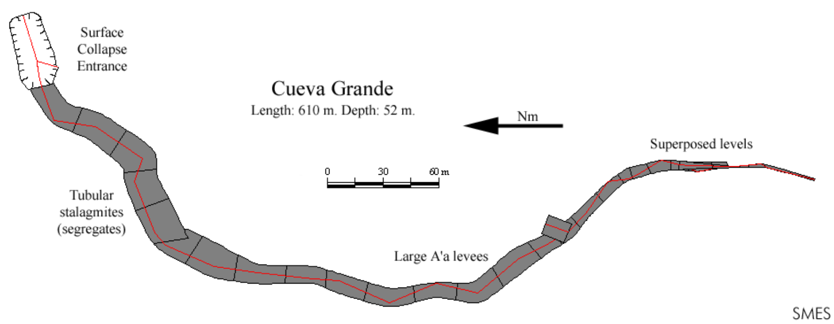

Figure 6. Map of Cueva Grande, a large master tube over 20 meters wide and high.

Figure 7. Lava drip stalagmites in Cueva Grande covering almost the entire floor of the passage.

Figure 8. Curling A'a levees on the walls of the deeper passages in Cueva Grande.

a crater about 15 centimeters wide but at least 3 meters deep, as sounded with a stick that didn't reach the bottom.

Lava tubes

Field work has resulted in the discovery, exploration and survey of 5 lava-tube caves, known in a downflow direction as Cueva Grande, Cueva Pelona, Cueva Redonda, Cueva de la Herradura and Cueva del Naranjo Rojo (Figure 2), for a total of nearly 3 kilometers of lava tubes mapped in this flow.

Cueva Grande: The entrance to this cave is located at the bottom of a surface depression about 4 kilometers from the vent, and just above the break in slope that marks the beginning of the steep descent towards the valley of Cuernavaca. It gives access to a huge tunnel (Figure 6) over 15 meters wide and high, with the floor covered in either breakdown blocks or huge, broken A'a *levees* or linings. After a hundred meters, the walls and floor, including many of the breakdown blocks, are covered by abundant drip stalagmites (Figure 7), while several tubular stalactites decorate the ceiling, proving that most of the collapse happened right after activity declined, the tube had emptied, and crystallization of the lava was producing the segregates that constitute the decorations (Allred & Allred, 1988a, 1988b). Further ahead large A'a levees line the walls, and on occasion have partially peeled and curled down (Figure 8). Eventually the cave narrows and the levees join to form a false floor. The upper level quickly ends in a lava sump, but the lower level continues past a narrow and very windy spot to a point almost 50 meters beyond the end of the upper level, where it closes down. Before the end, a narrow crack in the ceiling takes the air and allowed us to see into a possible continuation of the upper level. No cave is known between the end of Cueva Grande and the upper entrance of Cueva Pelona, making this an especially intriguing lead.

Cueva Pelona and Cueva Redonda are both located in the steepest and narrowest part of the flow. Both are sections of a large, multilevel master tube over 10 meters wide and 20 meters high. Cueva Pelona has two skylight entrances (Figure 9), and the area between the two presents evidence of continuous and sustained activity which caused thermal and/or mechanical erosion of

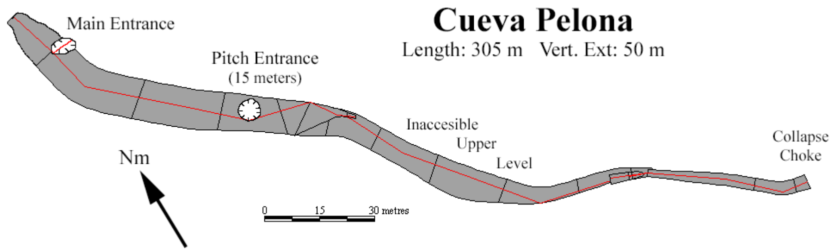

Figure 9. Plan view of Cueva Pelona. The outcrop of the Cuernavaca Fm. behind a lava lining is located between the two entrances.

Figure 10. Outcrop of the Cuernavaca Formation (below and to the right of the author's hand) on the wall of Cueva Pelona, covered by lava linings.

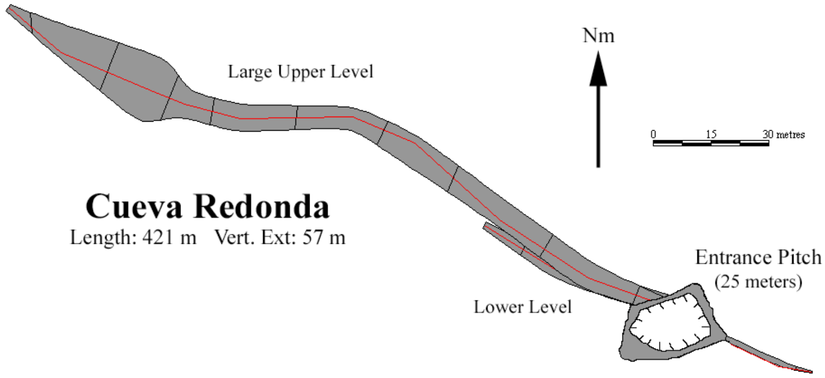

Figure 11. Plan map of Cueva Redonda. The entrance pitch of 25 meters was an open skylight during activity, as evidenced by primary features on its walls.

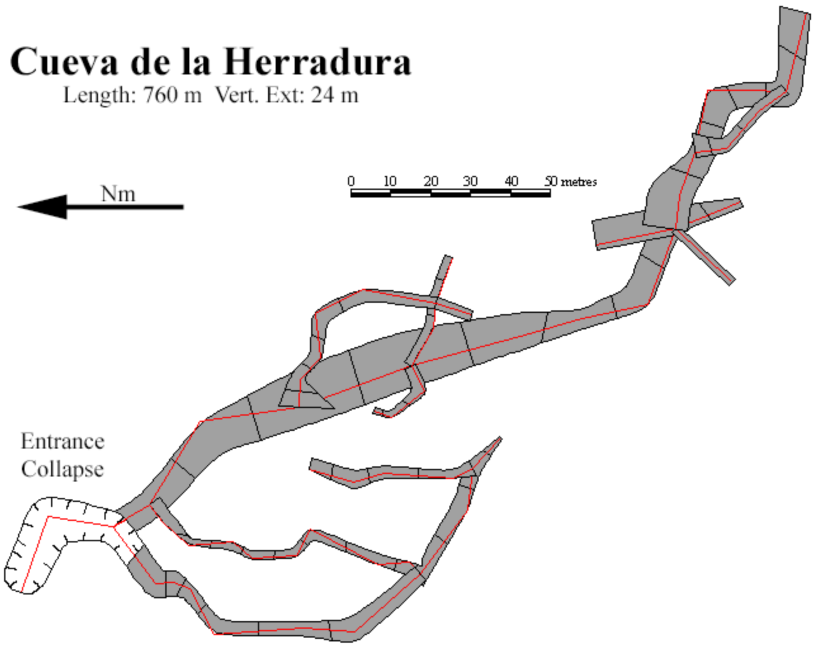

Figure 12. Plan map of Cueva de la Herradura, with a large main passage and upper level braided tunnels branching from it.

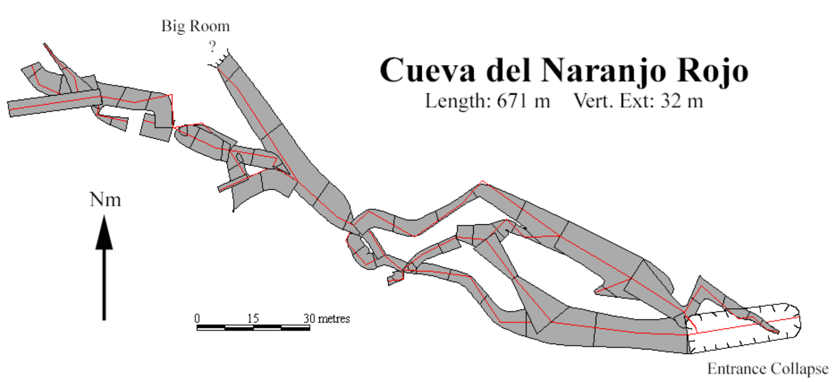

Figure 13. Plan map of Cueva del Naranjo Rojo, which contains a large multilevel master tube and upper level braided side passages, and is incompletely mapped.

the underlying lithology, made up of volcaniclastic agglomerates belonging to the Cuernavaca Formation, which can be seen behind a collapsed lava lining (Figure 10). Cueva Redonda is entered through a skylight over 30 meters deep, which was active during activity as shown by *levees* surrounding the 20 meter wide pit. It gives access to a short segment of tube which contains a vampire bat colony (Obispo Morgado *et al.*, 2004; they incorrectly refer to it as Cueva Pelona). A longer upper level can be reached halfway down the entrance pitch (Figure 11).

The lowermost caves (Herradura and Naranjo Rojo, Figures 12 and 13), in reduced slopes, also contain a master tube of large dimensions, but are further complicated by the presence of upper level braided side passages which mark the originally emplaced lava tubes, one of which pirated the lava from the others as it eroded a canyon tube downwards. The superposed levels on the master tube represent growth of successive crusts as the lava flow gradually eroded its floor.

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Surveyed Lava Tubes of Jalisco, Mexico

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La Cueva Cuata and La Madriguera de los Lobos are the only lava tubes surveyed in the Mexican state of Jalisco and so far the only lava tubes reported in Western Mexico (Jalisco, Colima and Nayarít). The caves are situated in CerroTequilizinta, 52 kms northwest of Guadalajara, in a canyon wall overlooking the Santiago River, at N20°55′08.3″ W103°45′11.6″. Both caves are in the Rio Santiago alkali basalts, which are from 1.3 to 0.4 million years old Their approximate location in Mexico is shown in Figure 1.

Cuata Cave

Cuata cave is 280.79 m long with passages varying in height from 1.9 m to .25 m and ranging in width from 15 m to 1 m. A map of the cave is shown in Figure 2.

Members of Grupo Espeleológico Zotz first investigated this cave in early 1990 and surveyed it during the same year. The cave can be reached via a paved road from Amatitán to the pueblo of Chome, after which dirt roads lead to a tequila distillery called La Taberna. From here it is necessary to hike northwest for one hour along a narrow trail which leads to La Barranca de Santa Rosa. La Cueva Cuata is one of numerous caves in a wall of a precipice on the south side of the Santiago River and at least 100 m above the river bed. Care must be taken in order to climb up to the cave entrance, but no gear or rigging are required (see Fig. 3).

The cave entrance is protected by a low, man-made wall at the very edge of the precipice. The entrance room, shown in Figure 4, is nearly 2 m high, 20 m long and 8 m wide. Dry, powdery sediment of an unknown depth covers the floor of this room. A seven-tiered, man-made religious altar of recent origin is found against the north wall of the room. This was placed here by a sect which believed this cave would be one of seven sites spared at the end of the world. A low passage connects this room to another entrance in the precipice wall.

Figure 1. Location of Cuata and Madriguera de los Lobos Caves in Mexico.

Figure 2. Map of Cuata Cave.

Figure 3. The approach to Cuata Cave requires an exposed climb high above the Santiago River.

The interior of the cave consists mainly of mud-or-clay-filled passages beneath an arched roof (Fig. 5). Trenches have been dug through the mud in some places to facilitate access.

Throughout most of the cave, the original ceiling appears to have spalled off long ago. However, 83 m south of the main entrance, lava stalactites, black in color and less than 4 cm long were observed in an indentation on the passage ceiling (Fig. 6). These were taken to be an indication that this cave is, in fact, a lava tube.

The cave contains a pool of water (The Black Lagoon), roughly 15 x 20 m and less than 60 cm deep, contaminated by the droppings of vampire bats which roost above it. At the far western end of the cave, an area of sticky clay is found. The cave continues in a westerly direction as a low, water-filled passage which was not explored.

La Madriguera de los Lobos

On April 6, 2006, John Pint and Sergi Gómez investigated the accessible holes beneath Tequilizinta Bluff. In one of these, lava stalactites were observed and in another, a lava stalagmite about 50 cm high and wide was found (Fig. 7). The largest of these holes is located directly underneath La Cueva Cuata and turned out to be a cave with passages totalling approximately 100 m in length, ranging in width from 25 m to 1 m. This cave was named Madriguera de los Lobos. A map of the cave is shown in Fig. 8.

The entrance is 7 m wide and 1.3 m high. Flat layers of rock in the entrance room appear to be layers of lava. The

Figure 4 (top). The entrance room viewed from the edge of the precipice. Note dry sediment on floor and altar in the distance.

Figure 5 (middle). Typical passage in Cuata Cave, less than 1 m high. One of three species of bats inhabiting the cave is shown in this photograph.

Figure 6 (bottom). Lava stalactites on a passage ceiling with double-A battery for scale.

Figure 7. Outdoor lava stalagmite found approximately 20 m south of La Madriguera de los Lobos.

floor of the cave is covered with powdery sediment, bat guano and, beginning about 60 m inside, what appears to be the dry scat (Fig. 9) of wolves or coyotes. Calcite stalactites less than 10 cm long were observed on the ceiling. Bats were found in several parts of the cave. In most parts of this cave the ceiling height is around 70 cm. About 80 m from the entrance, the roof rises and chunks of breakdown fill much of the space. Airflow through the breakdown was noted in this area, as well as the flight of bats in and out of a further extension of the cave. Because this breakdown area seemed rather unstable, no attempt was made to follow the air flow.

There are additonal photographs for this article in the supplementary material on the CD.

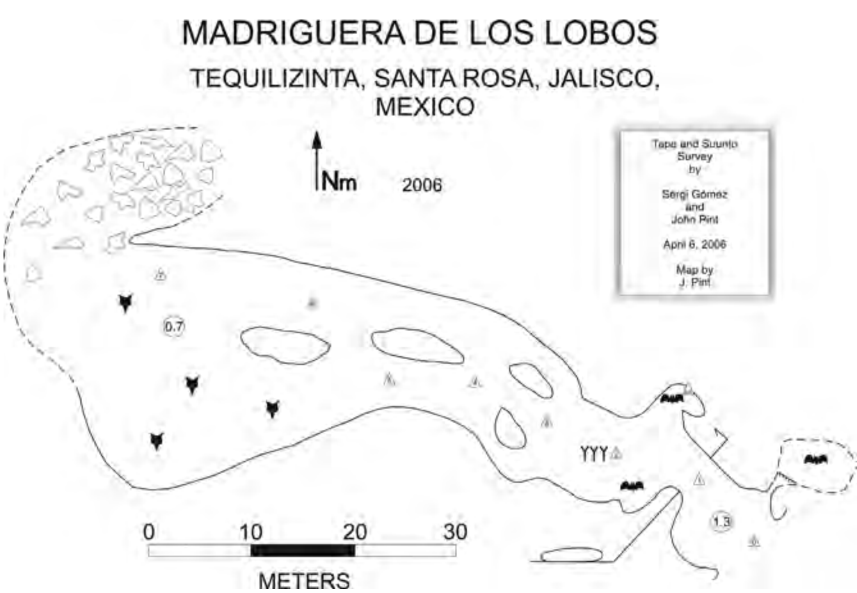

Figure 8. Map of La Madriguera de los Lobos Cave.

Figure 9. Typical sample of dry scat found about 50 m inside the cave.

Lava Tubes of the Naolinco Lava Flow, El Volcancillo, Veracruz, México

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Abstract

Six caves up to nearly a kilometer long have been discovered on the Naolinco lava flow, which was emmited by El Volcancillo 870 years ago and reached a length of about 50 kilometers. All of the caves seem to be remains of a master tube which probably fed most of the lavas that form the flow. Of particular interest is the fact that at least two of the caves capture and carry surface streams of considerable size. The water does not return to the surface until the spring known as El Descabezadero, the birthplace of the Actopan River.

Las Lajas Cinder Cones and lava flows

North of Cofre de Perote a series of small eruptive vents are called the Las Lajas Cinder Cones. Over a dozen volcanic vents have been recognized and some of them have been dated (Siebert and Carrasco-Núñez, 2002). La Joya cinder cone complex is one of the oldest, and produced about 20 km^3 of basaltic flows that extend about 14 kilometers SE to underlie the city of Xalapa, capital of the state of Veracruz, about 42,000 years B.P. Many younger volcanic vents and lava flows exist in the area (Fig. 1).

El Volcancillo

The youngest lava flows dated by Siebert and Carrasco-Núñez (2002) originated from El Volcancillo (2,700 m.a.s.l.), a twin crater located 4 kilometers southeast of the town of Las

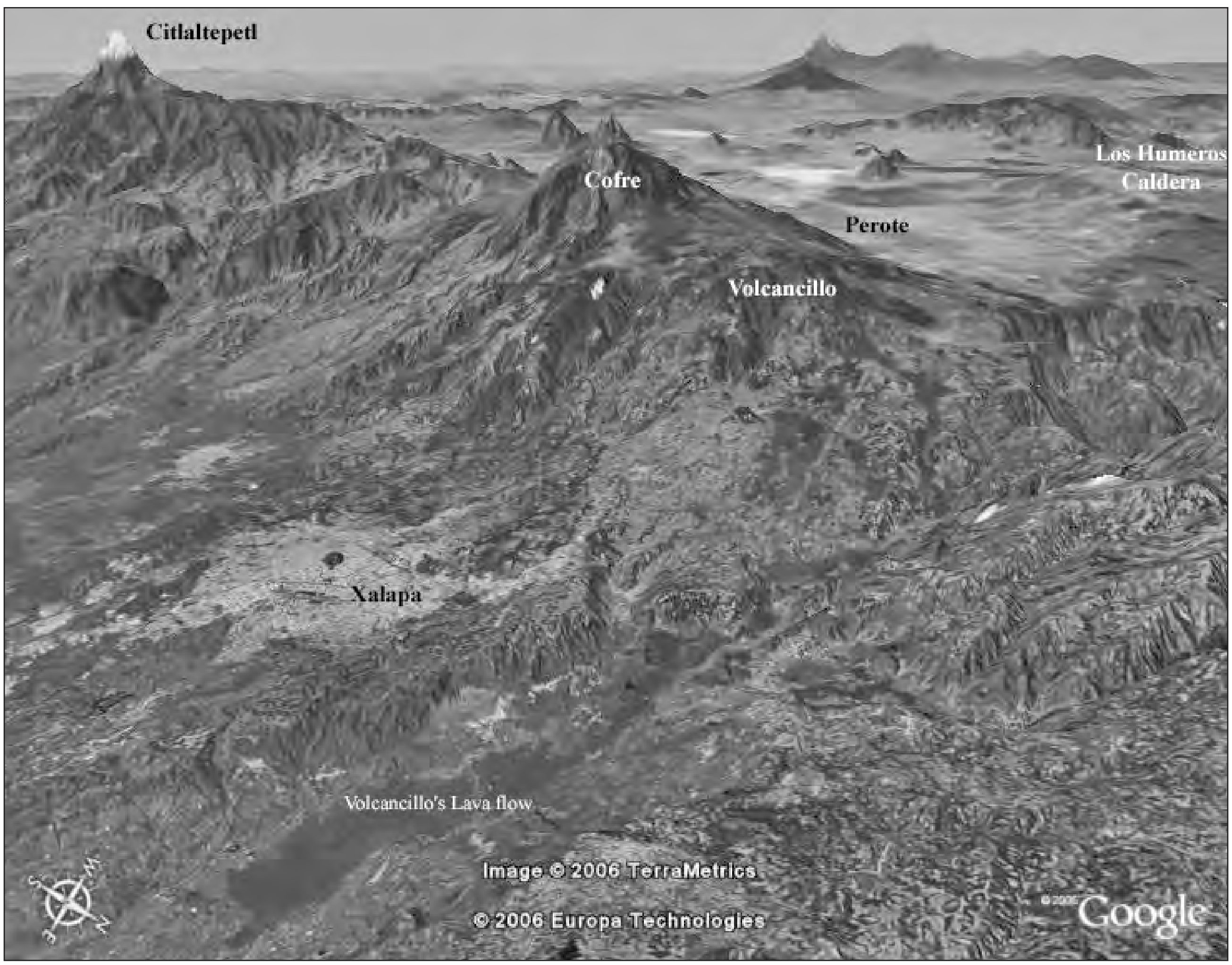

Figure 1. Las Cumbres volcanic complex and the Volcancillo lava flows.

Vigas which erupted 870±30 y.B.P. The cone complex straddles a sharp crested ridge between two valleys carved into the slope of Las Lajas volcano, a subsidiary cone of Cofre de Perote. It fed two lava flows that traveled down different drainages. The Toxtlacoaya A'a flow, originating from the southeastern crater, has a length of approximately 12 kilometers, while the Río Naolinco pahoehoe flow, which originated in the northwestern crater, traveled over 50 kilometers.

Toxtlacoaya lava flow

The eastern crater occupies the summit of a steep sided scoria cone that is breached in two places on its southern side. Large lava benches surround the inner crater and mark the highest stand of a former lava lake which overflowed the breach, generating a short lava flow which shortly stopped at the end of the first steep slope. We believe that most of the Toxtlacoaya lava flow issued not from the breached upper cone but from a pair of vents at the northeastern base of the cone, based on lava flow morphology. The lava flow crusted over forming a large lava tube with a big skylight, 20 meters in diameter, which overflowed frequently forming a small shield. Quarrying of a lower entrance and the building of an Oleoduct collapsed most of the cave, leaving a semi-natural rock arch giving the cave its name, Cueva del Arco (Figure 2)

Siebert and Carrasco-Núñez (2002) claim that the 35 meter thick lava pile visible on the walls of Cueva del Arco (Figure 3), actually 45 meters, according to our survey, represent the minimum thickness of the lava

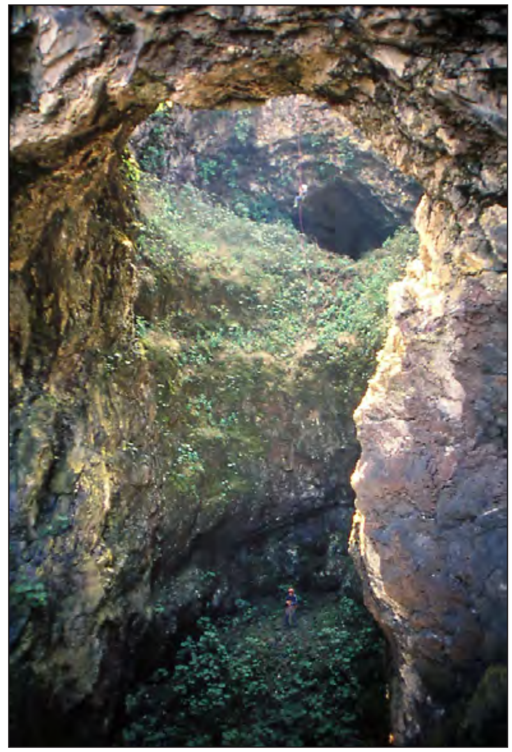

Figure 3. Cueva del Arco. Notice the two cavers, one on rope and the other at the bottom.

flow, and do not consider that the tube could have been originally much smaller, and the present height was caused by thermal erosion, as suggested by the passage cross section.

Naolinco lava flow

The western or main crater is 200 meters wide and 90 meters deep. It partially truncates the eastern scoria cone and was produced by collapse of a small lava lake that overflowed the western scoria cone. In both craters we find the same sequence of events: building of a scoria cone by lava fountaining, followed by the emission of lava which formed a lava lake. In the western crater, the scoria cone was overtopped over an arc of 180º by pahoehoe sheet flows, which were truncated by the crater collapse. The uppermost entrance to Cueva de El Volcancillo is exposed in the upper northern wall, and marks the main outflow of the Río Naolinco lava flow.

The whole of the Río Naolinco lavas were fed through lava tubes, as evidenced by numerous primary inflation structures such as tumuli, pressure ridges, inflation

Figure 2. Map of Cueva del Arco.

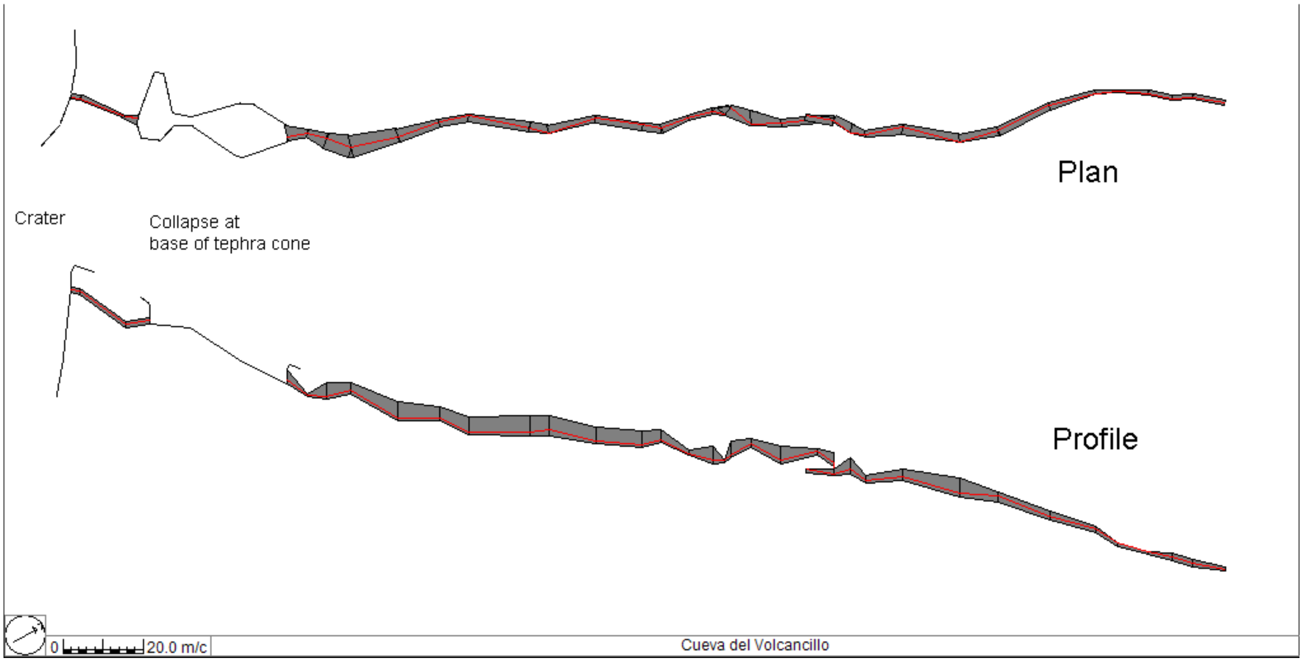

Figure 4. Plan map of Cueva del Volcancillo.

clefts and ropy textures throughout. After 15 kilometers and a steep fall near the town of Tlacolulan, the lavas entered the deep valley of the Naolinco River and followed it for nearly 35 kilometers. The lava flow ends at a narrow canyon west of the town of Chicuasen at an altitude of 360 meters, immediately beyond the popular Descabezadero Cascades, the birthplace of the Actopan River, which comes out at the contact of the lava flow with underlying conglomerates. With over 50 kilometers in length, it is one of the longest lava flows recognized in México.

To date, 6 different caves have been discovered on this lava flow, but not all have been surveyed properly, or even completely explored. They are possibly all part of what must have been a large master tube which probably fed most of the lava. Undoubtedly, many more caves probably exist and await discovery, exploration and mapping. The known caves will be described downflow:

Cueva de El Volcancillo: This cave is located right at the north side of the west crater. It is a tube segment 685 meters long, in two sections separated by a large collapse. The upper one goes for less than 50 meters between the crater wall and the surface collapse, after which the entrance to the main cave is encountered (Figure 4). It is a beautiful master tube with up to three superposed levels separated by the growth of wall *levees*. In those sections where the *levees* do not join, their surface texture is especially beautiful (Figure 5). After nearly 350 meters, a small skylight entrance is encountered, below which is a seven meter pitch which can be rigged with a wire ladder and a safety rope. Shortly afterwards the cave ends in breakdown.

Cueva de la Escalera: Located near Cueva de El Volcancillo, it is the probable downflow continuation of the same tube beyond the breakdown. It is a collapse of the ceiling of a large and deep tube, but it has not been entered yet.

Cueva del Río Huichila: This cave is a large segment of a master tube, beautifully preserved in sections, and with the added interest of containing a substantial river. It has been explored for 625 meters (Figure 6), through numerous pools which required swimming and frequent

Figure 5. The beautiful wall *levees* in Cueva de El Volcancillo.

Figure 6. Plan and profile of Cueva del Río Huichila.

rapids that have to be climbed around, to a skylight, but the cave continues unexplored beyond (Figure 7).

Cueva de El Tirantes: Small cave 278 meters long (Figure 8). It is located in the back "*patio*" of the "*El Gavilán*" restaurant on the Naolinco road, near the town of La Virgen, Municipio de Jilotepec, and was named in honor of the owner, a former AAA Wrestling referee. Unfortunately, one of the passages receives waste from bathrooms located above.

Cueva de La Higuera: This tube is relatively narrow but quite long at 625 meters. It has been explored to a breakdown choke but it may continue beyond (Figure 9). The entrance is in front of the "*El Gavilán*" restaurant, south of the previous cave. Both these caves are also known as Cueva de La Virgen, the name of the nearest town.

Cueva de Tengonapa: This lava tube is located near the town of the same name, in the Municipio of Tlacolula. It has been surveyed for 477 meters between two skylight entrances, but continues beyond in both directions (Figure 10). The upper portion contains two paralel and superposed tubes that lower down merge into a canyon shaped master tube over 10 meters in height. In the upper levels trash and vegetation from floods can be found, and locals relate that during the

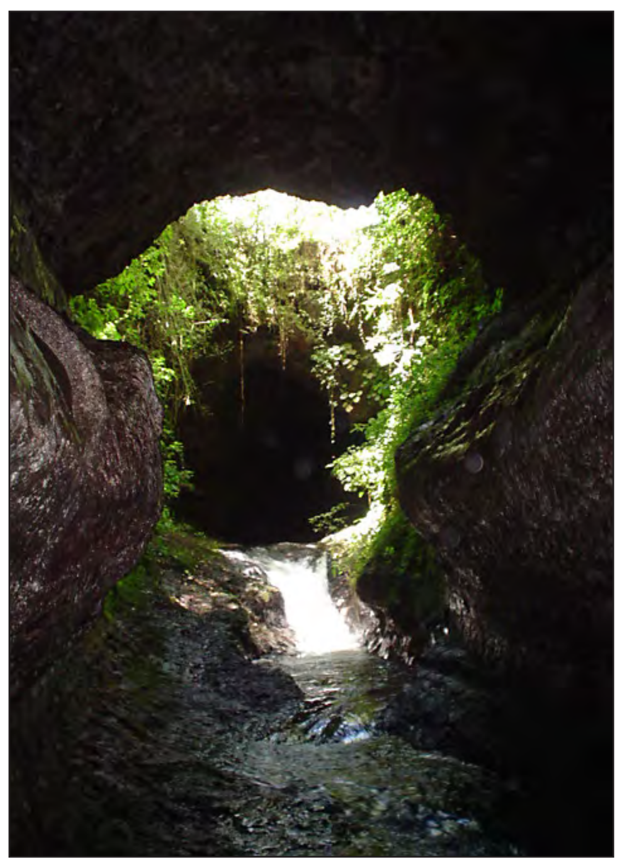

Figure 7. The Huichila River under one of the skylights in the cave.

Figure 8. Plan and profile of Cueva de El Tirantes.

Figure 9. Plan and profile of Cueva de la Higuera.

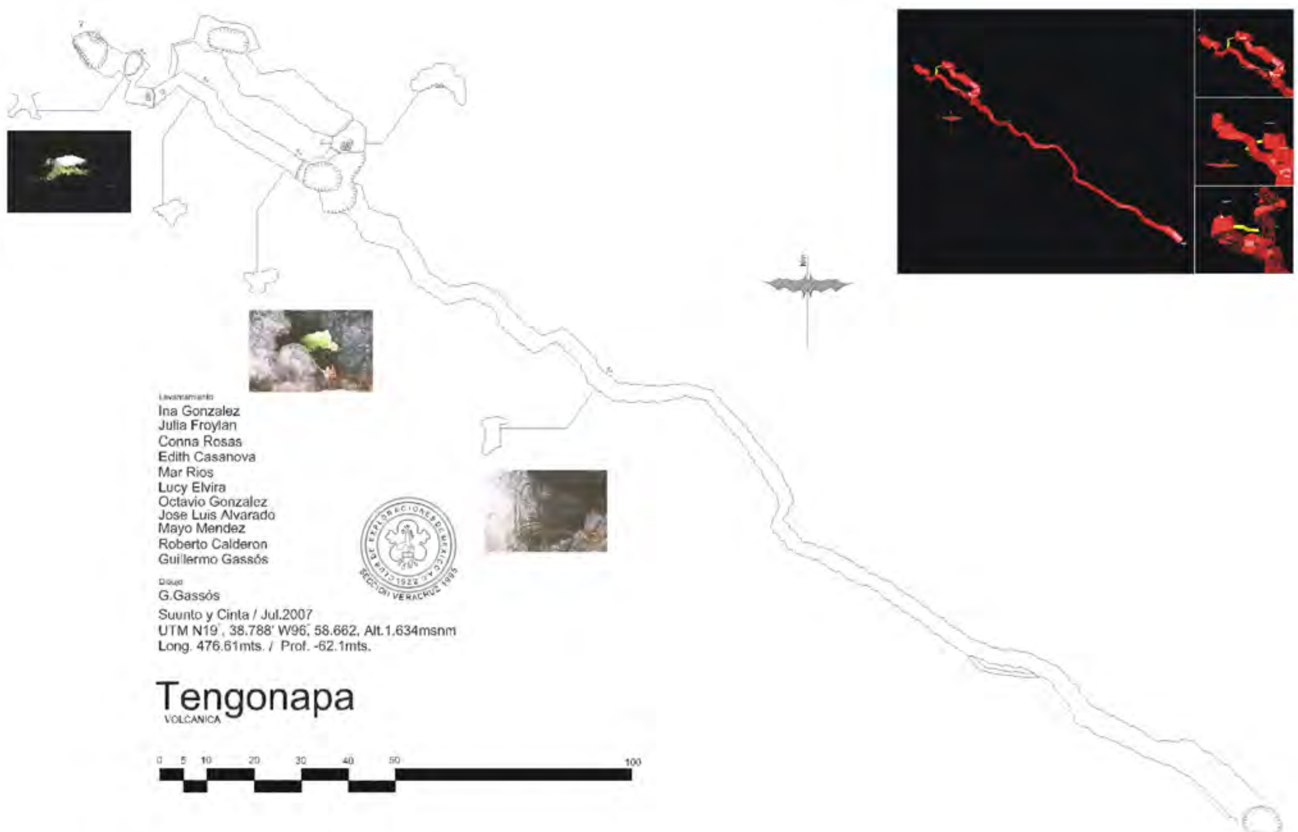

Figure 10. Plan and profile of Cueva de Tengonapa

Figure 11. El Descabezadero, birthplace of the Río Actopan and terminus of the Naolinco lava flow.

rainy season a river flows through the cave and washes away any trash they throw inside.

The presence of active streams in several of the caves is unusual. No springs are known except for El Descabezadero, at the downstream end of the lava flow, which gives birth to the Actopan River, so the water from the above caves probably resurges there (Figure 11). The known instances of pollution of some of the caves is therefore more problematic than usual, since those contaminants could easily be transported by the cave streams, polluting the entire Actopan basin.

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Possible Structural Connection between Chichón Volcano and the Sulfur- Rich Springs of Villa Luz Cave (a.k.a. Cueva de las Sardinas), Southern Mexico

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Abstract

Regional strike-slip faults may serve as groundwater flow-paths from the active Chichón Volcano to the Villa Luz Cave (a.k.a. Cueva de Las Sardinas, CLS). In this cave, located near Tapijulapa, Tabasco, several springs carry hydrogen sulfide. Previous studies have linked the CLS spring sulfur source to basinal water and an alkaline active magma volcano, but the groundwater flow paths still need to be reviewed. Understanding the sulfur origin in the cave will provide insights into the possible sources, the extreme microbial environment, the sulfuric acid speleogenetic mechanism (i.e. creation of caves by strong acid dissolution), the subsurface water-rock interactions and groundwater flow paths in the area. The volcano and CLS location in the Chiapas Strike-slip Fault Province, suggests a left-strike slip fault may be serving as a groundwater flow path, allowing deep-source magmatic water to contribute sulfur to the water that is dissolving the limestone at CLS. Detailed geological mapping of the surface and the caves in-between, coupled with chemical analyses of the cave and spring waters may help to prove this connection.

Introduction

Although Villa Luz Cave (a.k.a. Cueva de Las Sardinas, CLS) is forming in limestone, its groundwater flow-paths may be connected to the active Chichón Volcano by regional, siniestral strike-slip faults. Although previous studies suggest a possible contribution of volcanic sulfur to the cave waters [Hose *et al*., 2000; Spilde *et al*., 2004], the groundwater flow-path to accomplish this was not suggested. Although CLS is 50 kilometers east from the active Chichón Volcano, lateral faults in the area and the structures associated with it, can provide the necessary flow path for the sulfur-rich water. The study of other sulfur springs between the cave and the volcano will also help to provide evidence to support this hypothesis. Specifically the location, the geology, the water chemistry and isotope composition of sulfur, oxygen and hydrogen at three sulfur spring areas will be acquired and analyzed in order to accomplish this goal.

Chichón Volcano produced an unusually sulfur-rich magma in its last explosive eruption in 1982, leaving an active hydrothermal system. The unusually high sulfur concentration of that eruption has not yet been explained. Nevertheless, evaporitic subsurface deposits may influence Chichón hydrothermal water composition and/or act as a sulfur source to the Las Sardinas Cave sulfur springs. This cave is typified by the high sulfur concentration of most of the springs present in the cave. These conditions produce a sulfur-rich microbial environment resembling deep-sea hydrothermal-vents [Boston *et al*., 2006]. The hydrogen sulfide present in the cave reacts with the limestone enlarging the cave by the sulfuric acid speleogenetic mechanism (i.e. creation of caves by strong acid dissolution). The study of this system will provide insight to this process.

The understanding of the sulfur origin to Villa Luz Cave and sulfur springs in the area will help to identify the relevance of the possible sources as well as the subsurface water-rock interactions occurring.

A review of the geological setting and the main characteristics of the Chichón Volcano and the Villa Luz Cave, followed by the proposed methodology to test the volcano-cave groundwater connection will be presented in this paper. Further results and conclusions are not yet available because the main part of this project is still in progress.

Geologic Setting

Location: Villa Luz Cave is located 50 km east of Chichón Volcano, near the border of the states of Tabasco and Chiapas, southern Mexico (Figure 1). In addition to Chichón, Villa Luz Cave sulfur-rich spring water can be influenced by the Chiapas-Tabasco Oil and Gas Fields with high-sulfur content to the north, the ~5 Ma Santa Fe and Victoria granodiorite intrusive rocks to the west, and older andesitic flows to the north and southwest of the area.

Structural setting: CV and CLS are located in the north of the Strike-slip Fault Province defined by Meneses-Rocha, [2001]. The Strike-slip Fault Province occupies the Sierra de Chiapas, to the north with elevations ranging from 100 to 2000 m.a.s.l. This province is formed by upthrown and downthrown blocks, formed during a transtensional phase, bounded by lateral strike-slip faults. Northwest trending en-echelon anticlines with middle Cretaceous and Paleogene rocks in their center are present in most of the upthrown blocks while tectonic basins filled with Cenozoic rocks are present in the downthrown blocks [Meneses-Rocha, 2001]. The aforementioned author states that syndepostional tectonism is evidenced by local unconformities, thickness changes and lithologic variations along structural trends. The orientation of faults in this province is the basis for a further subdivision [Meneses-Rocha, 2001]: a) a western area, with variably oriented faults; b) a central area, with northwest oriented faults and, c) an eastern area, with west oriented faults. The eastern most part of this province is where our study area is located (Figure 2). The detachment surface of the central and western areas is comprised of Callovian salt deposits, while in the eastern area a Lower Cretaceous anhydrite (Cobán

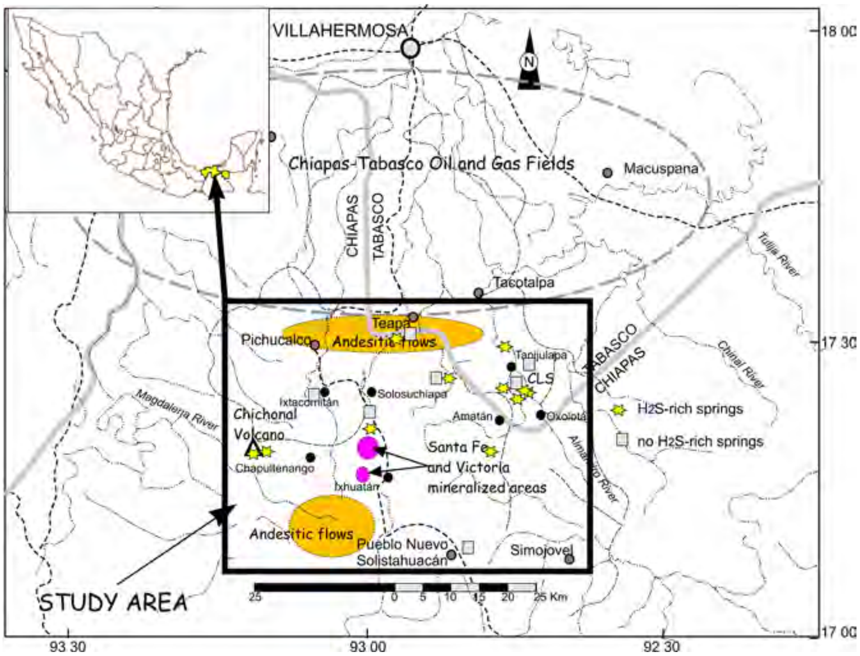

Figure 1. Location of the CLS (Cueva Las Sardinas or Villa Luz Cave) and Chichón Volcano (CV). H_2S-rich springs are presented by stars while no-H_2S springs are presented by squares. The possible sulfur sources to the sulfur-rich springs in CLS are also shown.

Formation) detachment is also identified (besides the aforementioned detachment level) (Figure 3). These detachment levels could provide sulfur to the groundwater feeding Chichón Volcano 1982 magma and/or the Villa Luz Cave springs. A basement involvement in some of the faulting is evidenced by the presence of Pliocene-intrusives (Santa Fe granodiorite, 5 Ma) and Pliocene-Quaternary volcanoes (Chichón Volcano) at the ends of some faults [Capaul, 1987; García-Palomo *et al.*, 2004; Meneses-Rocha, 2001].

Geologic history: Rocks from Cretaceous to Quaternary age outcrop in the area (Figure 4 and Figure 5). The basement is considered to be Paleozoic granites that crop out in the Chiapas massif and metamorphosed sediments south and east from the area, respectively. Paleozoic granitoids and Mississippian to Permian slightly metamorphosed sediments (shale, sandstone and limestone) are also present. The post-Permian - Upper Jurassic opening of the Gulf of Mexico produced discordant conglomerate, sandstone and shale-filled half-graben structures, probably syntectonic to salt and evaporitic deposits. Evaporite deposit extension in the area, shown in Figure 3, is responsible for the distribution of compressional salt tectonics [García-Molina, 1994] and for the deformational response in the different structural provinces. Basinal to shallow platform carbonates, to littoral and alluvial fan environment sediments interfingered during upper Jurassic times. The basinal facies served later as a hydrocarbon source. Carbonate sediments dominated Cretaceous deposition from the Yucatan Platform

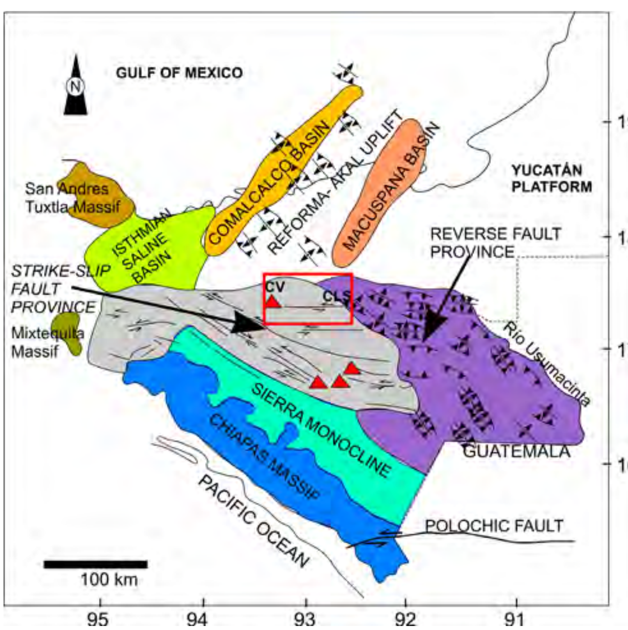

Figure 2. Structural provinces present in the study area. Chichón Volcano (CV) and Villa Luz Cave (CLS) are located in the Strike-Slip Faults Province. Volcanos from the Chiapas Volcanic Belt or Arc in the area are shown as triangles (Modified from Meneses-Rocha [2001]).

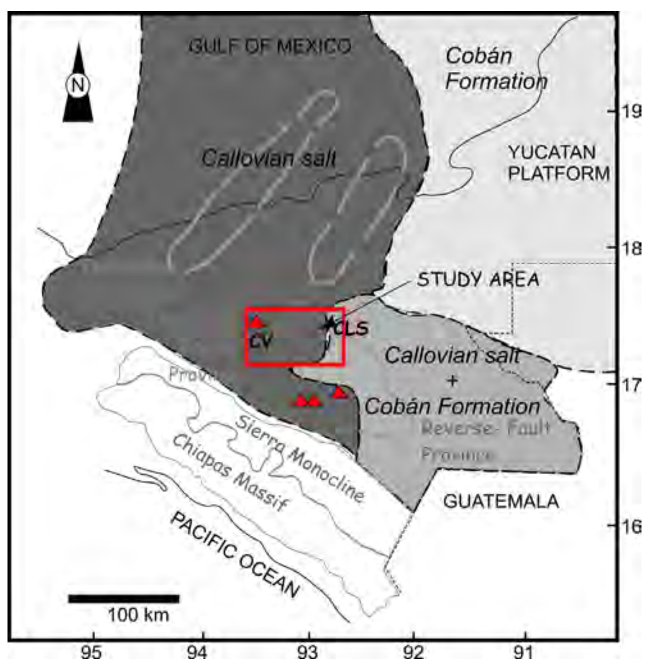

Figure 3. Type of evaporite deposit underlying the area (Callovian salt, halite or Cobán Formation, anhydrite). These deposits were one of the major controls on defining the structures present (modified from Meneses-Rocha [2001]).

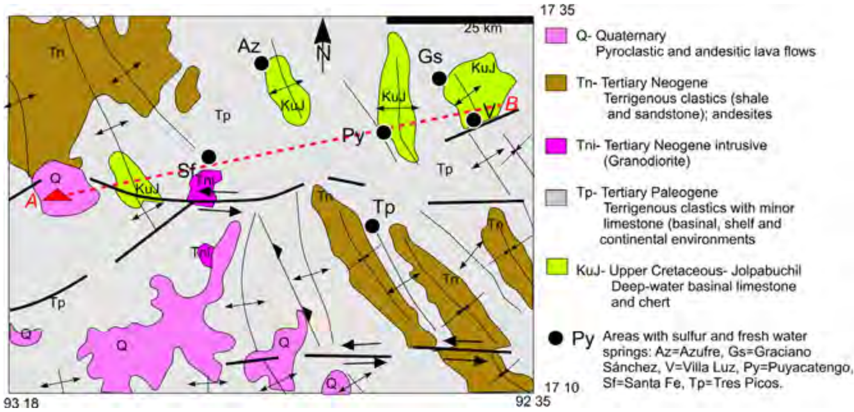

Figure 4. Generalized geologic map of the study area, showing the location of Chichón Volcano (CV) and Villa Luz Cave (CLS), as well as other sulfur spring areas. The orientation of the geologic section shown in Figure 5 is also shown (Modified from INEGI [1983] and Meneses-Rocha [2001]).

to the west of the Chiapas range, unconformably covering older rocks. This age sedimentary environments vary from supratidal to reef and pelagic. Between Paleocene and middle Eocene, during the Laramide orogeny, the area was subject to gentle deformation causing terrigenous sediments and interfingered carbonates to disconformably deposit in flexural basins [Meneses-Rocha, 2001]. The Cayman Trough insertion and Polochic-Motagua Fault began at the end of the Paleocene forming normal and lateral faults. From Late Eocene to Early Miocene, the Strike-slip Fault province movement along the faults was predominantly vertical, changing to sinistrally transcurrent at the beginning of the Middle Miocene (transtensional phase). During the late Miocene-early Pliocene, a coarse-continental sequence was deposited in response to normal block faulting of the basement caused by the shift of the main bounding faults. Meanwhile carbonate platform units deposited on the Yucatan platform and some parts of Chiapas. At the end of the Pliocene, a transpressive episode deformed some of the previously formed basins. This event was related to the rise of the Neogene Chiapas fold and thrust belt by basal decollement movement over the Jurassic salt, and recession of the shoreline to its present position. This last compression event relates to the intrusion of granitoid bodies. During the Quaternary, volcanic sediments were deposited in angular unconformity on the continental sediments.

The total sinistral shear across the Strike-strip Fault province is estimated to be of approximately 70 km, and the individual faults in this province has a displacement greater than 16 km [Meneses-Rocha, 2001]. The importance and participation of the structures present in the groundwater control are not fully understood yet.

Volcanic rocks associated with an arc have been present from the Permian until present [García-Molina, 1994].

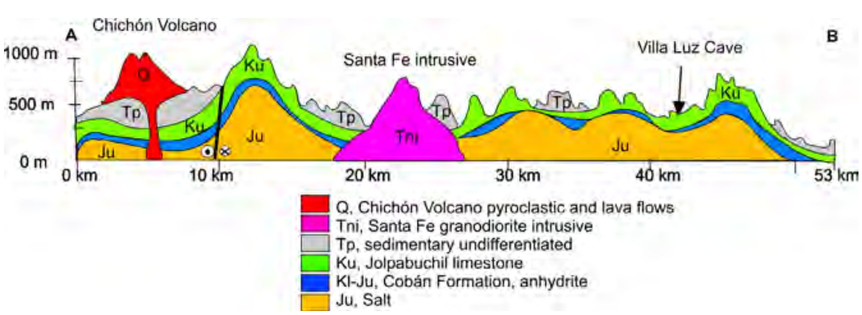

Figure 5. Geologic section of the study area showing a simplified interpretation of the geology (Figure 4, vertical thickness of the formations are not in scale). Ju=Upper Jurassic, Kl=Lower Cretaceous, Ku=Upper Cretaceous, Tp=Tertiary Paleogene, Tni=Tertiary Neogene intrusive, Q=Quaternary.

Chichón Volcano

Chichón or Chichonal Volcano is the youngest and western most K-rich andesitic volcano of the Chiapas Volcanic Belt or Arc (Figure 1 and 2), [Macías *et al.*, 1997], with deposits at least 8000 years old [Espíndola *et al.*, 2000]. Located in a still-debated tectonic setting [Espíndola *et al.*, 2000; De Ignacio *et al.*, 2003], it is proposed as one of the possible sources for the CLS cave sulfur-rich water springs [Hose *et al.*, 2000; Spilde *et al.*, 2004]. The Chichon volcanic cone was built on folded Cretaceous dolomitized limestone underlain by Jurassic evaporites and covered by alternating sequences of Tertiary shale and marl [Macías *et al.*, 1997], (Figure 5). Structurally, this volcano is located in a strike-slip regime, at the junction of three main structures (Figure 6): (1) the Chapultenango extension Fault System; (2) the NW-SE trend Buena Vista Syncline; and (3) the San Juan Fault System (strike-slip), with an E-W orientation. The latter is proposed as the K-alkaline magma feeding-system [Macías *et al.*, 1997; García-Palomo *et al.*, 2004]. These structural features control the pattern of rivers and determine the topographic irregularities around the cone [Scolamacchia and Macías, 2005].

After its last eruption, in March-April 1982, a crater lake formed and the associated hydrothermal system was redefined [Taran *et al.*, 1998; Rouwet *et al.*, 2004] with active fumaroles depositing elemental sulfur (Figure 7). Luhr and Logan [2002] estimate that 2.2 x10^{13} g of S were emitted on the 1982 CV eruption, from which 58 wt.% of the sulfur was present as anhydrite prior to eruption, with the remainder in a vapor phase, with $H_2S/SO_2 \approx 9$. These authors also discard a sedimentary provenance to the anhydrite based on sulfur isotopes, supported by chemical evidence indicating absence of hydrothermal fluid interaction with the underlying evaporites or basement rocks [Taran *et al.*, 1998]. Nevertheless, Espíndola *et al.*, [2000] suggest that the high-sulfur magma of the 1982 eruption, and probably previous eruptions, was created by a mafic magma injection into the underlying limestone.

Although the 1982 eruption produced anhydrite-rich pyroclastic deposits [Luhr and Logan, 2002; Taran *et al.*, 1998], the hydrothermal system until 1997 showed

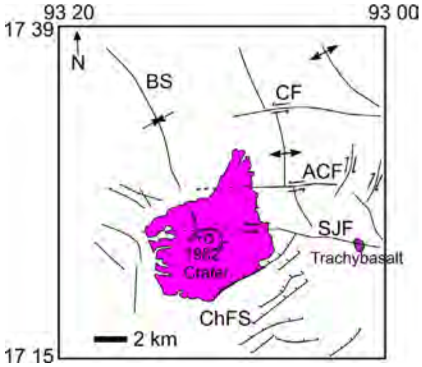

Figure 6. Plan view of Chichón Volcano (CV), showing the E-W lateral San Juan Fault (SJF) interpreted to control the magma-feeding system (modified from García-Palomo *et al*. [2004]) and which may serve as a groundwater flow-path for sulfur water from CV to Villa Luz Cave. Other major structures are: CF=Caimba Fault, ACF=Arroyo de Cal Fault, ChFS= Chapultenango extension Fault System, and BS=Buenavista Syncline.

relatively low sulfur content. Between 1998 and 1999, sulfate concentration increased in the lake water, decreasing in 2000 while H_2S/SO_2 ratio increased in the fumaroles [Rouwet, 2004; Taran *et al*., 1998; Tassi *et al*., 2003]. The variability of the sulfur concentration in the hydrothermal system may reflect magma movement [Horwell *et al*., 2004; Taran *et al*., 1998].

Villa Luz Cave (a.k.a. Cueva de las Sardinas, CLS)

CLS is located on the northeast side of the study area (Figure 1). The cave formed on a folded block of Cretaceous micritic limestone bounded to the south by a normal fault, with structure probably controlling the cave inlet's location [Hose *et al*., 2000]. Due to the normal fault orientation, it may represent a permeable conduit connecting the cave to the San Juan lateral Fault at the Chichón Volcano (Figure 4).

The first studies of CLS focus mainly on the fish present [Gordon and Rosen, 1962]. Pisarowicz [1994] attracted international attention to the cave, resulting in further studies [Estrada B. and Mejía-Recamier, 2005; Hose *et al.,* 2000; Langecker *et al*., 1996; Northup *et al*., 2002; Plath and Heubel, 2005; Plath *et al*., 2006; Spilde et al., 2004; Boston *et al*., 2006]. Plath *et al*., [2006] also present a brief review of the studies history at Cueva de las Sardinas and a summary of the cave fish research. Hose and Pisarowicz, [1999] provide a detailed map and description of CLS, (Figure 8) while Hose *et al*., [2000] comprehensively describe CLS, including the cave's speleogenetic mechanism, based on detailed morphologic and chemical measurements. They also conducted preliminary biological analyses emphasizing the microbiological importance in the cave development. At least 26 springs have been identified in CLS (Figure 8). Based on their chemical nature and physical appearance, Hose *et al*. [2000] classify the springs in the cave as two end members: A and B. End member A is characterized by $[H_2S]$= 300-500mg/l and $[O_2]$< 0.1mg/l. This water is slightly supersaturated with calcite and undersaturated in gypsum and dolomite; recognizable in the cave by elemental sulfur coating the walls above the spring (Figure 9), white bacterial filaments on the wet rock surfaces, and pyrite deposits on the sediments/rocks covered by water. Spring water B has $[H_2S]$ <0.1mg/l and $[O_2]$ <4.3mg/l. These inlets are characterized by travertine precipitation and red-yellow iron oxides, calcite and dolomite supersaturation and undersaturation in gypsum. AB water results from the mixture of the first two springs end members. AB composition water is the most abundant present in the cave (pH, P_{CO2} and SI similar to B and characterized by white coloration probably produced by colloid-size sulfur particles [Hose et al., 2000]. Based on total dissolved solids and general chemistry, a similar origin and composition was proposed for the A and B springs inside the cave, suggesting oxidation of H_2S in the B springs before arriving to the CLS. The causes or controls for the water oxidation are still unknown. In this paper, we will refer mainly to the A-member springs as sulfur-rich springs, focusing on its possible connection to the Chichón Volcano.

In Villa Luz Cave, sulfur-rich springs are actively dissolving bedrock (i.e., Sulfuric Acid Speleogenetic mechanism) while supporting abundant sulfur-based microbial life and providing energy to the cave ecosystem [Hose et al., 2000]. Hydrogen sulfide degassing from the spring water oxidizes to elemental sulfur or sulfuric acid. The latter one reacts with the limestone to produce selenite crystals or gypsum paste (Figure 9).

Figure 7. A view of Chichon Volcano crater lake from the west rim and sulfur deposits on the internal west crater wall associated to the fumaroles.

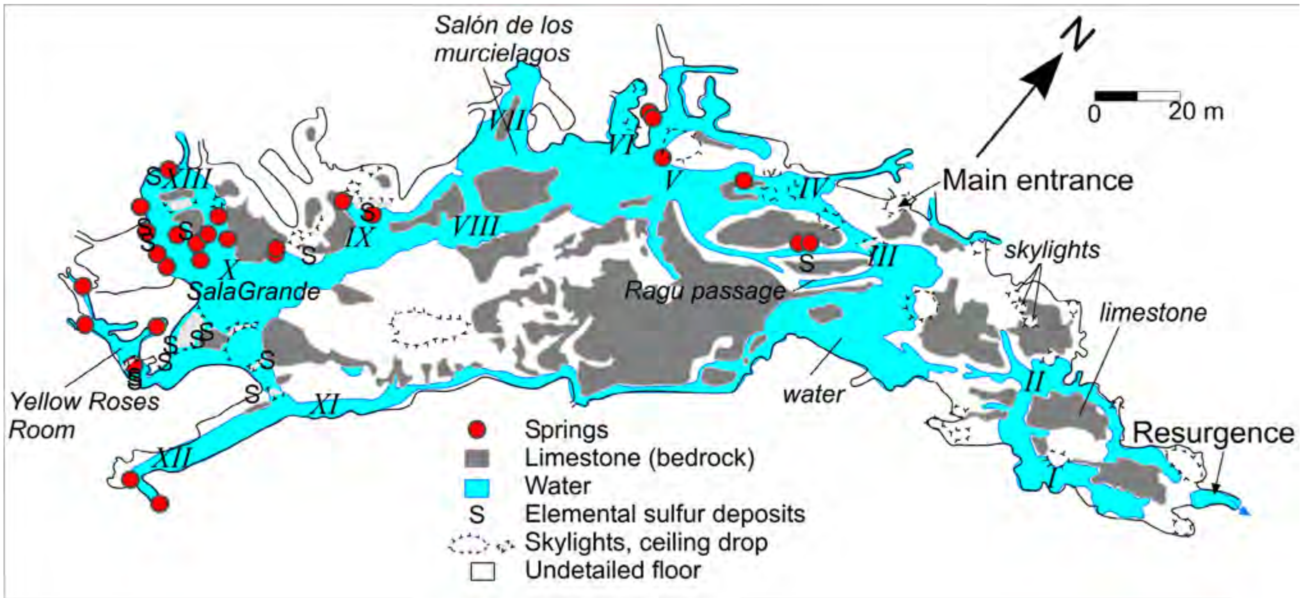

Figure 8. Simplified plain view of Villa Luz Cave (a.k.a. Cueva de las Sardinas, CLS) emphasizing the location of springs (red circles), streams skylights and limestone columns. The position of the main entrance, resurgence and areas with elemental sulfur is also included (Surveyed by Pisarowicz et al, [1998]; map modified with permission of Bob Richards). The approximate location of chambers (*I-XII*) from Gordon and Rosen [1962]; Plath et al. [2006] is integrated for reference.

Although different sources have been suggested for the sulfur origin of the cave springs, the dominant hypothesis is that basinal water [Hose et al., 2000] is influenced by the active, anhydrite-rich magma of Chichón Volcano [Spilde et al., 2004]. Nevertheless, neither the relationship with other possible sulfur sources in the area, nor the groundwater flowpaths, nor the controls on this flow are well understood. Sulfur-rich oil and natural gas fields [García-Molina, 1994], a Tertiary age skarn system (Figure 1) [Castro-Mora, 1999; Pantoja-Alor, 1968], a thick underlying evaporite layer [García-Molina, 1994], and decomposition of organic matter under anoxic conditions [Stoessell et al., 1993] could also be potential hydrogen sulfide producers.

Previous evidence of connection: Based on He isotopic relations of one gas sample and water samples from four springs Spilde *et al*. [2004] determined that at least 22% of the gas at CLS has a magmatic component (mixing of mantle and crustal sources), while 6% of the water has a hydrothermal origin, and the rest of meteoric origin.

Several other sulfur springs have been identified between CV and CLV (Figure 1). From the identified springs, only those at Villa Luz Cave, at Cueva Luna Azufre [Pisarowicz., 2005] and a small cave north from CLS [Siegel and Amidon, 2006] (GS, Graciano Sánchez in Figure 4), have been found to be associated with caves; the rest of them are either covered by alluvial deposits, underwater and/or too small to be humanly entered. The only sulfur-spring that has been further studied, besides the ones at CLS, is at El Azufre, Teapa, Tabasco [Hose, personal communication; Nencetti et al., 2005; Spilde et al.,

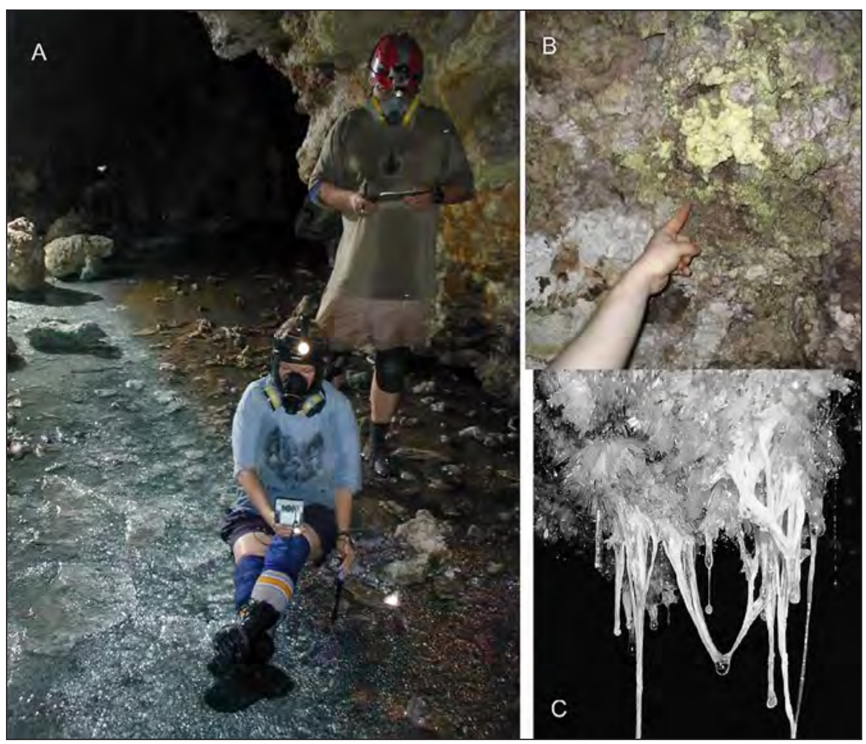

Figure 9. Photographs of Villa Luz Cave: A. End member springs, H_2S-rich in the left and H_2S- poor to the right [Hose *et al*., 2000], (Photograph by Kenneth Ingham); B. Sulfur deposits on the ceiling, associated to H_2S-rich springs; and C. Selenite deposits with biofilms (snottites) (Photograph by Kenneth Ingham).

2004; Taran, personal communication]. Hose [personal communication] found a good correlation in the sulfur concentration and other chemical parameters of El Azufre area sulfur-rich springs with those of Villa Luz Cave (Figure 4). Also, El Azufre springs were the only ones rich in H_2S from those sampled by Nencetti *et al*. [2005]. Based on gas and/or water samples from nine springs in the Sierra de Chiapas, south of the study area, Nencetti *et al*. [2005] proposed a close association between the thermal spring location and the Cenozoic volcanic centers. They also suggested a strong fault and fracture control on the spring presence, as well as a mixture between shallow aquifer water and a more saline member, with higher rock-water interaction.

Therefore, a geologic and geochemical characterization of the springs between Chichón Volcano and Villa Luz Cave will help to determine the permeability/connectivity between both, as well as possible groundwater fluid flow-paths which may be of help to understand water and oil migration in the area.

Methodology

The determination of the Chichón Volcano (CV) - Villa Luz Cave (CLS) connection is part of the first author's Ph.D. studies which the development of this project is still in process. The project general methodology and justification is discussed below.

Background: A review of the geological and water chemistry information available in the area from different sources, including surface and subsurface geology, river water chemistry and weather conditions provide initial data for the project. Subsurface stratigraphic variations will be determined by log correlation of available wells. The characteristics at depth of the structures present in the area will be determined based on the available interpreted seismic sections.

Preliminary field and laboratory analysis allowed the identification of other sulfur springs areas in-between CLS and CV. Based on these data three smaller regions with sulfur springs were selected for further geological mapping and water sampling: 1) Santa Fe region; 2) Puyacatengo region; and 3) Villa Luz region (Figure 4). This will provide an east-west section from the volcano to the cave where concentration variations can be determined, for example sulfate, H_2S, cations concentration, etc.

Geological mapping: Geological mapping will focus on the selected study regions. Since the study area is highly vegetated, the mapping techniques to be used in the selected study regions are outcrop mapping combined with geologic sections focusing on lithologic contacts and structures [García-Palomo *et al*., 2004; Marshak and Mitra, 1988]. Previously identified structures within the study area [Meneses-Rocha, 2001; INEGI, 1983, Castro-Mora, 1999], will also be reviewed in the field. Lineations controlling the surface and groundwater movement will be determined at different scales. Satellite radar images will be analyzed to determine preferential regional lineation direction (Figure 10), while cave maps in the selected regions will be studied to determine preferential local groundwater flow directions. Instances of caves and karst surface terrain will be documented and serve as alternative outcrops in highly vegetated areas of the study area [Dasher, 1984]. Available cave maps and locations from the Caves of Tabasco Project of the National Speleological Society will enable further geomorphologic and structural evaluation. Joints and structures will be measured at an outcrop level close to the springs to determine main structures involved and its relation to major structures.

Rock samples will be taken for petrographic analyses. Samples with sulfides, sulfates or elemental sulfur will be processed for sulfur stable isotopes.

Springs identified will be classified according to Bögli [1980] and major field parameters measured on each of them, including: pH, temperature, conductivity, dissolved oxygen, alkalinity. Air temperature measurements will help to detect the presence of hydrothermal water, discarding altitude differences. The information collected at each spring will include its geographic location, the host lithology, associated geological characteristics and classification.

Diagenesis in some cored-rock samples of oil/exploratory wells in the area will be examined in thin sections to provide the extent of sulfur mineralization/sulfate reduction and/or related processes occurring at depth and their relative timing (samples provided by Exploration and Production Department of the Mexican Oil Company, PEMEX).

Water sampling and chemical analysis: According to the classification of the springs in the selected regions and their major chemical parameters, some of them will be selected for further

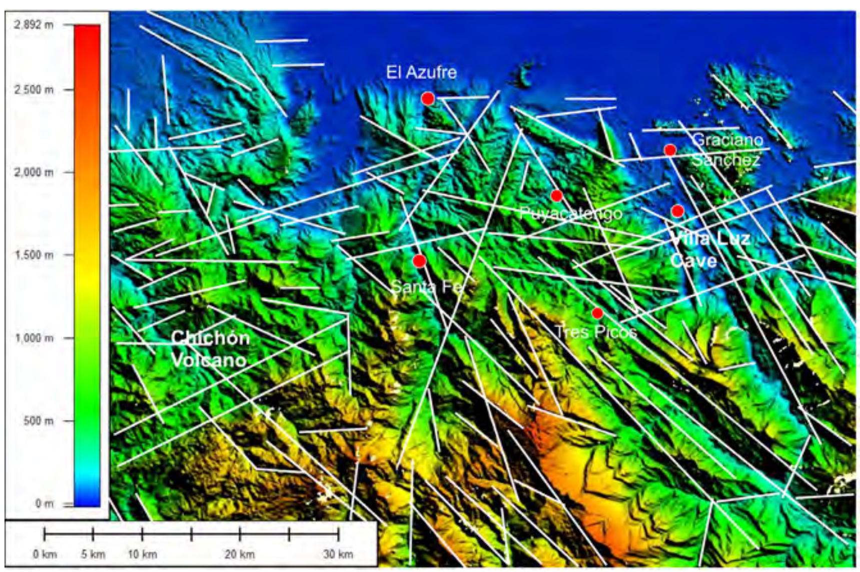

Figure 10. Major lineations on a radar image of the study area (white lines), showing the location of Chichon Volcano, Villa Luz Cave, and other sulfur springs regions (Santa Fe, Puyacatengo, El Azufre, and Graciano Sánchez sites). Darker color represents lower elevation above sea level (Radar image from http://www.dgadv.com/dowdem/, modified with Global Mapper). [The color elevation scale on the version on the CD is easier to understand.]

sampling and water analysis. Rainwater and produced water from producing oil wells in the area will also be analyzed for comparison. The water samples will be analyzed for cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (SO_4^{2-}, Cl^-, F^-, NO_3^-) [Greenber *et al*., 1992]. These are the most commonly used elements to classify water because their concentration in water reflects water-rock interactions and groundwater sources [Appelo and Postma, 1993]. Cation samples will be acidified with nitric acid and analyzed by ICP-OES. Samples for anions will be filled without air space and analyzed by Ion Chromatography. Separate samples will be collected for δD- $\delta^{18}O$, and total carbon analysis.

Sediment and rock samples of the sulfur springs will be taken for the stable isotopic analysis of the sulfides precipitated, while the dissolved sulfate will be precipitated with barium chloride [Bottcher, 1999; DeCaritat, 2005; Rajchel, 2002]. $\delta^{34}S$ of both precipitates and $\delta^{18}O$ of the sulfate precipitate will be determined, to compare the source and reactions occurring in the H_2S and the water sulfate, determine the source of oxygen to the sulfate and the biological participation in these reactions [Hoefs, 2004].

Expected results

D-O isotopes of the analyzed water samples will help to determine the input of meteoric (rain) water, and evaporation/condensation in the sulfur springs of Villa Luz Cave and along the east-west transect.

Sulfur isotopes are one of the main tools that will be used to determine the possible connection between the cave and the volcano. Isotopic concentration is expressed as $\delta^{34}S$ [Hoefs, 2004] relative to CDT (Canyon Diablo Troilite Standard). Mantle $\delta^{34}S$ is near 0‰, so Chichon Volcano sulfur values may be close to this value, unless the magma is assimilating sedimentary anhydrite, while if sulfates are just coming from the subsurface anhydrite, they will show limited variability ($\delta^{34}S$~+17± 2‰) compared with the values spread in marine sulfides (-5 to –35‰) [Condie, 2005]. Since microorganisms strongly prefer the lighter isotope, ^{32}S, sulfate reducing bacteria will produce negative $\delta^{34}S$ values in organic sulfides [Canfield, 2001]. Therefore biological participation in the cave or along the groundwater flow-path may be identified. The relation Na-Cl in the groundwater may indicate the influence of the Callovian-salt in the groundwater, which may be related to an increase in permeability along the detachment level or salt ascension.

The coupling of all the elements mentioned above will provide a better description of the relationship/connectivity between the Chichón Volcano and the Villa Luz Cave. General chemistry and stable isotopes analysis of some preliminary samples are being analyzed in order to determine a better sampling/mapping strategy for the main field work planned to start on January 2007.

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Investigation on the Lava Tube Cave Located under the Hornito of Mihara-yama in Izu-Oshima Island, Tokyo, Japan

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Abstract

A lava tube cave recently found under the hornito of Mihara-yama in Izu-Oshima island, located in the Pacific Ocean at 120km south of Tokyo, was surveyed and investigated by the Vulcano-Speleological Society. This lava cave was formed inside of 1951 eruption lava flow deposited at the edge of inner crater of Mihara-yama. The lava tube cave consists of a flat region and a sloped region whose total length is about 40m. Inside of the lava tube cave, general characteristics such as lava stalactites and lava benches can be found. Two important lava characteristics, yield strength and surface tension, were obtained from the observation of this lava tube cave. By using a simple model of steady state flow in circular pipe for analysis based on Bingham characteristics of lava flow in the tube (T.Honda,2001) and from the height and slope angle of the lava tube on the sloped region, the yield strength of the lava can be obtained as 50000 dyne/cm^2. This value is very near to the value calculated as 43000 dyne/cm2 by G.Hulme(1974) for 1951 eruption lava flow configuration observed by T.Minakami(1951). From the pitch of lava stalactites on the roof surface (3 to 4cm), the surface tension of lava was determined as 600 to 1000 dyne/cm. This value agrees well with the extrapolated value obtained by I.Yokoyama (1970) in the melting lava surface tension measurement experiments in Laboratory.

Introduction

The hornito with lava tube cave is located on Izu-oshima island south of Tokyo in the Pacific Ocean. Izu-oshima island, located on the volcanic front of the izu-Ogasawara (Bonin) arc, consists of Mihara-yama which has large outer crater and small inner crater. This hornito and lava cave were formed inside of 1951 eruption lava flow deposited at the edge of inner crater of Mihara-yama. Its lava flow with temperature of 1200~1150 degree is basaltic, with silica content of 52~53%[1].

The existence of the hornito of Mihara-yama has been well known since the eruption of 1951 of Mihara-yama. The formation process was also remotely well observed by volcanic researchers at that time and precisely described in the scientific papers[1,2,3]. However, since the eruption, any research inside of the lava tube cave under the hornito has not been tried though the accessibility is

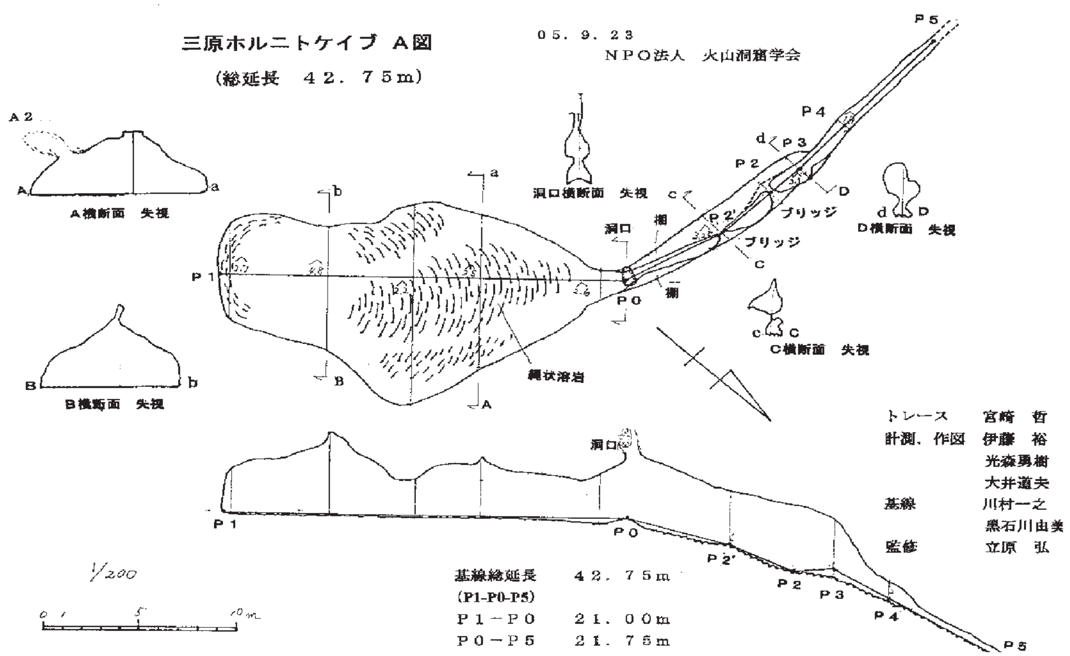

Figure 1. Horizontal and vertical cross section of the lava tube cave under the hornito. (Right side is crater side, left side is outer sloped crater wall side).

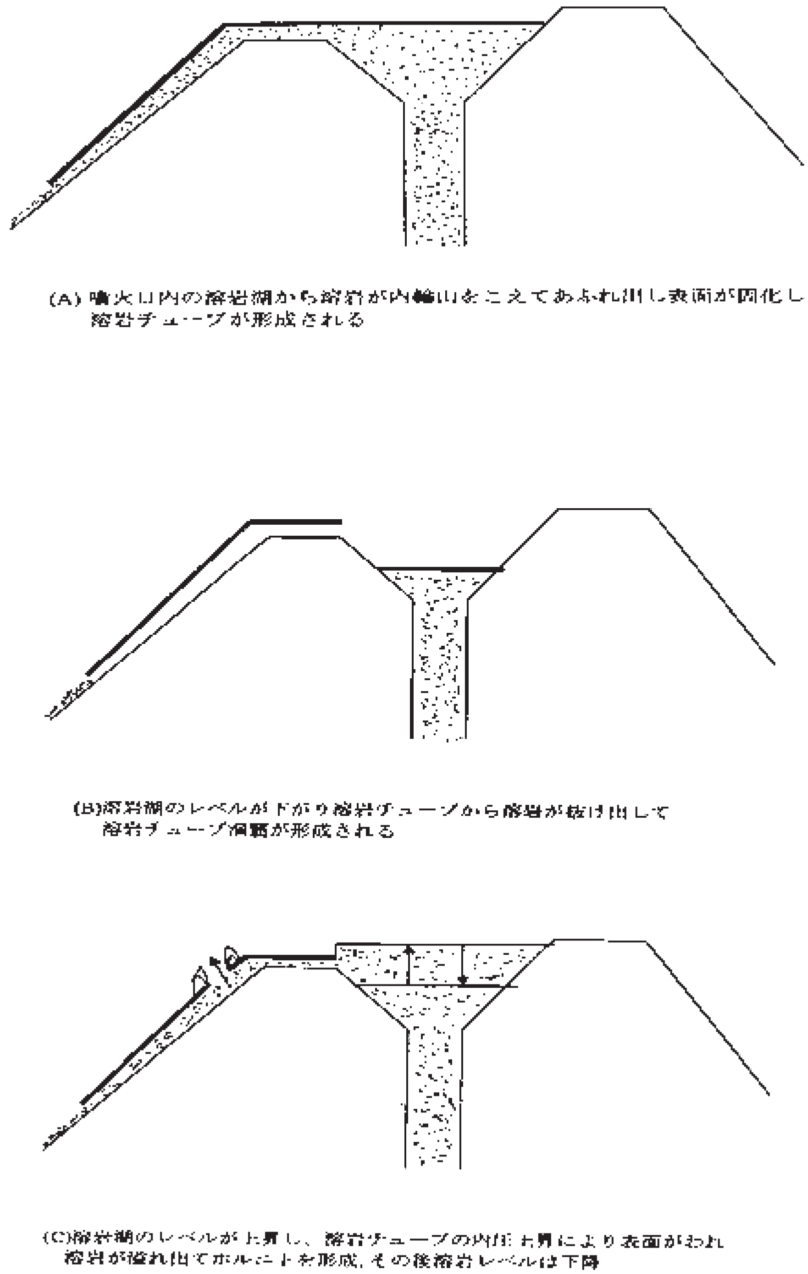

Figure 2. Simplified model of formation process of the lava tube cave and hornito: (A) The lava supplied from the underground will get over the edge of the crater, and flow down though the slope to the foot. (B) The cooled surface of lava flow becomes solid and inner fluid lava will drain out when the supply of the lava from the crater is terminated. (C) The eventual level change of lava will exercise the additional pressure on the solid inner surface, the surface will break and inner fluid lava will eject and accumulate around the hole.

very good. Recently in 2005 and 2006, members of Vulcano-Speleological Society of Japan investigated the hornito and the lava tube cave.

Configuration and formation process

General configuration of the lava tube cave is shown in Fig.1. The lava tube cave consists of a flat region on the edge of the inner crater and a sloped region in the outer slope. The total length of the cave is about 40m.

Formation process of the lava tube cave and hornito is schematically shown in Fig.2. The lava supplied from the underground will get over the edge of the crater, and flow down though the slope to the foot. The cooled surface of lava flow becomes solid and inner fluid lava will drain out when the supply of the lava from the crater is terminated. Thus the lava tube cave will be formed. The formation of hornito seems be only parasitic. When the solid surface has partially a vulnerable part and the eventual level change of lava will exercise the additional pressure on the solid inner surface, the surface will break and inner fluid lava will eject and accumulate around the hole. Based on this model, we can obtain the important physical property of lava: yield strength.

Discharge mechanism, modeling, assumption and analysis

In modeling the discharge mechanism of this type of lava tube, we used an inclined circular tube model for the sloping section of the cave. Regarding the inclined circular pipe, the discharge mechanism of lava tube caves already has been established, based on Bingham characteristics of intratubal lava flow[4,5,6]. A simple model of steady state isothermal laminar flow in inclined circular pipes was used for analyses. Flow characteristics were studied as a function of parameters such as tube radius, viscosity, yield strength of lava and slope inclination. A critical condition

Table 1. Relation between slope angle and height of the lava tube cave of sloped configuration area.

Location of lava cave in the sloped area	Slope angle(α)	Height(2R)
Upper reaches	15 degree	~3.5m
Intermediate reaches	25 degree	~2.5m
Lower reaches	30 degree	~1m

Table 2. Yield strength obtained from the critical condition.

Name of volcano	SiO_2 fraction of lava	Obtained yield strength	References
Mihara-yama	52~53%*	5x10^{4}dyne/cm^2 4.3x10^{4}dyne/cm^2[7]	*T.Minakamil (1951)[1]
Mt.Fuji	49.09~51.3%*	2.5~5.0x10^{4}dyne/cm^2[6]	*H.Tsuya(1971)[8]

was determined for the discharge parameters in which the yield strength plays a dominant role. The equation ($\varrho g \sin\alpha$)R/2=f_B is the limiting condition to determine if the fluid in the tube can be drained out. Here, α is angle of slope or inclination of tube, ϱ density of the fluid, g gravity acceleration, R radius of the tube, r_B radius of the flowing position where Bingham yield stress takes f_B.

For given and known relation between slope angle and diameter (height) of the tube, this critical condition can give the yield strength f_B. This critical condition means that when the yield strength of Bingham fluid is higher than the shear stress at the wall, there is no flow of fluid, as a consequence, no drainage of fluid from the tube.

From Table 1, f_B=5x10^4 dyne/cm^2 can be obtained for the lava of Mihara-yama.

The deduced yield strength from lava of the caves was found to be in good accordance with yield strength (4.3x10^4 dyne/cm^2) as estimated by other methods[7].

In summary, obtained basaltic yield stress from slope angle and height of some lava caves(see Table-2)are also reasonable values as compared with the yield stress obtained for Mt.Fuji[6].

Observation of inside surface

Inside of the lava tube cave, lava stalactites are positioned periodically on the surface of the ceiling wall as shown in Fig.3. From the periodical pitch of the stalactites, we can obtain the surface tension of the lava. The pitch will be critical wave length of the occurrence of instability of thin liquid film attached on the surface of the ceiling of the lava tube cave. The pitch is shown as $2\pi(\sigma/g\varrho_L)^{1/2}$, where σ is surface tension of liquid ϱ_L is density of liquid, g is gravity acceleration.

From the pitch of lava stalactites on the roof surface (3 to 4cm), the surface tension of lava was determined as 600 to 1000 dyne/cm. This value agrees well with the extrapolated value obtained by I. Yokoyama et al.[9] in the melting lava surface tension measurement experiments in Laboratory.

Conclusions

The lava tube cave under the hornito of Mihara-yama, though this is a small scale lava tube cave, is a typical lava tube cave which can be explained by discharge mechanism of lava by gravity under the solidified surface of lava flow.

As a results of this study, Bingham fluid model seems to be well applied for an explanation of formation process of lava tube cave. Obtained yield strength has a well accordance with the results obtained by other method. As for surface tension, it seems to be obtained by simple model of instability of liquid film attached on the roof surface. The estimated surface tension agree with the experimental results by melting the lava in the Laboratory.

Figure 3. Lava stalactite on the ceiling wall surface in the lava tube cave.

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Recent Contributions to Icelandic Cave Exploration by the Shepton Mallet Caving Club (UK)

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Introduction

The Shepton Mallet Caving Club (SMCC) first became involved with cave exploration in Iceland (and indeed Vulcanospeleology) with the club's 21st Anniversary Expedition to Raufarhólshellir in 1971. In the following years club members made a series of visits to the country, exploring and surveying many lava tube caves. The last of these visits was in 1975.

The club's links with Iceland were renewed 25 years later in 2000 with participation in the Laki Underground Expedition (in conjunction with Bournemouth University), led by Chris Wood. Following the success of the second Laki expedition in 2001, club members decided to return to Iceland to carry out more work.

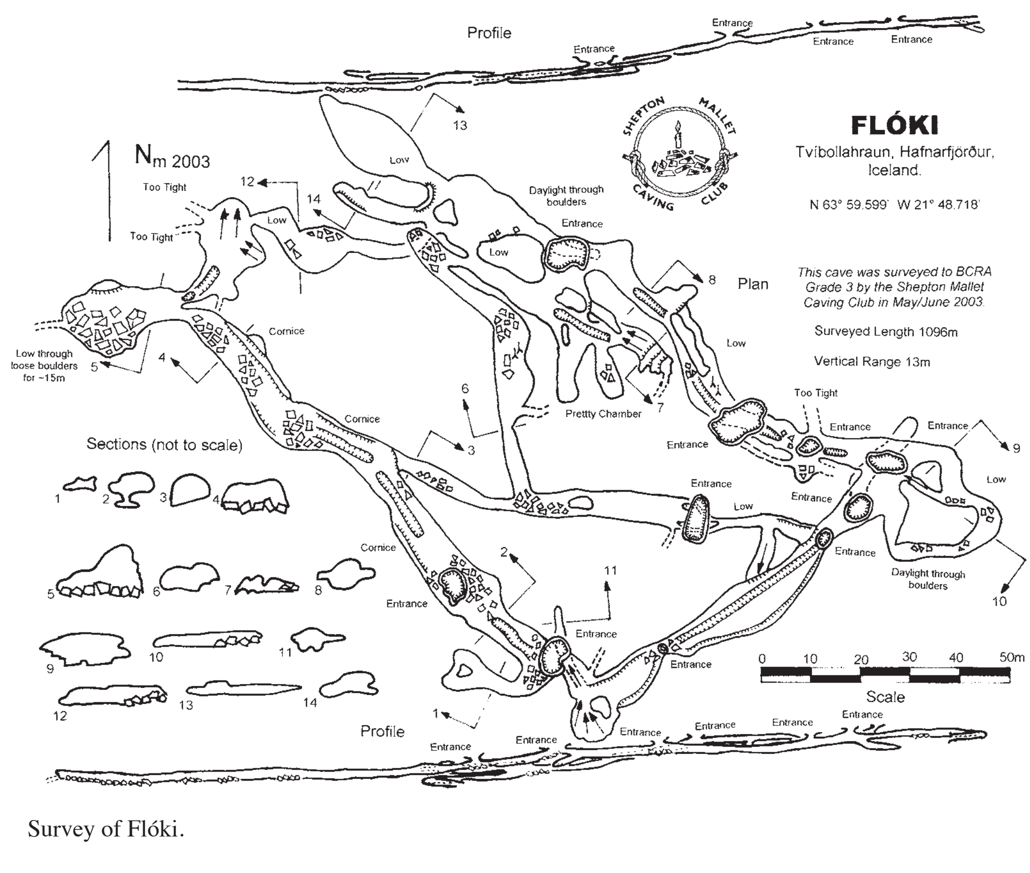
This paper describes the highlights of three visits to Iceland since the second Laki Underground Expedition. These visits were in May 2003, June 2005 and August 2005 and cover work on the Reykjanes Peninsula in southwest Iceland, and the Ódáðahraun lava fields in central Iceland.

The material contained in this paper is drawn from the full reports of these expeditions which have been published in the Shepton Mallet Caving Club Journal.

Reykjanes Peninsula

The Reykjanes Peninsula forms the south western extremity of Iceland. The area is attractive for visiting cavers since access is relatively easy by Icelandic standards and there are plenty of caves to visit. Despite the proximity to Reykjavík, there is still much exploratory and surveying work to be done in the area. The SMCC have carried out work across all areas of the peninsula, but only the most significant activities are highlighted below.

Flóki. This cave lies in the Tvíbollahraun Lava not far from Hafnafjörður and has been known for many years.



Survey of Flóki.

The cave name translates as "the tangled one" due to its complex nature. Prior to the SMCC visit in 2003 the cave was unsurveyed, the only maps being sketches of dubious accuracy. This had resulted in uncertainty as to the length of passage in the cave, with estimates ranging from 500 – 900m.

Our survey showed a total passage length of some 1096m, making Flóki only the 8th known cave over 1km in length in Iceland. The cave is mostly made up of a complex of low crawls connecting small windows to the surface. There are however some sections of larger walking height passage. As well as its complex nature the cave is notable for its fine floor formations, often made even more spectacular due to the vivid red colour of some of the lava.

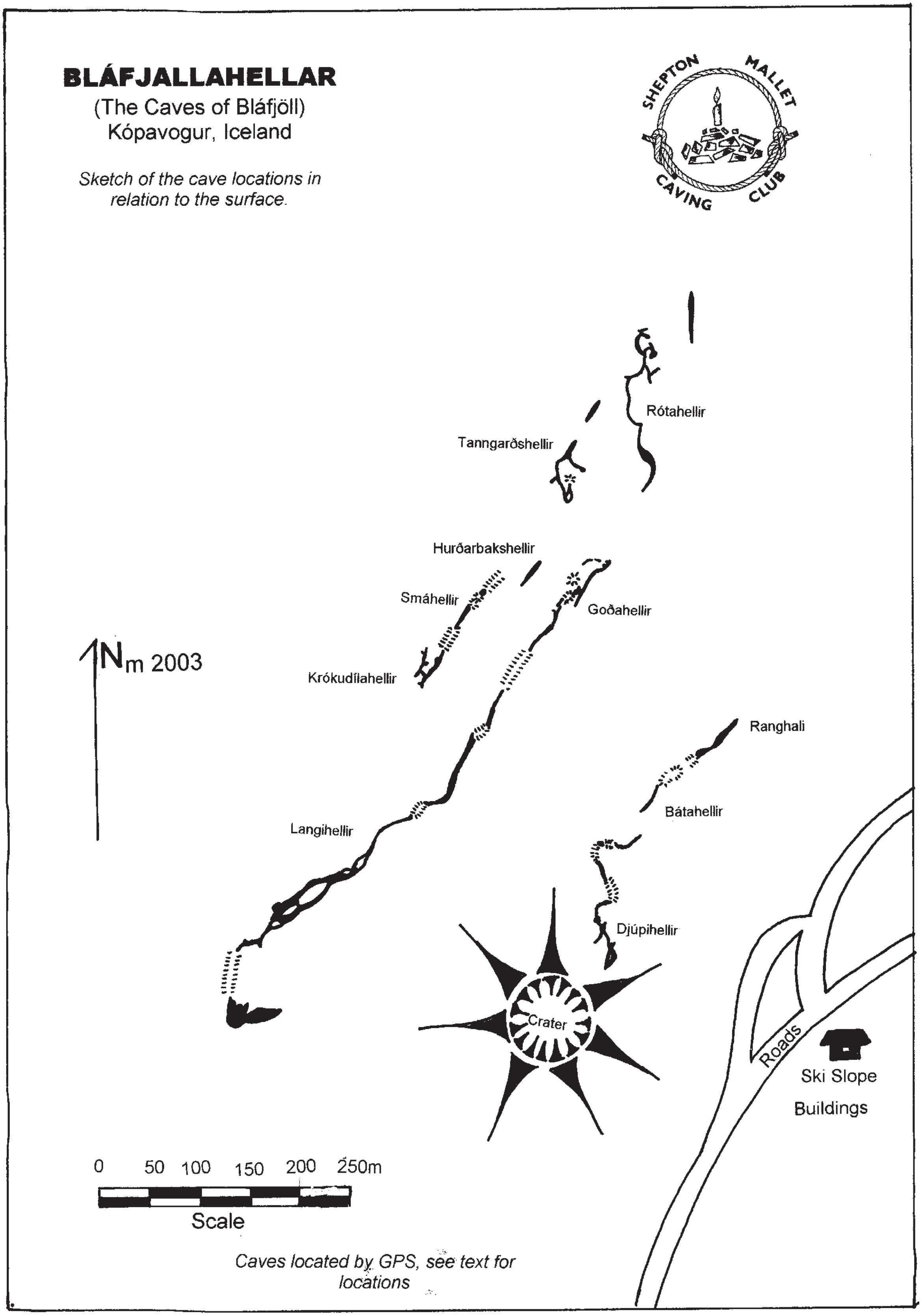
Bláfjöllhellar. This is a series of well known caves close to the ski centre just outside of Reykjavík. Prior to the SMCC visit only one of these caves (Djúpihellir) had received an accurate survey. During the 2003 expedition all the major caves were surveyed, and those surveys were tied together with a

Top right: Unusual formations in Flóki(Terence Fitch).

Middle right: James Begley in Flóki (Tim Ball).

Bottom right: Floor formations in Rósahellir (Séan Howe).

Below: Flóki has some impressive floor formations (Terence Fitch).



Map of the Bláfjollhellar.

Tanngarðshellir (Séan Howe).

surface survey. This allowed a map to be constructed showing the relationship of these caves for the first time.

The major caves surveyed included: Langihellir (660m) which consists of a large walking size passage, with some braiding at the upstream end. Rótahellir (380m), a series of low crawls close to the surface and Djúpihellir (220m) which is a fascinating multi-level system including a 15m shaft to the surface. As well as the major caves, two smaller caves are worth noting due to their fine formations Tanngarðshellir (158m) with it bright red floors and Rósahellir (80m) due to its extraordinary floor patterning

Leitarhraun. Our interest in this lava flow was awakened by Hellarannsóknafélags Íslands discovery of a major new cave (Búri) in early 2005. SMCC members were invited to survey the cave in June 2005. From this visit it was clear that Búri was part of a much larger system, including the well known caves of Arnahellir and Arnaker, and during a visit in August 2005 the other caves presumed to be part of the same system were also surveyed (except for the protected Arnahellir). This survey shows that there is significant potential to enter new cave between Arnahellir and Búri. Hellarannsóknafélags Íslands have started to dig through the boulder chokes which terminate both caves in the hope of major discoveries, and even a possible connection.

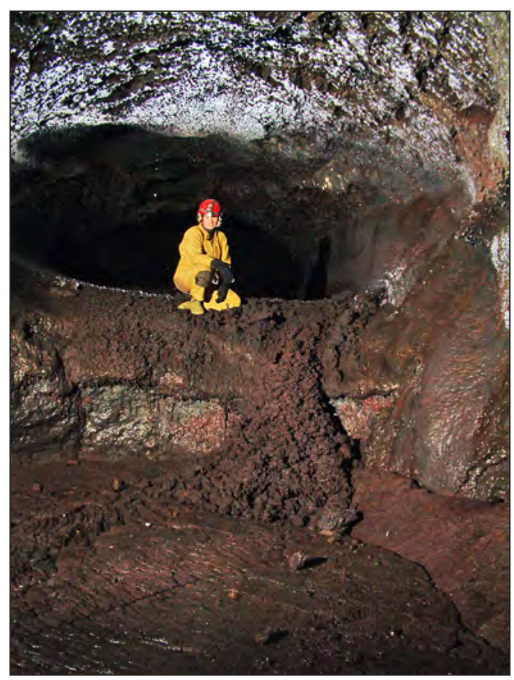
The two major caves in this system, Búri and Arnaker both consist of very large passages (up to 15m in diameter).

Ódáðahraun

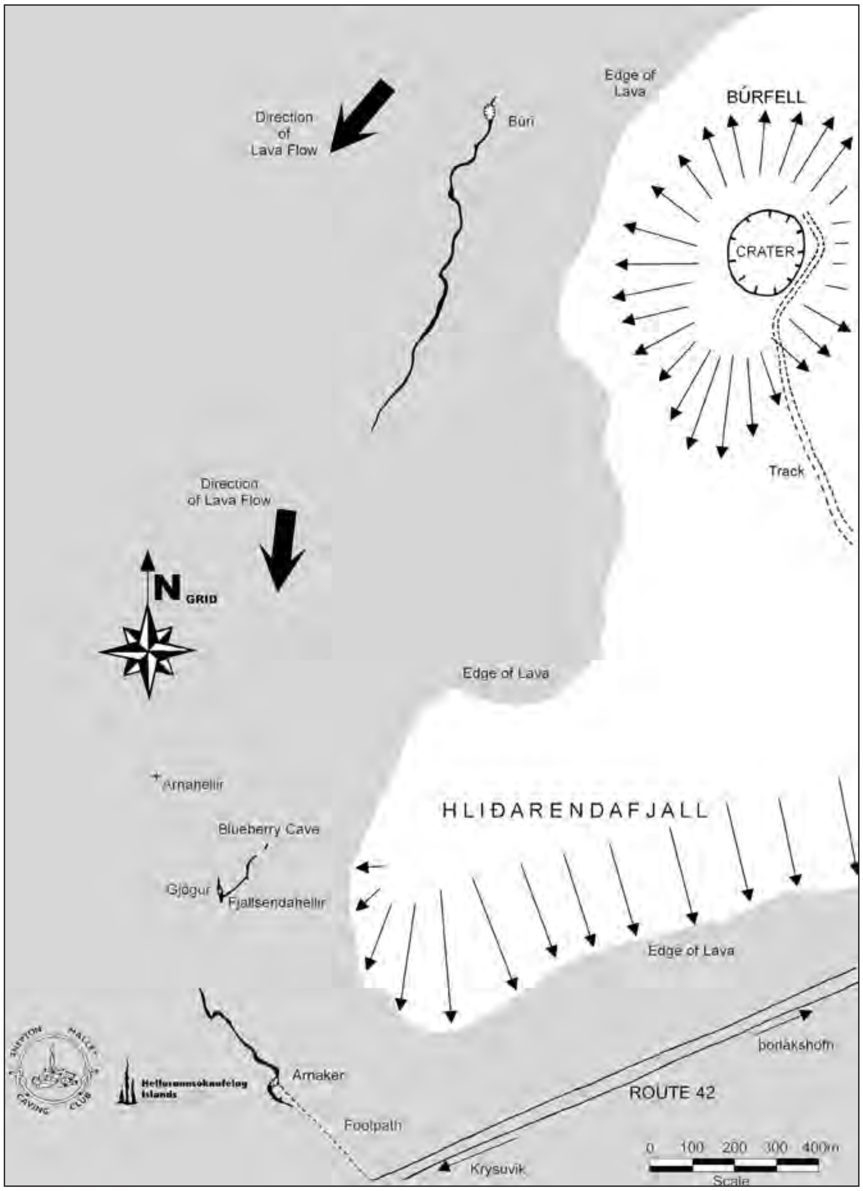
The SMCC expedition to this area in August 2005 was without doubt the most ambitious visit we have yet made to Iceland. The Ódáðahraun is Europe's largest area of lava at 6,000km^2 and lies in the heart of Iceland, to the north of the vast Vatnajökull icecap. Potential cave areas were physically remote and required long walks to reach them. Work in 2005 was severely hampered by unseasonal snow falls.

Lofthellir. Prior to our expedition

Main Passage in Búri (Ed Waters).



Lava Fall in Búri (Ed Waters).



Map of the Leitahraun.

this cave was the longest known in the area. The cave was discovered by Hellarannsóknafélags Íslands in 1990? After a short dig to enlarge a constriction. Beyond this the cave passage is very large and liberally decorated with fine ice formations. As the cave had never been accurately mapped, it was surveyed during our visit. Despite excellent potential all efforts to extend the cave or find other caves nearby failed to enter significant new passage.

Bræðrafell. Bræðrafell is an acient weathered volcano that nestles against the slopes of the huge Kollottadyngja shield volcano. It is also the location of a small hut owned by the Akureyri walking club, and more interestingly cave entrances had been reported in the area. The emplacement of the lava flows in this area is somewhat complex. Certainly Björn Hróarsson's observations do not match those of previous geologists.

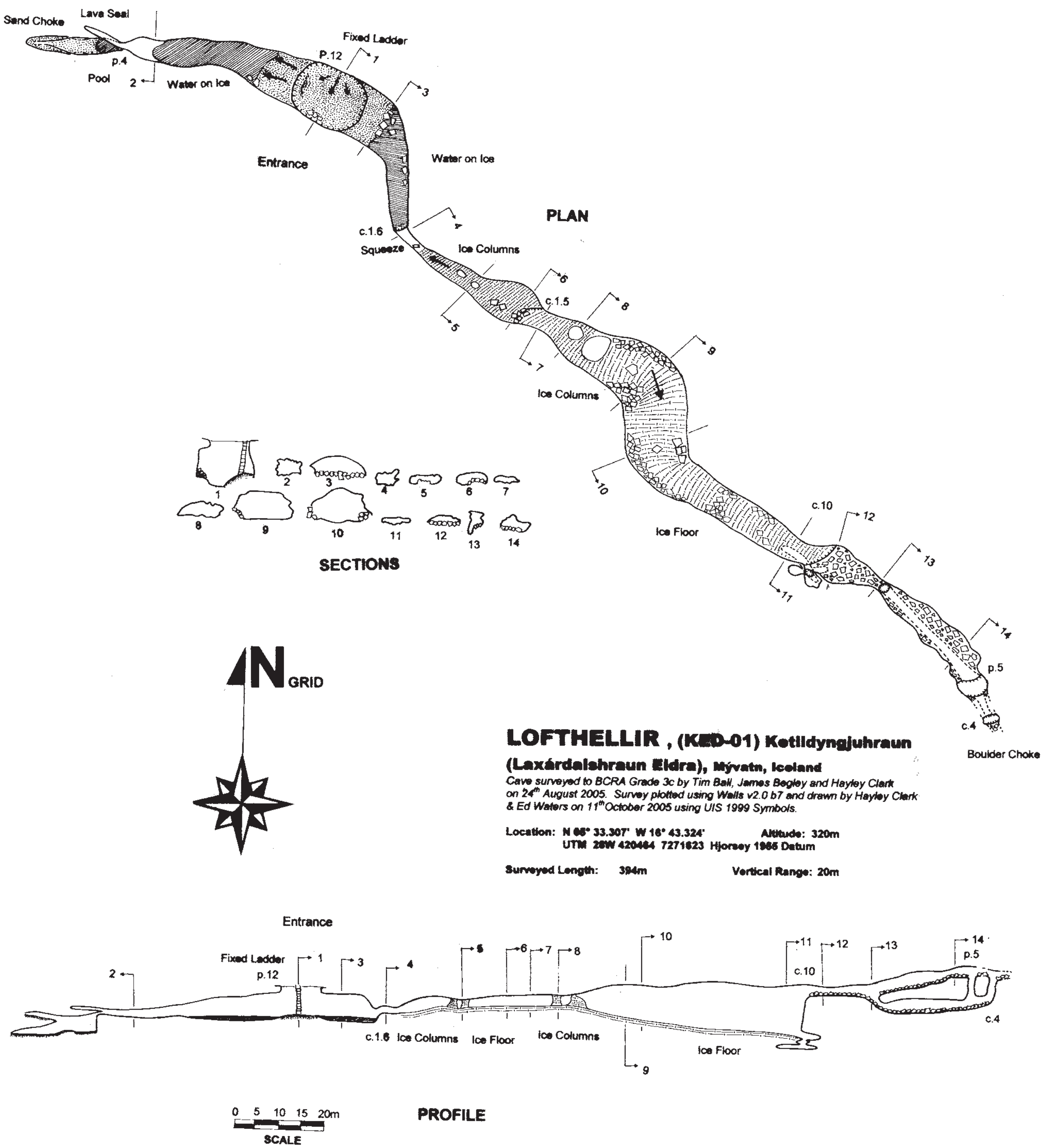
Major caves mapped were:

Fjárhólahellir lies about 2km west of the hut, and the approximate location was given by Kári Kristiansson. This approximate location coincided with interesting features on the aerial photographs which proved to be the cave. Our survey gives a total passage length of 452m of generally large passage, some of which contains large quantities of sand. It is unknown how much of this cave had been entered before.

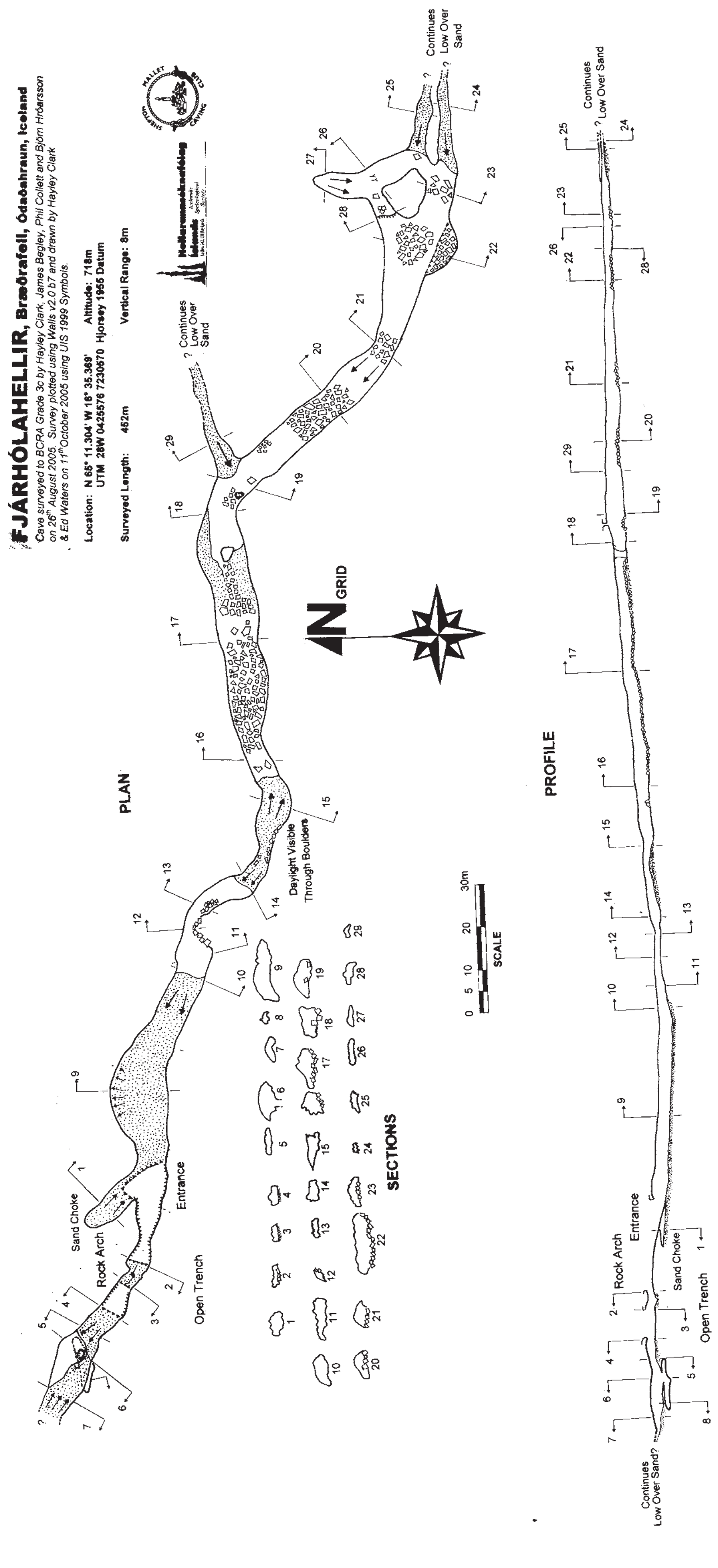
Hellingur had been noted by Kári, but not descended as it was vertical. The

The large main passage of Lofthellir is decorated by fine ice formations (Keith Batten).

Entrance to Lofthellir.



Survey of Lofthellir. A larger version is included in the supplementary material on the CD.



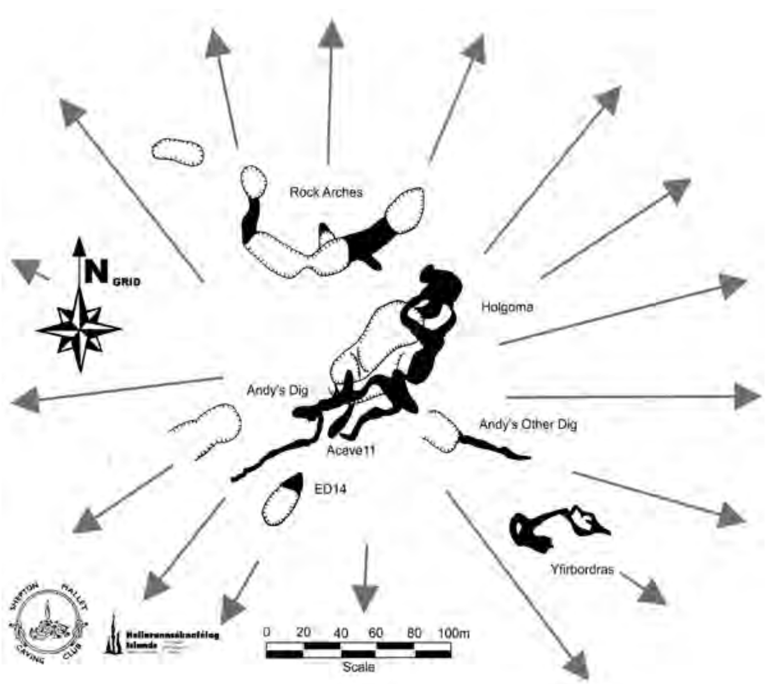
Survey of Fjárhólahellir. A larger version is included in the supplementary material on the CD.

Lava Formations in Hellnigur (Keith Batten).

first descent and survey of this cave was carried out during August 2005. The entrance pitch proved to be 15m deep, and leads to over 500m of generally large passage, some finely decorated by lava stalagmites and straws. The cave is formed in a low hill, and may represent a feeder for a rootless crater (there is a large hornito close to the entrance) from a larger tube (now sadly full of lava) beneath.

Situated about 300m from Hellingur is another low hill which also contains a series of caves, the Holgóma Group. The longest of these is Holgóma. Again passages are generally large and are sealed with lava at a similar level to the base of the hill. This again suggests that the caves fed some form of rootless crater. In Holgóma is an unusual formation, named the Marmari Drottning (Marble Queen) by Kári. This is a 0.8m high lava stalagmite which is encrusted with white crystals (probably gypsum).

Fjárhóladyngja / Litladyngja. This is a large shield volcano about 10km south of Bræðrafell. There were reports of cave entrances on this mountain, and the aerial photos indicated several interesting features. Unfortunately only a brief reconnaissance to the area was possible, and a planned return was prevented by a worsening of the weather. Thus our visit merely confirmed the presence of significant caves, one of which has now been partially explored. Much work remains to be done here.



Relationship of Caves at Bræðrafell.

Terminal Chamber in Hellingur (Keith Batten).

Future Work

There remains a huge amount of speleological exploration and mapping to be carried out all over Iceland. In the areas we have been working in there are still many sites around the Reykjanes peninsula that are partially explored or unmapped. In addition new entrances are still being found as a matter of course.

In the Ódáðahraun the partially explored caves at Litladyngja clearly need to be fully explored and surveyed. However there also remains many thousands of square kilometres of lava to examine. Most of this is extremely remote, and detailed examination of aerial photos will be the best way to prioritise research.

In the short term hopefully Björn Hróarsson's new book on Icelandic caves should be available later this year, and will identify all known Icelandic volcanic caves. Hopefully this will spur a new generation of Icelandic cavers to take up the gauntlet of speleological research in the country. At present most of the serious work is carried out by foreigners and only a couple of Icelanders.

Passage in Holgóma (Keith Batten).

Holgóma, Main Chamber (Keith Batten).

"Marmari Drottning" a large lava stalagmite encrusted with secondary minerals.

Any caver wishing to visit Iceland is strongly advised to contact Hellarannsóknafélags Íslands (Icelandic Speleological Society)

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[Additional maps and photographs associated with this article appear in the supplementary material on the CD.]

Prospects for Lava-Cave Studies in Harrat Khaybar, Saudi Arabia

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Introduction

Lava-cave entrances have been observed in several parts of Harrat Khaybar, Saudi Arabia, and one lava tube has been surveyed. Strings of collapses up to 25 km long indicate the possibility that very long caves may be found in this lava field. The fact that an important ancient caravan trail skirts the western fringe of Harrat Khaybar, suggests that archeological studies of caves in this area may prove fruitful.

Harrat Khaybar

Harrat Khaybar is located north of Medina in western Saudi Arabia, between 39° and 41° longitude E and 25°and 26° latitude N (Fig. 1). It has an area of approximately 12,000 square km. The lavas and volcanoes in Harrat Khaybar are mildly alkaline with low Na and K content and include alkali olivine basalt (AOB), hawaiite, mugearite, benmoreite, trachyte and comendite. The age of the Khaybar lavas ranges from ~5 million years old (orangish flow field) to post-Neolithic (reddish-orange lava flows), to historic (black lava flows).

Roobol-Camp reports

Roobol and Camp (1991) reported the existence of lava-tube caves up to 10 m high on Harrat Khaybar. In one of these caves—located in a flow from Jebel Qidr Volcano—delicate lava stalactites were observed. A 100-meter-long lava tube in southern Harrat Khaybar was found to contain a fumarole at its deepest point. Roobol and Camp also describe numerous collapses along whale-back formations. These strings of collapses are up to 25 km long and in some cases are situated up to 25 km from the source volcanoes (Roobol and Camp, 1991).

Dahl Rumahah

Dahl Rumahah (also spelled Romahah) is registered as number 176 in Pint, 2002 and is located 169 km NNE of Medina in the northern part of Harrat Khaybar, at 25°56′N, 39°54′E, in a black lava flow. A map of the cave is given in Figure 2.

Dahl Rumahah is described in Pint, 2004 and Pint 2006. The cave is 208 m long and has a horizontal entrance 1 m high by 1.5 m wide, set in a small depression. A long, low wall outside the entrance channels rainwater into the cave, which local people say was used as a reservoir. Most of the cave is a single, nearly flat, northwest-trending passage from 1.5 to 7 m wide and 2.5 m high. Rooms north of station 7 and south of station 11 terminate in very low crawls which may be connected. In September of 2003, it was found that dry sediment

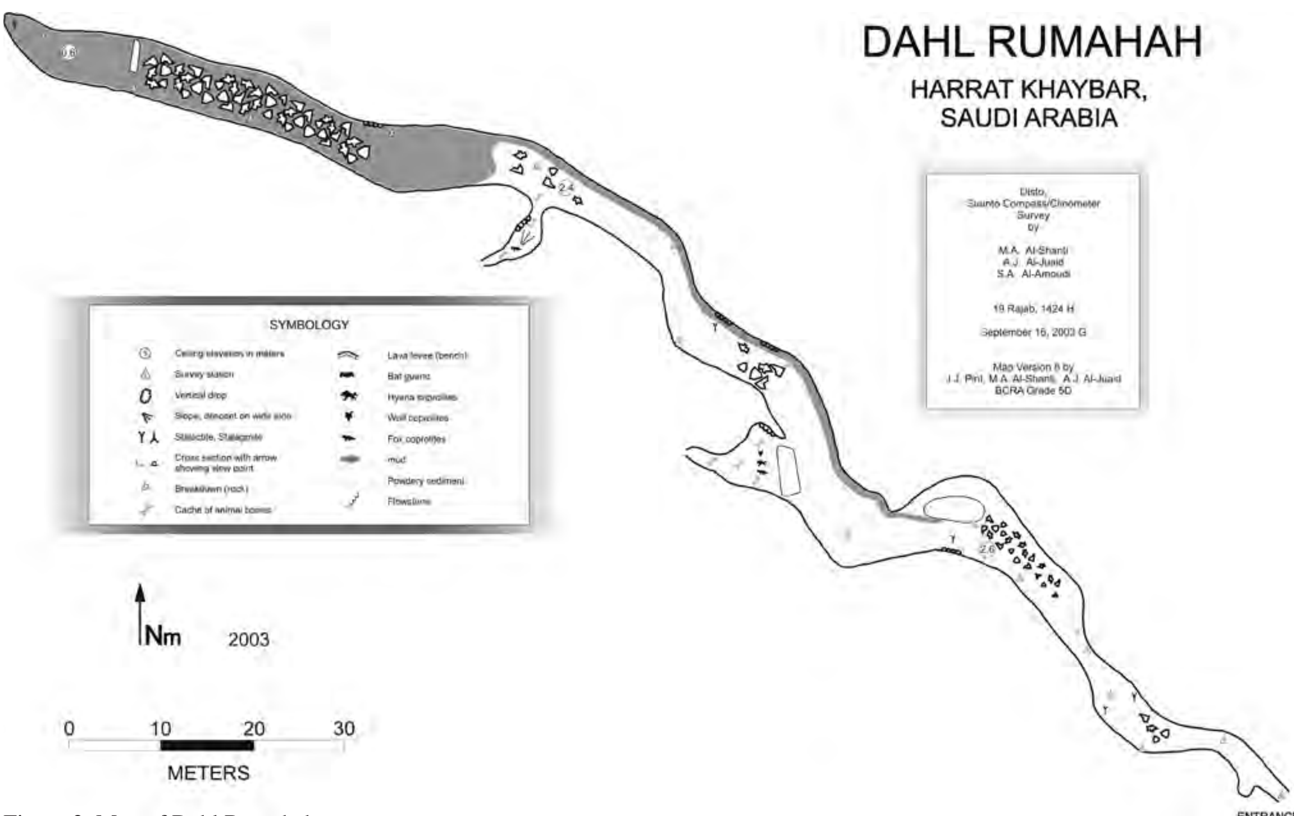

Figure 2. Map of Dahl Rumahah.

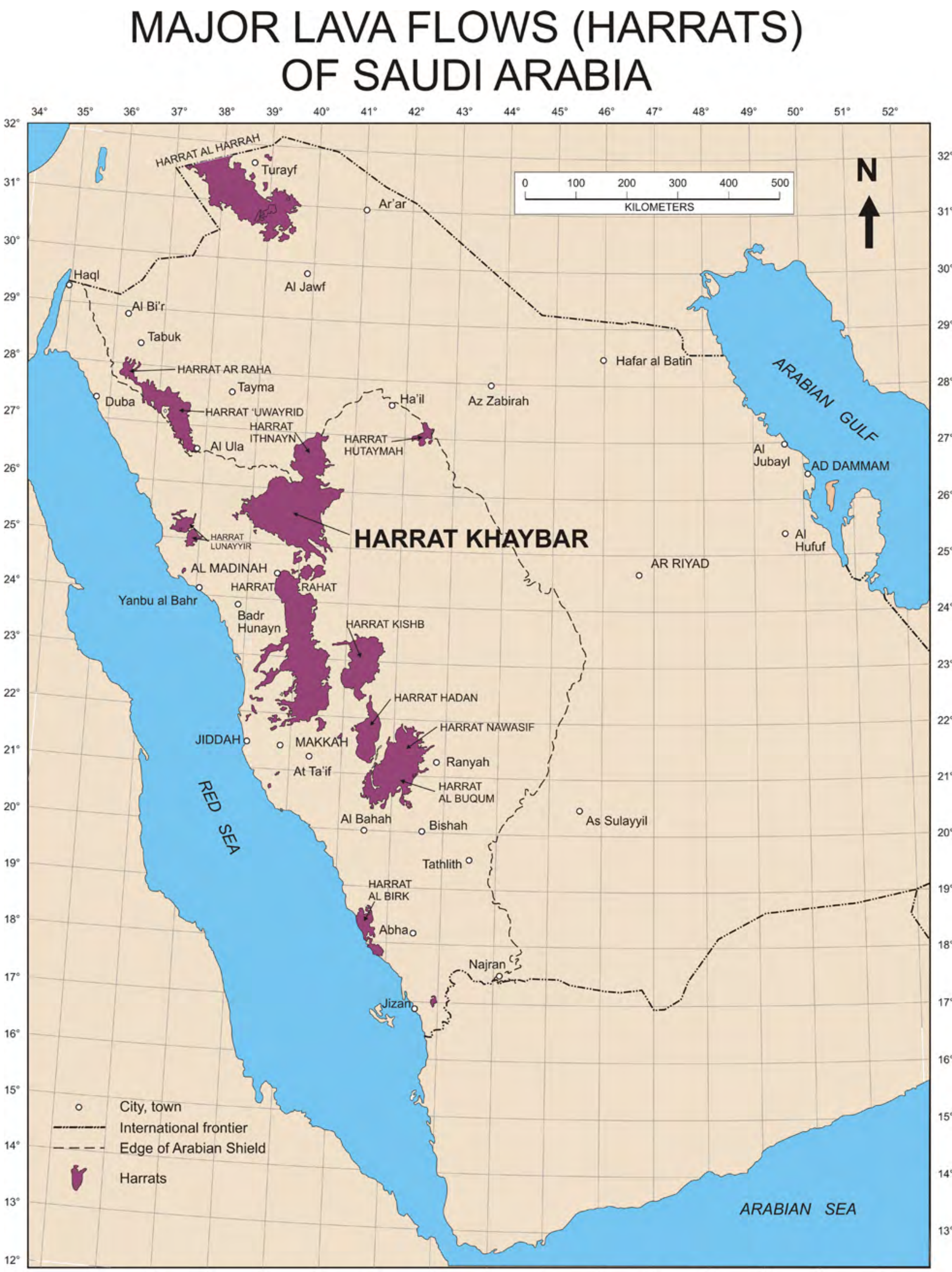

Figure 1. Location of Harrat Khaybar lava field in Saudi Arabia.

covered the floor of the southeast part of the cave while mud floored the northwest portion and occurred along part of the eastern wall. Water droplets and cave slime cover the ceiling at the far northwestern end of the cave. A natural bridge 1.5 m thick crosses the passage near its western end. Calcite-rich percolation water leaked through ceiling cracks, producing white stalactites, curtains and flowstone. There is a large area of bones, including hedgehog and porcupine quills, mixed with desiccated hyena, wolf and fox coprolites. The highest radon level noted in Saudi caves was found in Rumahah: 119 Pci/l. The cave's temperature was measured at 25°. Within a period of four hours the relative humidity rose from 68% to 74% at one point in the cave.

The radon level found in this cave seems high for a lava tube. It is possible that radon gas is entering the cave through cracks in the floor. The complete skeleton of an unknown animal is found in this cave, cemented to the floor by calcitic speleothems. There is evidence (including construction of a water-retaining wall) that this cave has long been used as a water reservoir.

Figure 3. Collapse entrance to Dahl Um Quradi in Harrat Khaybar.

Figure 4. Entrance to an unnamed lava tube in the Jebel Qidr flow. Photo by Uwe Hoffman.

Um Quradi Cave

In February of 2003, an attempt was made to survey Dahl Um Quradi, a lava tube located in southern Harrat Khaybar. Just outside the cave entrance, a member of the team was seriously injured and had to be rescued by helicopter, resulting in the cancellation of the survey. However, it was noted that the cave has a walk-in entrance measuring 2 x 3 m and a vertical (collapse) entrance 4 m in diameter and ca. 5 m deep (Fig. 3). This lava tube may be 100-200 m long. Information from several sources suggests that there are other lava tubes in the area, but data is not available at this time. (Pint 2006)

Collapses on Jebel Qidr

Sometime in the late 1990's, German explorer Uwe Hoffman visited the basaltic stratovolcano Jebel Qidr, located near the center of Harrat Khaybar. At the foot of the volcano, he observed and photographed collapses which appear to be in lava tubes, one of which is shown in Fig. 4. In 2004, J. Pint, S. Pint and A. Gregory traveled to Jebel Qidr with the hope of entering these caves. Lack of time did not permit visits to these caves, but the apparent entrances to several other lava tubes on the flanks of Jebel Qidr were observed and photographed by A. Gregory (Fig. 5). According to Roobol et al. (2002), this volcano may have last erupted in 1800 A.D., suggesting that lava caves in this flow may be among the youngest and most pristine in Saudi Arabia.

Proximity to archeological sites and ancient trails

The National Geographic Society's Genographic Project is based on evidence that all modern human beings are descendants of people who left Africa 50,000 to 70,000 years ago. These emigrants apparently followed two basic routes: one around the northern tip of the Red Sea and the other via the Bab Al Mandab at the southern end of the Red Sea. Those who followed the latter route and then traveled north on foot would quickly have found that the interior of the Arabian Peninsula was as harsh and unfriendly in the past as it is today, as has recently been proven by the attempted dating of stalagmites taken from limestone caves in the interior of

Figure 5. Apparent entrance to a lava tube on the high flanks of Jebel Qidr. Photo by Arthur Gregory.

Saudi Arabia. The U/Th dating method indicated no stalagmite growth for at least the last 400,000 years, implying that the interior of the Arabian Peninsula has been arid for at least this long a period (Fleitmann et al., 2004).

The most practical route north from what is now Yemen, would have been along the shore of the Red Sea itself or slightly inland, where people would have been forced to make their way between or alongside the vast lava fields which cover 89,000 square kilometers of the Arabian Shield.

Following the edge of the lava fields would have provided one very practical advantage: access to water. Most lava fields are very efficient collectors of rain water, which frequently drains from the lava fields at their edges. The ancient settlement of Khaybar, in fact, is located at the western edge of Harrat Khaybar precisely because water is abundant. Here, in fact, are found the ruins of Sed Kasaybah or Kasaybah Dam which is thought to be at least 1000 years old.

Some of the lava caves in Harrat Khaybar are natural water catchments. One of these is Dahl Rumahah, whose entrance, even in recent years, was disguised by local peoples because of its usefulness as a reservoir. If ancient peoples sought these caves in their search for water, it is possible that they then took advantage of them for shelter from the elements, for caching food supplies, or for hiding valuables. A typical year-round cave temperature of 25° C would have offered relief from the unbearable heat of the area in the summer and escape from the cold winds and frigid temperatures of winter. Today, artifacts may lie buried in the sediment which typically covers the original floors of Saudi lava tubes. Powdery sediment covering the floor of one such lava tube, Hibashi Cave in Harrat Nawasif-Buqum was found to be up to 1.5 m deep and up to 5.8±0.5 ka old, measured by Optically Stimulated Luminescence (Pint et al., 2005).

To date, 50% of the lava tubes studied in Saudi Arabia have exhibited evident signs of man-made constructions outside or inside the cave entrances. Flat, aerodynamically shaped throwing sticks—possibly Neolithic—have been found in lava caves as well as large quantities of bones, horns and coprolites (Roobol et al., 2002, Pint et al., 2005).

Dahl Rumahah, the northernmost known lava cave in Harrat Khaybar, lies only 22 km south of a major Neolithic rock-art site with hundreds of petroglyphs. Much of the western edge of Harrat Khaybar lies alongside the old Nabatean Incense Trail connecting Yemen and Petra. Unfortunately, no archeological or paleontological studies have yet been carried out in any limestone or lava cave in Saudi Arabia.

Conclusions

1. Harrat Khaybar offers excellent possibilities for the discovery of many lava caves in its ancient and recent flows. This lava field may house some of the longest lava caves in the world.

2. Archeological and paleontological surveys of the caves in Harrat Khaybar should be undertaken because of their proximity to archeological sites and ancient migration and trade routes.

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Al-Fahda Cave (Jordan): The Longest Lava Cave Yet Reported from the Arabian Plate

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The northeastern region of Jordan is volcanic terrain, part of a vast intercontinental lava plateau called the Harrat Al-Shaam. The centre is formed by young alkali olivine basaltic lava flows, the Harrat Al-Jabban volcanics or Jordanian Harrat (Al-Malabeh, 2005). The top most and therefore youngest flows are ca. 400 000 years old (Tarawneh et al., 2000). There we explored, surveyed and studied a total of twelve lava caves since September 2003, among them six lava tunnels (one has two caves) and five pressure ridges caves. A total of 2,525 m of passages have been surveyed until September 2005. This includes the 923.5 m long Al-Fahda Cave (Lioness Cave) that lies about 85 km east of Al-Mafraq, and 18 km northeast of Al-Safawi (Fig. 1). It was surveyed September 16th and 19th 2005 by the authors (Figs. 2 to 5). It is currently the longest reported from the Arabian Plate (J. Pint, pers. comm.). Table 1 gives the pertinent topographic data of the lava tunnel.

Al-Fahda Cave was found by the first author (Al-Malabeh) on a field trip in the Harrat by following an anthropogenic line along which stones had been cleared away. It led from a wadi Rajil (830 m a.m.s.l) in the north downslope to the main entrance of the cave (730 m a.m.s.l). It appears to have been a channel, designed to fill the cave with water during winter rains and used as a reservoir throughout the year (Fig.6). If this ever was very successful must be doubted, but mud cracks in the floor sediments and some rough "retention" walls indicate that water does enter the cave occasionally and that its management was attempted.

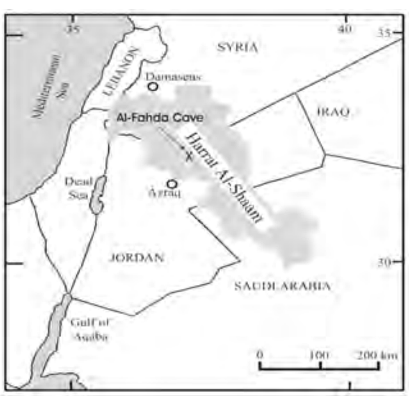

Figure 1. Location map of Al-Fahda cave and the extent of Harrat Al-Shaam (altered after Al-Malabeh, 1994).

Two entrances exist (Fig. 3). The main entrance (Fig. 7) gives access to the cave stretching for almost 490 m downslope (makai) and almost 190 m upslope (mauka). The tunnel is on the one hand amazingly wide (7.5 m) but also very low (average 1.2 m). The surveyed slope, with little guaranty to its accuracy, apparently is less than one degree (8.6 m altitude change on 755 m). This is very low, even when compared to the lower reaches of Hawaiian lava tunnels, and an important observation since it shows why the Harrat lava could spread so far: they were tube-fed pahoehoe lavas.

The cave shows, compared to Hawaiian tunnels (see data in Kempe, 2002; Kazumura, Keala and Huehue, some of the longest caves on Hawaii have sinuosities of 1.30, 1.25 and 1.2), a rather low sinuosity (1.13), in spite of the fact that it has a lower slope than the mentioned Hawaiian caves (1.51°, 1.51°, 4.58° resp.). The intuition that there should be a reverse relation between slope and sinuosity can therefore not be proven. The winding of the cave should have provided for a "Thalweg", i.e. a path along which the lava flow was maximal with slip-off and undercut slopes to the sides depending on curvature.

The main entrance (to which the surface channel was directed) is a "cold puka", i.e. a roof collapse at the apex of a 15 m wide hall, dating much later than the activity of the cave. Breakdown blocks allow easy access to the highest section of the cave.

The second, much smaller entrance, 60 m to the NE of the main puka, poses a riddle: it is situated to the side of the cave.(Fig. 8). It was certainly opened by humans, who removed blocks from a natural hole. A low crawl descents to the NW, gradually enlarging and joining the main tunnel after 15 m. This passage appears not to be a lava tube, but a wide and low separation between two lava sheets. Where the passage descents to the main tunnel we noticed remains of ceiling linings. Also benches composed of stranded and welded thin plates are found on both sides of the lower passage. This bench can be followed into the main tube, mostly makai. The next larger deposit is at St. 32 (niche or cove) and at St. 33. Each niche is smaller than the one before. These benches occur mostly on the southern wall, but also on the northern wall at Station 15. These lava benches mark a lava high-stand, when small solidified lava plates floated on the surface of the lava and stranded on the walls opposite to the main flow velocity (slip-side of flow). On the benches between stations 15 and 14 we find stalagmites, composed of lava blisters (Fig. 9), pressed out of the ceiling, a rather interesting formation, suggesting that the degassing and solidifying of the primary roof was still going on at the time when the lava subsided in flow to below the platy benches. Both the lining and the existence of the benches prove that the passage existed when the lava was still actively flowing. It therefore appears that the 2nd entrance passage resulted from the upward bending of the top flow sheet in an axis more or less perpendicular to the flow.(Fig. 10). It opened early on in the formation of the tube, when the surface sheets were still partly plastic. This mechanism explains also the niches found at St. 32 and 33. This interpretation could be tied together with the observation that the cave is widest at the 1st entrance where the cave makes a notable 90° turn (Fig. 3). This turn could be caused by the lava flowing against a pre-existing surface obstacle, such as the side of a previous flow, a pressure ridge or any other form of lava tumulus. It could then have been deflected to the north, causing the partings of the sheet due to the shear caused by the top lava sheet pressing against the obstacle. The hot lava immediately intruded these niches and since flow in them was slow, deposited floating lava plates. Only the 2nd entrance passage, which rose upward was not clogged. Evidence on the floor of the passage clearly shows, that this branch of the cave does not have anything to do with the a'a flooring.

The cave does not have much breakdown, indicating a very stable roof. The entrance puka reveals that the primary roof is composed of two pahoehoe sheet only, the upper one being 2.5 m thick and the lower one being 1.2 m thick. This may explain the long-term stability of the roof, which caved in geologically recently only at one of its widest spots.

Surface loess has been washed into the cave through cracks and through the entrance, covering the original floor in the upper stretches and for some part in the lower stretches, but leaving some of the original floor uncovered. Were it is visible (between St. 14 and 50), we find the floor astonishingly to be composed of small a'a rubble, wall to wall (Fig. 11). Only at the lower end, where the cave branches, crude pahoehoe ropes are found with their flow lobes pointing makai (Fig. 12). The a'a ends mauka of this junction (St. 50) in a sort of terminal wall. It is conceivable that this a'a forms the final flow event in the tunnel, shortly before is became too cool to keep lava flowing. It may also represent a later event that invaded the cave after it was

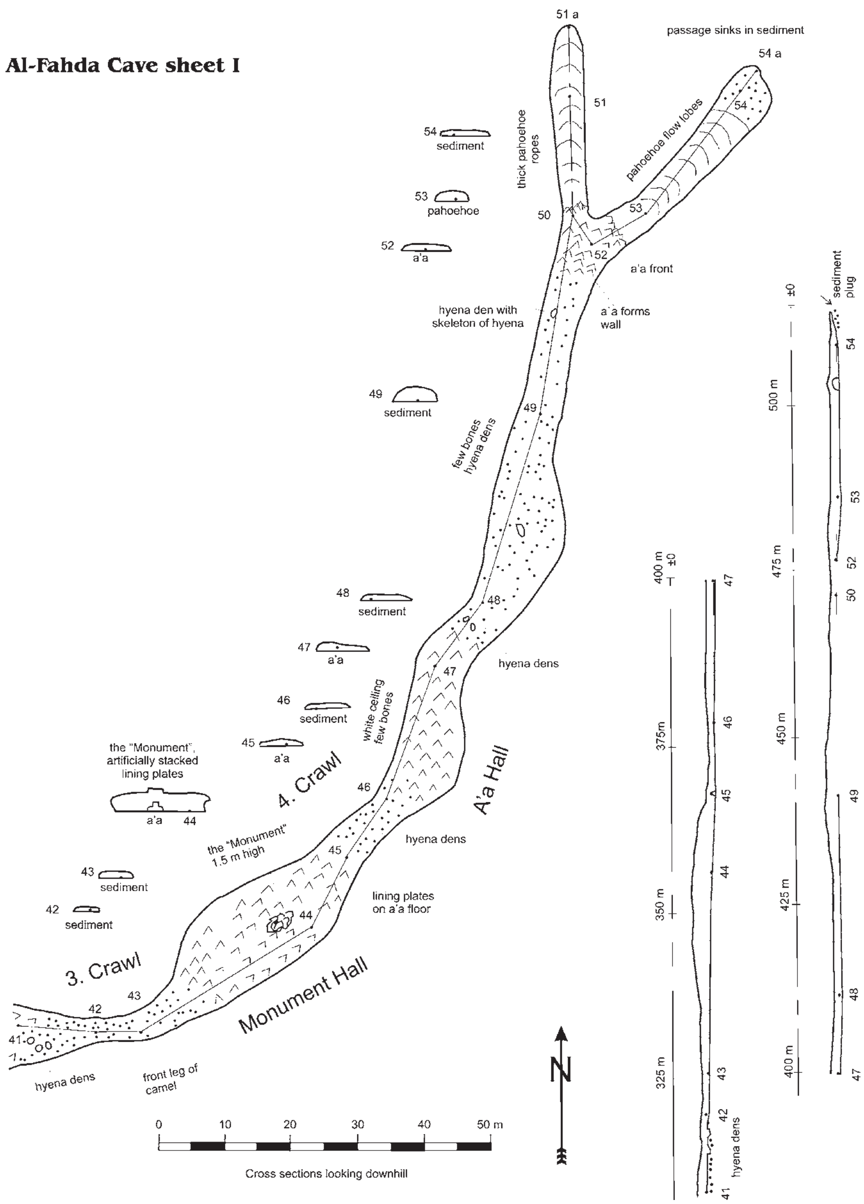

Figure 2. Map of Al-Fahda Cave (by the authors), sheet 1. The uphill and Mahmoud´s passages. Larger versions of map figures 2–5 are in the supplementary material on the CD.

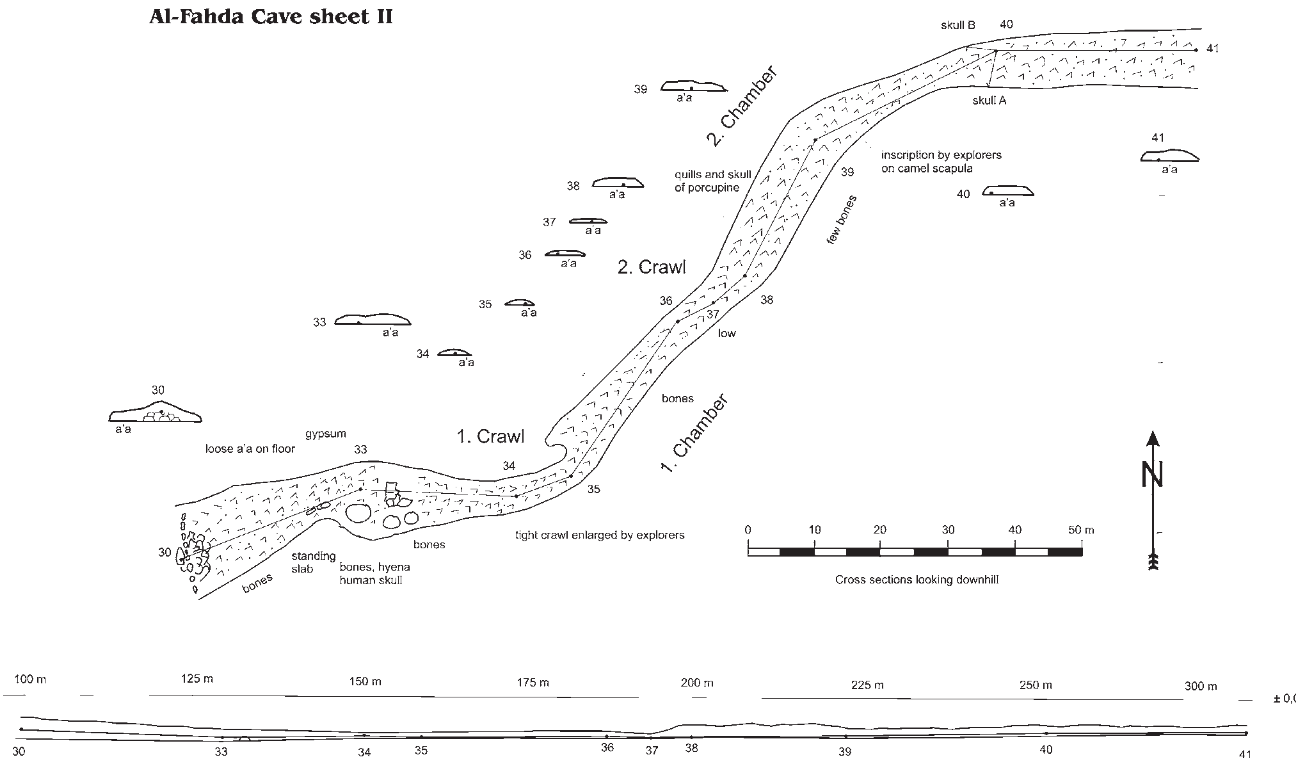

Figure 3. Map of Al-Fahda Cave (by the authors), sheet 2. The Mud, Large and A'a Halls. Also the both entrances.

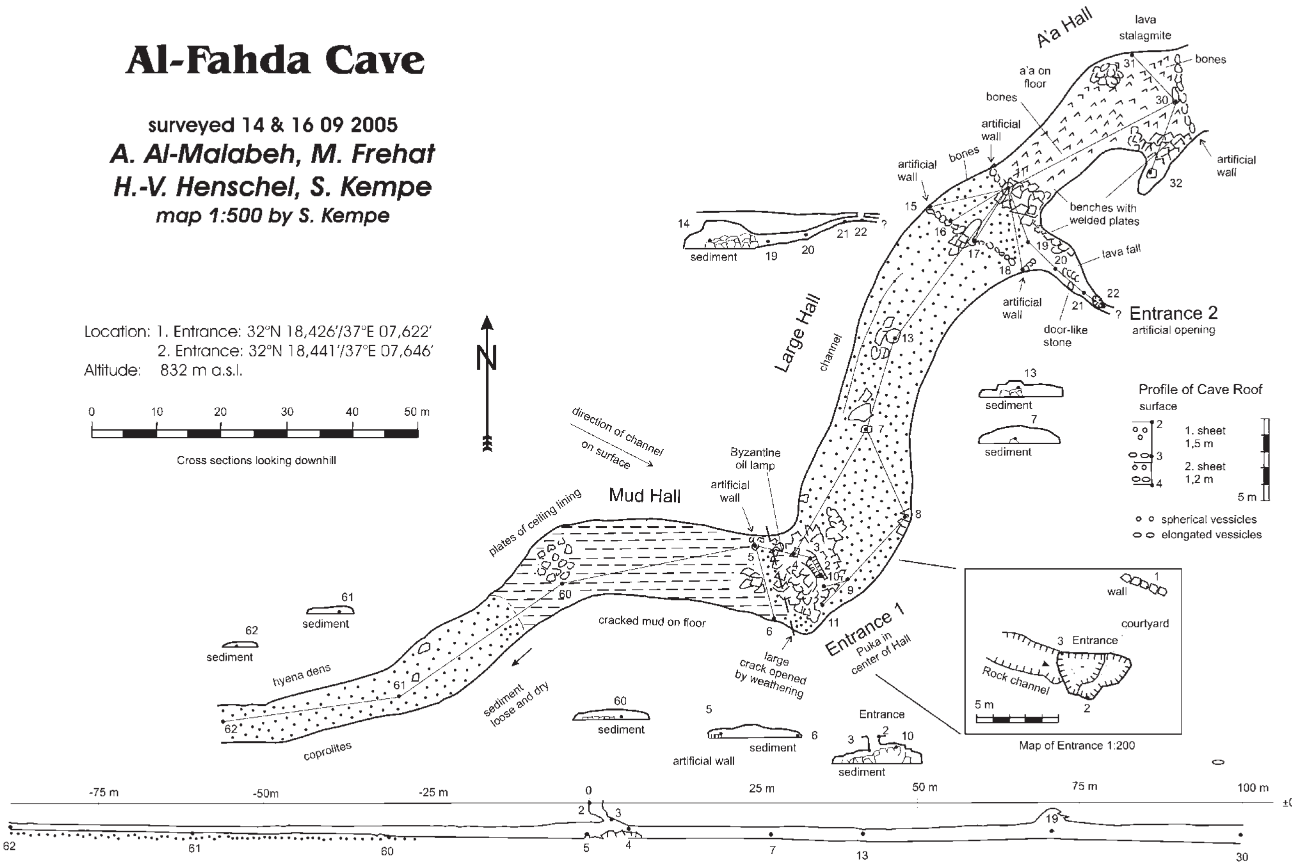

Figure 4. Map of Al-Fahda Cave (by the authors), sheet 3. The Crawl Halls.

Al-Fahde Cave sheet III

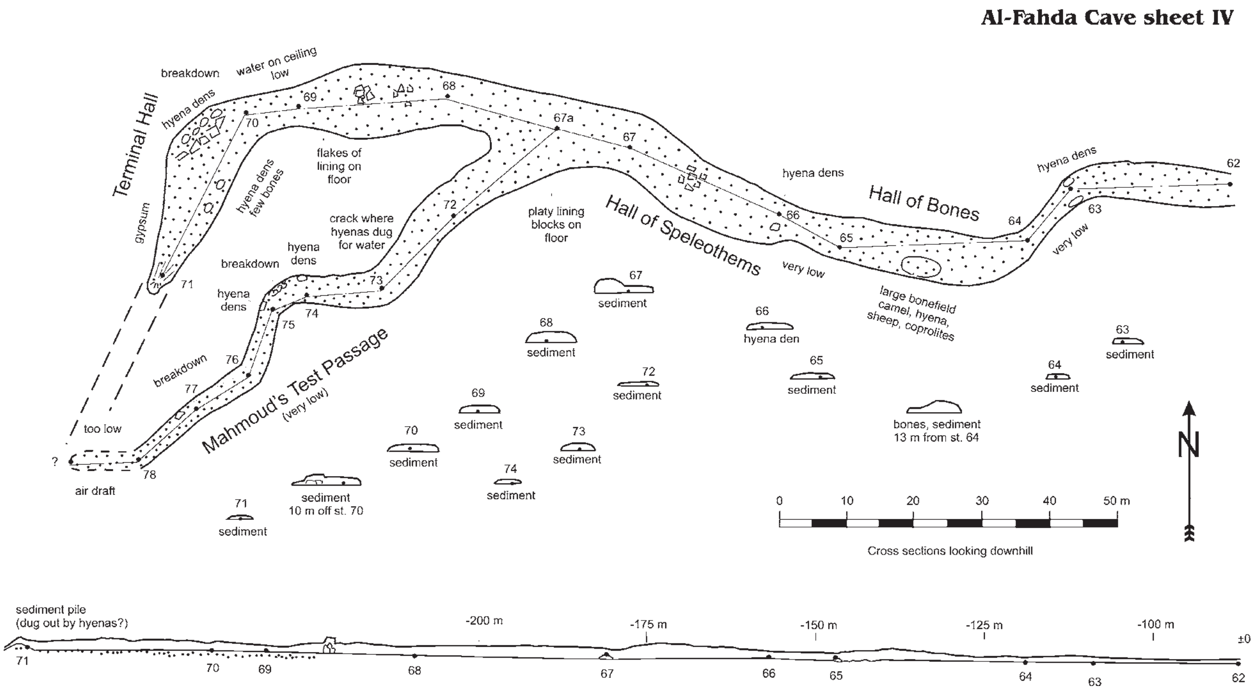

Figure 5. Map of Al-Fahda Cave (by the authors), sheet 4. Monument and, Pahoehoe and terminal Halls.

Figure 6. Anthropogenic channel consists of unworked stones led from Wadi Rajil in the north down slope to the main entrance.

Table 1. Survey results of Al-Fahda Cave.

Stations	Horizontal	Length m
2-54a	Main survey makai	488.60
8-11	Back of entrance	18.68
19-22	To second entrance	14.46
50-51a	W-passage of terminal split	28.45
4-5	Connection makai mauka	6.05
5-71	Mauka passage	266.21
67a-79	Mahmoud's Test Passage.	101.07
Total		**=SUM(ABOVE) 923.52**
	Main Passage length	
4-54a	Makai Passage	482.86
4-67a	Mauka Passage	187.10
67a-79	Mahmoud's Test Passage	101.07
Total		**771.03**
	End-to-end (as the crow flies)	**684.00**
	Sinuosity (771.03/684)	**1.13**
2-54a	**Vertical (entrance to deepest point)**	**-6.74**
71-54a	**Vertical extent of Main Passage**	**-8.41**
71-54a	**Horizontal length**	**755.12**
Slope 1	**slope (°) (tan^{-1} (8.41/755.12)***	**0.64°**
Slope 2	**slope (°) (tan^{-1} (8.41/684)**	**0.70°**
Width	**Maximal at St. 8**	**17.5**
	Minimal at St. 64	**3.55**
	Mean width main passage (39 stations)	**7.51**
Height	**Maximal St. 14**	**4.67**
	Mean height main passage (39 stations)	**1.21**

* This is the slope of the path the primary flow followed over the terrain.

Figure 7 (above). Main Entrance of Al-Fahda Cave.

Figure 8 (right). The second entrance, 60 m NE of the main entrance.

Figure 9 (below). Stalagmites composed of lava blisters.

evacuated by the original lava flow. This interpretation appears however less likely since invasion into a cold tube should stop very quickly due to fast cooling of the low volume of the invasion. Intrusive flows are known in Hawaiian caves, such as the Kazumura lava which intruded the mauka end of the Keala Cave and can be followed for 190 m with the characteristics of a surface pahoehoe flow (Kempe, pers. observ.). The a'a fill seems to explain the very low height of the tunnel compared to its large width and its level floor. It would also explain why we only found a few benches and other flow indicators: they were simply buried by the late lava event. How far mauka of st. 14 the a'a extends, is difficult to say, but the low nature of the mauka tunnel seems to suggest, that it extents all the way to the present end. Digs through the sediment may help to solve this question.

The cave is also remarkable for its paleontological and biological value: It was (is?) visited by hyenas (stripped hyena, *Hyena hyena*) all the way to both ends (Fig. 13). According to a search of the literature (D. Döppes, Darmstadt, pers. comm.) this is so far the furthest distance of hyenas penetrating caves on record. Since the cave is so low, the hyenas must have been crawling through some of the low spots, just as the modern cave explorer does. The hyenas also dragged in an appreciable amount of bones, among them at least three human skull caps (Fig. 14). Most of the bones appear though to be camel bones. But remains of sheep, gazelle,

Figure 10. The second entrance passage resulted from the upward bending of the sheet in an axis more or less perpendicular to the flow.

porcupine, and hyenas were also noticed. The hyenas also left plenty of coprolites, which might be interesting objects to study, possibly revealing much about the ecology of these animals throughout thousands of years and possibly even longer time periods. In the sediment-covered section (Fig. 15) we find many hyena dens, mostly along the walls, that the animals seem to prefer. Sometimes the sediment appears to form a ridge in the center of the passage due to the digging activity of the carnivores along the sides. In one instance we even think that they were digging for water along a crack. Parts of the ceiling were still wet in mid-September, suggesting that the hyenas may have been going into the caves not only for shelter, to consume bones, give birth or die, but also in search of water.

Human presence is seen also in the cave. Low walls (Fig. 16) or retaining dams have been erected at stations 5, 15-18, 14 and 30. Actually, the makai part near the entrance up to St. 30 could house comfortably a large number of people. However, the cave appears to be rather clean and has not been used for sheep shelter as have some of the other caves in the area. Two very intriguing findings were made. First of all we found a pile of lining plates stacked by people on a large breakdown block near station 44, i.e. 330 m from the entrance. To get there, we had to move rocks in one of the crawl ways. Whoever stacked the stones must have been an ardent caver. So far we do not see any possibility to date this "Monument"

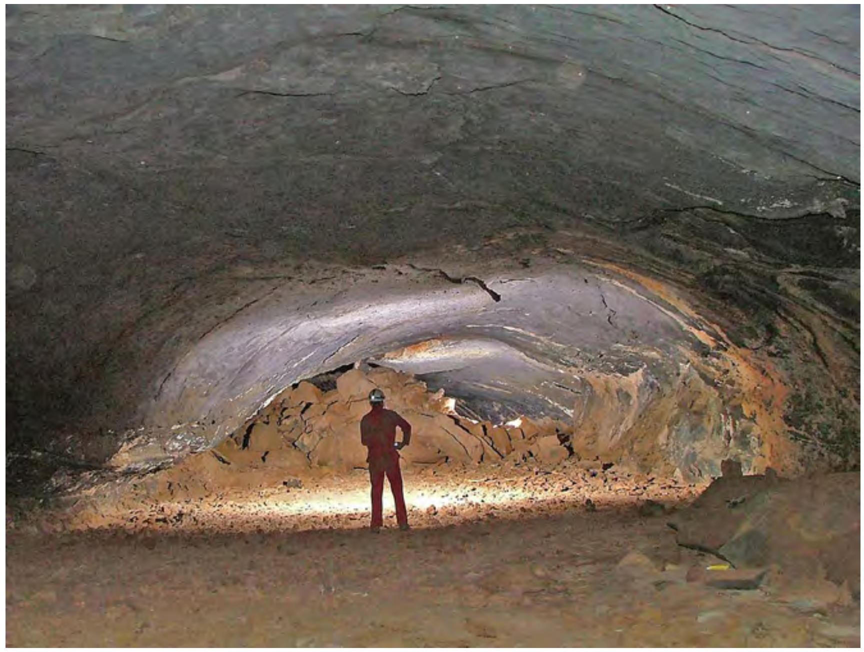

Figure 11. A´a small rubble stones cover the downhill section from wall to wall.

Figure 14. Human skull cap (St. 40) one of three skulls found in the downhill section.

Figure 12. Pahoehoe ropes found at the lower end of the terminal Hall.

Figure 13. A dead hyena in its den nearby the end of the terminal Hall.

Figure 15. Sediment covers the floor of the uphill section, Mud Hall, west of the main entrance.

Figure 16. Panorama view of the man-made artificial wall (St. 30).

Figure 17. Monument formed of stacked stones (man-made) in the Monument Hall.

(Fig. 17). Next we found (S. Kempe) a well preserved Byzantine oil lamp (Fig. 18), forgotten in a ceiling pocket near the entrance ca. 1500 years ago. It is now at the Hashemite University to be studied. At the surface we found a series of walls and crescent-shaped shelter walls along with pottery shards and a few (Neolithic?) flint flakes. All this suggests that both paleontological and archeological investigations in the cave might give valuable data on the history of the Jordanian desert.

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Figure 18. A well preserved Byzantine oil lamp discovered in a ceiling pocket near the main entrance.

State of Lava Cave Research in Jordan

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The northeastern region of Jordan is volcanic terrain, part of a vast intracontinental lava plateau, called the Harrat Al-Shaam (Fig. 1). The centre is formed by young alkali olivine basaltic lava flows, the Harrat Al-Jabban volcanics, or Jordanian Harrat (Al-Malabeh, 2005). The top most and therefore youngest flows, collectively known as Bisriyya Formation, are ca. 400 000 years old (Tarawneh et al., 2000). We have explored, surveyed and studied a total of 14 lava caves since September 2003. Altogether 2,544 m of passages were surveyed until May 2006 (Table 1). Of this 1,486 m, or close to 59 % of the total, was surveyed in September 2005, among them the 923.5 m long Al-Fahda Cave (see Al-Malabeh et al., this volume). The caves represent six lava tunnels (one has two caves), five pressure ridges caves and two caves of doubtful origin.

Of the six lava tunnels (Abu Al-Kursi has two caves) so far investigated three are rather wide, Al-Fahda Cave, Al-Badia Cave (Beer Al-Hamam) (Fig. 2, 3), and the two Abu Al-Kursi Caves (Fig. 4), while Al-Howa (Fig. 5a, b), Hashemite University Cave (Fig. 6) and Dabie Cave (Fig. 7) are of smaller dimensions. All have very low gradient, in the case of Al-Fahda as low as ca. 0.7°. Lava falls, so often encountered in Hawaii, were not found in these caves. Benches and shelves marking older flow levels occur in Dabie Cave (Fig. 8), Al-Fahda and in one place in Hashemite University Cave. Branching is rare, apart from Al-Fahda Cave only Hashemite University Cave displays branching.

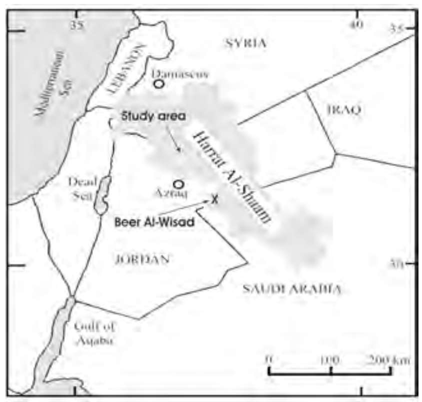

Figure 1. Study area and extent of Harrat Al-Shaam (altered after Al-Malabeh, 1994).

Apart from Al-Fahda Cave, speleologically, Hashemite University Cave is the most interesting. Hashemite University Cave is reached through a collapse hole at the crest of a ridge. There the primary 7 m thick roof is exposed consisting of only three pahoehoe layers (see Fig. 6). The mauka passage (uphill) apparently running NW is blocked by breakdown but from the north another low passage filled with sediment joins. The open tunnel leads makai (downhill) for about 180 m where the cave opens up to a nearly circular room of almost 20 m diameter and ends in a lava sump

Table 1. List of currently (May 2006) known and surveyed lava caves in Jordan, sorted by total passage length.

Name of Cave	Latitude	Longitude	Stations	Length m	Stations	Depth m	Direction	Altitude m	Type
Al-Fahda Cave	32°18'	37°07'	complex	**923.5**	2 to 54	6.7	SW-NE	832	Lava Tunnel
Al-Badia Cave	32°07'	36°49'	32 to 23	**445.0**	1 to 23	17.2	NW-SE		Lava Tunnel
Hashemite University Cave	32°14’	36°34’	21 to 35	**231.1**	1 to 23	10.0	NW-SE		Lava Tunnel
Al-Ameed Cave	32°13’	36°33’	complex	**208.0**	2 to 31	4.0	SW-NE		Pressure Ridge
Dabie Cave	32°10'	36°55'	0 to 14	**193.6**	0 1to 13	1.8	NW-SE	893	Lava Tunnel
Abu Al-Kursi East	32°15'	36°39'	20 to 34	**153.7**	1 to 34	12.2	W-E		Lava Tunnel
Al-Howa	32°18'	36°37'	complex	**97.1**	2 to 6	10.8	SW-NE		Lava Tunnel
Al-Hayya Cave	32°17'	36°34'	1 to 11	**81.3**	1to 9	4.2	NW-SE	911	Pressure Ridge
Abu Al-Kursi West	32°15'	36°39'	2 to 18	**77.1**	2 to 18	8.1	N-S		Lava Tunnel
Azzam Cave	32°17'	36°36'	13 to 25	**44.1**	1 to 25	4.2	NNW-SSE		Pressure Ridge
Al Ra'ye Cave	32°17'	36°34'	1 to 6	**42.0**	1 to 34	3.5	NW-SE	911	Pressure Ridge
Dahdal Cave	32°17'	36°35'	5 to 12	**28.9**	1 to 12	0.0	SW-NE		Pressure Ridge
Beer Al-Wisad	31°46’	37°28’	11-3-7	**11.4**	1-2-7	11.5	NE-SW	615	Pit (unknown)
Treasure Pit	30°51’	35°24’	Complex	**7.2**	2 to 11	5.8	NE-SW	960	Tunnel ?
Total				**2544**					

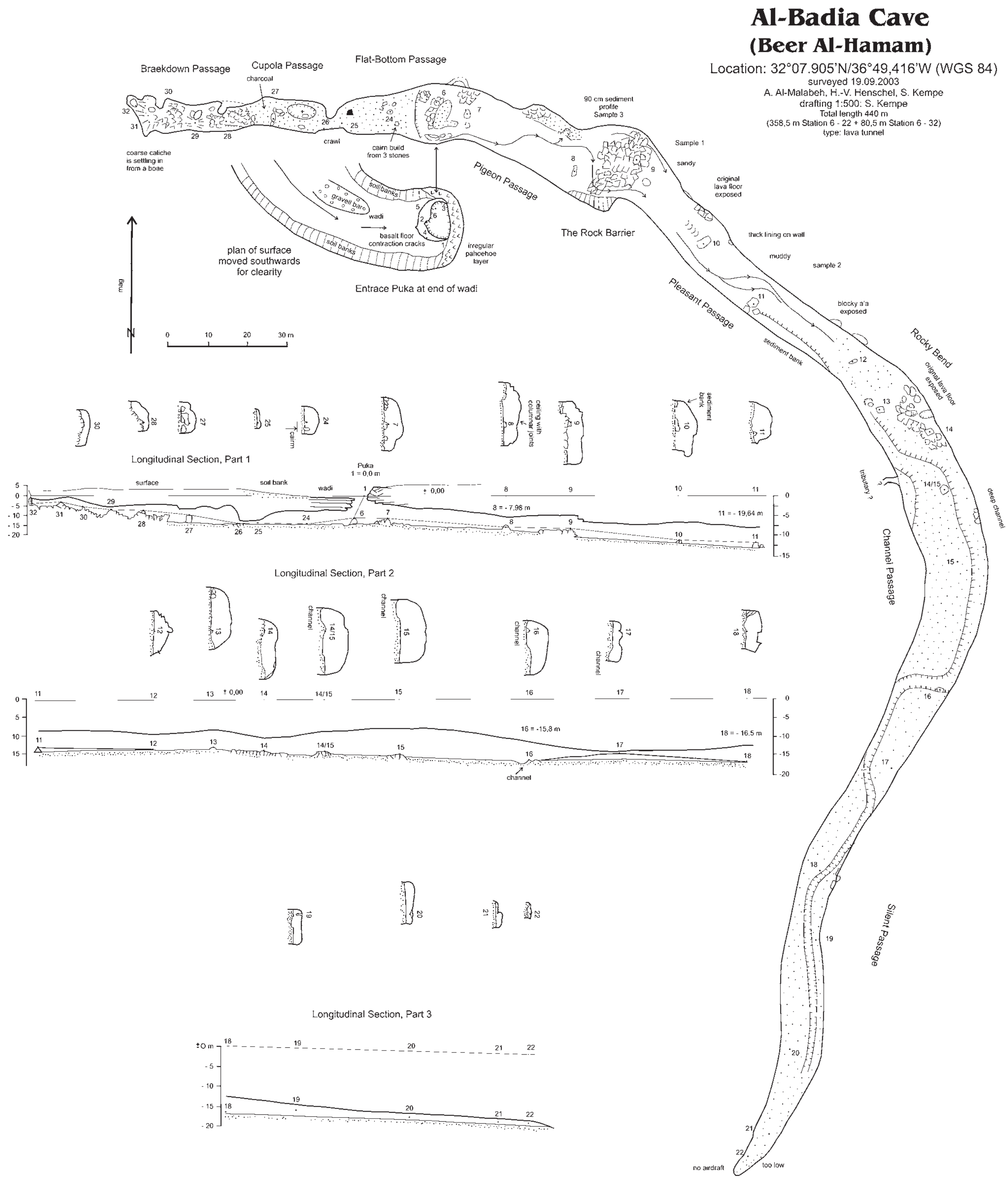

Figure 2. Map of Al-Badia Cave (by the authors). The cave is entered through a large breakdown hole, overhanging on all sides. This hole acts as a sink for a short wadi at times of heavy rains that has filled the cave with sediments.

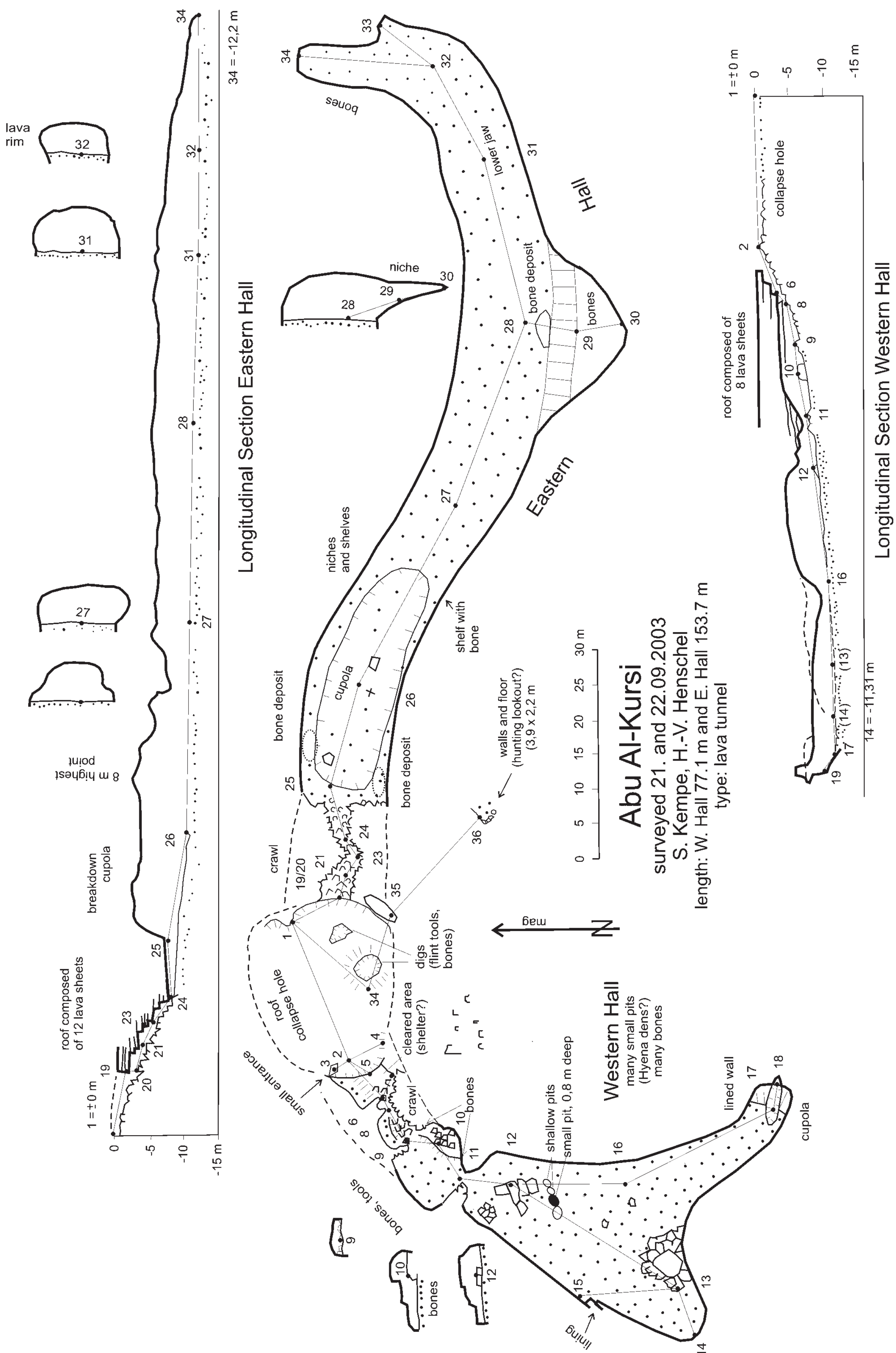

Figure 4. Map of Abu Al-Kursi (by the authors). Abu Al-Kursi has two separate caves (East and West) separated by a breakdown depression.

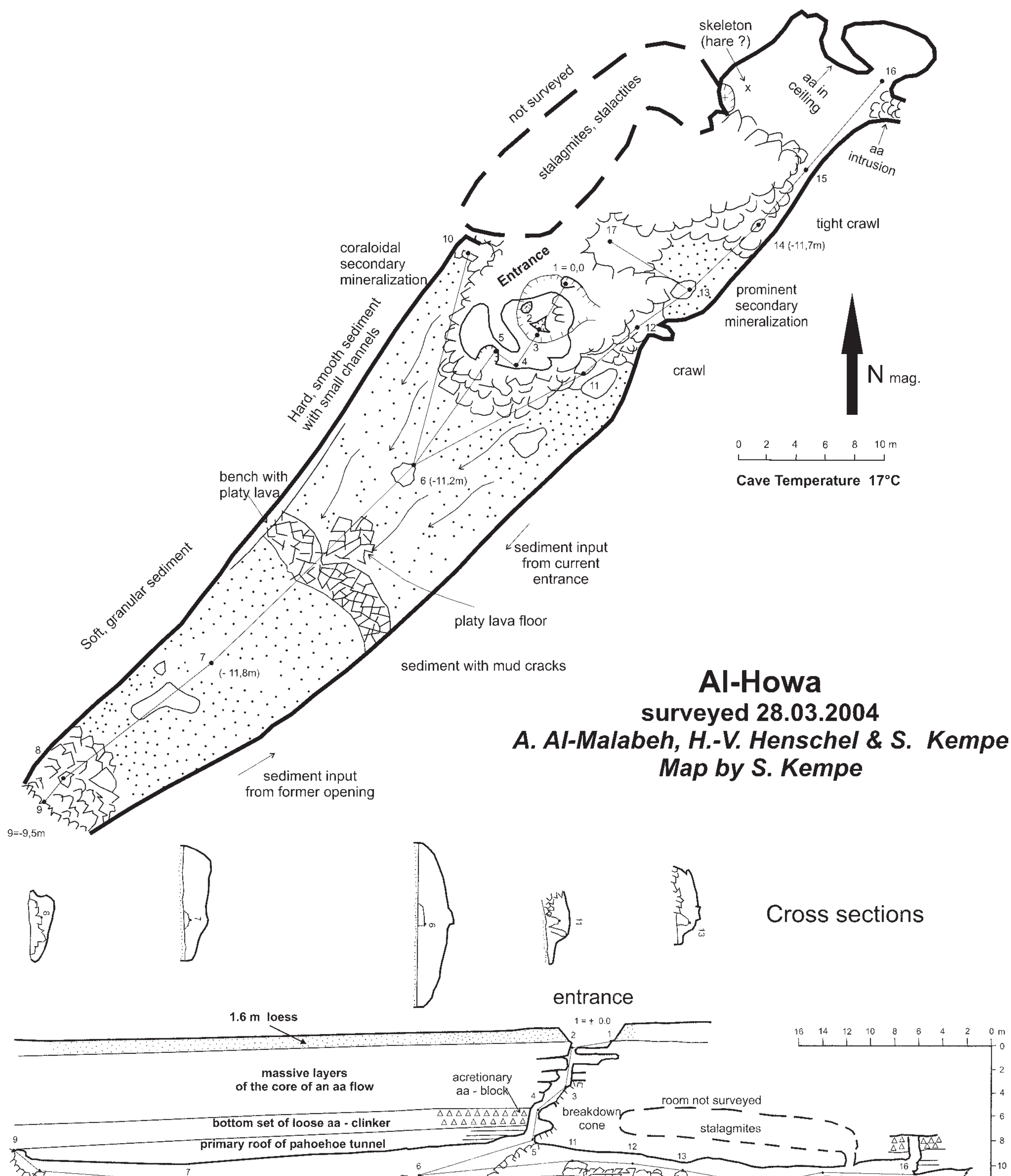

Figure 5. Map and longitudinal section of Al-Howa (by the authors). Note that the cave containing pahoehoe flow has been overridden by a later a‘a flow. This flow has broken through the roof at both ends of the cave, closing it off. The current entrance is through a later breakdown hole in the center of the cave.

Figure 3. Entrance of Al-Badia Cave. It forms a sink in a small wadi. It is ca. 5 m deep and overhanging on all sides, exposing the uninterrupted lava sheets of the primary ceiling.

Figure 8. Panorama of Dabie Cave with prominent benches on both sides of the passage.

Figure 9. Panorama view of the terminal hall of Hashemite University Cave. The floor consists of thick ropy pahoehoe.

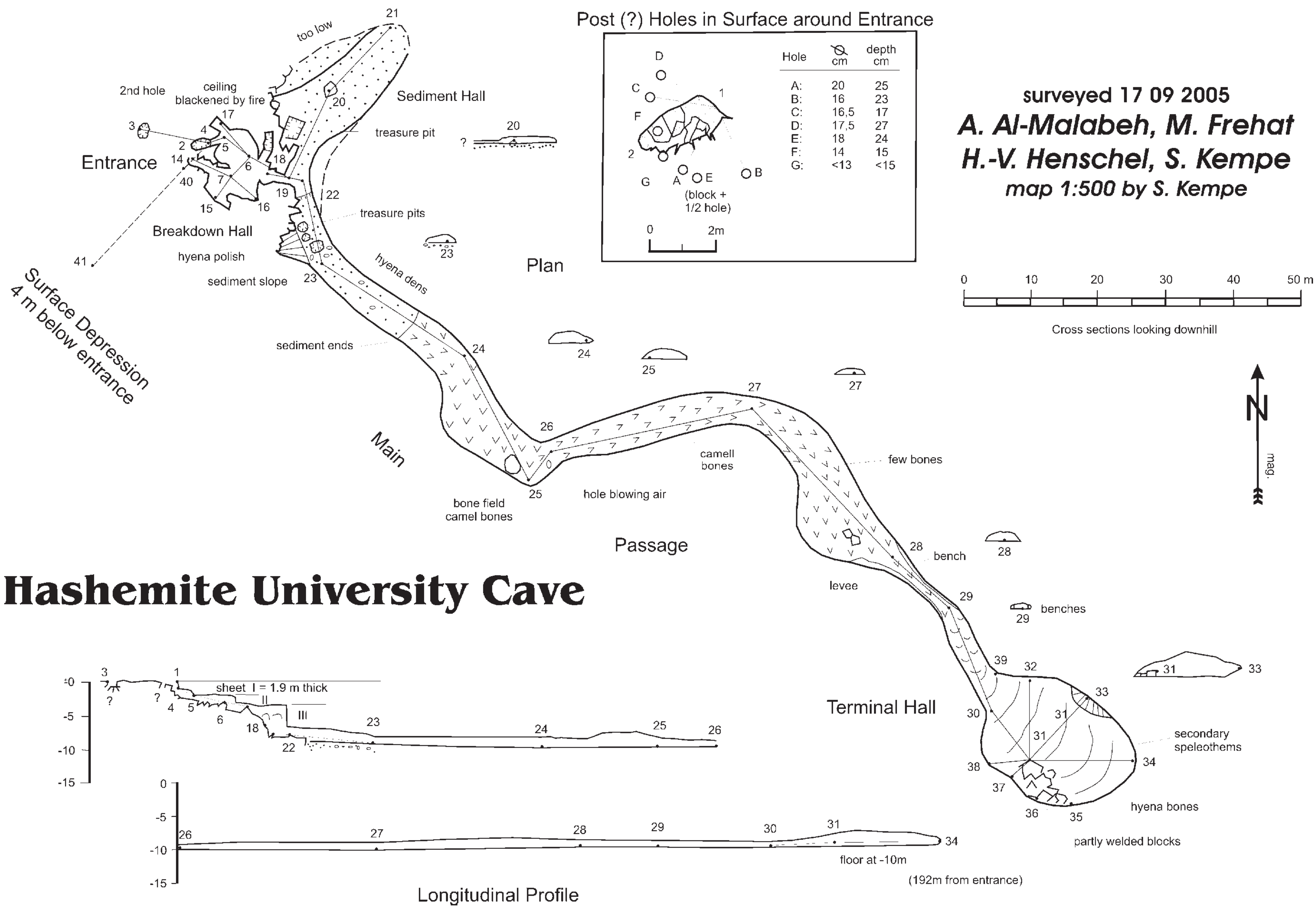

Figure 6. Map of Hashemite University Cave (by the authors). Entrance is through a breakdown hole.

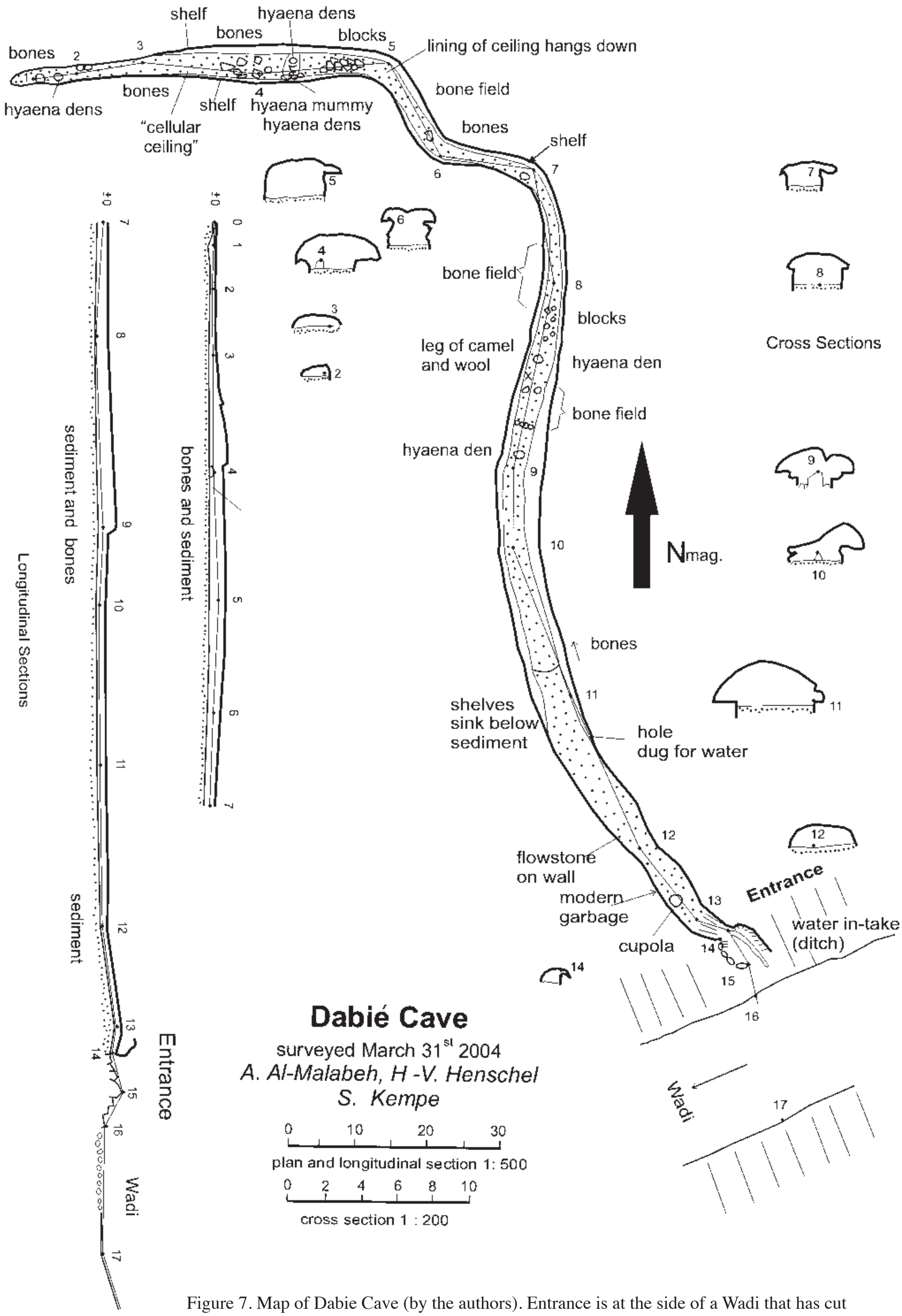

Figure 7. Map of Dabie Cave (by the authors). Entrance is at the side of a Wadi that has cut through the lava flow. A small channel used to divert water into the cave.

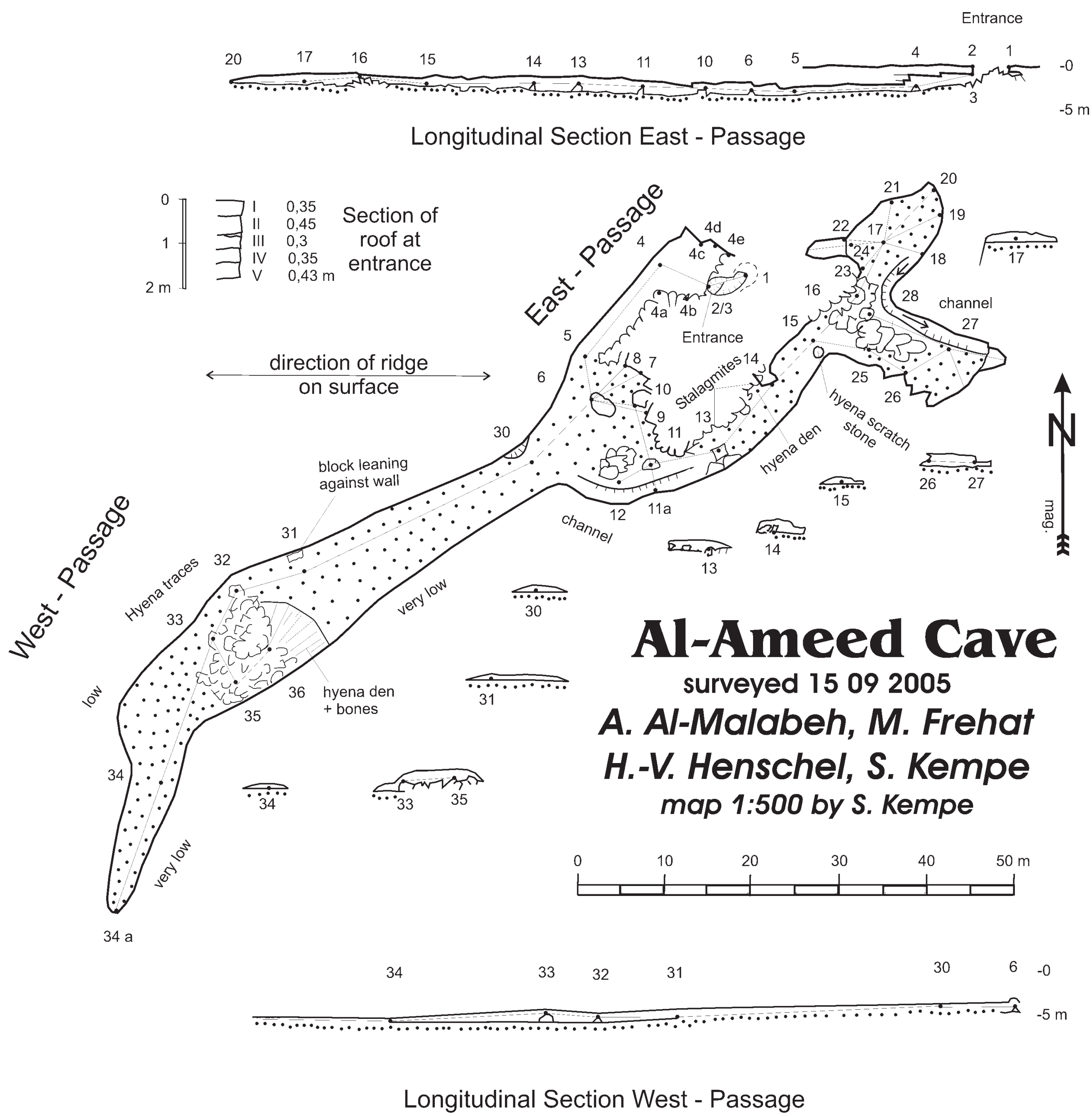

Figure 10. Map of Al-Ameed Cave (by the authors). Entrance is through centrally collapsed low and wide hall below up-domed lava sheets.

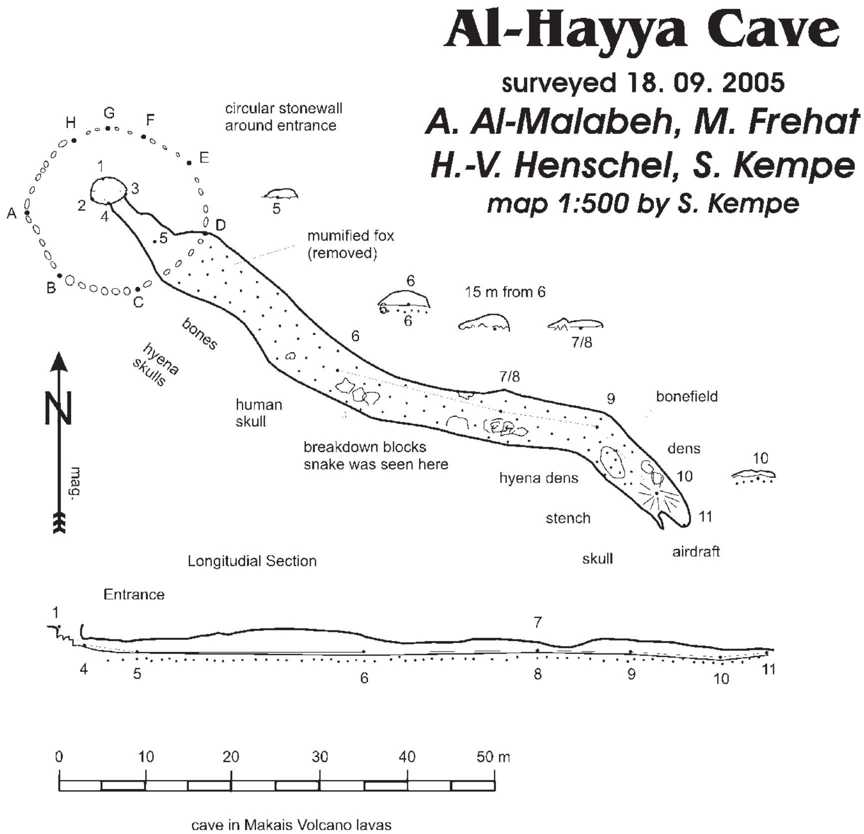

Figure 11. Map of Al-Hayya Cave (by the authors). Entrance is through a collapse hole which possibly dissects the cave in to two parts. The western part is yet unknown.

Figure 14. Pit of Beer Al-Wisad.

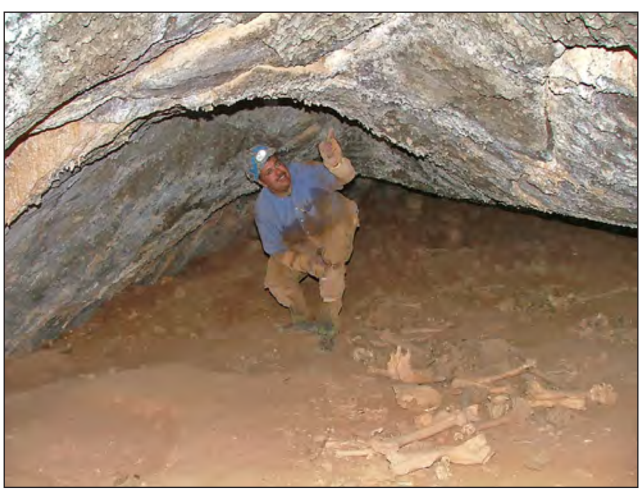

Fig 12. Passage view of Al-Hayya Cave. Bones (mostly from camel) in foreground are “left-overs” of hyenas.

Figure 13. Pillow basalts of Miocene age near Beer Al-Wisad.

(Fig. 9). In a way, this is similar to the lava sump at the end of Thurston Lava Tube (see Kempe et al., this volume). It poses a geological riddle since one would expect that the back-up of the residual flow in the tunnel might close the cave at a narrow point but not at a wide passage. One possible solution of the riddle could be the assumption that we are standing on top of a secondary ceiling. A blowhole, situated near station 26, indicates that there is an open passage underneath, giving some credibility to this hypothesis.

The proportion of pressure ridge caves and their length are an interesting finding. When compared to the population of lava caves on Hawaii, we find lava tunnels to be in majority. Here we use the term "pressure ridge cave" collective for a class of caves which does not show signs of lava flowing gravitationally through them. These cavities rather seem to have been created by doming the lava surface sheet either by lateral compression or by lifting them up through lava injection with consecutive drainage of the lava. This upward doming often occurs with axes perpendicular to the direction of pressure (Ibrahim & Al-Malabeh, 2006). Considering that the lava in Jordan forms rather thick sheets, low, but wide and astonishingly long caves may result.

The longest pressure ridge cave we surveyed up to date is Al-Ameed Cave (Fig. 10), with over 200 m in length. Actually, the cave seems to consist of two caves under two different tumuli connected by an over 30 m long, low, but wide passage. The tumulus with the entrance collapsed centrally, so that the cave leads around the breakdown almost in full circle. One can stand at only a very few places, the rest of the cave is too low and the north-eastern and south-western ends of the cave sink in the sediment fill.

The newly surveyed pressure ridge cave of Al-Hayya Cave (Snake Cave) and Al Ra'ye Cave (Sheep Cave) are of a different nature. They are elongated cavities which are comfortably high at their centres and of moderate width. Al-Hayya averages ca. 1 m high and 4.6 m wide (Fig. 11, 12). Al-Ra'ye Cave has been used as a free-of-charge sheep pen for the winter. Al-Hayya opens in the centre of a tumulus, but then leads away from the tumulus without giving access to the interior cavity below the tumulus, if there is any, while the collapse entrance to Al-Ra'ye is not bound to a tumulus. Several other tumuli nearby have central collapses, but stones need to be removed to access their caves. These stones have been placed in the past to prevent hyenas from using the caves as hiding places.

Beer Al-Wisad (Arabian for Pillow Pit) in one of the most outstanding features in the Jordanian Harrat. It is a pit located in pillow lava. This lava is one of the oldest exposed flows in the Harrat (Miocene). The pillows are spheroidal and have about 40 – 70 cm in diameter (Fig. 13). The entrance of the pit is not wider than 1 m and bellows out downward (Fig. 14). At a depth of 9 m the massive, melanocratic basalt ends and is underlain by a ca. 50 cm thick sheet of layered basalt. This is followed downwards by vesicular basalt; its vesicles are filled with secondary minerals. Along this layer a chamber of about 11 m length and 5 m width is developed. Here we also find at two or there places peck marks made by a very slender tool. The floor is partly covered by a pile of sand, shifted-in down the entrance and partly covered with pigeon dirt (dung, eggshells, twigs). The pit appears not to be anthropogenic, it is not a man-made well or quanat and the peck marks seem to be of a more recent age (treasure hunters?). It remains a riddle how it could have formed naturally within a layer of massive pillow basalts and even extending into underlying strata. Due to the high age of the lavas, one would expect that the pit – if it would have formed during the deposition of the lavas - would be filled either with playa or aeolian sediments. It is hoped that further petrological investigations might give clues about the pit's genesis.

All in all, we are still at the beginning of lava cave research in Jordan, and when we began detailed work three years ago we would not have thought that we would encounter such a variety of caves. We are even more astonished that these caves are still partly accessible considering their great age.

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Thurston Lava Tube, the Most Visited Tube in the World. What Do We Know about It?

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Survey by Stephan Kempe, Matthias Oberwinder, Holger Buchas, Klaus Wolniewicz

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Thurston Lava Tube (or Keanakakina, i.e. Tunnel of Thurston, keana meaning "the cave" and kakina being the Hawaiian Name of Thurston), is a celebrated tourist attraction in the Hawaii Volcanoes National Park. It is visited daily by hundreds, if not more than a thousand tourists. Since the National Park does not open any other cave for regular visits, it is also the only cave readily accessible to the tourist in Hawaii. Hardly any other lava tube in the world can match its popularity. In spite of its many references in literature not much is known about the speleogenesis of this cave and previously published maps have not been very detailed (Powers, 1920; Wood, 1979; Halliday, 1982). In order to get a more detailed view we surveyed it on March 9th, 1996 in high precision, using a digital compass and level mounted on antimagnetic tripods to keep instruments at a fixed distance from the rock (Figs. 1a,b,c; 2). We also used forward and backward shots to eliminate any magnetic influence of the rock (which is small anyway according to long-term experience from surveying in Hawaiian caves). We also measured width and heights every 5 m into the cave. The most important results are summarized in Table 1 below.

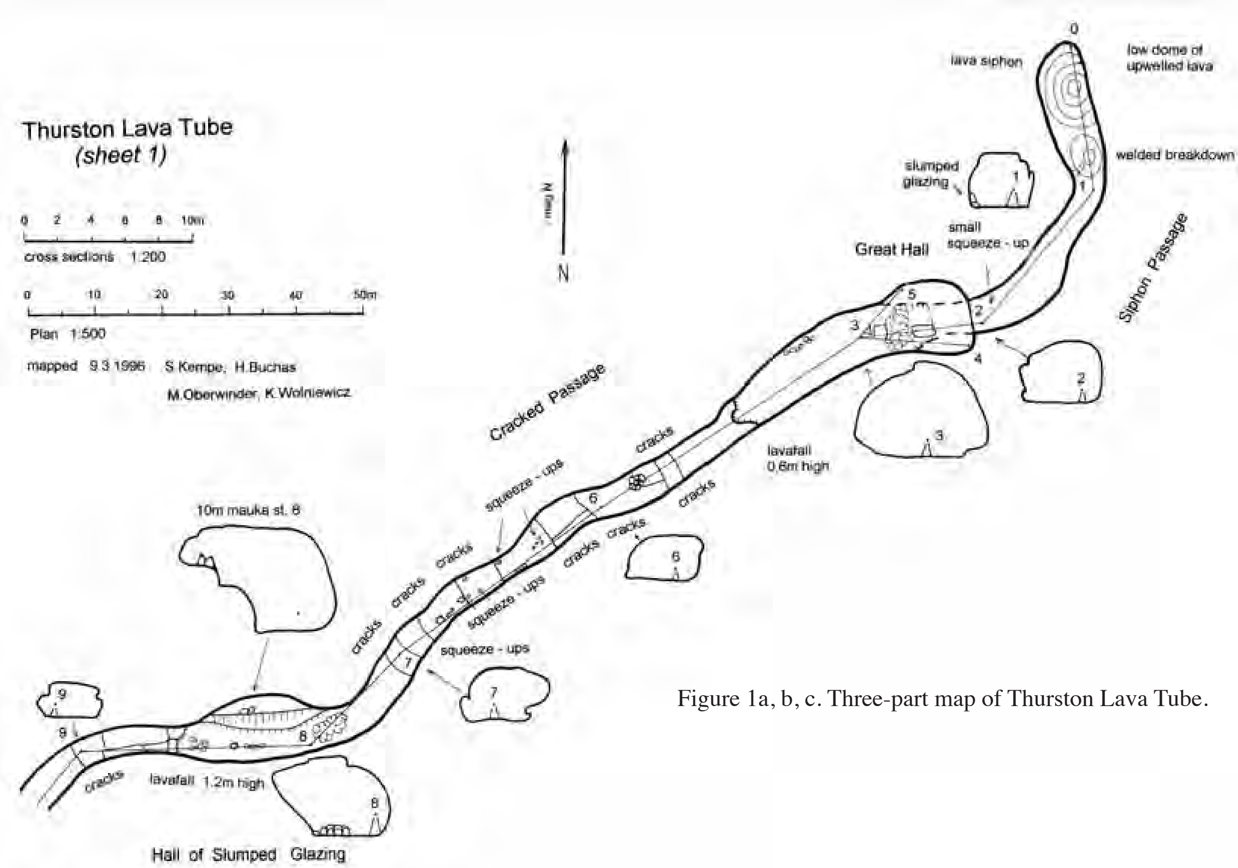
The cave was discovered 1913. Halliday (1997) reported an account signed by Wade Warren Thayer in the visitors' book of the Volcano House stating: "*On Aug.2nd a large party headed by L.A. Thurston explored the lava tube in the twin Craters recently discovered by Lorrin Thurston, Jr. Two ladders lashed together gave comparatively easy access to the tube and the whole party, including several ladies, climbed up. No other human beings had been in the tube, as was evidenced by the perfect condition of the numerous stalactites and stalagmites. Dr. Jaggar estimated the length of the tube as slightly over 1900 feet. It runs northeasterly from the crater and at the end pinches down until the floor and roof come together. . . .*"

Figure 3. Entrance of tourist section over a bridge that leads across part of an elongated collapse structure, called Kaluaiki.

The cave has two openings used as an entrance and exit for the tourist trail. The primary entrance is reached via a bridge (Fig. 3). It opens in the wall of an elongated collapse hole, called Kaluaiki, most probably very near to the site of the former vent that delivered the lava producing the cave. The other entrance is a ceiling hole, caused by roof collapse much after the cave has cooled (Fig. 4). Here the tourist is led out of the cave via a stone staircase. The tourist section (Fig. 5) is lit by yellow lights in order to minimize lampenflora. The path is covered with gravel (and often with puddles) obliterating the original floor structure. Beyond the stairs, a gate is installed with a sign advising tourists to visit this part of the cave only with proper lighting, announcing that this section is 343 m long (357 m would be correct).

Vulcanologically the cave is important since it is situated very near to the original vent of the Ai-la'au Shield, the site of the last massive summit eruption of Kilauea (Holcomb, 1987) that lasted from about 500 to 350 aBP. The Ai-la'au lavas cover a very large area east of Kilauea Caldera all the way to the ocean near Hilo. They were tube-fed pahoehoe lavas, containing not only the longest lava cave known (Kazumura Cave) but also a number of other very long lava tunnels (Keala Cave, John Martin Cave, Pahoa Cave). Since Thurston runs underneath the highest point of the Ai-la'au shield (the 3840 foot contour), it appears to be the tube that sustained the last active flow, possibly producing the lava which reportedly invaded Kazumura (Allred & Allred, 1997). Thurston is heading 45°N, ending just inside the Park Boundary. It is aiming at a prominent flow bulge at the NE of the Shield. The upper end of Kazumura runs in parallel slightly less than a kilometre further to the north near the highway (Allred et al., 1997). This makes is unlikely that both caves belong to the same lava flow, unless the northward turn of Thurston shortly before its end indicates a sharp bend in the tunnel system (Fig. 6).

When comparing the sinuosity and slope of the cave with those of others in



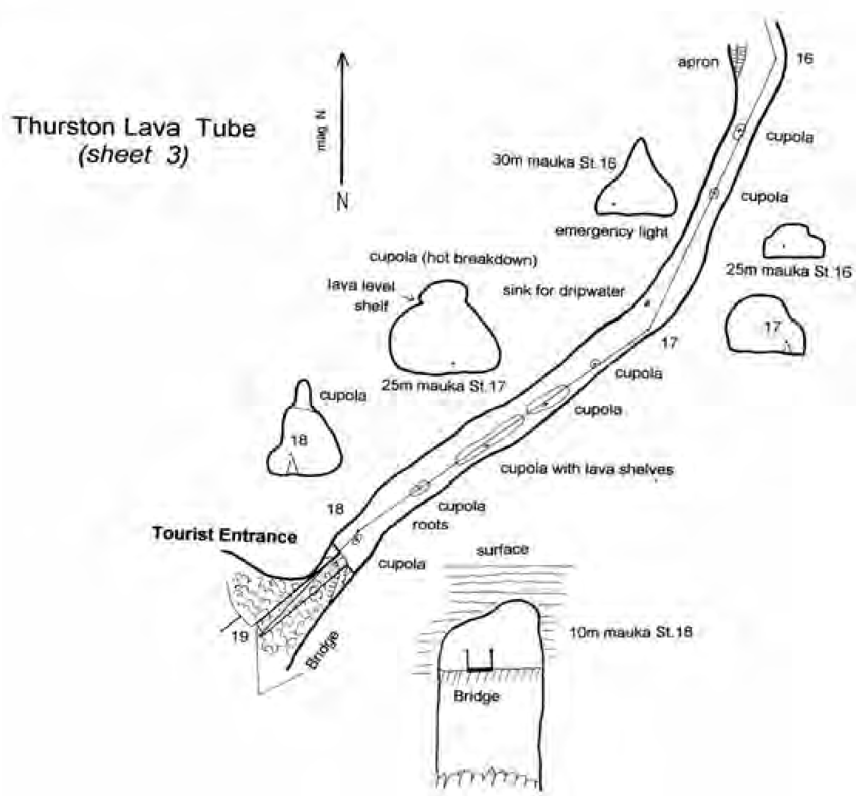


Figure 1a, b, c. Three-part map of Thurston Lava Tube.

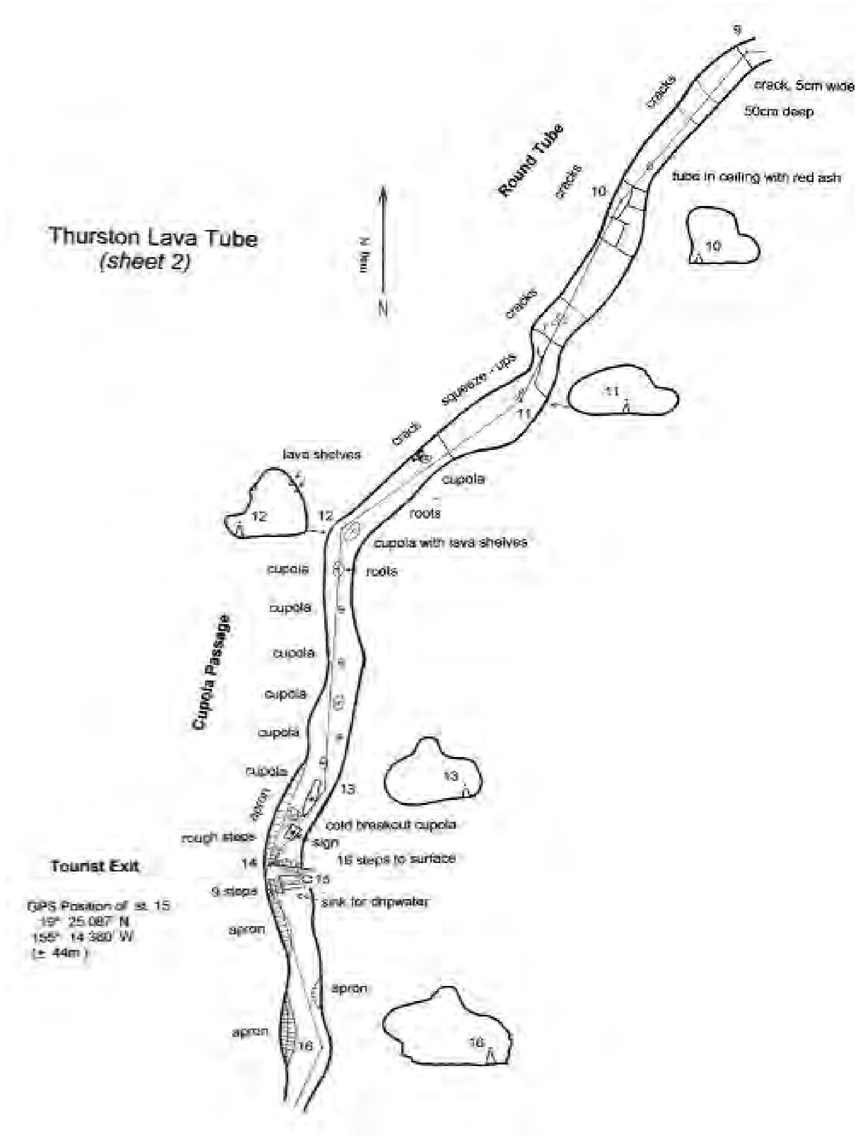


Figure 4. Exit with artificial staircase, looking mauka.

Figure 5. Tourist section looking makai.

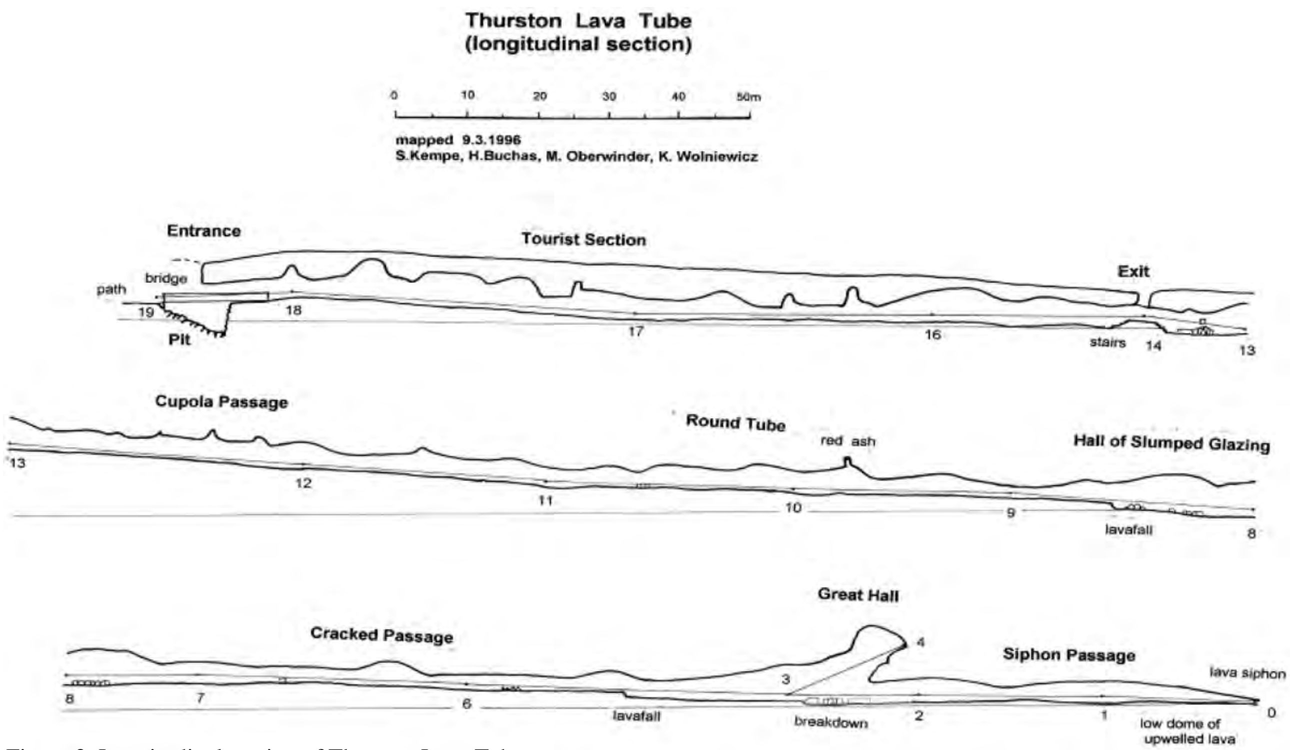


Figure 2. Longitudinal section of Thurston Lava Tube.

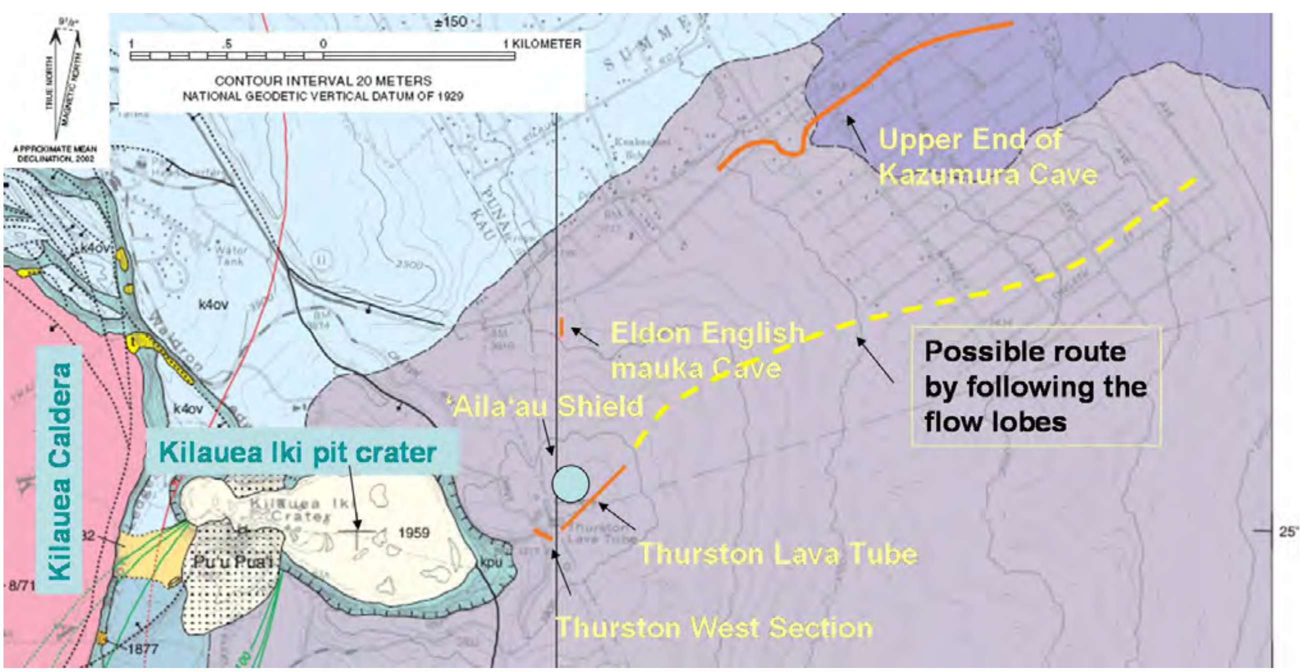


Figure 6. Modified clip of USGS Kilauea geological map (Neal & Lockwood, 2004).

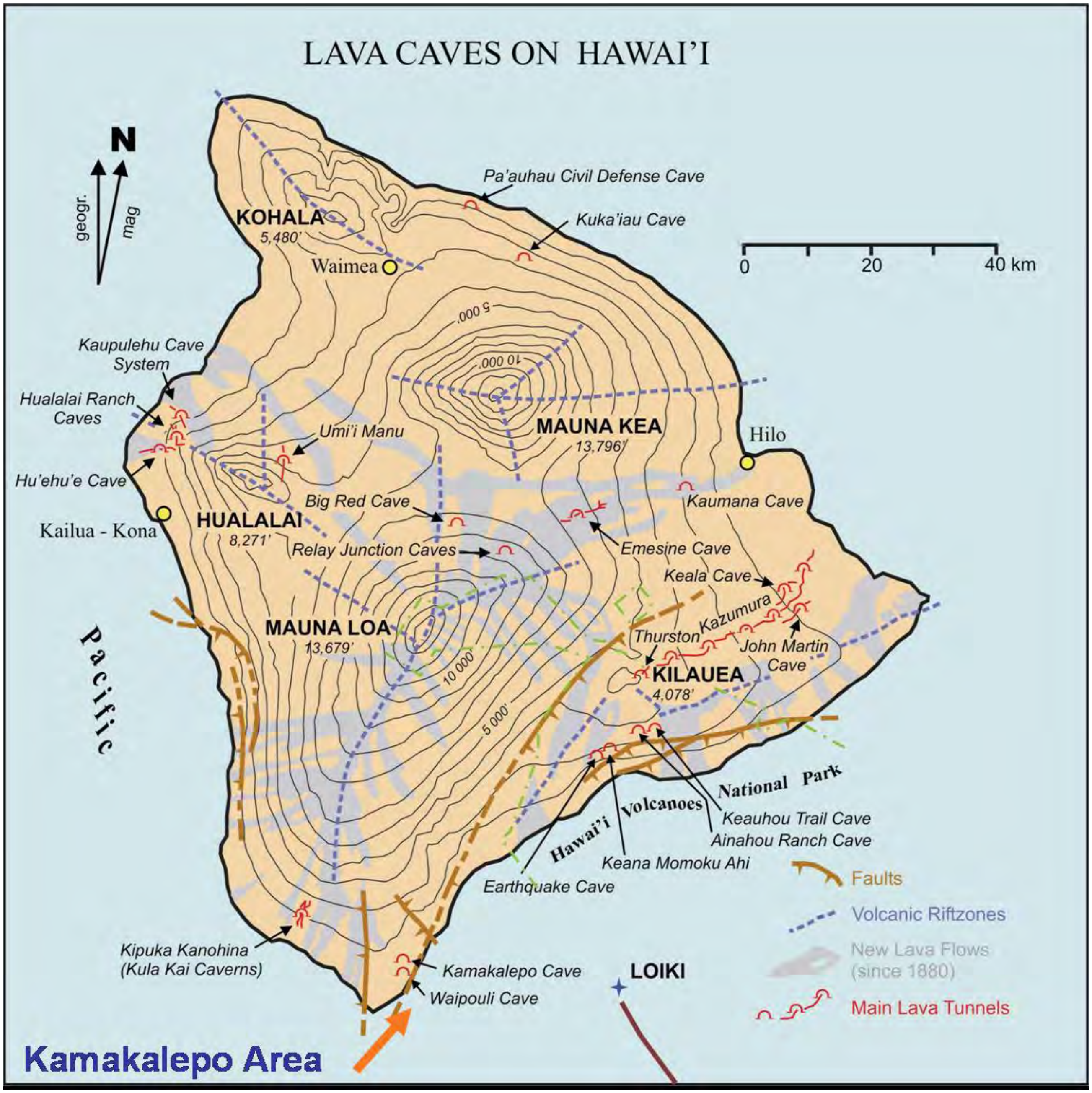


Figure 7. Map showing locations of some of the major lava caves on Hawaii.

Figure 8. Typical cross-section of Thurston Lava Tube.

Figure 9. Thurston Lava Tube ends in a Chamber, were the ceiling sinks below the floor that appears to consist of material up-welled from below forming a low bulge.

Figure 13. The floor of Thurston Lava Tube is devoid of the otherwise in lava tunnels typical flow-structures.

Figure 10. The first lava fall viewed mauka. The undercutting of the bottom sheet is clearly visible.

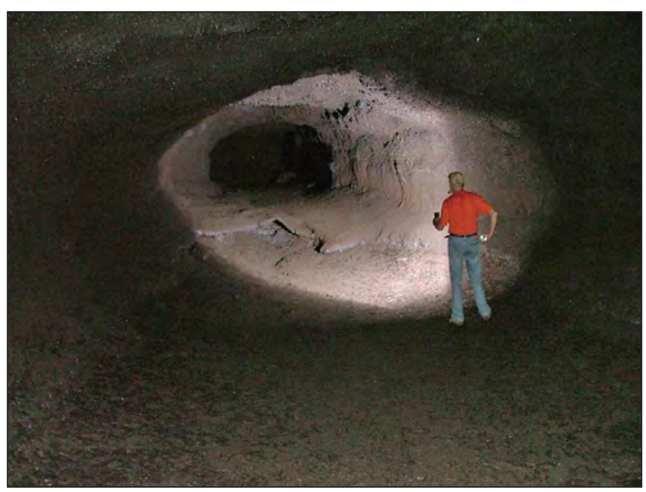


Figure 11. The second lava fall viewed mauka. The bottom sheet seems to have been warped, i.e. it was still plastic when the erosive back-cutting of the lava fall occurred.

the flow field (at least for those for which we have data) (Fig. 7) Thurston shows similar characteristics (Table 2).

When inspecting the cave, a series of questions arise. For the casual observer the cave appears strangely dull, without many detailed features (Fig. 8). Also the typical smooth, continuous glazing found in lava tubes is mostly missing. And finally the cave ends at a kind of lava "sump", which poses quite a puzzle (Fig. 1a and 9).

However, the more careful observer will notice several interesting details. Among them is the presence of two lava falls (Figs. 10, 11), below which the cave is wider and higher than above. When viewed mauka (uphill) one can see the undercutting of the former bottom sheet of the tube and of the wall linings. Also ledges are present (Fig. 12), bent downward at the lip of the lava fall. One can follow them for some distance upstream, indicating that the final flow in the cave did not fill it entirely.

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

Powers (1920) suggested that the "Great Hall" (Figs. 1, 2), shortly before the end of the cave is actually a window (caused by breakdown of the intervening ceiling in between) up into another tube above Thurston, explaining why the cavity has an upward rising floor above the Thurston tube. This certainly merits a closer look and if it were true, then Thurston may not represent the latest flow from the shield.

The floor is astonishingly devoid of flow lobes (Fig. 13), indicative of very hot conditions when the flow stopped, not allowing sufficient cooling of the surfaces skin to be rippled. In the lower part, many cracks are noticed in the floor and walls, forming large polygons. Cracks, possibly caused by cooling, extend deep into the floor (Fig. 14), deeper than the thickness of the bottom sheet of the cave is extending (which is just a few cm thick), again indicative of very hot conditions far beyond the bottom sheet of the cave. There is also a significant number of squeeze-ups (termed "volcanoes" by Powers, 1920) (Fig. 15), partly related to the cracks, forming very flat, glazed mounds, again indicating very hot conditions when they where extruded from the underlying lava by the expanding gas during solidification. On the walls many runners occur, partly "bleeding" in series out of horizontal partings in the wall (Fig. 16).

Overall, ceiling, walls and floor are irregular on the cm-scale. The mm-thick, continuous, and shining glazing, so typical for most lava caves, is missing (Fig. 17), possibly being destroyed by the ongoing degassing of the lava surrounding the cave after the evacuation of the cave, again speaking for sustained and very hot conditions. Also the typical cylindrical lava stalactites are missing, save for short stumps (Fig. 18). They may, however, have been removed over the years by visitors since the initial description of the cave talks of a "rich decoration" (see above).

Regarding the lava "sump" at the end of the cave (Fig. 9), the floor appears

Figure 12. Ledge of former lava-stand. It bends downward at the lip of the lava falls.

Figure 14. The floor is criss-crossed by deep cracks.

Table 1. Survey data Thurston Lava Tube.

location: Tourist Exit	N19°25.027'	W155°14.469'
location: Road side of entrance puka	N19°25.087'	W155°14.380'
length (from the beginning of cave roof - which is 13.5 m mauka of St. 18 above entrance bridge - to lava sump end at St. 0)	inclined	horizontal
Total cave (m)	490.84	490.08 (St 0 to St.18= 476.576 m)
Wild section (m)	357.43	356.76
tourist section (m)	133.41	133.32
Total survey length (m)	531.75	(total of 19 Stations)
as the crow flies (m)	432.5	
width (m)	max. 10.5	min. 3.5
height (m)	max. 11.5	min. 1.6
Total lava fall height (m)	1.8	8.96% of total vertical
slope (°) ($\tan^{-1}$ (20.08/476.576))*	2.413	
Entrance	side of collapsed crater at ca.1195 m, 3920 ft elevation	
End	lava sump	

* Because the cave roof starts earlier than the cave floor, we can use only the cave floor length, which is shorter than the total cave length, in order to calculate slope.
[for comparison length by Powers (1920): 1494 feet total (455 m), straight: 1360 feet (425m); slope 2.5°]

as if the lava welled up from underneath. Powers (1920) already noted its "convex" surface. No flow lobes or ropy textures are noticed which would indicate that the flow in the cave just filled the tube to the roof at a low spot. Thus it is not entirely inconceivable that Thurston represents an upper level of a much larger conduit system, as suggested by the hypothesis of Halliday (1982), stating that the cave is part of a "Jameo System", i.e. a multi-leveled lava conduit. The fact that the cave floor starts further makai than the cave roof, i.e. that "something" collapsed right underneath the present entrance, could be taken as a hint towards the existence of a cave below. If this is so, then the two caves above each other were certainly not created by down-cutting and consecutive formation of a secondary ceiling separating a canyon-like tunnel. Such separations are clearly later additions and can be recognized at cross-sections (Kempe, 2002). Inspection of the lava below the cave at its entrance shows that there the floor of Thurston is not a secondary ceiling. If Thurston belongs to a multi-storied cave system, then it must have formed during an increase in eruption volume, exceeding the capacity of the lower tube and establishing a contemporaneous upper conduit above it, which, when lava supply subsided, fell dry and was sealed at the end by lava up-welled from the lower conduit. Technically speaking only the end of Thurston might possibly fulfil the criteria of a secondary ceiling.

Another feature speaks also against

Figure 15. One of many low, dome and cone shaped mounds on the floor that seem to be squeeze-ups from below.

Figure 16. Runners form where residual melt is squeezed out from the cooling lava of the walls.

Table 2. Topographic data of some of the tubes from the Ai-l'au flows.

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

1: Allred et al., 1997; 2: Kempe 1997; 3 4; 5: unpublished data; 6: Wood, 1980; 7: Kempe et al., 1997. Volcano: K, A: Kilauea, Ai-la'au

the hypothesis that the floor of Thurston is a secondary ceiling within a larger, canyon like tunnel, and that is the presence of the two lava falls in the cave. Both indicate that the floor formed by active flow because these falls show clear signs of their back-cutting (Figs. 10, 11). Thus, if we assume the presence of multi-storied conduits, then they must have been established by consecutive overflow events, creating several caves on top of each other. Such situations have rarely been documented. Parts of Kulakai Cavern could represent such a cave type, based on the geological mapping of its surface (Bienkowsky & Kauer, 2002; unpublished).

On the far side of the collapse crater another section of cave was found, as reported by W.R. Halliday and J. Martin (Halliday, 1992) (Fig. 7). It has a NW-SE direction, at a 90° angle from Thurston. Its relation to Thurston and to a presumed multi-story tube system remains unclear from the available map (Halliday & Martin, unpublished) both with regard to its slope and altitude.

The correct interpretation of the nature of Thurston lava tube is intimately associated with the question of where the Ai-la'au vent exactly was. Holcomb (1987) suggests it was at the eastern notch of the Kilauea Iki collapse structure. There vertical lava sheets are preserved. However, the topographic high is to the east of it, above Thurston Lava Tube (Fig. 6). Therefore it is conceivable, that Kilauea Iki served as a gas vent, while a second vent produced the final lava flows. It could have been below the Kaluaiki collapse crater. Otherwise one would need to explain how the topographic high came about.

This question and some of the others posed in the paper suggest that we do not understand the speleogenesis of Thurston Lava Tube very well, in spite of the fact that it may be the most visited and the most often mentioned lava tube world-wide.

Figure 17. The surface of Thurston Lava Tube is quite irregular; the smooth glazing otherwise typical for Hawaiian lava tubes is largely missing.

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Figure 18. This is an exceptionally "well decorated" section of Thurston Lava Tube which is otherwise devoid of spectacular stalactites.

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Geology and Genesis of the Kamakalepo Cave System in Mauna Loa Picritic Lavas, Na'alehu, Hawaii

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The Kamakalepo Cave System (first mentioned by Bonk, 1967 and Kempe, 1999) consists of four larger sections of a once much longer tunnel in Mauna Loa lavas. It is situated south of Na'alehu, Hawaii (Figs. 1, 2, 3). The system is entered through two pukas (holes) (Fig. 4): Lua Nunu o Kamakalepo (Pigeon Hole of the Common People) and Waipouli (Dark Waters). Both of these pukas give accesses to uphill (mauka) and downhill (makai) caves totalling almost 1 km in length (Table 1) (Figs. 5, 6, 7, 8). Within the Lua Nunu Puka, a small cave along the W-Side has also been discovered (see Fig. 6). Two further pukas belong to the system, "Pork Pen Puka" (mauka of Lua Nunu) and "Stonehenge Puka" (makai of Waipouli) for which no local names are known. Pork Pen Puka is a depression set into the roof of Lua Nunu Mauka, the bottom of which is a secondary ceiling to the cave below. Stonehenge Puka is a 60*40 m large and up to 20 m deep crater, which not only issued lava as a rootless vent but from which large blocks were swept out that today mark its rim (and therefore the puka bears a certain resemblance with the real Stonehenge) (Fig. 9).

Waipouli is occupied by a 200 m long lake (see Fig. 8; Fig. 10), ending in a ca. 30 m long underwater cave, first explored by German divers in 2000 (i.e., Herbert and Christine Jantschke, Andy Küchl, Wolfgang Morlock). The lake level is 34 m below the surface and shows tides. Depending on groundwater discharge rate it contains either fresh or brackish water. The lake is up to 10 m deep and sometime a halocline can be observed at depth. The groundwater has a temperature of around 20°C and is low in dissolved CO_2, suggestive of a high altitude source.

The Kamakalepo System is formed by very olivine phenocryst-rich, picritic lavas of high density and moderate vesicularity (Fig. 11). Olivines are up to 3 mm in size and iddingsitized along fractures, coloring them giving them brown. Similar flows, belonging to the same age group crop out further to the west, from which one ^{14}C age is available, dating the flows to 7360±60 a BP.

Lua Nunu plus Pork Pen and Stonehenge form two local kipukas, i.e. they are situated on topographic crests, not overrun by later lava flows. They are covered only by a relatively thin layer of ash (a few decimetres) possibly wind-deposited and derived from the thicker genuine Pahala Ash deposits mauka. The three pukas formed when the flow was still active (so called "hot pukas") and they served as rootless vents, issuing lava, thereby forming local shields that rose above the surrounding topography. In contrast to this the site of Waipouli was covered by two consecutive a'a-flows (Upper and Lower Waipouli Flows) (Fig. 12 and Fig 13). The Waipouli Puka therefore is a "cold puka" collapsed thousands of years after the activity of the tube. Detailed geological mapping (by Philip Stankiewicz and Stephan Kempe in 2000, unpublished; Fig. 13) of the area shows the presence of a series of up to ten individual post-ash flows, among them a wide-spread black pahoehoe flow that thinly covered much of the area (Table 2).

This black pahoehoe played a vital role in transforming the Kamakalepo System to its present state by intruding it at several places. First of all, it (or a lava comparable to it) entered a puka of the Kamakalepo system mauka that today is no longer visible. From there it flowed down the tube eventually sealing its

Figure 10. View of the underground lake in Waipouli from the entrance (note small rubber dingy in about a distance of 30 m from the lake shore).

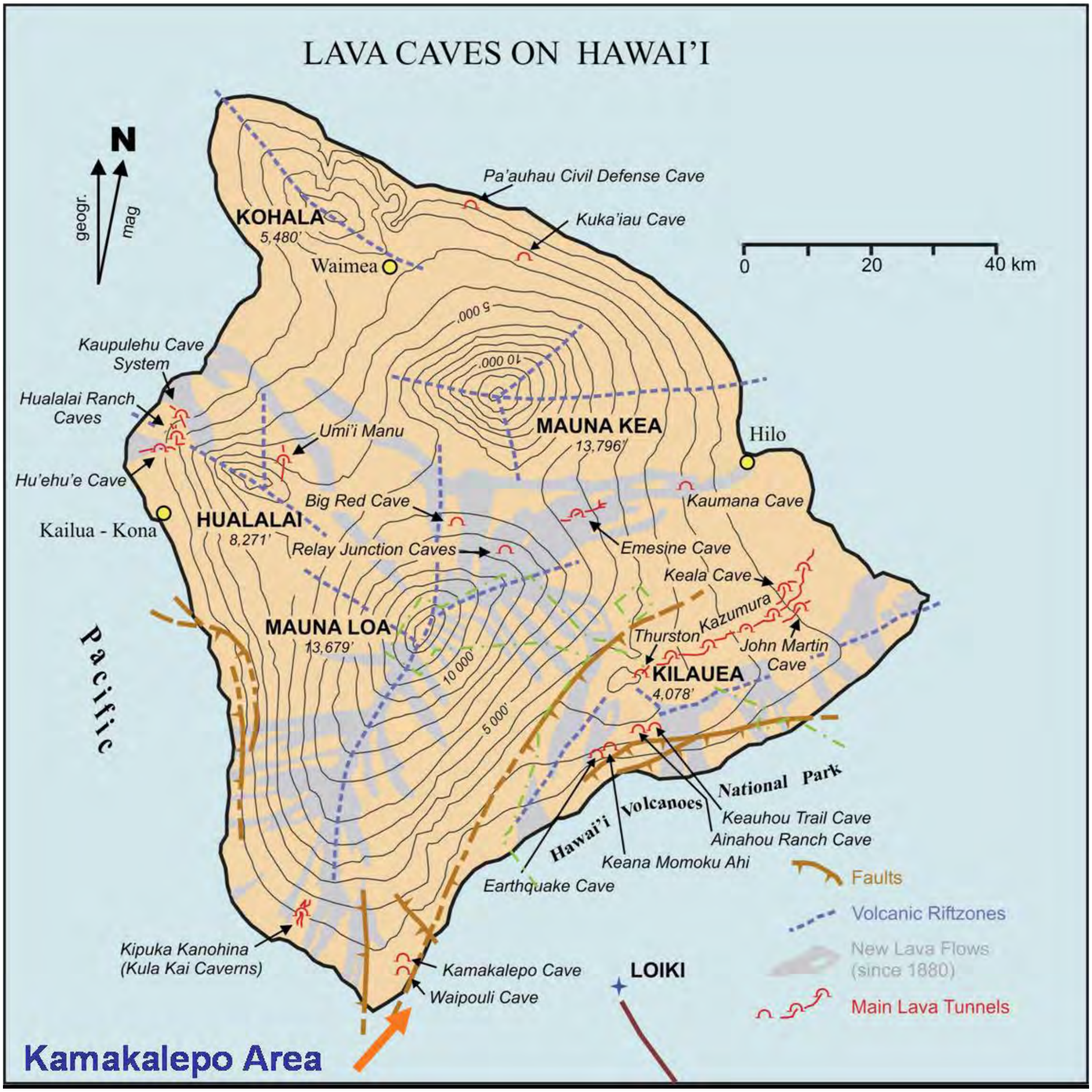

Figure 1. Map of Hawai'i with major cave systems.

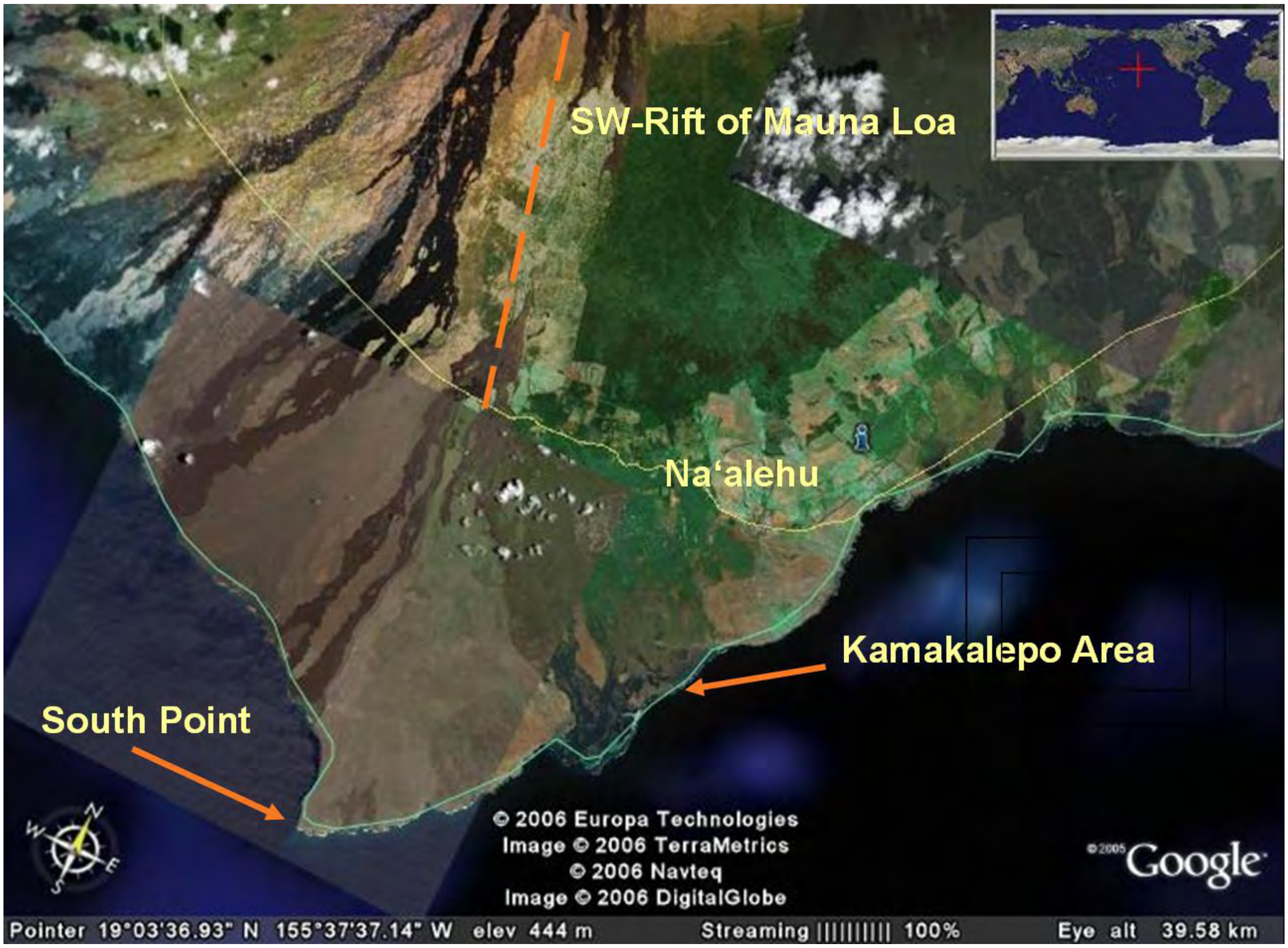

Figure 2. Google Earth picture of the southern tip of the Island of Hawai'i.

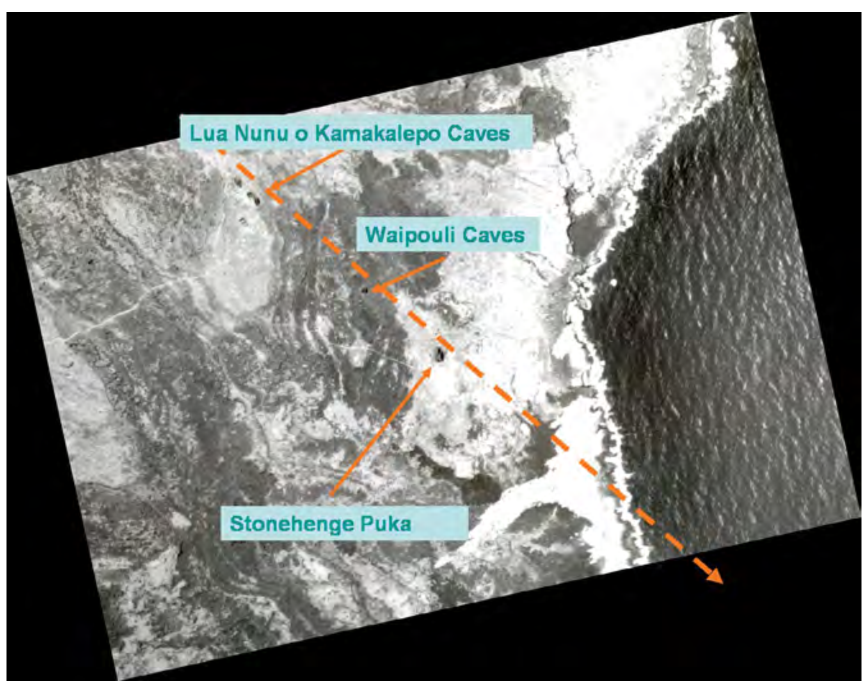

Figure 3. Aerial picture of Kamakalepo area. The light area is marks the grass-covered "Pahala Ash" outcrop.

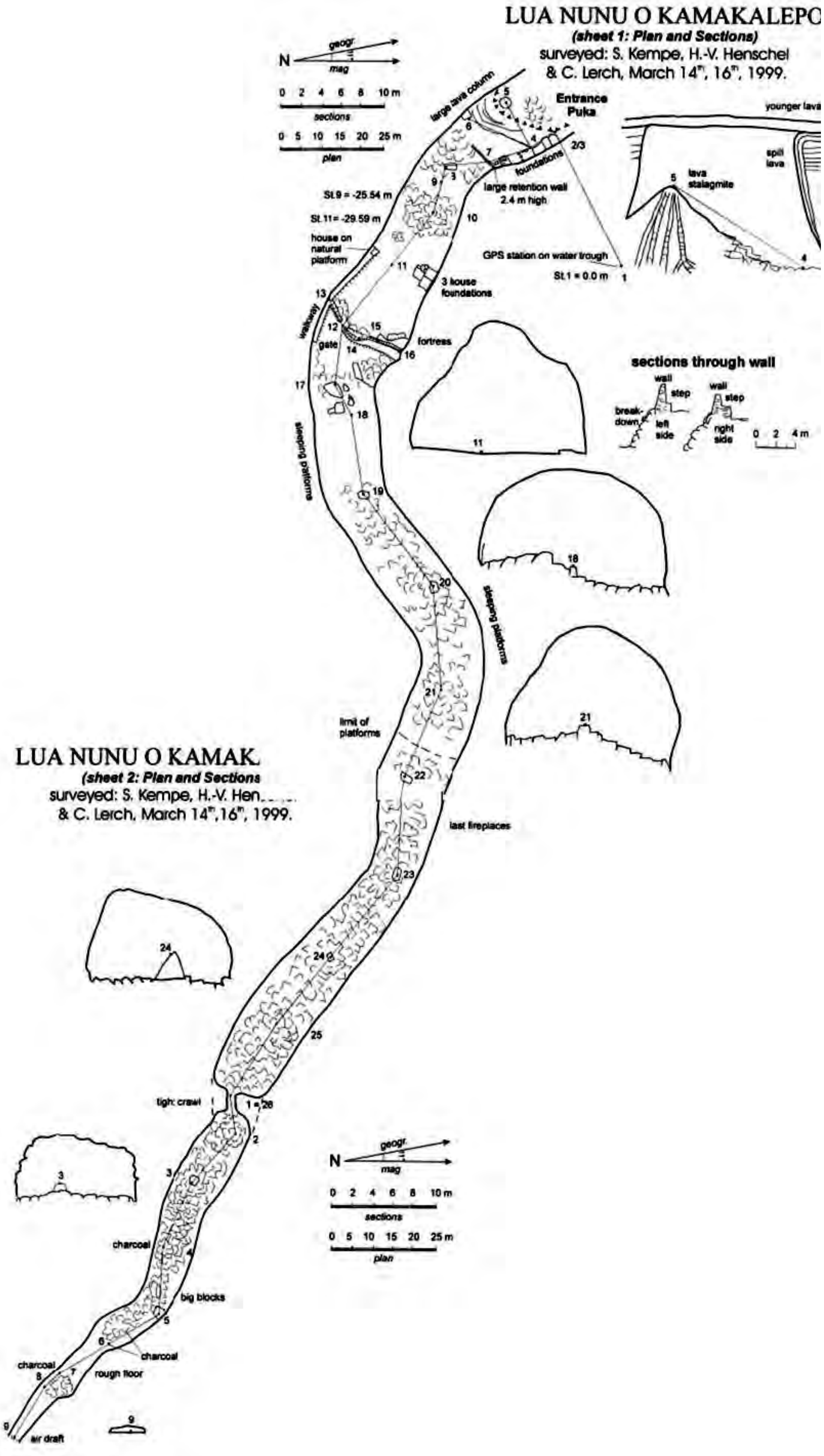

Figure 5 a. Map of Lua Nunu o Kamakalepo Mauka Cave.

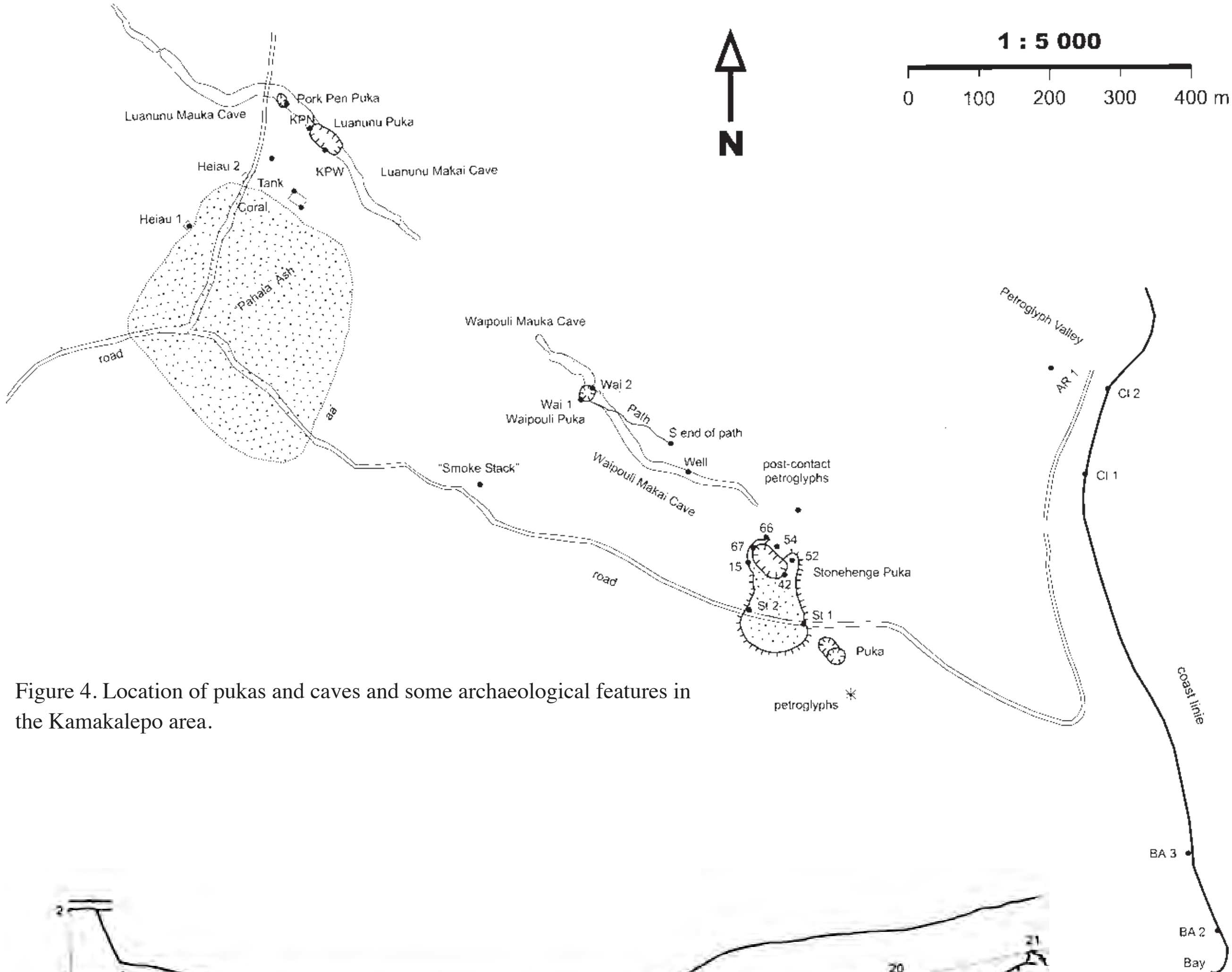

Figure 4. Location of pukas and caves and some archaeological features in the Kamakalepo area.

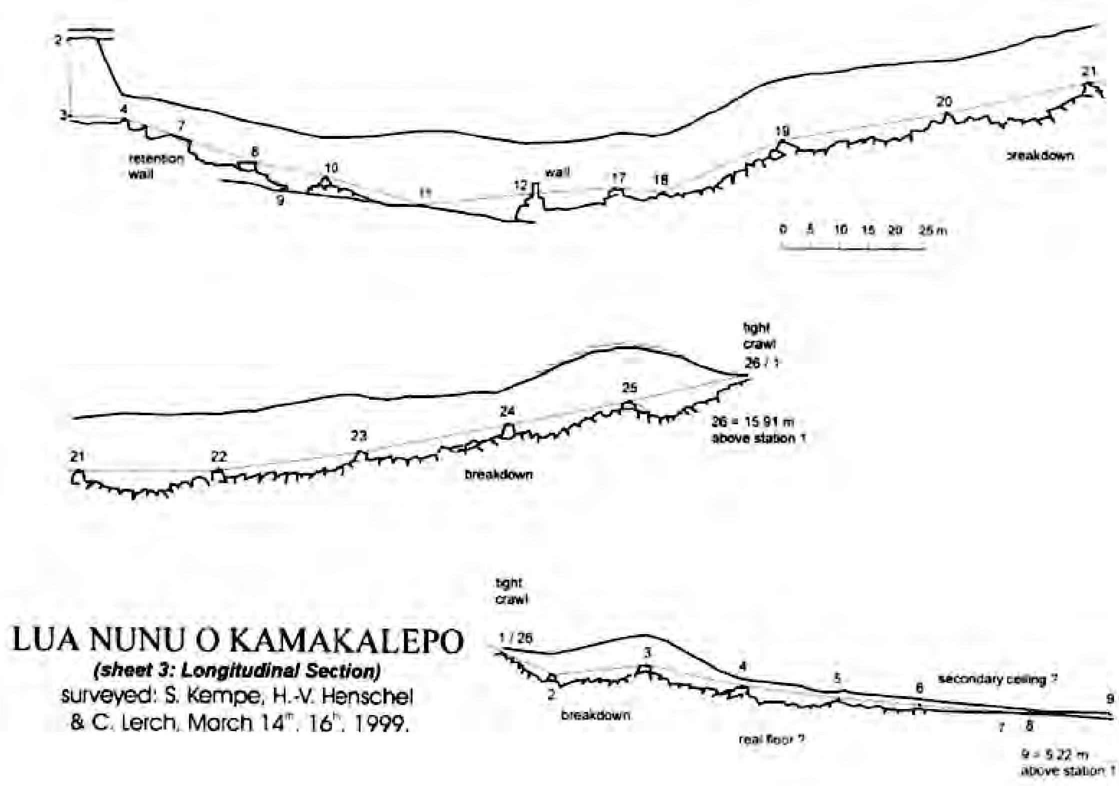

Figure 5 b. Longitudinal section of Lua Nunu o Kamakalepo Mauka Cave.

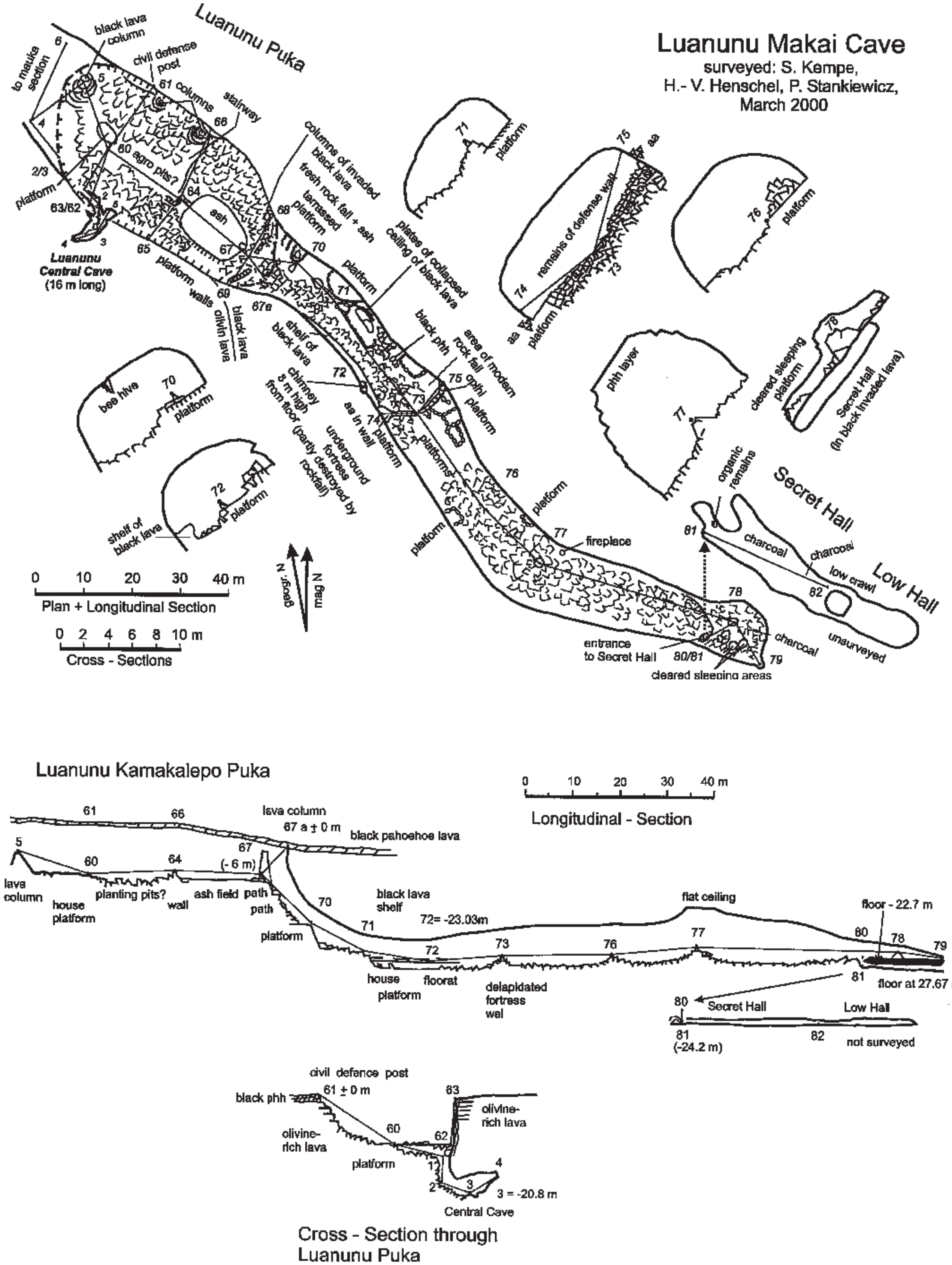

Figure 6. Map and longitudinal section of Lua Nunu o Kamakalepo Makai Cave.

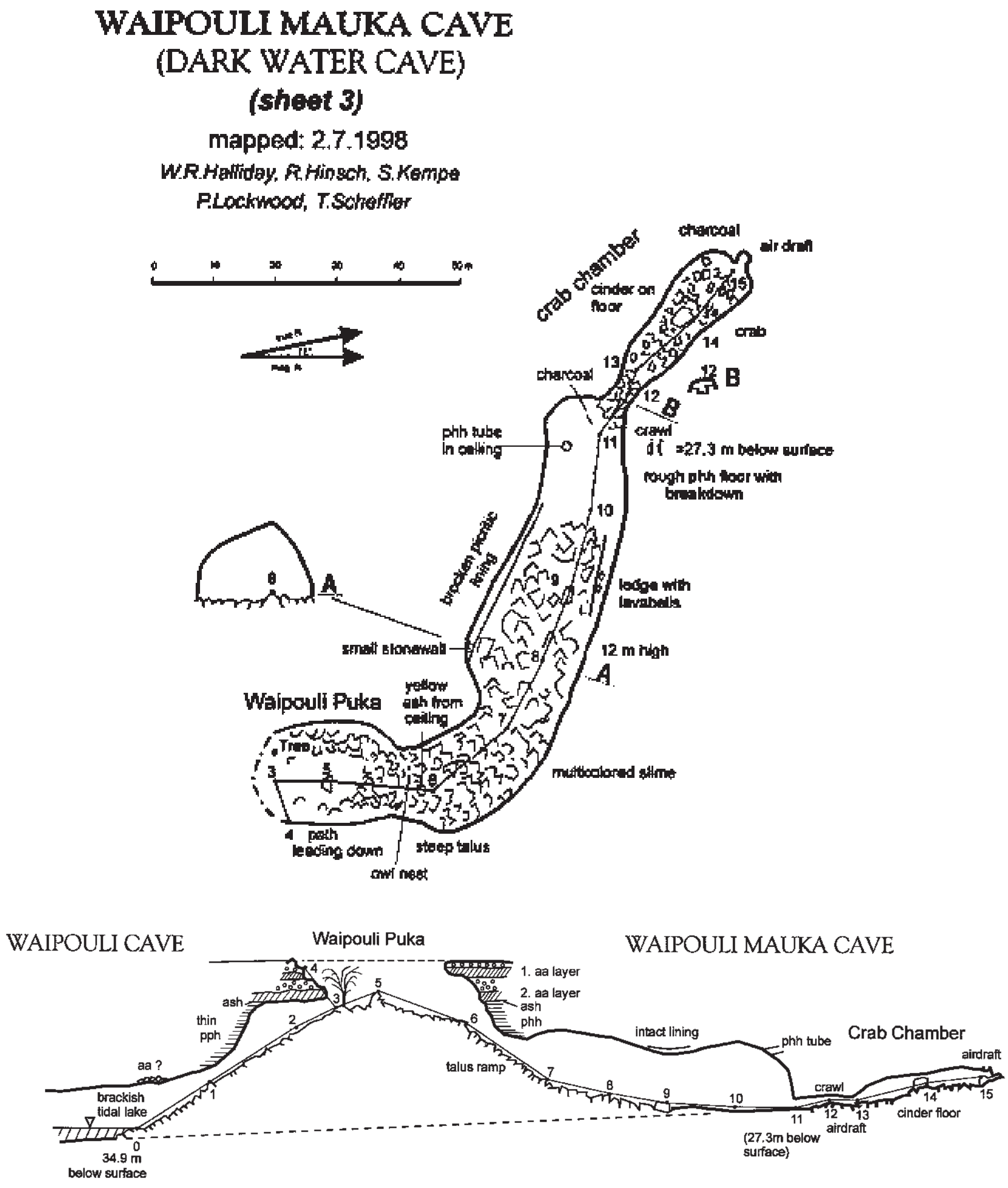

Figure 7. Map and longitudinal section of Waipouli Mauka Cave.

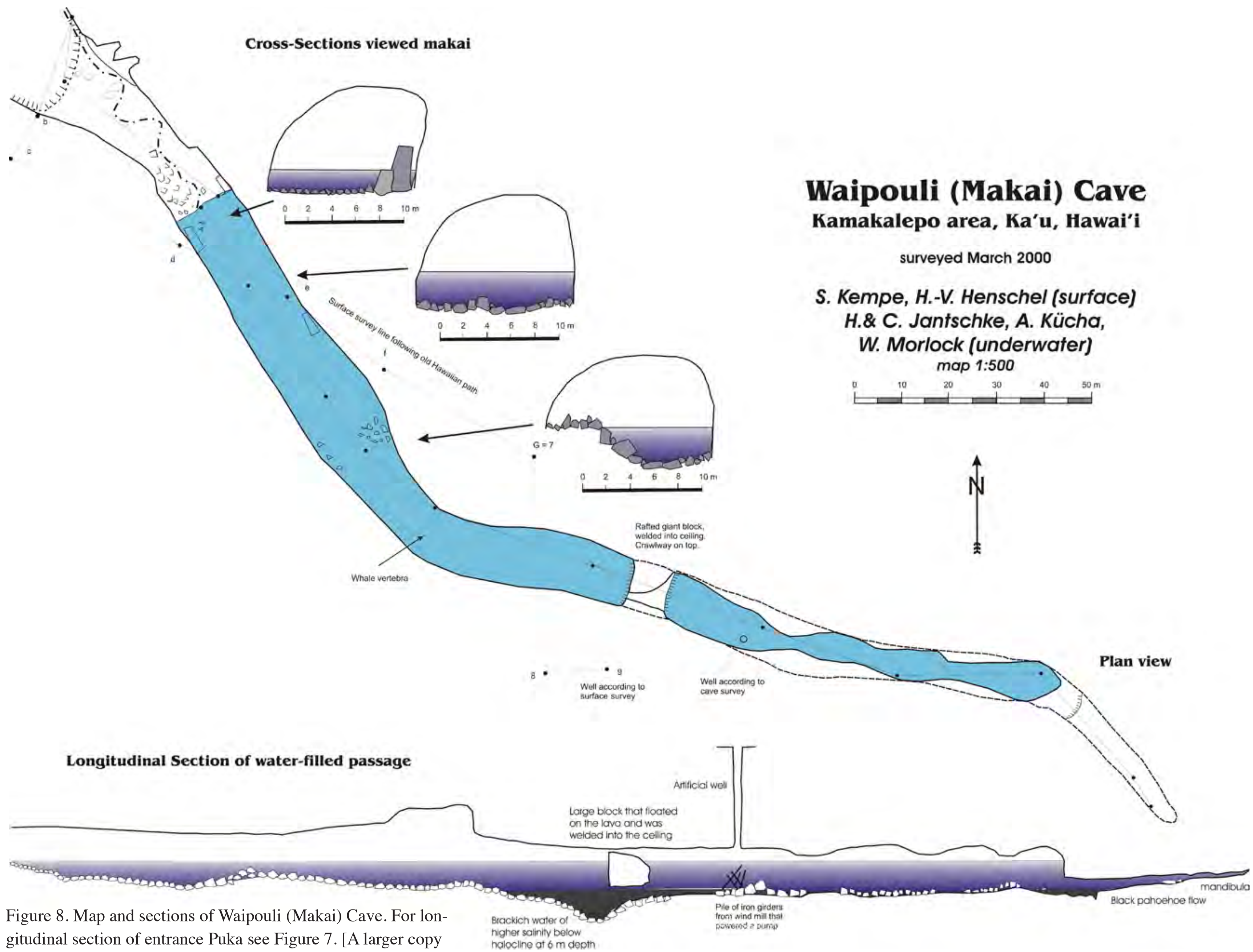

Figure 8. Map and sections of Waipouli (Makai) Cave. For longitudinal section of entrance Puka see Figure 7. [A larger copy of this map appears in the supplementary material on the CD.]

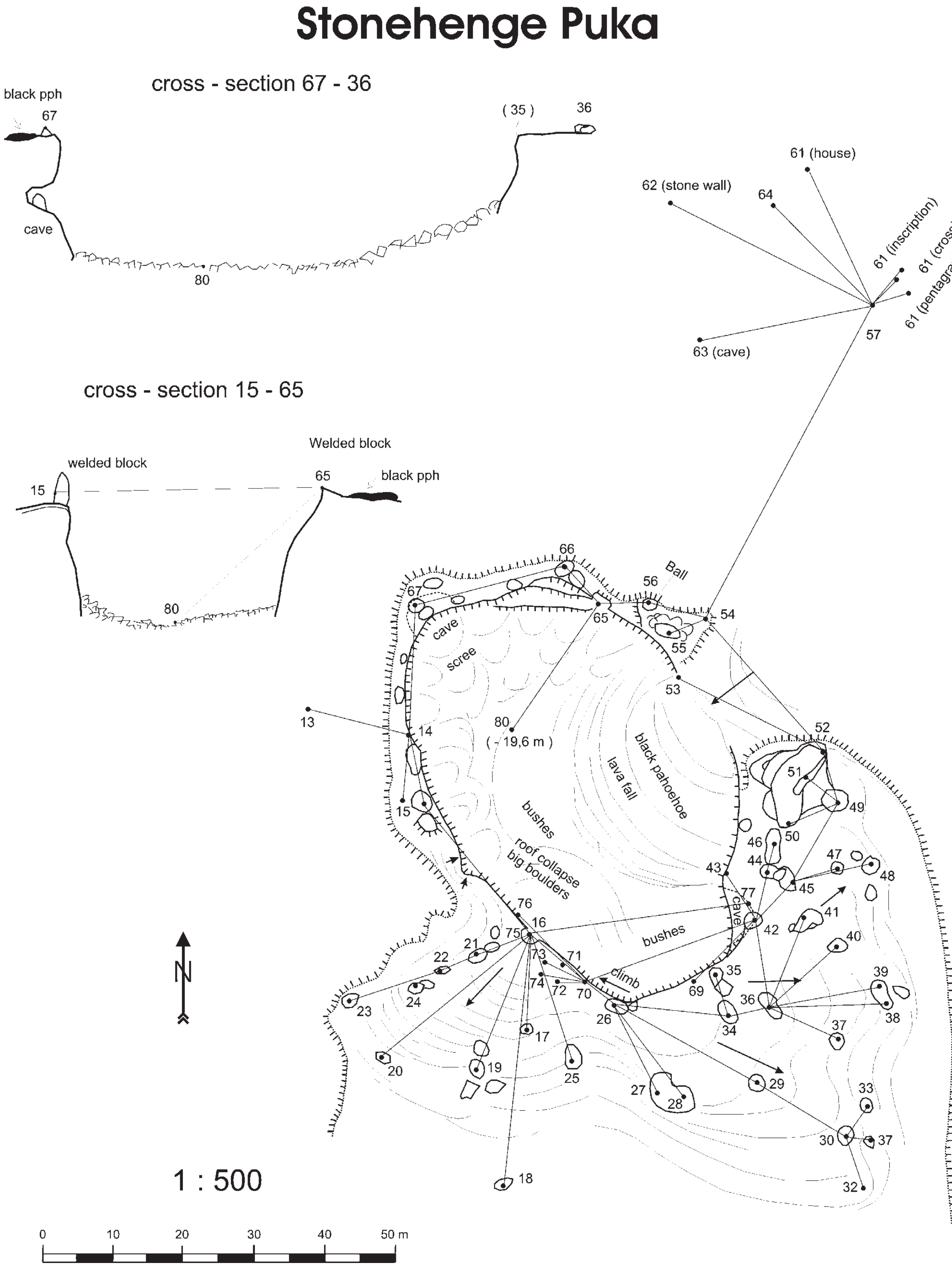

Figure 9. Map and cross-section of Stonehenge Puka.

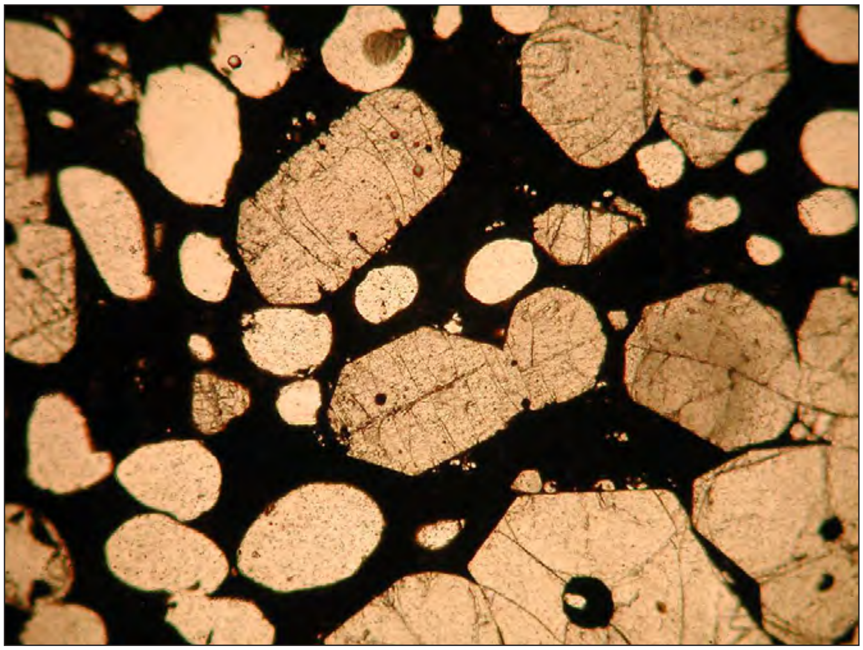

Figure 11. Petrographic thin section of the Kamakalepo-Waipouli-Stonehenge olivine vesicular picrite (plain light). The groundmass consists of opaque oxides; plagioclase is absent both as phenocrysts or in the groundmass; olivine is euhedral, forming a glomeroporphyritic texture with two generations of crystal sizes (large and medium-sized). Section from sample of Stonehenge Puka. (Petrographic description pers. com. A. Al-Malabeh, Hashemite Univ. Zarka, Jordan).

Figure 12. View of the Waipouli Puka looking west. Note the two a'a flows overriding the Kamakalepo tunnel system before the puka collapsed (so-called "cold puka").

upper end. Enough heat was transferred into the system to oxidize much of the surface in the mauka part of Kamakalepo rendering it hematite-red. The black lava apparently was only stopped by breakdown. Further down, the black pahoehoe flowing on the surface intruded the Pork Pen Puka situated on top of the Lua Nunu Mauka section filling it partly. Next the black lava cascaded into Lua Nunu from its eastern and southern rims forming veritable curtains and large stalagmitic columns (Fig. 14). Inside the tunnel the lava flowed mauka, covering the original floor up to a point where it was stopped by breakdown. Makai it flowed all the way into Waipouli Mauka Cave or even further, thereby sealing the connection between Luna Nunu and Waipouli caves. In Waipouli Mauka Cave, its surface reappears as rough a'a while it is still pahoehoe in the Lua Nunu Makai section; there it even formed its own tube that can be entered. The Hawaiians deliberately hid this "Secret Passage" (campe Fig. 6). Finally, large volumes of the pahoehoe intruded Stonehenge Puka through a breech of its rim in the east, sealing the former entrances to the tunnel below at both ends (Fig. 15). Internally, it had enough head to flow a few hundred meters mauka to seal the lower end of Waipouli, where is appears underwater covered with glass shards, indicating that the tube was water-filled already at the time of the black pahoehoe intrusion (Figs. 16, 17). The makai section of Stonehenge was probably filled completely.

The pukas give opportunity to study the roof sequence of the Kamakalepo System. Two profiles were inspected in more detail: that of the Lua Nunu Mauka (Fig. 18) and that of Waipouli Makai (Fig. 19). These sections show that the formation of the cave itself appears to have been a complex process. The evidence that the primary cave roof at those profiles was formed by repeated inflation of pahoehoe sheets is inconclusive. Such a process would have produced a roof consisting of a set pahoehoe sheets stacked upon each other, with the oldest sheet on top, having a rope pattern on its surface (e.g., Kempe, 2002). This mode of tube formation is observed in present day Kilauea lavas (e.g., Hon et al., 1994) and is applicable to most of the long lava tunnel caves so far known on Hawaii.

The profiles show that the cave roof is composed of a very thick stack (in Waipouli Makai 18 m thick) of thin-bedded pahoehoe, often showing surface ropes. These sheets are intercalated with a few, relatively thin a'a layers. It appears that these sheets are overbank lavas, produced from root-less vents situated mauka. Multiple vertical linings appear in the ceiling of Waipouli Mauka, on the walls of Lua Nunu, and on the walls of Stonehenge Puka indicating that at those places the roof of the cave was open and lava emerged to form thin, irregular overbank lava sheets. In both of the profiles we were able to identify the one pahoehoe sheet which became the ceiling interface of the evolving tunnel below. It is marked by glazing on the lower side and, in case of the Waipouli Profile, by conical stalactites. This ceiling was thickened downward by multiple accretionary linings, well visible in the roof of Waipouli Mauka. This lining also extends downward to cover the walls in thick sheets. In some of the places the lining has sagged or slid from the wall behind. In the Waipouli Profile two a'a layers were noticed behind the lining, indicating that the lava flow has cut down into pre-existing layers. These are also of picritic lava, probably belonging to a related but earlier flow of the same volcanic activity.

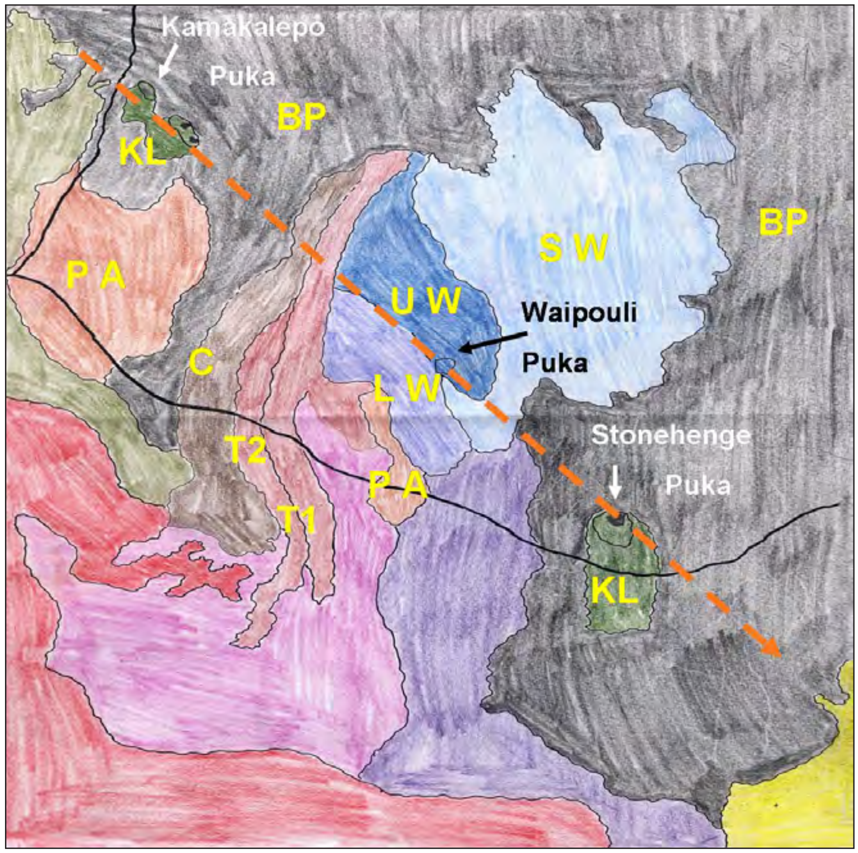

Figure 13. Geological map of the Kamakalepo area (by P. Stankiewicz, 2000, unpubl., University of Darmstadt). Stratigraphy (from top to bottom). Black Pahoehoe Flow (BP); Clover A'a Flow (C); Table-top A'a I and II flows (T1, T2); Upper Waipouli A'a Flow (UW); Lower Waipouli A'a Flow (LW); S Waipouli A'a Flow (SW); "Pahala" Ash (PA); Kamakalepo Lava (7360±60 a BP) (KL). Further flows, younger than the Kamakaleopo Lava but older than the Black Pahaehoe Flow occur to the SW; yellow marks a thin layer of wind-driven marine carbonate sands. [The color version of this figure in the PDF file is clearer.]

The evolving lava conduit therefore enlarged downward, until it was large enough to accommodate the flow, ceasing the overbank activity. It is conceivable, that the Kamakalepo System formed by the often cited mechanism of a crusting over channel, but the internal structure of the roof is not entirely clear to accept this hypothesis. Specifically, observations of the roof structure about 100 m into the Waipouli tunnel show a more regular picture. Here the primary roof consists of a stack of pahoehoe sheets covering the tunnel uninterrupted from one side to the other. This clearly speaks for the inflationary mode of tube formation. It is possible that this was the general mode of formation and that the primary roof collapsed in places, forming rootless vents and overbank

Figure 14. View of large stalagmite created by black pahoehoe lava intruding the pre-existing Lua Nunu o Kamakalepo Puka. View is from the mauka cave entrance south.

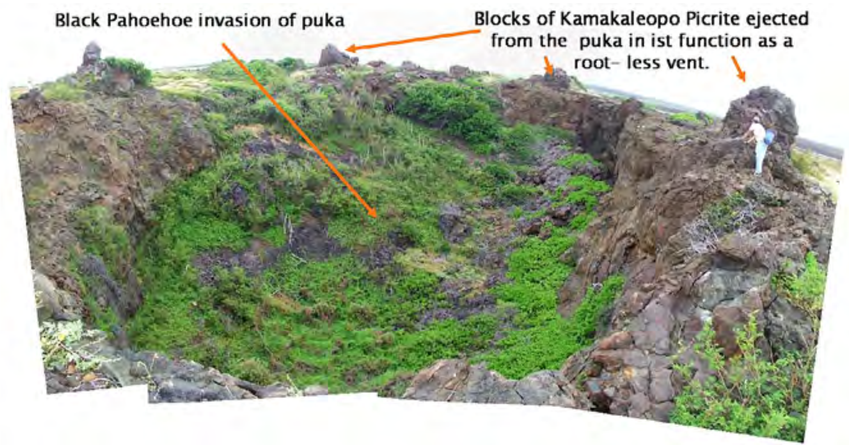

Figure 15. Panorama view (south) of the 60 m long and up to 20 m deep Stonehenge puka. Its rim is marked by large agglomerated lava boulders ejected from the puka when it served as a root-less vent when the Kamakalepo lava tunnel overflowed. From the SE the puka was later intruded by the black pahoehoe lava, marking the youngest lava event in the area.

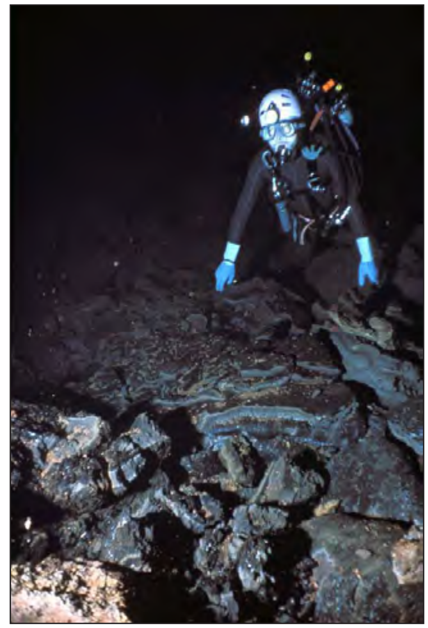

Figure 16. Underwater photograph of the black pahoehoe lava at the end of the Waipouli (makai) Cave. (Picture by A. Kücha, for scale. first author).

Table 1. Length of Kamakalepo Cave System (north to south).

Lua Nunu o Kamakalepo Mauka (of this mauka of crawl)	416.8 m (111.5 m)
Lua Nunu Central Cave	26 m
Lua Nunu o Kamakalepo Makai	169.6 m
Waipouli Mauka	125.5 m
Waipouli Makai	260 m
Total	997.9 m

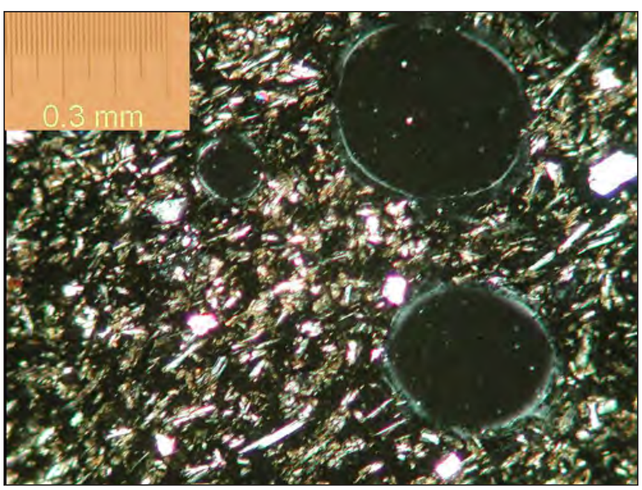

Figure 17. Petrographic thin section (polarized light) of Waipouli terminal black lava intrusion of olivine-plagioclase vesicular glassy basalt. Composition is about 40% glass, 40% vesicles, 15 % microlitic plagioclase and 5 % phenocrysts of euhedral olivine and plagioclase (no pyroxene phenocrysts). Glasses are slightly to medium palagonitized (yellow to light brown rims of vesicles). (Petrographic description pers. com. A. Al-Malabeh, Hashemite Univ. Zarka, Jordan).

Figure 20. At the end of the lake in Waipouli (makai) Cave, a huge block (ca. 12 m wide, 8 m long and 6 m high) that floated on the lava in the tunnel is welded into the ceiling.

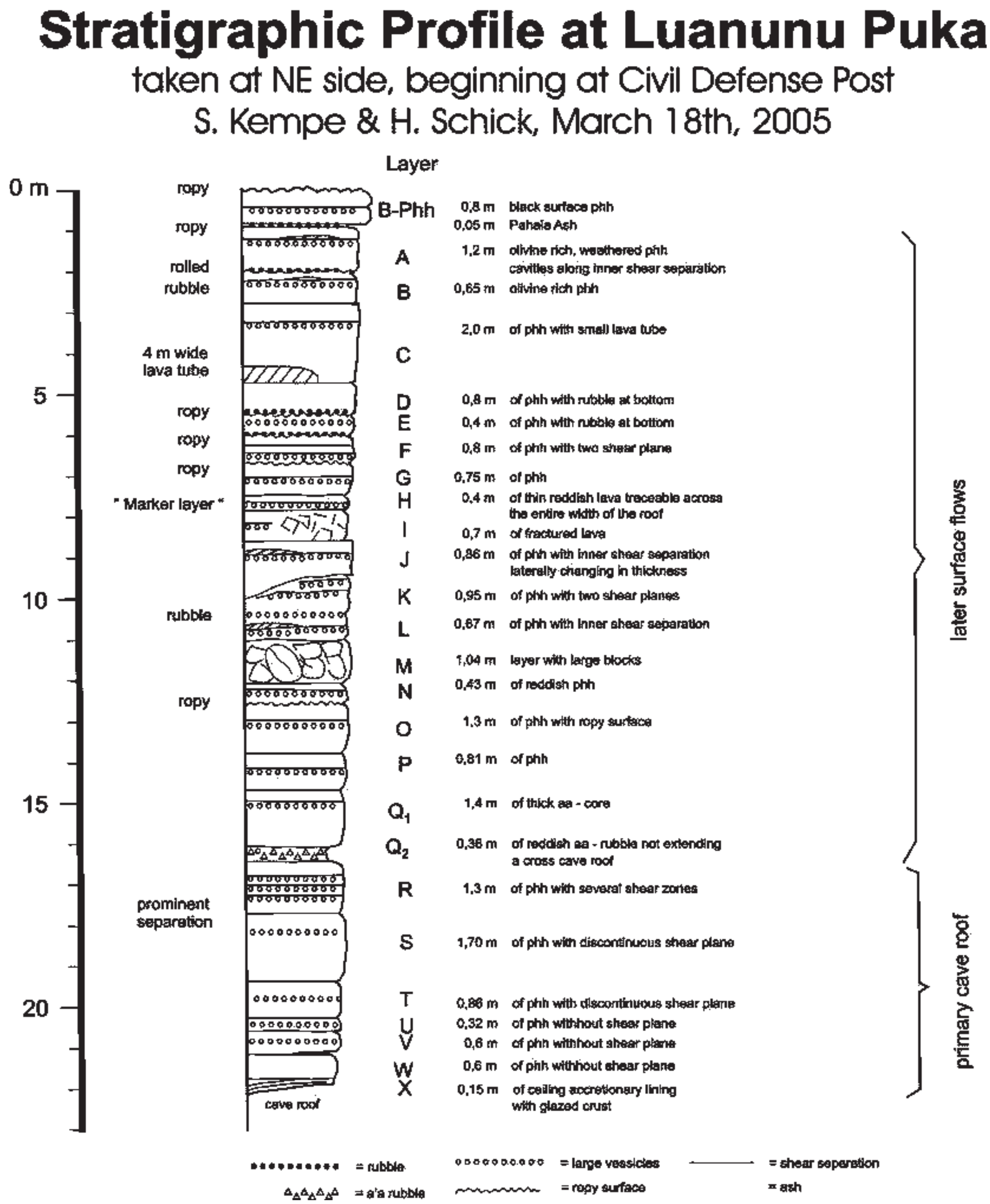

Figure 18. Stratigraphic profile of the Luna Nunu o Kamakalepo Puka at the mauka entrance.

Table 2. Stratigraphy of the lavas forming and overlying the Kamakalepo-Waipouli-Stonhenge Cave System (rock identification pers. com. A. Al-Malabeh, Jordan, 2006).

Order	Lava flows	Thickness	Rock type
8	Black Pahoehoe Flow	ca. 1 m	Olivine-pyroxene vesicular basalt
7	Clover A‘a Flow	ca. 2 m	Basalt
6	Table-top A‘a I and II flows	ca. 2 m	Olivine-plagioclase-pyroxene vesicular basalt
5	Upper Waipouli A‘a Flow	2.8 m	Olivine-pyroxene vesicular basalt
4	Lower Waipouli A‘a Flow	3.7 m	Olivine-plagioclase-enstatite vesicular basalt
3	S Waipouli A‘a Flow	ca. 3 m	Olivine-pyroxene-plagioclase vesicular basalt
2	"Pahala" Ash	ca. 1m	Palagonitized volcanic ash
1	Kamakalepo-Waipouli-Stonehenge Lava	>25 m	Vesicular picrite (no plagioclase) with matrix of oxides. Olivine slightly iddingsitized.

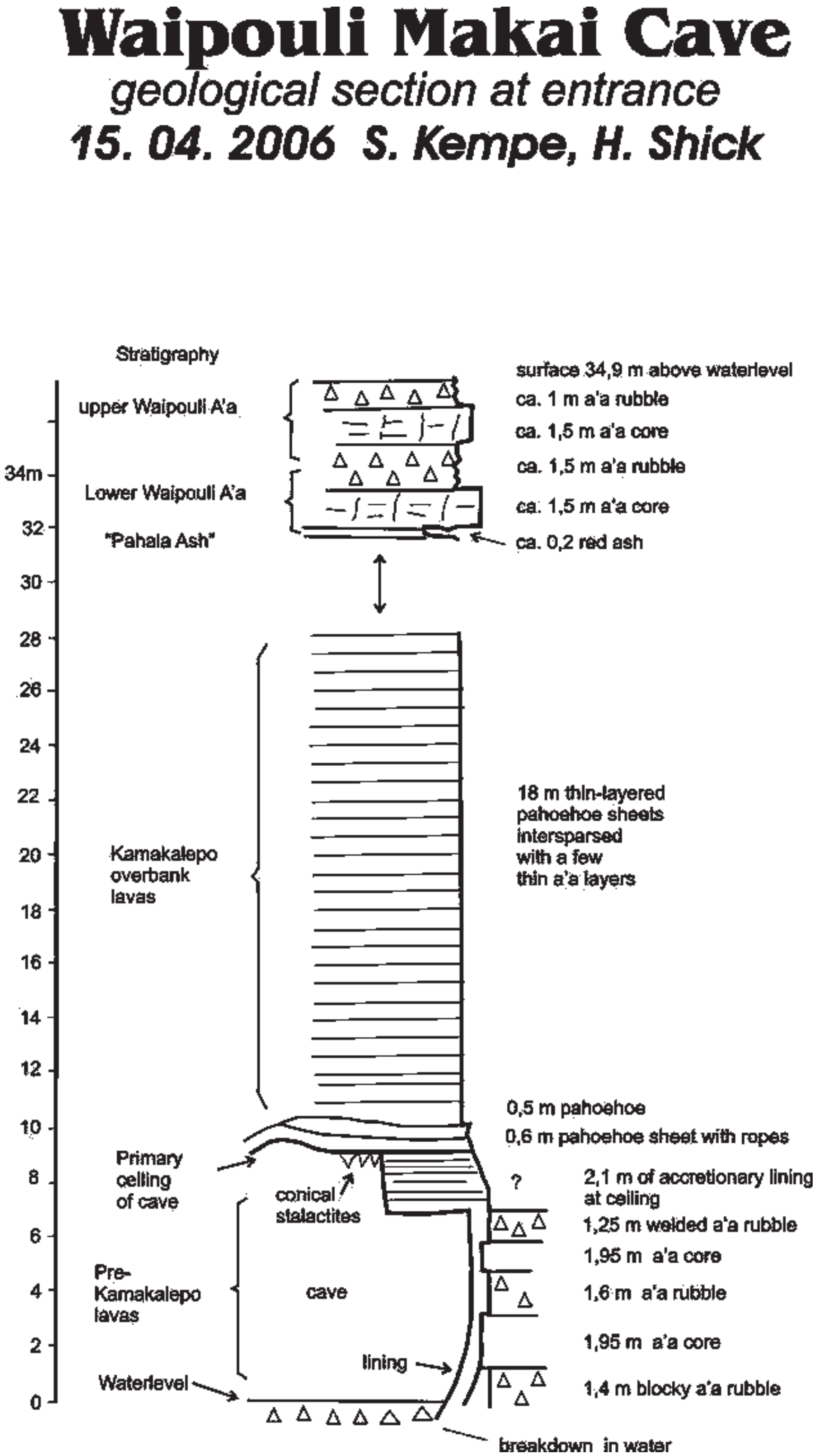

Figure 19. Stratigraphic profile of the Waipouli Puka at the makai entrance.

lavas locally. In any case, the resulting cavity was enormous, at one place 23 m wide and 13 m high. It is the widest and oldest lava cave reported from Mauna Loa thus far. The flow it sustained must have been substantial since in Waipouli Makai a block 12 m wide, 6 m high and 8 m long, was carried as a floater on the lava, jammed into the ceiling and welded to it (Fig. 20; compare Fig. 8 for location).

All of the caves and their surrounding contain ample traces of past occupation by Hawaiians (see Kempe et al., this volume).

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Archaeology of the Kamakalepo/Waipouli/Stonehenge Area, Underground Fortresses, Living Quarters and Petroglyph Fields

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South of Na'alehu, Hawaii, near the coast, a small outcrop of ash is found that is clearly visible on aerial photographs as a lemon-shaped light spot. It belongs to one of the agriculturally valuable "Pahala Ash" sites that sustained early Hawaiian populations (Kirch, 1985). The area called Kamakalepo is just East of South Point, where similar soils provided for some of the earliest settlements on Hawaii. The area under investigation (Fig. 1) contains unique archaeological features both above and below ground (Bonk, 1967; Kempe, 1999) and has been studied by the authors over the last several years.

A large cave system consisting of four sections of a once much longer tunnel in Mauna Loa lavas (see Kempe et al., this volume) was used extensively by the native Hawaiians. The system is entered through two pukas: Lua Nunu o Kamakalepo (Pigeon Hole of the Common People) now overgrown by acacia shrubs (Fig. 2) and Waipouli (Dark Waters) (Fig. 3). Both of these pukas give accesses to uphill (mauka) and downhill (makai) caves, totalling together 1 km in length (see Table 1 and Figs. 5 to 8 in Kempe et al. this volume) Two further pukas belong to the system, "Pork Pen Puka" (mauka of Lua Nunu) and "Stonehenge Puka" (makai of Waipouli) for which no local names are known. Pork Pen Puka is a depression set into the roof of Lua Nunu Mauka Cave, the bottom of which is a secondary ceiling to the cave below. Stonehenge Puka is a large root-less vent with rafted blocks around its perimeter, 60*40 m wide and up to 20 m deep (see Fig. 9 in Kempe et al., this volume).

Underground, the caves of the Lua Nunu are the ones used primarily (maps see Figs. 4 and 5). An old, now mostly obliterated path led down from the NE rim. The other sides of the puka are overhanging. Within the puka small outcrops of Pahala Ash exist, possibly forming field plots or agropits. Retaining walls are found at both entrances providing for level ground on which foundations of huts are still noticeable (Fig. 6). The main features are two large defence walls across the cave erected by stacking breakdown blocks. The wall in the Makai Cave, 40 m inside the entrance, collapsed mostly (compare Fig. 6 for location), but the one in the Mauka Cave, ca. 60 m into the cave, is well preserved (compare Fig. 5 for location). It has all the characteristics of a medieval defence wall: It is ca. 2 m high and up to 1 m thick and because it was erected on breakdown it reaches 3.7 and 5.5 m above the floor (Fig. 7). It stretches from wall to wall and due to its convex-mauka curvature, is reaches a length of almost 25 m (the cave being 23 m wide and 14 m high in its centre). A doorway slightly off the middle (Fig. 8) of the wall admits access and platforms behind the wall (Fig. 9) permit the defenders to throw sling stones and spears at the attackers. Sling stones (wave-worn pebbles) are found on the floor at places (Fig. 10). The defenders would stand in the dark, while the attackers would be outlined by daylight coming in from the entrance. Behind the wall, Bonk (1967) counted 102 sleeping platforms these extend well into the zone of complete darkness. Charcoal and seafood shells and some fish bones can be found everywhere, suggesting that the place has in fact served its purpose. Charcoal dating is in progress to find out when the cave has been in use. Artifacts have been collected in 1908 by Meineke and 1967 by Bonk. In the far back of the cave, we opened a

Figure 2. Southward panorama view of the large Kamakalepo puka. Note person on left for scale and post at rim of puka. This post used to hold a sign marking the cave as a civil defence shelter in the 1950ies.

crawl, giving access to more than 100 m of additional cave (see Fig. 4). Even here we found a few charcoal bits on the floor, suggesting that the Hawaiians had already explored this section, albeit by a now collapsed crawl.

Underground fortifications have been described from other caves on Hawai‘i. An specifically elaborate example is the Cave of Refuge on the Hakuma Horst in Kalapana, Puna District. There the defense function was obtained by narrowing the entrance to the cave to a crawlway that could be entered by attackers only one at a time (Kempe et al., 1993). La Plante (1993) reported about fortifications (defense walls, fortified crawlways) from the Puna District (most probably Pahoa Cave) without giving details about locations or constructional dimensions. Small defense walls, now crumbled seem to have protected the cave passages below Keala Pit as well (Kempe & Ketz-Kempe, 1997). More

Figure 3. Eastward panorama view of the Waipouli Puka. Note the person climbing down the only path into the puka and down to the lake in the makai section of the cave.

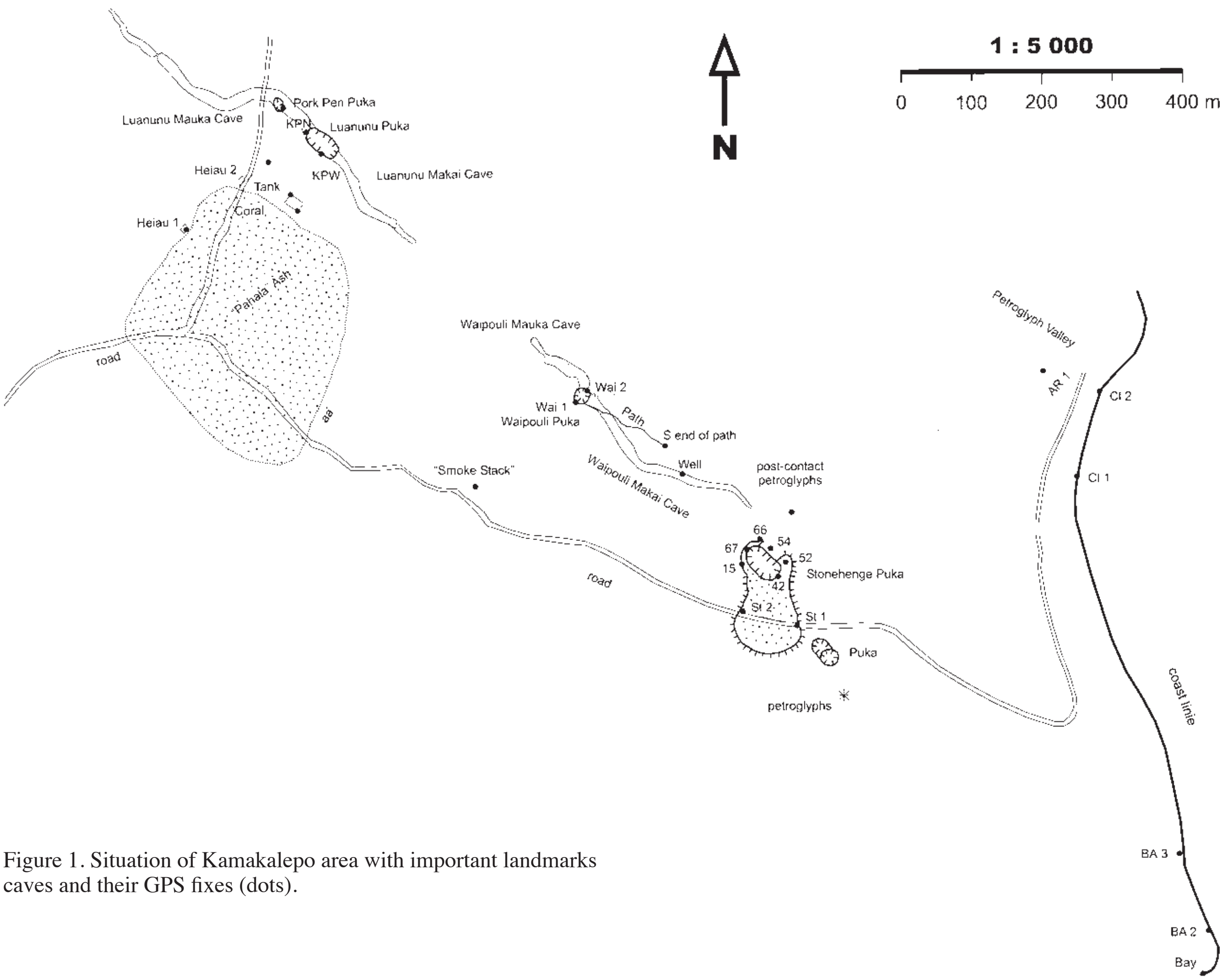

Figure 1. Situation of Kamakalepo area with important landmarks caves and their GPS fixes (dots).

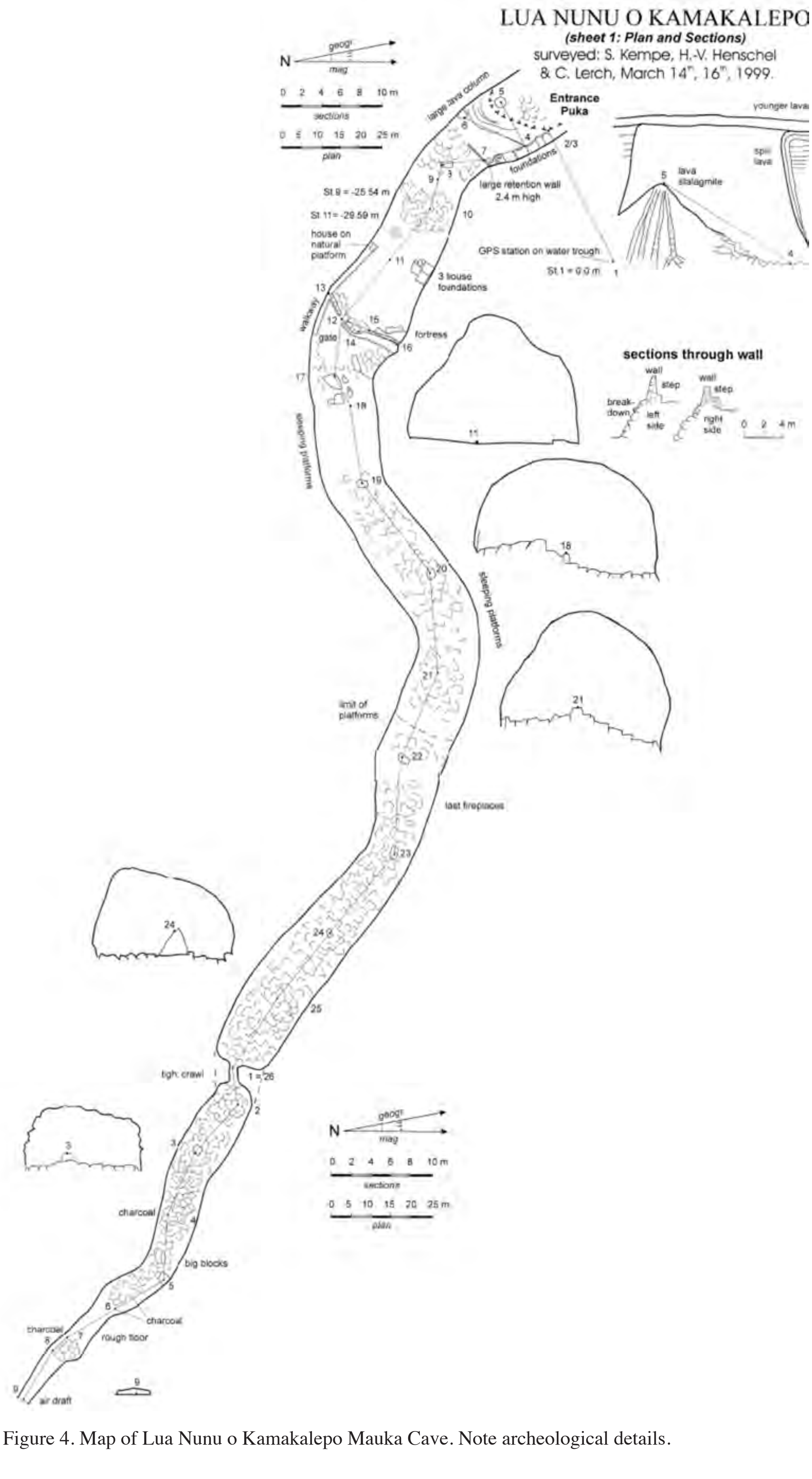

Figure 4. Map of Lua Nunu o Kamakalepo Mauka Cave. Note archeological details.

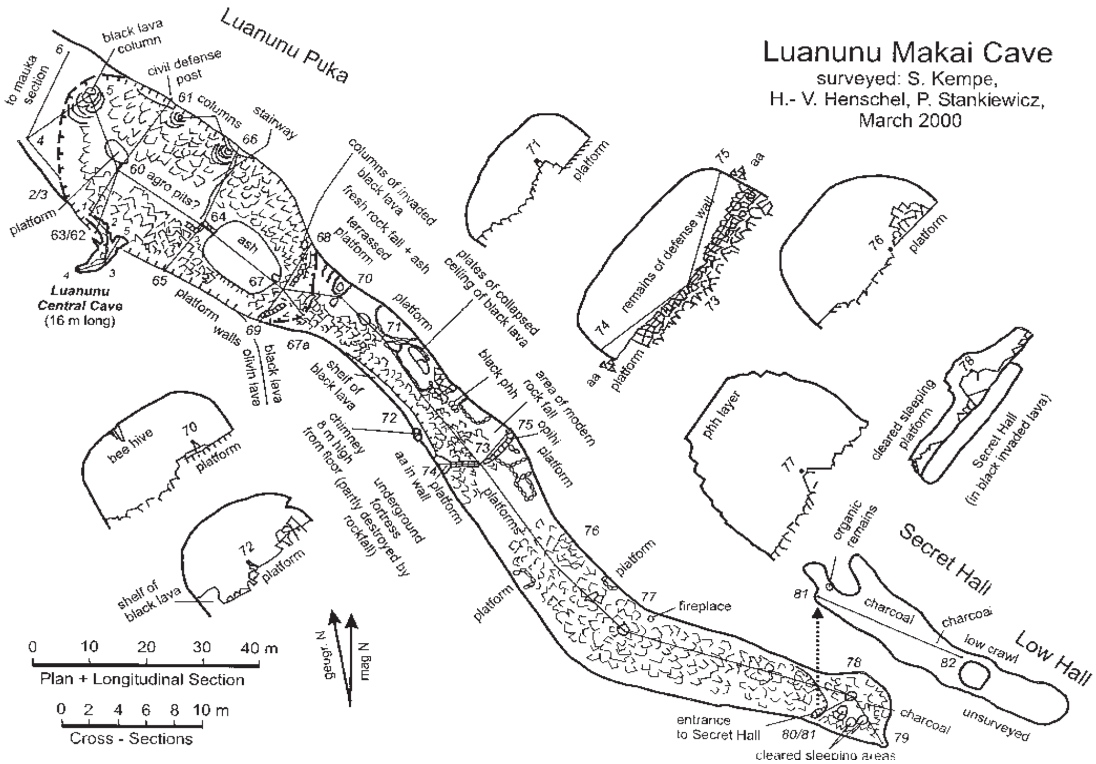

Figure 5. Map of Lua Nunu o Kamakalepo Makai Cave. Note archeological details.

Figure 6. View from the inside of the Lua Nunu o Kamakalepo Mauka Cave towards the entrance with 2.4 m high retaining wall and sections of the old path leading into the cave.

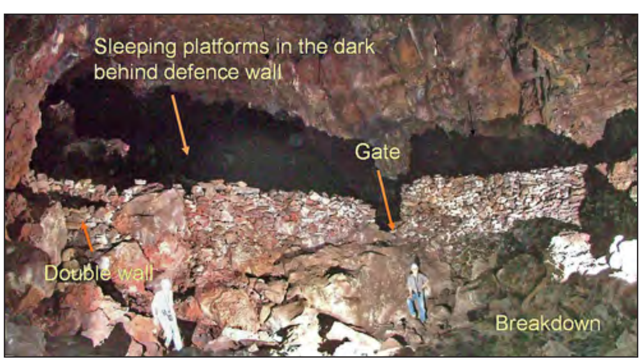

Figure 8. View of the gate from the inside. Note the entrance of the cave 60 m away in the background.

Figure 7. View mauka of the 25 m long defense wall in the Lua Nunu o Kamakalepo Mauka Cave. Note persons for scale and gate at the center of the wall.

Figure 9. Fighting platform behind the southern side of the defense wall.

Figure 10. Sling stones were used in the defense of the cave and are found scattered over the floor.

Figure 11 (left). Weathered whale vertebra from the deeper part of the lake in Waipouli Makai Cave.

Figure 12 (right). Opening of an over 20 m deep well dug by farmers to pump up water for cattle from the Waipouli lake.

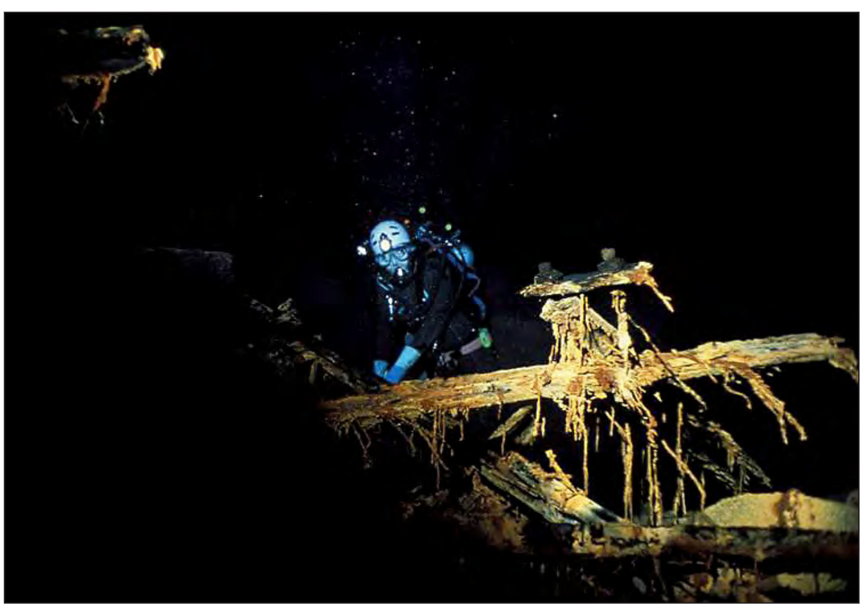

Figure 13. The girders of the wind mill providing power to the pump were thrown into the lake of Waipouli. These are now settled by iron-oxidizing bacteria forming spectacular underwater "rusticles" (Scale. first author, picture by A. Kücha).

Figure 14 (above). Small heiau (platform for a hut or small temple) at the northern edge of the Kamakalepo ash plain used formerly for agriculture.

Figure 16 (right). A beachrock (carbonate cemented lava and marine carbonate sands) placed at the southern end of the path from Waipouli Puka to mark the begin of the path in the dark.

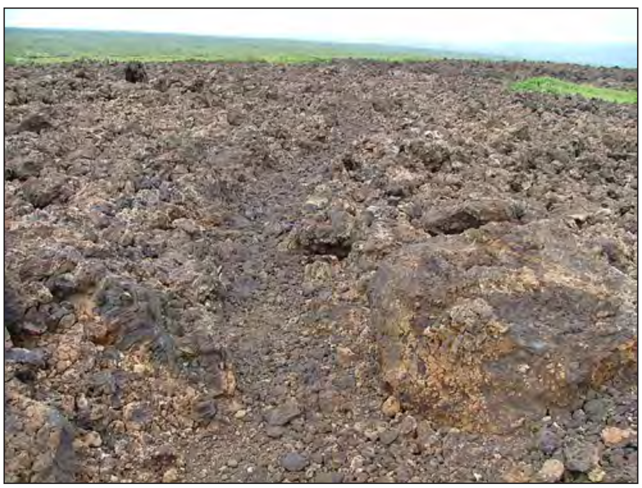

Figure 15. Old Hawaiian path leading across the a‘a from the Waipouli Puka southeastward.

Figure 17. A petroglyph of a pentagram, most probably post-contact.

Figure 18. A petroglyph of an elaborated cross, most probably post-contact and Christian in meaning.

Figure 19. A dagger and an inscription of post-contact times.

Figure 20. A southward panorama view across Petroglyph Valley, an evacuated lava channel. In an area of 50*50 m 92 petroglyphs were counted.

Figure 22. The picture of a male primate being with a long tail, possibly a monkey brought by sailors to the island in the early post-contact period.

Figure 21. Various petroglyphs of human figures, some are simple stickmen, other have a triangular body.

Figure 23. Examples of simple stickmen petroplyphs, right with a penis (male) left without (female).

Figure 24. Petroglyphs of humans with double-lined bodies.

data probably exist in internal reports of various agencies without ever having been published.

The Lua Nunu o Kamakalepo Makai Cave has also been fully explored by the Hawaiians. Platforms and fire places extend almost 100 m into the cave. At the makai end, the black pahoehoe lava that intruded the puka secondarily (compare Kempe et al., this volume) forms a separate, less than a meter high tube. It was also entered by the Hawaiians as bits of charcoal on the floor indicate. We found its entrance closed artificially by rocks, probably to hide the entrance of this chamber of last refuge (see "Secrete Hall" on map, Fig. 5).

Both of the Waipouli Caves show little signs of Hawaiian presence. In the mauka sections, just a few places with charcoal are found and a few bits of seafood shells. The floor is too rough to be of any use. The makai part is filled by a brackish water lake that is caped by freshwater at times of high groundwater flow. We found one large beach stone on the steep entrance slope and a whale vertebra in the water (^{14}C dating in progress) (Fig. 11). The water was extensively used in the 20th century when a motor was set up at the entrance on a concrete platform and water was pumped up for cattle. Also, an over 20 m deep well was dug through the cave roof (Fig. 12) and the water was pumped up by a wind mill for cattle. Part of its collapsed trestle was thrown into the well shaft and landed in the water of the cave, where it now forms interesting "rusticles" under water (Fig. 13).

Stonehenge Puka was also used by Hawaiians: Its southern wall is overhanging and provided some natural shelter. Here a few very small platforms were erected (see Fig. 9, Kempe et al., this volume).

Above ground the area shows many signs of usage. First of all there is a beach stone paved path, giving access to the area from the west (mauka). The area south of Lua Nunu is covered by ash and could have been used for agriculture, explaining the presence of the underground settlement. At the western rim of the ash plain, just a few meters on the overlaying bare lava, we found two small heiaus, compact stone platforms used either for dwelling huts or religious purposes (Fig. 1 for location; Fig. 14). The Pork Pen Puka has stone walls along its perimeter and throughout its centre, suggesting that it was used to keep pigs in there. At the eastern side of the ash outcrop, there is a rectangular structure build from pahoehoe plates which probably also was a pen either for pigs, or for goats and cows if erected after contact. Nearby, a shallow cave was found, showing also signs of occupation.

Paths connected the Lua Nunu with Waipouli (mostly overgrown now) and led towards the coast from Waipouli eastward (Fig. 15). At the end of the path a large block of carbonate containing beachrock was placed (Fig. 16), obviously a well-visible signal to guide the traveller to the beginning of the path across the Waipoli a‘a.

Within the studied area, three sites with petroglyphs occur. The one furthest to the south has mostly animal figures. The second one, north of Stonehenge, is composed of post-contact petroglyphs: It displays a pentagram (Fig. 17), a large cross made from five squares each of it inscribed with a + and a X (Fig. 18), and a sabre with a two line inscription reading: "KA IEIE PALA" and "IKA UA NOE" (the Mellow IeIe, a plant, and Strong Misty Rain; possibly the names of two lovebirds) (Fig. 19).

To the north an area the size of 50*50 centered at around 18°N59,979′, 155°E 35,823′ (Old Hawaiianm) is covered by almost a hundred petroglyphs (Fig. 20). It is situated at the seaward end of a shallow valley. We divided the glyphs into ten areas with GPS centers as listed in Table 1.

The petroglyphs are of a mixed composition, simple stickman occur next to more complicated full body pictures (Fig. 21), both in frontal as in lateral views. Two of the larger figures have long tails, suggesting they might have depicted monkeys (one of them clearly a male specimen) (Fig. 22), thus placing the petroglyphs into the early post-contact time. Some of the glyphs have been almost obliterated by later pound-marks; others have apparently not been completed. The area abounds with pound marks and marks made by sharpening tools. A total of 92 glyphs were identified that distribute among several types as shown in Table 2.

It is interesting to note that a variety of styles is present. The group of simple stickmen with arms and legs bend at right angles dominates; male and female glyphs occur with a similar frequency (Fig. 23; Table 2 first line). One of the male stickmen has two lines extending down its head, like indicating long hair. Five stickmen have one hand raised as if in greeting. A few stickmen have simple spread legs like in an inverted "Y". The triangular-bodied figures appear all without a penis and could therefore possibly all be labeled as female, a conclusion not unreasonable. The figures with an open circle as head and a double line as a body have a variety of hands (Fig. 24), mostly with three fingers, but one even has five fingers and toes. Interesting are the figures shown in side-view (Fig. 25), among them a quite large figure in Area 8 (Fig. 26). The two ape-like glyphs are among the largest. One, with a penis, is shown in side view (A6) (Fig. 22), the other (A8) is shown in frontal view with a long thin tail between the legs. Otherwise, no clear animal pictures are seen. One glyph representing a sort of

Table 1: Petroglyph groups in the Petroglyph Valley, Kamakalepo area.

N°	Min	E°	Min	Area
18	59963	155	35828	Area 1
18	59963	155	35824	Area 2
18	59969	155	35822	Area 3
18	59968	155	35828	Area 4
18	59976	155	35831	Area 5
18	59979	155	35823	Area 6 Apeman Group
18	59981	155	35819	Area 7
18	59987	155	35818	Area 8
18	59997	155	35820	Area 9
18	59983	155	35828	Area 10

Table 2: Classification of petroglphys from Petroglyph Valley, Kamakalepo area (read: 3A2 = 3 specimens in Area A2).

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

triangle and two curved lines issuing from it could be taken for the image of the head of a goat (Fig. 27).

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

Area 9 features a vertical slab which is pounded upon forming a spot about 1 m in diameter (Fig. 28); the surfaces of the inclined slabs below are also heavily abraded. Both slabs contain traces of almost erased stickmen. We interpret this area as a sling-stone practice target. Behind the slabs, a ca. 5 m long cave extends, which contains four bamboo poles of unknown age.

Apart from the petroglyps, the valley is heavily impacted by Hawaiian quarrying (Fig. 29): all along the rims of the valley the upper lava layers have been dug up, partly down to 2 to 3 m, and piles

Figure 25. Sideview of a full-bodied human figure with exaggerated hands.

Figure 26. Large (possible male) human figure with toes and fingers.

Figure 27. Possible glyph of a goat, again a sign of post-contact date of some of the petroglyphs.

of broken rocks litter the perimeter of the quarries. Quarrying has been going on also in the area between the Petroglyph Valley and Lua Nunu. Many of the sites display longitudinal grooves caused by grinding. What exactly the rock was quarried for remains unknown since no intermediate products were noticed.

The archeological evidence - specifically the number of sleeping platforms behind the defense walls - suggests that the Kamakalepo area sustained a sizeable population. At peak times it may have counted several hundred people. Clearly the area was still settled in early post-contact times as illustrated by petroglyps of monkeys, a dagger, a Christian (?) cross and an inscription. Writing was introduced to the islands after 1820. The only directly accessible water in the area is the lake in Waipouli. Paths leading towards it suggest that it was used by the Hawaiians intensively, in spite of the fact that not much archeological evidence is found inside. Any stairways or walls may have been obliterated either by later rock fall or by the farmers in the early 20th century. This water supply is, however, treacherous and in times of drought the water turns brackish, salty enough to make it even unfit for cattle. In times of drought drip water in the caves ceases also, which is, in other areas of the island, a major source of water (compare Martin, 1993; Kempe & Ketz-Kempe, 1997). Therefore timing of the Kamakalepo settlement may have been feasible only under a different climate condition, such as the Little Iceage, when more groundwater may have been available. We collected some charcoal and animal bones to be dated in order to constrain the time of occupation much better.

Figure 28. This near-vertical slab features multiple pound-marks, possibly a training target for shooting sling-stones.

Figure 29. One of the many “quarries” of the area where Hawaiians dug up stones.

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Use of ATLANTIS Tierra 2.0 in Mapping the Biodiversity (Invertebrates and Bryophytes) of Caves in the Azorean Archipelago

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Abstract

In this contribution the software ATLANTIS Tierra 2.0 is described as a promising tool to be used in the conservation management of the animal and plant biodiversity of caves in Macaronesia. In the Azores, the importance of cave entrances to bryophytes is twofold: i) since these are particularly humid, sheltered habitats, they support a diverse assemblage of bryophyte species and circa 25% of the Azorean brioflora is referred to this habitat and ii) species, either endemic or referred in the European red list due to their vulnerability (19 species) or rarity (13) find refuge there. Cave adapted arthropods are also diverse in the Azores and 21 endemic obligate cave species were recorded. Generally these species have restricted distributions and some are known from only one cave. ATLANTIS Tierra 2.0 allows the mapping of the distribution of all species in a 500 x 500 m grid in a GIS interface. This allows an easy detection of species rich caves (hotspots) and facilitates the interpretation of spatial patterns of species distribution. For instance, predictive models of species distribution could be constructed using the distribution of lava flows or other environmental variables. Using this new tool we will be better equipped to answer the following questions: a) Where are the current "hotspot caves" of biodiversity in the Azores?; b) How many new caves need to be selected as specially protected areas in order to conserve the rarest endemic taxa?; c) Is there congruence between the patterns of richness and distribution of invertebrates and bryophytes?; d) Are environmental variables good surrogates of species distributions?

Introduction

The study of Azorean cave fauna and flora only started in 1988 with two expeditions of "National Geographic" under the supervision of Pedro Oromí (Univ. de La Laguna) and Philippe Ashmole (Univ. de Edinburg) and with the support of the speleological Azorean group "Os Montanheiros" (see Oromí *et al*. 1990, González-Mancebo et al. 1991). After those two expeditions in 1988 and 1990, the University of the Azores and "Os Montanheiros" performed most of the biospeleological work in the Azores (see Borges & Oromí 1994, 2006, Gabriel & Dias 1994). In the Azores, the importance of cave entrances to bryophytes is twofold: i) since these are particularly humid, sheltered habitats, they support a diverse assemblage of bryophyte species and circa 25% of the Azorean brioflora is referred to this habitat and ii) species, either endemic or referred in the European red list (ECCB 1995) due to their vulnerability (19 species) or rarity (13) find refuge there. Cave adapted arthropods are also diverse in the Azores and 21 endemic obligate cave species were recorded (Borges & Oromí 2006). Generally these species have restricted distributions and some are known from only one cave (Borges & Oromí 2006).

There is a general agreement among scientists that biodiversity is under assault on a global basis and that species are being lost at greatly enhanced rates due to human processes such as habitat loss and fragmentation, invasive species, pollution and global climate change

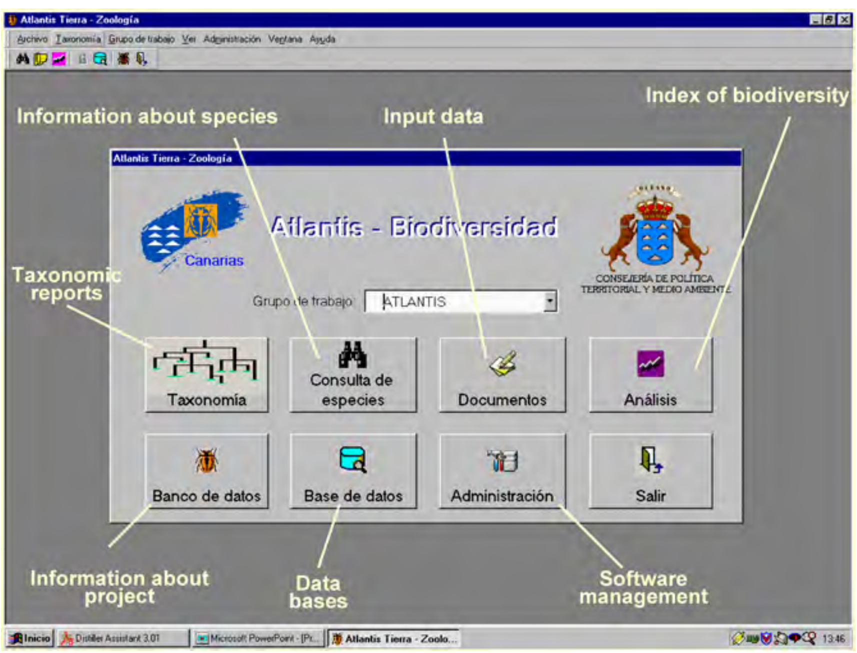

Figure 1. Entrance window of ATLANTIS Tierra 2.0, in which it is possible to observe eight possible entrance gateways, the most relevant being the taxonomic reports ("Taxonomía"), information about species ("Consulta de espécies") and data analysis ("Consulta de análisis").

(Lawton & May 1995; Chapin et al. 2000). Moreover, some recent studies indicate that there are some concerns related with invasive species and the conservation of native biodiversity in the Azores (Silva & Smith 2004, Borges et al. 2006).

In this contribution, a new software, ATLANTIS Tierra 2.0, is described as a promising tool to be used in the conservation management of the animal and plant biodiversity of caves from the Azores.

ATLANTIS Tierra 2.0

Since 1998 the Government of the Canary Islands as been conducing an important project on biodiversity, Project BIOTA (see Izquierdo *et al*. 2001, 2004). A Visual Basic software, called ATLANTIS Tierra 2.0, was developed for biodiversity data storage. With this database it will be possible to gather detailed information about all species on the surveyed geographical areas of interest. This software has several important tools, namely a taxonomic tool and a conservation management analysis tool (Fig. 1) that allows the calculation of species richness, their rarity or complementarity in all 500x500 m cells of a particular island or, in any special area in one island.

With this software all the information we could think of about a species (e.g. the cavernicolous ground-beetle *Trechus montanheirorum*) is available in clicking the **information about species** ("**Consulta de espécie**s") window (see Fig. 2). In this window it is also possible to check the detailed distribution of the species in a 500 x 500 m scale (Fig. 3). With this tool we may also investigate the distribution of the species throughout time in asking for its distribution in different time intervals. To each signalized 500 x 500 m grid cell correspond a cave for which the species was signalized in the literature.

However, it is in the data analysis facility that ATLANTIS Tierra 2.0 is more interesting in terms of its application in a conservation management study. As an example in Fig. 4 we see the species richness of the European Rare Bryophytes (ECCB 1995) in caves from Graciosa Island (Azores). The grid-cell with the highest number of species corresponds to the location of Furna do Enxofre, currently a volcanic pit protected by law and under the special management of the Government. In Fig. 4 we can see also the list of species in grid cell with the highest number of species and that list could be exported to another software (e.g. Excel).

Very important in conservation management studies is to ask: "Ho many sites are needed to include all species of interest at least once?". To answer this question, we could use the complementarity procedure, in which we get the minimum set of caves that combined have the highest representation of species (see Williams 2001). ATLANTIS

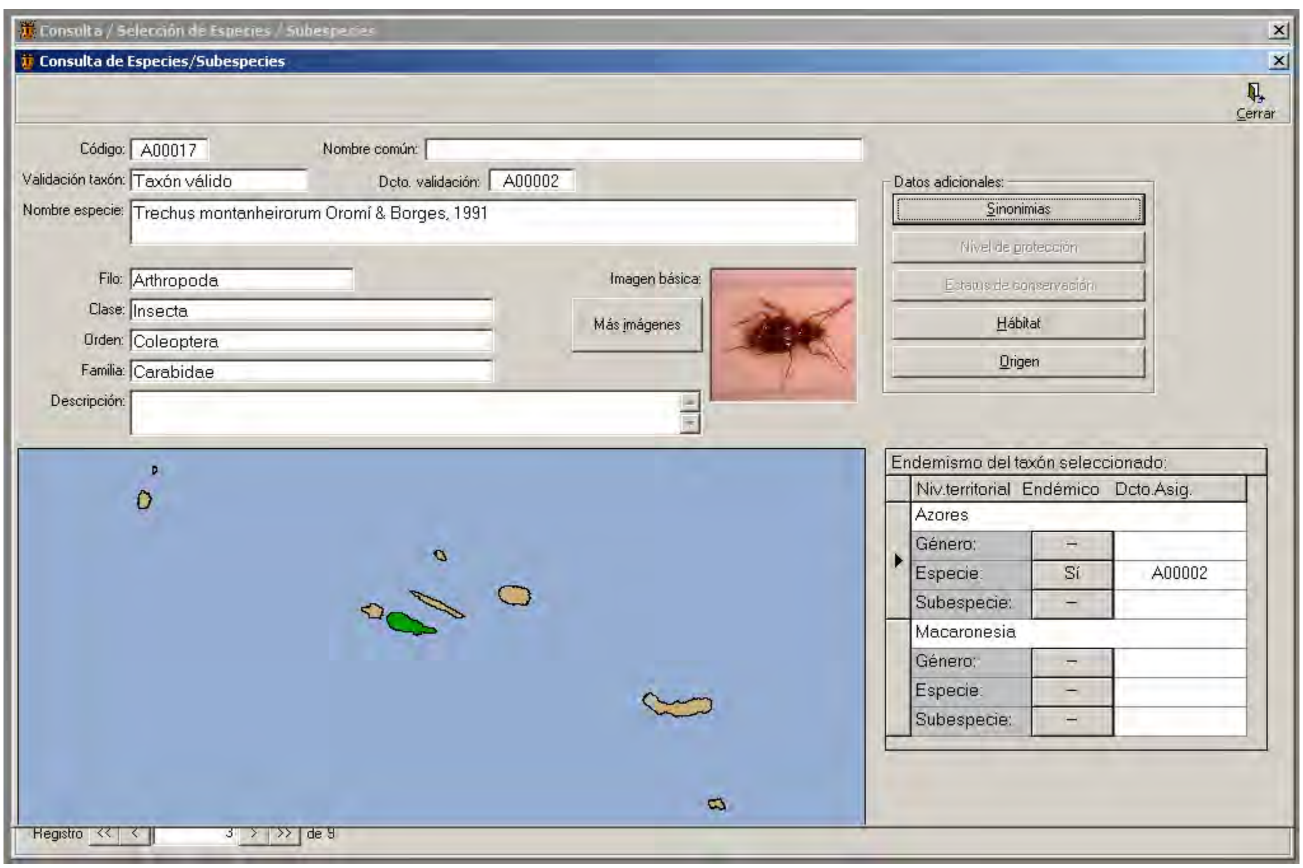

Figure 2. Species management window of ATLANTIS Tierra 2.0, in which it is possible to observe the nomenclature of the species, a picture, the distribution of the species in the archipelago (green island) and other relevant information concerning the habitats, conservation status, biogeographical origin, etc.

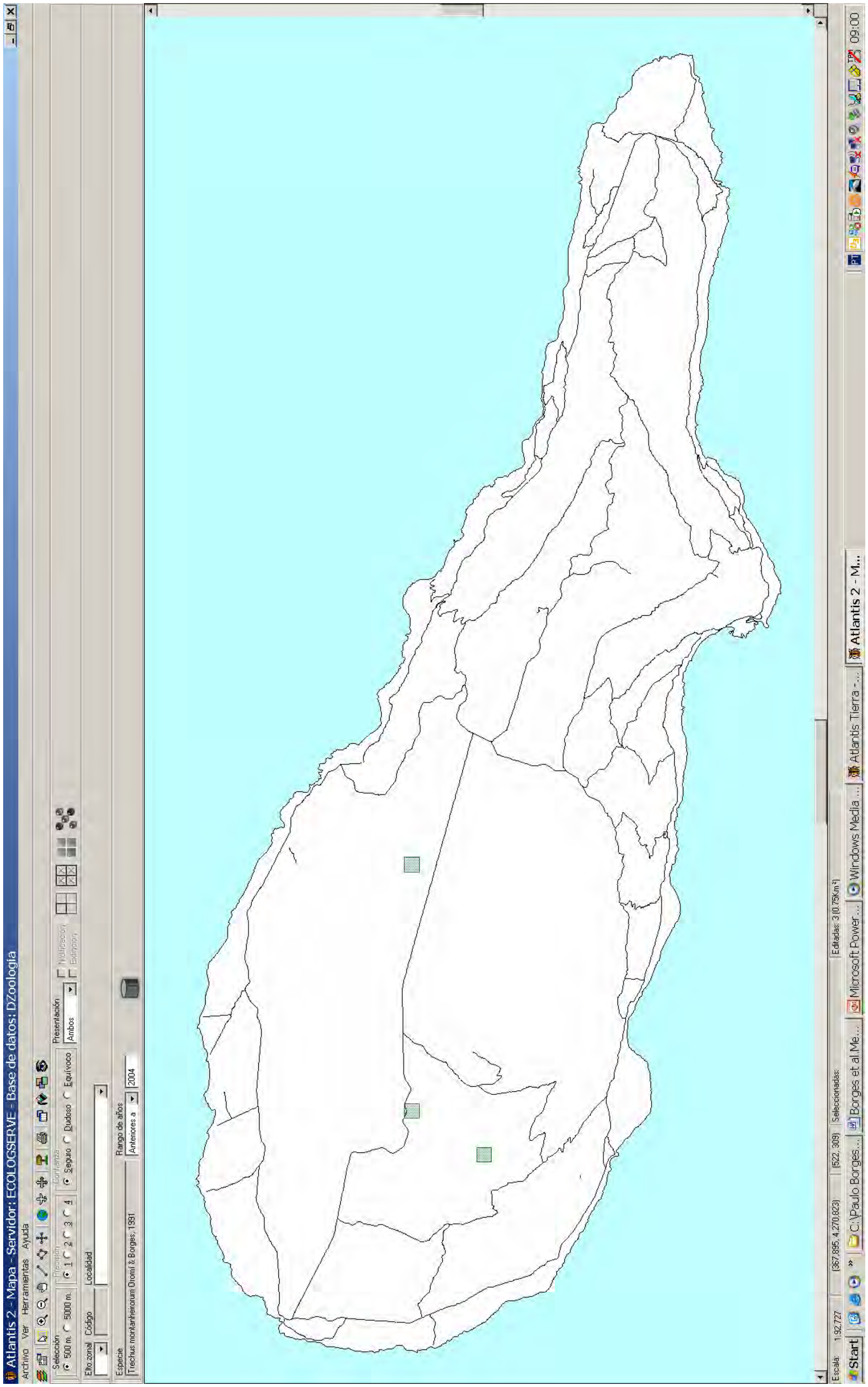

Figure 3. Species managment window of ATLANTIS Tierra 2.0, in which it is possible to observe the detailed distribution of *Trechus montanheirorum* in the island of Pico (lines are main roads in the island).

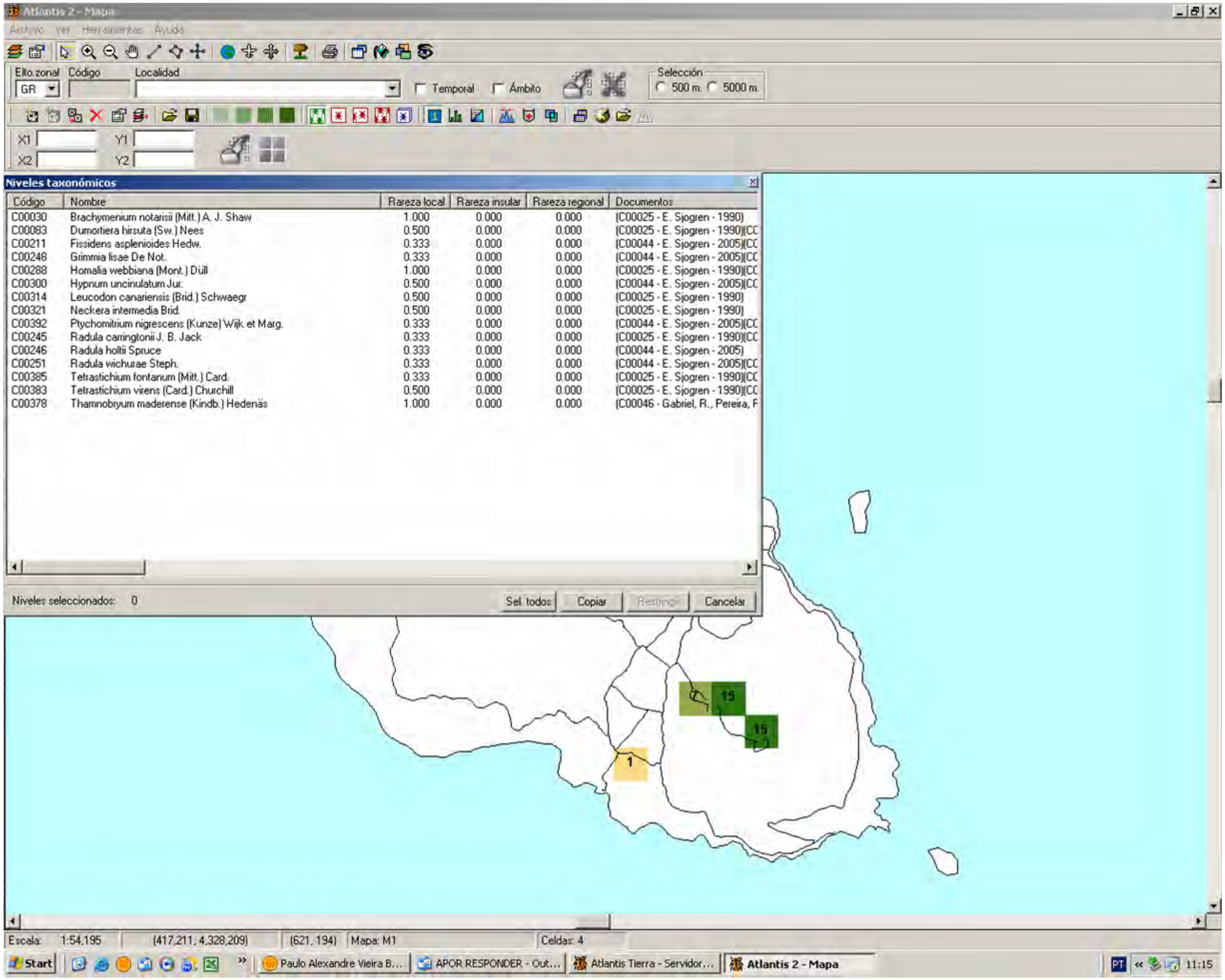

Figure 4. Data analysis window of ATLANTIS Tierra 2.0, in which it is possible to observe the number of bryophyte species in the European Red List present in caves from Graciosa Island (Azores). The list of species in the window corresponds to the grid cell with 15 species (Furna do Enxofre).

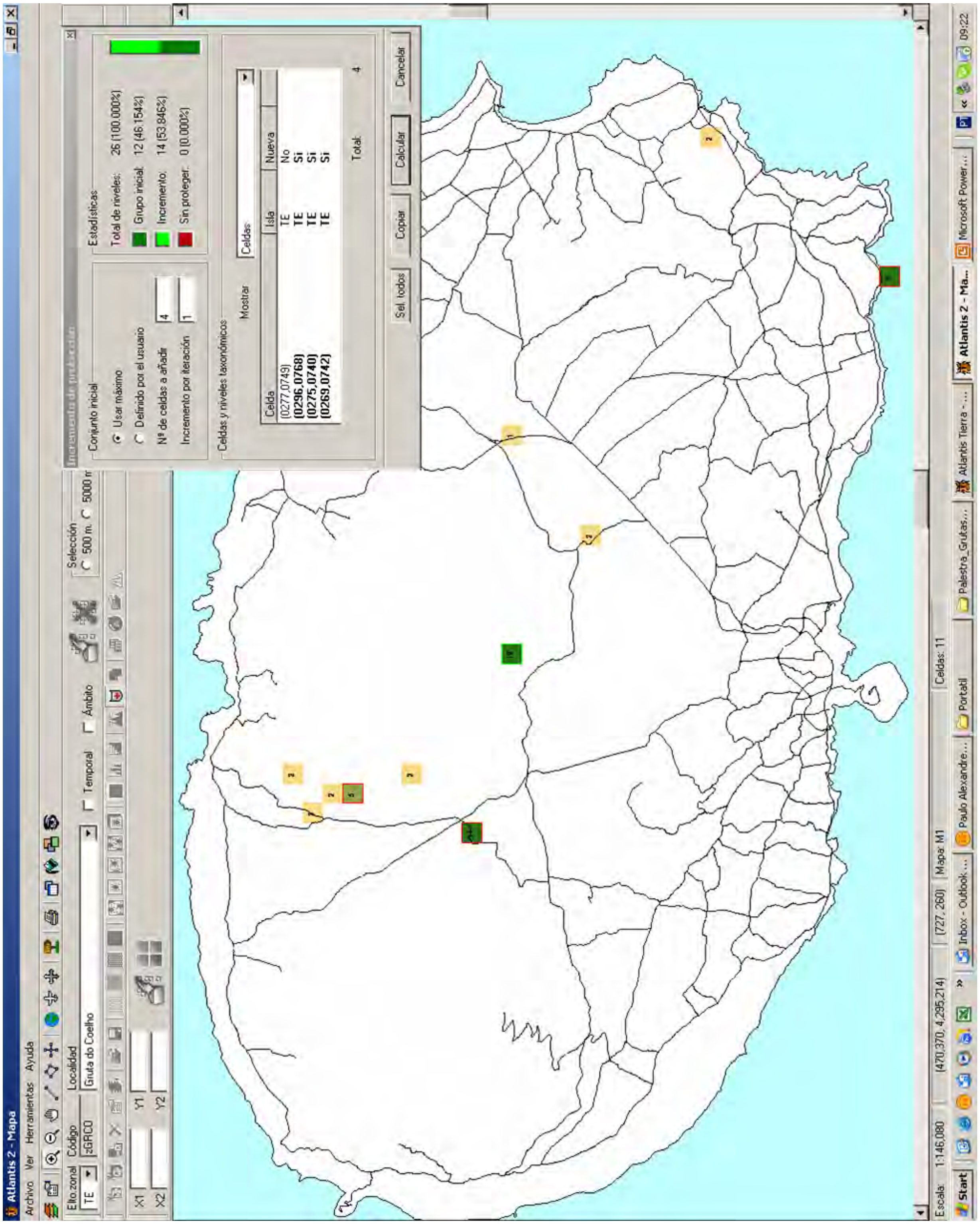

Figure 5. Data analysis window of ATLANTIS Tierra 2.0, in which it is possible to observe the four grid-cells that are necessary to include all the endemic arthropods occurring in caves from Terceira island (see text for further explanations).

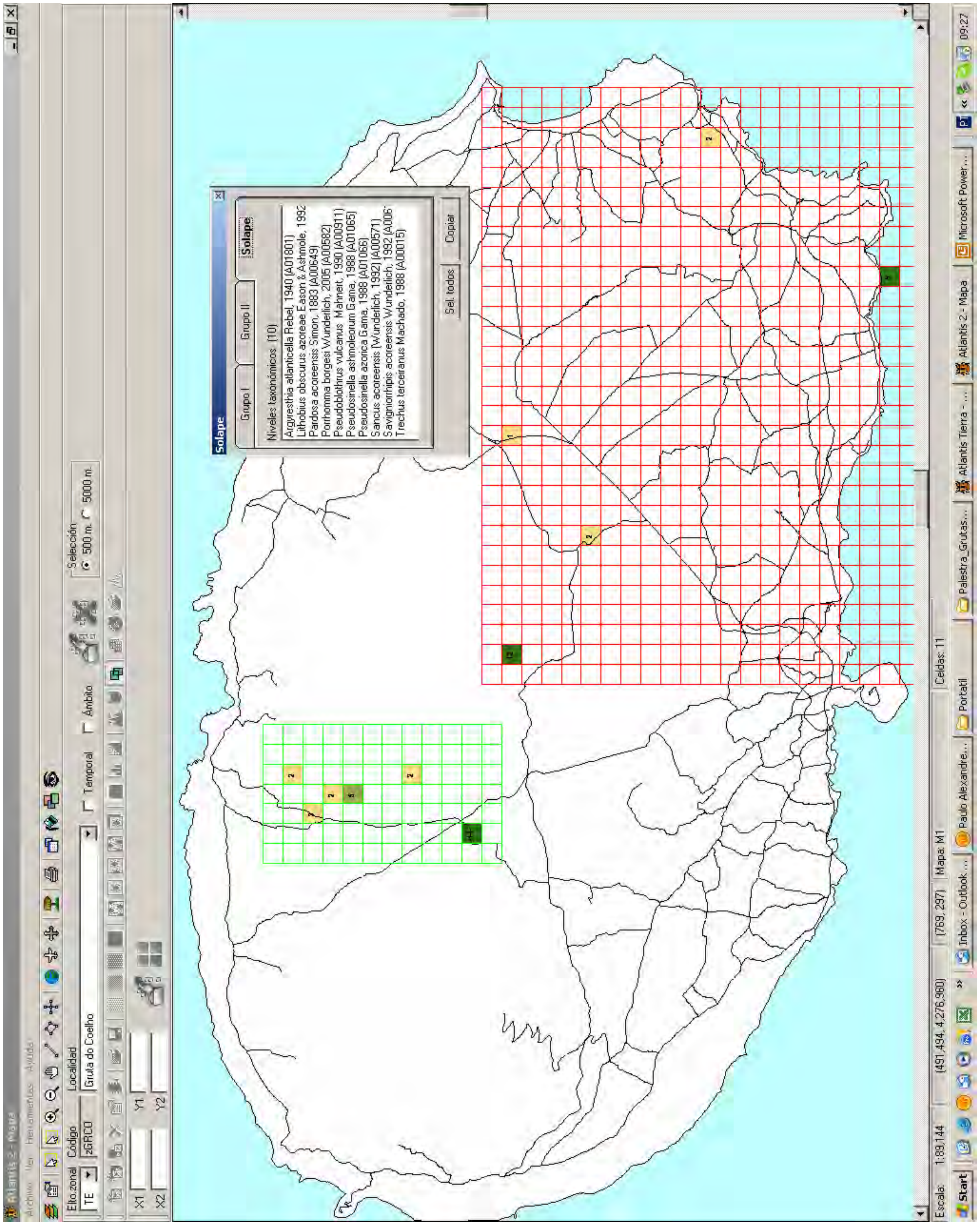

Figure 6. Data analysis window of ATLANTIS Tierra 2.0, in which it is possible to observe the list of endemic arthropods that occur in two distinct cave systems at Terceira island (see text for further explanations).

Tierra 2.0 uses the heuristic suboptimal simple-greedy reserve-selection algorithm: first, the grid-cell with the highest species richness is selected. Then, these species are ignored and the grid-cell with the highest complement of species (that is, the most species not represented in the previous selected grid-cell), and so on, until all species are represented at least once. One good example of the application of the complementarity procedure is showed in Fig. 5, in which only four out of the eleven grid-cells with caves are necessary to protect the 26 endemic arthropod species occurring in the caves of this island. Those four grid-cells are signalized with a green dark border (the first selected grid-cell) and with a reddish dark border (the three other selected grid-cells). Therefore, with only four caves well managed we may protect all the endemic arthropod species know to occur in caves at Terceira Island (Azores). However, we should call attention to the fact that the complementarity procedure could be made more complex asking for the minimum set of caves that combined have at least each species represented twice, therefore assuring that species are protected in more than one place.

Another important facility available in ATLANTIS Tierra 2.0 is related with the investigation of the species composition in different areas of a region. For instance, we could have the list of species that are common in two different cave systems (Fig. 6). We could also get the list of species for each cave system and by exclusion obtain the lists of species that are exclusive to each cave system.

Conclusion

There is some urgency in the conservation of the diverse community of mosses and liverworts (Bryophyta) as well as of the rich cave adapted arthropods occurring in the Azorean lava tubes and volcanic pits. The general pattern that emerges is that ATLANTIS Tierra 2.0 will be an important tool not only for the Azorean Government in managing the territory and designing natural protected areas, but also for research in de areas of applied ecology and conservation.

Using the ATLANTIS Tierra 2.0 new tool we will be better equipped to answer the following important questions: a) Where are the current "hotspot caves" of biodiversity in the Azores?; b) How many new caves need to be selected as specially protected areas in order to conserve the rarest endemic taxa?; c) Is there congruence between the patterns of richness and distribution of invertebrates and bryophytes?; d) Are environmental variables good surrogates of species distributions?

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Bryophytes of Lava Tubes and Volcanic Pits from Graciosa Island (Azores, Portugal)

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Abstract

Mainly due to historical reasons, the bryophyte flora of Graciosa Island is the poorest of the Azores (119 species), and it is especially scarce of rare and endemic species. However, Lava Tubes (Furna da Maria Encantada, Furna do Abel, Galeria Forninho) and Volcanic Pits (Furna do Enxofre) seem to offer refuge to some interesting plants. Previous studies have recorded, among others, the European endemic moss, *Homalia webbiana*, present only in four of the nine Azorean Islands and with a distribution of less than 10 localities known in the archipelago. The main purposes of this project were: i) to update with field work, the bibliographic records of bryophytes that may be observed in the volcanic formations of Graciosa; ii) to identify, in those formations, endemic bryophyte species (from the Azores, Macaronesia and Europe) and species with a conservation risk associated, according to the European Committee for the Conservation of Bryophytes (ECCB). The results show that although no endemic plants from the Azores were found at this point, six European and four Macaronesian endemic species were confirmed in the entrances of these volcanic formations, including one Vulnerable species and three rare species, according to ECCB criteria. In conclusion, besides the rich geological interest of the caves in Graciosa, their entrances continue to harbour rare or endemic bryophytes, not commonly found on other parts of the island, possibly due to the greater stability of these habitats. This is an additional reason to preserve the caves and a further possible motive of interest to all that visit them.

Introduction

Bryophytes include mosses (Bryopsida), liverworts (Marchantiopsida) and hornworts (Anthocerotopsida), all of which are small primitive plants that occupy a wide variety of habitats and substrates. Bryophytes assume an important

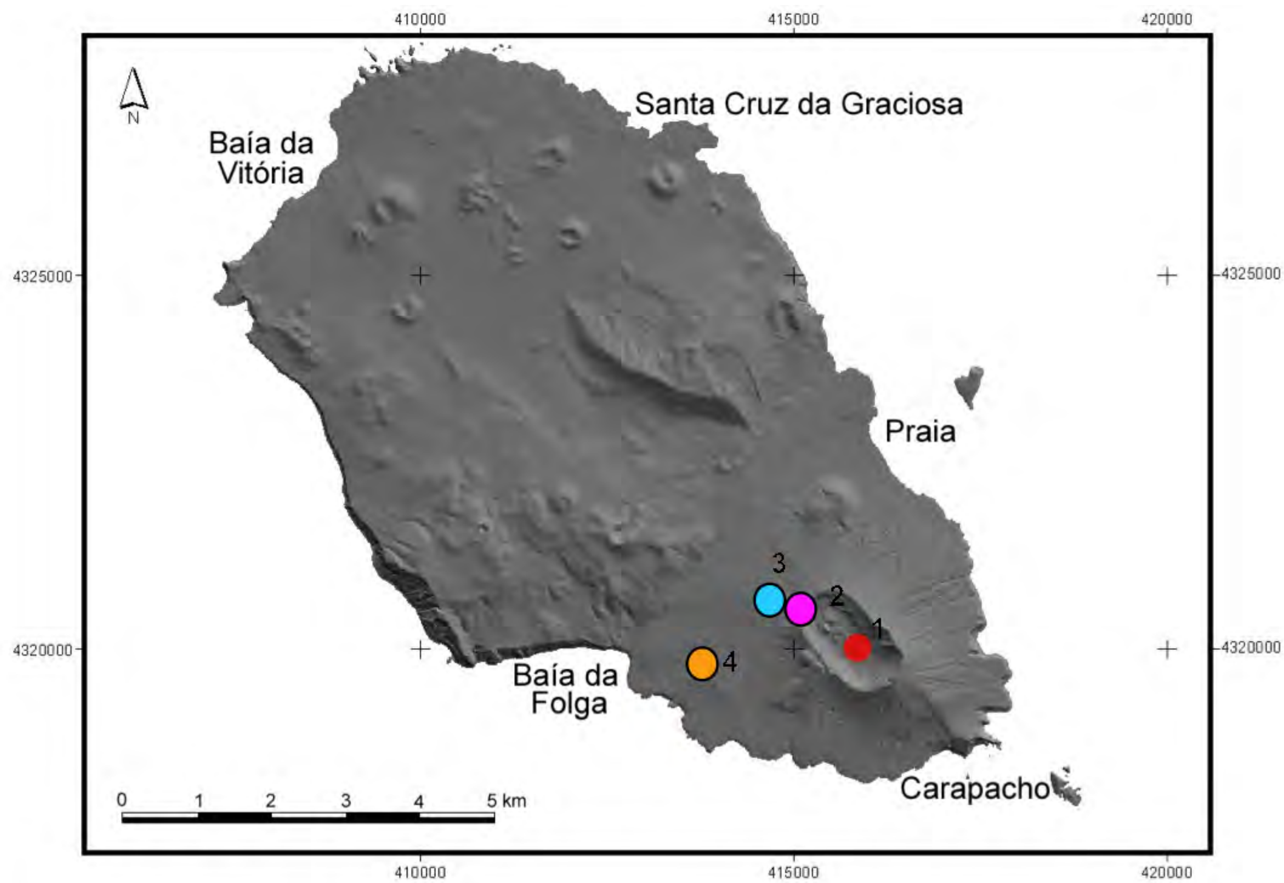

Figure 1. Sampled cave sites of Graciosa Island (Azores archipelago, Portugal). (1, Furna do Enxofre; 2, Furna da Maria Encantada; 3, Furna do Abel; 4, Galeria Forninho).

functional role in the ecosystems where they occur, performing water interception, accumulation of water and their mineral contents, decomposition of organic matter and physical protection of soils. Many bryophyte species are used as bioindicators, and their presence is associated with atmospheric and aquatic purity (Gabriel *et. al.*, 2005).

The Azores Archipelago offers a great variety of habitats for bryophytes, due to the diversity of microhabitats and available substrata, and to the hyperhumid conditions they provide (Gabriel & Bates, 2005). Mainly due to historical reasons, Graciosa Island is the poorest island of the Azores regarding the number of bryophytes (119), especially of rare and endemic species. However, Lava Tubes (Furna da Maria Encantada, Furna do Abel, Galeria Forninho) and Volcanic Pits (Furna do Enxofre) seem to offer refuge to some interesting plants. Previous studies have recorded, among others, the European endemic moss, *Homalia webbiana*, present only in four of the nine Azorean Islands and with less than 10 localities recorded in the archipelago.

The main purposes of the project were: i) to update with field work, the bibliographic records of bryophytes that may be observed in the volcanic formations of Graciosa; ii) to identify in those formations, endemic bryophyte species (from the Azores, Macaronesia and Europe) and species with a conservation risk associated, according to the European Committee for the Conservation of Bryophytes (ECCB).

Material and methods

Graciosa is the northernmost island of the central group of the Azorean archipelago (39º05′N, 28º00′W), and the second smallest of the Azores (61.7 km^2). This is the most levelled surface island of the archipelago, with more than 90 % of its surface below 300 m; its highest point is Pico Timão, at 398 m altitude. The island has four villages: Luz, Guadalupe, Praia and Santa Cruz, which is the largest and most important one.

Four cave entrances from Graciosa were purposefully sampled by one of us (FP) during June and July of 2005 (Figure 1): Furna do Enxofre; Furna da Maria Encantada; Furna do Abel and Galeria Forninho. All bryophytes were collected to newspaper bags, with

Table 1. List of bryophyte species found in the entrance of four caves in Graciosa Island in June and July 2005. Their rarity value (#) is specified in Table 2.

Cave		Species
Furna da Maria Encantada		Anthoceros punctatus
		Bryum canariense
		Campylopus polytrichoides
		Fossombronia caespitiformis
	#	Frullania azorica
		Frullania tamarisci
		Lejeunea lamacerina
		Lunularia cruciata
	#	Marchesinia mackaii
	#	Myurium hochstetteri
		Porella obtusata
		Pterogonium gracile
	#	Radula wichurae
		Scorpiurium circinatum
Furna do Abel		Conocephalum conicum
		Epipterygium tozeri
	#	Fissidens coacervatus
	#	Frullania azorica
	#	Frullania microphylla
		Hypnum cupressiforme
		Porella obtusata
		Radula lindenbergiana
	#	Radula wichurae
		Scorpiurium circinatum
	#	Tetrastichium fontanum
Furna do Enxofre		Calypogeia arguta
	#	Fissidens luisierii
		Heterocladium wulfsbergii
	#	Homalia webbiana
		Lejeunea lamacerina
		Leucobryum juniperoideum
		Plagiochila bifaria
		Plagiothecium nemorale
		Riccardia latifrons
	#	Tetrastichium fontanum
	#	Tetrastichium virens
		Thamnobryum maderense
Galeria Forninho		Chiloscyphus coadunatus
		Epipterygium tozeri
		Lejeunea lamacerina

Table 2. Status and endemic area of the bryophyte species found on Graciosa cave entrances. Status according to the European Red List of Bryophytes (ECCB, 1995) (K, unknown status; R, rare species; V, vulnerable species; NT, not immediately threatened in Europe); endemism area (Macaronesia, Mac; Europe, Eur).

Status	Endemic	Species
NT	Eur	Frullania azorica
	Eur	Frullania microphylla
	Eur	Homalia webbiana
	Eur	Marchesinia mackaii
	Eur	Myurium hochstetteri
K	Mac	Fissidens luisierii
R	Eur	Tetrastichium fontanum
	Mac	Fissidens coacervatus
	Mac	Tetrastichium virens
V	Mac	Radula wichurae

reference of place and date of collection, substrate, and different observations concerning the ecology of the plant. Bryophyte samples were air dried.

The specimens were identified in the laboratory of the Departamento de Ciências Agrárias, University of the Açores. Nomenclature follows Gabriel *et al.* (2005). The following floras were used for the identification: Hedenäs (1992) and Smith (1978) for mosses and Schumacker and Váña (2000), Smith (1990) and Paton (1999) for liverworts and hornworts. The confirmation of the identification of some species was done by Dr.[a] Cecília Sérgio (LISU, University of Lisboa, Portugal), Professor René Schumacker (University of Liége, Belgium) and Professor Erik Sjögren (University of Uppsala, Sweden).

Results and discussion

Thirty two species of bryophytes may be found at the entrances of the four caves surveyed in Graciosa Island (Table 1), which corresponds to more than a quarter of all the bryophytes known to that island (26.9 %). The large volcanic pit, "Furna do Enxofre" and the small cave "Furna da Maria Encantada" are the richest caves surveyed with 12 and 14 bryophyte species, respectively.

The results show that although no endemic plants from the Azores were found at this point, six European and four Macaronesian endemic species were found at the entrances of these volcanic formations, including one Vulnerable species and three rare species, according to ECCB criteria. Hence, ten bryophytes are listed in the European Red List of Bryophytes (ECCB, 1995), either due to their rarity or to their biogeographically restricted area, endemic species (Table 2).

Those ten species may be found in other islands and habitats, however it is important to note the presence of the vulnerable Macaronesian endemic liverwort, *Radula wichurae* and the European endemic moss *Homalia webbiana*, that is very rare in the Azores. The moss may only be found at four of the nine islands of the Archipelago (Flores, Graciosa, S. Jorge and Santa Maria) and has been recorded for less than ten localities in them.

Conclusions

About a quarter of the bryophyte flora of Graciosa Island may be found at the cave entrances accessed in this study. Although this habitat harbours mostly species found on other habitats, it also serves as a refuge to ten species, currently listed in the European Red List of Bryophytes (ECCB, 1995).

In particular, the presence of *Homalia webbiana* was confirmed at the entrance of Furna do Enxofre, a classical locality, previously referred by González-Mancebo, Losada-Lima & Hérnandez-Garcia (1991). This European endemic moss is very rare on the Azores, where there are less than 10 localities known for the species.

In conclusion, besides the rich geological interest of the caves in Graciosa, their entrances continue to harbour rare or endemic bryophytes, not commonly found on other parts of the island, possibly due to the greater stability of these habitats. This is an additional reason to preserve the caves and a further possible motive of interest to all that visit them.

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Cueva del Diablo: a Bat cave in Tepoztlan

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Abstract

In Mexico, almost half of the 140 species of bats use caves as alternative or primary roosts. One volcanic cave that houses important colonies of these animals is *Cueva del Diablo* in Tepoztlan, Morelos, central Mexico. At least three bat species have been reported in this cave. One of them, the Mexican long-nosed bat (*Leptonycteris nivalis*), is of particular importance in economical and ecological terms. This species migrates from central to northern Mexico and southern United States in mid spring and come back in mid autumn. In Mexico, L. nivalis is classified as a threatened species, and in the U.S. as an endangered one.

Owing to the fact that Cueva del Diablo is the only known roost in which this species mates, the cave was proposed by us as a sanctuary to the CONANP (National Commission of Natural Protected Areas) in 2004. In addition to this proposal, the PCMM (Program for Conservation of Mexican Bats) has conducted environmental education efforts in the region as an attempt to modify the negative ideas about bats and to share the information concerning their importance and that of caves for them.

Other PCMM studies conducted in this cave focus on the diet of the species and understanding its mating system, among the first studies on those subjects for this species. This document represents a compilation of those works in Cueva del Diablo with emphasis in their importance for the general conservation of bats and caves.

Introduction

With 1116 extant species recognized worldwide, bats are second only to rodents in terms of total number of species (Simmons, 2005; Wilson and Reeder, 2005). Diversity of bats is noteworthy not only by quantity but also because their evolutionary radiation has led the group to an unparalleled ecological and morphological diversification. Bats occupy several trophic guilds, from primary consumers to predators; they roost in many types of natural and human-made structures in numbers from a few animals to millions, creating the greatest concentrations of warm-blooded vertebrates (Medellín, 2003).

There are 9 families of bats in Mexico that comprises 64 genera and 140 species, 15 of which are endemic (Tejedor, 2005; Ceballos *et. al*., 2002). The Mexican bat fauna is rich because of the country's complex topography, the fact that Mexico contains virtually every known vegetation type (Rzedowski, 1978), and because it has three distinct biogeographical elements: neotropical, neartic (the limits of which are entirely contained within Mexico's borders), and endemic (Medellín, 2003).

Chiropterans play several major ecological roles in many ecosystems. Insectivorous bat species are the primary consumers of nocturnal insects, and given the relatively large volumes consumed (up to 100% of body weight per night) and the long distances traveled (several km per night), these bats are thought to play a major role in regulating nocturnal insect population and intransporting nutrients across the landscape (Kunz and Pierson, 1994). Bats are major predators of nocturnal flying insects, and an important biological control agents of insect pests (Russell, *et. al*. 2005; Medellín, 2003), including cucumber beetles, June bugs, corn borers, Jerusalen crickets, leafhoppers and noctuid moths which are important agricultural pests on such crops as corn, spinach, pumpkins, cotton, potatoes or tomatoes (Whitaker, 1993).

Bats are pollinators and seed dispersers for a number of ecologically and economically important plants (Kunz and Pierson, 1994). They pollinate plants associated with tropical and subtropical dry areas, such as agaves, cactus and a variety of tropical trees (Arita and Wilson, 1987). They disperse seeds occurring in the plant families to which figs and relatives belong, like Moraceae and Piperaceae, among others (Fleming, 1987). Worldwide, there are more than 750 plant species that have been listed as visited by bats (von Helversen and Winter, 2003). Flower – visiting bats in Mexico are represented by 12 species, most of which have restricted distribution; two of them are endemic to the country, two others to Middle America and ten use caves as a main or alternative roost (Arita and Santos del Prado, 1999).

Despite the importance of bats for ecological processes and for humans, this group of animals is facing great population declines and extinction pressures worldwide (Hutson *et. al*., 2001). About 24% of bats (248 species) are considered at risk by the IUCN (2006): 32 critical endangered, 44 endangered and 172 vulnerable. Mexico has a similar percentage of species at risk but at a national level: 12 under special protection, 15 threatened and 4 endangered, including 5 endemic species (SEMARNAT, 2002).

Over the past 400 years, at least 9 species of bats have become extinct (IUCN, 2006). Bat populations in many countries are thought to have declined over the past 50 – 100 years, and although the evidence for such reductions is often circumstantial, there are cases where declines have been well documented (Mohr, 1972; Stebbings, 1988; Rabinowitz and Tuttle, 1980; R. A. Medellín, pers. obs.).

Factors behind the decline of bat populations are often related to human destruction of habitat and roosts

(Medellin and Gaona, 2000). An increasing human population brings with it extra demands for land, resources and food, which often results in the degradation, destruction or fragmentation of certain habitat types with a concomitant effect on bat populations (Hutson *et. al.*, 2001). Impacts of agriculture and its derivatives (e. g. reduction of fallow periods, overgrazing, loss of important plant species for bat foraging, replacement of natural vegetation with cash crops and monoculture as a result of that, use of pesticides that affects insect fauna and are potentially sub-lethal for bat's breeding performance, among others), as well as industrial activities, fire, deforestation, introduced predator species or pollution, can affect negatively bat populations (Hutson *et. al.*, 2001).

Linking bats to witchcraft and magic has given rise to many of the fears people have about them (McCracken, 1992). Within the same topic, the feeding habits of the vampire have been so exaggerated and confused with Old World legends that the animal is of particular interest. It has been considered a threat both to people and to their domestic animals in Latin America (Nowak, 1994), where, as an ironic fact, populations of vampire bats have increased sharply in areas to which European livestock have been introduced (Hutson *et. al.*, 2001). Common vampire bat is extensively persecuted as a vector of rabies, that is transmitted to cattle and other ungulates on which it feeds, although its incidence is low (<1%). The main method of control is the use of anticoagulants applied to individual bats captured by mist nets, which are dispersed to other individuals in the roost by allogrooming (Brass, 1994). However, roosts have also been burned, gassed and dynamited, with the loss of large populations of harmless or beneficial bats as well as other cave fauna (Hutson, *et. al.*, 2001).

The importance of bat caves

Indeed, roost site disturbance and destruction is another great threat for bats, and this can be represented by the loss or alteration of trees and buildings, guano mining, deliberate destruction, or not regulated tourism or caving (Hutson, *et. al.*, 2001).

Roosting ecology of bats can be viewed as a complex interaction of physiological, behavioral, and morphological adaptations and demographic response. These animals spend over half their lives subjected to the selective pressures of their roost environment. For many bats the availability and physical capacity of roosts can set limits on the number and dispersion of roosting bats, and this in turn can influence the type of social organization and foraging strategy employed (Kunz, 1982). Roosts are important sites for mating, hibernation, and rearing young. They often facilitate complex social interactions, offer protection from inclement weather, promote energy conservation, and minimize risks of predation (Villa-R, 1967; Kunz and Lumsden, 2003).

Underground sites, both natural (e. g. caves) and artificially created (e. g. mines), are crucial to the survival of many bat species worldwide (Hutson *et. al.*, 2001). In relation to other roosts, caves stand out because of their extended use among these organisms (Avila, 2000). A great proportion of world's bats can be considered cave – dwellers and, probably, caves host more individuals than other roosts, even combined (Hill and Smith, 1984). Besides that, great dimensions and complex topography in one cave only can offer several perch sites for different individuals or colonies (Medellín and López – Forment, 1985; Hill and Smith, 1984; Kunz, 1982) as well as different microclimates (Medellín and López – Forment, 1985).

In Mexico, there are over 10 000 caves (Lazcano, 2001), mostly karstic but also in sandstone, and a few caves inhabited by bats are volcanic in origin. Almost half of the country's bat species use caves as primarily or alternative roosts (Arita, 1993). However, a survey made by Ruiz (2006) yielded a total of only 442 Mexican caves with information on bats.

Cueva del Diablo

One of the relatively well known bat caves in Mexico is Cueva del Diablo, located in Tepoztlán, Morelos. This municipality belongs to the Transvolcanic belt physiographic province, in the Anahuac Lakes and Volcanoes subprovince, where Volcanic Sierra of Ajusco, the Chichinautzin volcano and Tepozteco Sierra stand out (Caballero, 2004).

Flora in Tepozteco Sierra encircles the transition zone between the subtropical evergreen, the template (oak and pine) and the tropical deciduous formations (Hoffman *et. al.*, 1986). The cave is located in the latter type of vegetation, characterized by a semi-warm wet climate with summer rain (A) C (w_2) (w) i g (García, 1986) and in an altitude of 1850 masl. In summer, it presents an average external temperature of 28°C during day, which decreases while entering the cave down to 16°C in the majority of internal chambers.

A full description of the cave was made by Hoffman *et.al.* (1986). This refuge has a volcanic origin, from a subterranean lava flow that stopped, and eventually forms a various chamber's system with a 1 937m length (including all the ramifications) and a maximum depth of 110m respect the entrance (Hoffman *et. al.*, 1986).

Tepoztlan represents a transition point between neartic and neotropical faunas, and a confluence center of migratory species. In Cueva del Diablo there are three main bat species according their presence in the cave: *Leptonycteris nivalis*, *Pteronotus parnellii mexicanus* and *Desmodus rotundus* (Hoffman, 1986) and isolated captures of *Anoura geoffroyi* (Edmundo Huerta, pers. comm.), *Artibeus jamaicensis* (Rodrigo Medellín, pers. comm; Gabriela López, pers. comm.) and *Myotis velifer* (Rodrigo Medellín, pers. comm; Gabriela López, pers. comm.)

The naked – backed bat, moustached bat or leaf – lipped bat (Nowak, 1994) *Pteronotus parnelli* (Gray, 1843) is basically an insectivorous one (Fleming, 1972; Novick and Valsnys, 1964) and there are reports where a single colony of 600 000 individuals can consume between 1900 and 3000 kg of insects per night (Ortega, 2005). It normally perches in caves, preferring internal chambers with high humidity and temperature (Alvarez, 1963). In Cueva del Diablo, this bat locates in tunnel 20, sharing space with *Leptonycteris nivalis* (Caballero, 2004; Hoffman *et. al.*, 1986). *P. parnellii* distribution in Mexico goes through the neotropical zone from Sonora and Tamaulipas to Yucatán and Chiapas (Ortega, 2005), but it reaches north Argentina and Paraguay (Jiménez Guzmán y Zúñiga, 1992; Ramírez – Pulido *et. al.*, 1983). Although its conservation status is unknown, this bat is one of the most abundant and it can survive even in disturbed zones, so it's not considered at risk (Ortega, 2005).

The common vampire bat, *Desmodus rotundus* (E. Geoffoy, 1810) characterizes for its feeding habit, which consists basically in blood from different mammals (primarily cattle). They can drink 20ml of blood per individual per day and take 40 minutes feeding (Greenhall, 1972). Colonies are commonly comprised by 20 – 100 individuals, but there are reports of groups from 500 to 5000 bats (Crespo *et. al*., 1961). *D. rotundus* can live in caves, crevices, dark constructions and trees (Suzán, 2005). These bats can transmit the paralytic rabies virus, which causes economical loss in Latin America (Hoare, 1972). Also from the neotropical region, this bat's distribution goes from north Sonora and Tamaulipas in Mexico to Argentina (Villa - R, 1967).

Leptonycteris nivalis (Saussure, 1860), the Mexican long – nosed bat, is the largest Mexican glossophagine bat species. As other nectarivorous bats, it has short ears and leaf nose, and the face and tongue are elongated (Arita, 2005). It occupies a great variety of habitats, from template to tropical and desert zones, principally in transition areas between coniferous and tropical deciduous forests ones. Its distribution is restricted to North America, from south Texas and New Mexico, where it establishes from June to August, to central Mexico where it remains during winter (Arita, 1991; U. S. Fish and Wildlife Service, 1994). It seems fluctuations in numbers of this bat respond to food availability (Fleming and Nassar, 2002; Schmidly, 1991; Easterla, 1972) and the migratory movements follows the "nectar corridors" formed by the flowering plants that comprises their diet (Fleming et. al., 1993). But despite some anecdotal information about this subject, no detailed study has been conducted on the specific factors that may influence bat abundance, reproduction and growth, especially as these factors are related to food availability and roost site conditions (Arita and Martínez del Río, 1990). This basic information is essential for the conservation and management of *L. nivalis* (U. S. Fish and Wildlife Service, 1994).

At the same time, there is little information about its diet and reproductive pattern. A few studies found that they fed on nectar from flowers of *Agave* and some convolvulaceous, bombacaceous and cactacean, as well as other agavaceous plants (Sánchez, 2004; Téllez, 2001; Butanda-Cervera *et. al*., 1978; Alvarez and González, 1970; Villa-R, 1967).

It appears that mating occurs in southern Mexico during winter and females occupy northern caves (Texas and New Mexico, and northern states of Mexico) to form maternity colonies in late spring and summer (Tellez, 2001; Davis, 1974; Easterla, 1972). The migratory behavior of *Leptonycteris nivalis* is reflected in its seasonal presence both in the United States and in northern and southern Mexico (Tellez, 2001; Cockrum and Petryszyn, 1991; Moreno – Valdez, 1998; Easterla, 1972).

Caves are the main roosts of four of the nectar – feeding Mexican bats and another six species use caves as alternative roosts (Arita and Santos del Prado, 1999). The former is the case of *L. nivalis*, a colony species that roosts in caves, mines, tunnels and occasionally in unused buildings, hollow trees and sewers (Pfrimmer and Wilkins, 1988). Some cave populations, like those in Cueva del Diablo, can be composed by thousands of individuals (Hoffman et. al., 1986; Easterla, 1972).

Research

Research works concerning bats in Cueva del Diablo had been made primarily by the Laboratory of Vertebrate Ecology, Institute of Ecology, UNAM. These investigations are important contributions to the knowledge about the priority species *Leptonycteris nivalis* and that of this cave for it.

Manual de bioespeleología (Biospeleology manual), Anita Hoffman, José Palacios Vargas and Juan B. Morales-Malacara (1986)

Alter 6 years imparting 11 Field Biology courses focused on biospeleology at the UNAM, Hoffman *et. al*. decided to publish this work in 1986. It was made as a guideline in Spanish for biospeleologists, to encourage for more studies and to share results of those years of research.

The publication includes a recompilation of historic data about general aspects of caves, and more specifically, about biospeleological studies made in Mexico. Also, it presents a brief relation concerning cave animals and ecological features of that fauna and its environment. This manual describes materials and methods to carry out researches of this matter and exposes the results of the eleven expeditions made in several caves of Morelos and Guerrero states.

They visited 8 caves in two states from September 1977 to March 1983. They described the caves including flora and fauna and elaborate the maps for five of them in Morelos and three in Guerrero. Also, they took samples, according the *biotopos* for: bat fauna and its symbionts, water fauna, guano fauna, little about interstitial fauna, and floor and wall fauna. A total of 75 families, 135 genera and 206 species new reports for the country are presented in this work and 10% of the latter are first – known cave species for Mexico and for the science.

Concerning Cueva del Diablo, two excursions allowed to compile information about location, climate, vegetation, geology and a full internal description of the cave, including a complete map. With regard to flora and fauna, they reported: 8 species and genera and 6 families of eumycota (true fungi); 9 species and genera and 11 families of arachnids; 8 species, 10 genera and 10 families of mites; 1 genera and 2 families of centipedes; 1 family of millipedes; 10 species, 25 genera and 23 families of insects; and 3 species, 3 genera and 2 families of bats.

In relation to cavities *biocenosis*, bat populations constitute an important factor in the establishment and development of many other populations of cave organisms, because their feeding habits contribute, through guano, with a great variety of nutrients. Also in its bodies, bats house lots of parasites and guests.

*Migración de los murciélagos – hocicudos (*Leptonycteris*) en el trópico mexicano* (Migration of long - nosed bats (*Leptonycteris*) in tropical Mexico), Juan Guillermo Téllez Zenteno (2001)

This work proposes the existence of a segregation feeding mechanism that allows niche segregation between *Leptonycteris curasoae* and *L. nivalis* and it try to prove the hypothesis of altitudinal movements of these bats. Reproductive patterns, population fluctuations and feeding habits of the species were studied using stable carbon isotopes in 11 caves located in tropical Mexico.

Genus *Leptonycteris* selects migratory behavior in the tropics based on the seasonal availability of food also making markedly seasonal its presence in the region around autumn and winter.

The lesser – long nosed bat presents only one reproductive pulse in the tropic, when females form great maternity colonies in the tropical deciduous forest.

The first report of a known mating refuge for the Mexican long – nosed bat in Cueva del Diablo its made in this research. The results indicate that there's only one reproductive pulse for this species, represented by the testicular activity of males and the copulations which occur mainly in November and December. It is probable that pregnant females of *Leptonycteris nivalis* are the ones that establish maternity refuges north during spring – summer. It seems also that unlike *L. curasoae*, it only appears to be one population through out the whole range of distribution for the Mexican long – nosed bat.

L. nivalis resulted much more specialized in CAM resources than *L. curasoae*, because it presents a limited use on C_3 metabolic derivatives. Out of this, it could by say that there is an ecological mechanism of feeding segregation between *Leptonycteris* species when both occupy tropical deciduous forest in Cuenca del Balsas. This in turn can be the reason for the overlapped distributions of these species in Mexican tropic.

Some results of this investigation had been useful to propose Cueva del Diablo to become sanctuary and to better understand the migratory, feeding and reproductive behavior of two ecological and economical important Mexican bat species.

Observaciones sobre la conducta reproductiva de Leptonycteris nivalis *(Chiroptera: Phyllostomidae) en Tepoztlán, Morelos, México* (Observations on reproductive behavior of *Leptonycteris nivalis* (Chiroptera: Phyllostomidae) in Tepoztlan, Morelos, Mexico), Luis Antonio Caballero Martínez (2004)

Based on observations and recordings with infrared cameras, this study is an attempt to describe the social structure and mating behavior, period and system of *Leptonycteris nivalis* during its stay in Cueva del Diablo. This species occupy the cave from September to February where a great fluctuation in group composition make difficult to establish a well defined social structure. According to the results, preliminarily it can be proposed that the Mexican long – nosed bat had established in Cueva del Diablo a promiscuous mating system conformed by multi-male and multi-female groups, with no evidence of harem or lek formation, territory defense, courtship or marked sexual dimorphism and where apparently mating is not random.

Mating period matches the resource availability peak in the zone and it's restricted to the last two weeks of November and first two of December with approximately one month duration, when male's testicular measures and weight are maximums. The latter together with a promiscuous mating can indicate presence of spermatic competition.

It is probable births occur in May during migration, and that maternity colonies could establish in northern Mexico and southern U.S. This way, gestation period lasts 6 months, which is considered to long for bats, so probably a fertilization or embryonic development delay take place in *L. nivalis*. Possibilities of polyestrous reproductive pattern in this species are almost none, so it probably presents a monoestrous one.

It is necessary to make more observations on the conduct of this bat all along its migratory trajectory, as well as genetic studies to confirm the data obtained during this study, but still it presents important information concerning reproductive ecology about the Mexican long – nosed bat that corroborate the importance of Cueva del Diablo for the species and contributes to the knowledge about it. This in turn can be another argument to apply strict protective measures that can guarantee a reduction in the number of persons that enter the cave, at least during the mating season of the species.

Dieta del murciélago magueyero mayor Leptonycteris nivalis *(Chiroptera: Phyllosomidae) en la Cueva del Diablo, Tepoztlán, Morelos* (Diet of the Mexican long–nosed bat *Leptonycteris nivalis* (Chiroptera: Phyllostomidae) in Cueva del Diablo, Tepoztlan, Morelos), Leslie Ragde A. Sánchez Talavera (2004)

This study documents plant species that conformed the diet of the Mexican long – nosed bat during its stay in Cueva del Diablo, although samples collection was made also in two mines north of the country in the same period. A great part of this bat's diet in the cave comprises no – CAM metabolism plants. Results identified 7 plant genera in 5 families: Cactaceae, Bombacaceae, Convolvulaceae, Fabaceae and Agavaceae, being the most represented species *Ipomoea arborescens* in first place and *Agave* sp. as second. Two new species of agaves were determined as part of the *Leptonycteris nivalis* diet and no differences between sex's and monthly diets were observed.

One of the steps the "Mexican long – nosed bat *Leptonycteris nivalis* recovery plan" (U.S. Fish and Wildlife Service, 1994) proposed, and the former research covers in some extent, is the necessity of an inventory about plant species this bat consume as food, according to sex, age, period and locality. Based on the knowledge of the foraging habitat this species use, they can be settled more and better decisions about protection and conservation of *Leptonycteris nivalis*.

Conservation and environmental education

According to Arita (1993), an effective plan for the conservation of Mexican cave bats would require a double strategy: the protection of caves with unusually high diversity and multispecies populations, and the management of cave bats of special concern (fragile, vulnerable and endemic species).

Certain analysis suggest that the Mexican long – nosed bat has declined in numbers over the past 30 years (Jones, 1976; Wilson *et. al*., 1985), probably due to some of the human activities mentioned before. Currently this species is listed as Endangered by the IUCN (2006), and as Threatened by the NOM-059 in Mexico (SEMARNAT, 2002) since 1991.

In 1994 was approved the "Mexican long – nosed bat *Leptonycteris nivalis* recovery plan" between Mexico and the United States, where the steps to change risk status of the species to a lower category are outlined (U. S. Fish and Wildlife Service, 1994).

Additionally, the PCMM (Conservation Program for Mexican Bats) begins its work to recover and to conserve the habitat and populations of bats that inhabit the country. To protect these animals, the program has a strategy based on three main axes: research (surveys, population size estimates, migration, ecology, reproduction, diet, genetics, and economic value, among others), environmental education (school programs, radio shows, traveling exhibits, community work, arts and crafts) and conservation actions (stewardship and protection by local communities, management plans, legal protection). The program carried out an initial prioritization process to identify the most important caves. Those priority caves contained large colonies of migratory bats and also faced imminent or ongoing damage by neighboring human population (Medellín, 2003). However, the PCMM has evolved so that is no longer limited to migratory bats, but include endemic species and those facing conservation threats that have been added in the Mexican list of species at risk (SEMARNAT, 2002).

The PCMM is now firmly assembled as a binational, multiinstitutional partnership based at Institute of Ecology, UNAM, with the participation of many other organizations. Currently, the program has presence in 18 states of México, where 26 caves are being monitored and 2 – 4 caves are added annually. The program has also initiated a vampire control operations in potentially problem areas, where it works with locals, researchers and public servers of environmental, cattle rising and health sectors. Priority caves where the program is working, have maintained the bat populations stable or they have increased (Medellín, 2003).

Cueva del Diablo was first monitored in 1996, when PCMM estimated 5 000 Mexican long – nosed bats; in winter 2001 – 2002 the numbers increased to 8000 – 10 000 (Medellín, 2003). Despite the importance of these bats, and of the cave for them, there's no legal protection actually for the cave and for the bat populations in it.

However, the PCMM also has achieved conservation success in the legislative arena. As a result of the promotion of the program in different venues, PCMM was called by the federal government to contribute to the recently passed Law of the Ecological Balance and Protection of the Environment. The PCMM suggested that all caves, natural crevices, and sinkholes be protected by law, because their importance for bats and for the recharge of aquifer. At the same time, the program's personnel contributed to the creation of a new category of federally protected areas, namely sanctuaries. A Sanctuary is a small area where it is necessary to protect an important population of particular species or an important segment of biological diversity, and where all resource extraction is banned. Caves are obvious, natural, and immediate candidates for this category (Medellín, 2003).

Following this idea, a group of researchers and students, coordinated by Dr. Rodrigo A. Medellín (chief researcher in the Institute of Ecology, UNAM and director of the PCMM) elaborated a study that proposes 10 priority caves with ecological and economical importance for become sanctuaries (in process), which was presented to the CONANP (National Commission for Natural Protected Areas) in 2004. Inside this proposal is Cueva del Diablo, because of its great colony of the threatened migratory nectarivorous bat *Leptonycteris nivalis*, its importance as a mating roost for this species (Tellez, 2001) and because vandalism and visiting are very common in the cave.

Concerning Cueva del Diablo, the PCMM had agreed with the local, state and federal authorities to work in the cave and with communities surrounding it since 2000. They'd developed a series of manual and educative activities for children and adults to show the benefits of bats and for the people to lose their fear about these animals. The program divided bats in six groups according to their feeding behavior (insectivorous, frugivorous, carnivores, ichthyophagous, hematophagous and nectarivorous) and created educational material that includes a natural story about each one and activity books for teachers and children. In the case of Cueva del Diablo, *Flores para Lucía la murciélaga* (Flowers for Lucía the bat) is the material which had been being used in four schools of four communities in Tepoztlan. At the same time, there have been made TV reports, manual workshops with the community's women and the exposition "Los murciélagos, un mito en nuestra cultura" (Bats, a myth in our culture) with a great people attendance.

The PCMM has future plans for this cave, as to work in another community and to run an evaluation of program's achievements. In other areas, the initial results of the evaluation of knowledge acquired and retained by the children through the pre – and post – exposure questionnaire – surveys indicate 70% retention knowledge about bats three years after exposure. Furthermore, new children entering the program in previously targeted schools, show a greater level of knowledge in pre – exposure questionnaires, indicating intra – community knowledge transfer from older to younger siblings. This, in turn, indicates that the process of bat conservation is being learned and adopted by the communities themselves as an activity of their own (Medellín, 2003).

Conclusions

Bats offer several ecosystem services, which are essential for natural environment and human welfare. Caves represent important sites where many bat species roost, mate, give birth and rear young. However, both bats and caves are facing threats often related with human activities and lack of information. Cueva del Diablo is a critically important cave for understanding, conservation, and recovery of an endangered, migratory pollinivorous bat species. This cave has already provided very important information about this little-known species. At least 50% of what is known about it comes from this cave.

Although a great effort has been maid to change these conditions, there is still a lot of work to do. Conservation of this and other caves and bats is urgently needed. This can only be conducted through collaboration across countries, disciplines, and sectors of society. It's necessary to change the general mistaken image people has about bats by sharing the information obtained in research, and environmental education programs had proved to be a good way to fulfill such task.

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Troglobites from the Lava Tubes in the Sierra de Chichinautzin, Mexico, Challenge the Competitive Exclusion Principle

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Introduction

The Sierra de Chichinautzin is located south of Mexico City and north of Cuernavaca, in Mexico. This volcanic mountain range had, in relatively recent times, (Holocene) at least seven lava flows with the formation of lava tubes (Espinasa-Pereña, 1999). Multiple caves of great extension can be found in this mountain range, including the Cueva del Ferrocarril, the largest lava tube in the Americas, at about 6 km, and Cueva de la Iglesia, at about 5 km. A detailed description of most of the cave systems in the area can be found in Espinasa-Pereña (1999, 2006).

Some of the Sierra de Chichinautzin lava tubes are inhabited by cave adapted silverfish insects (Cubacubaninae: Nicoletiidae: Insecta). Nicoletiids are one of the most important and common representatives of cave adapted fauna in the Neotropics and southern North America. While studying the relationships within the subfamily Cubacubaninae, Espinasa et al. (in press) included three troglobitic individuals from three different lava tubes from the Sierra de Chichinautzin: Cueva de la Iglesia, Cueva del Aire, and Cueva del Naranjo Rojo. Contrary to what might be expected due to the geographical proximity of the caves, the sequence data from five loci showed that the individuals belonged to two different species. The individual from Cueva de la Iglesia actually appeared to be more closely related to a species from a near surface locality, the town of Alpuyeca, than to its neighboring troglobite (Fig. 1).

The purpose of this study is to better understand how many species of troglobitic nicoletiid insects inhabit the lava tubes of the Sierra de Chichinautzin, their distribution, and their dispersal capabilities among caves.

Material and methods

Samples were collected by hand and deposited in 95% ethanol. Dissections were made with the aid of a stereo microscope. Total DNA was extracted from one leg of each individual using Qiagen's DNEasy® Tissue Kit. Molecular data have been obtained for 13 terminals, sometimes including more than one individual per locality (Table 1)

Markers were amplified and sequenced as a single fragment using the 16Sar and 16Sb primer pair for 16S rRNA (Edgecombe et al., 2002). Amplification was carried out in a 50 μl volume

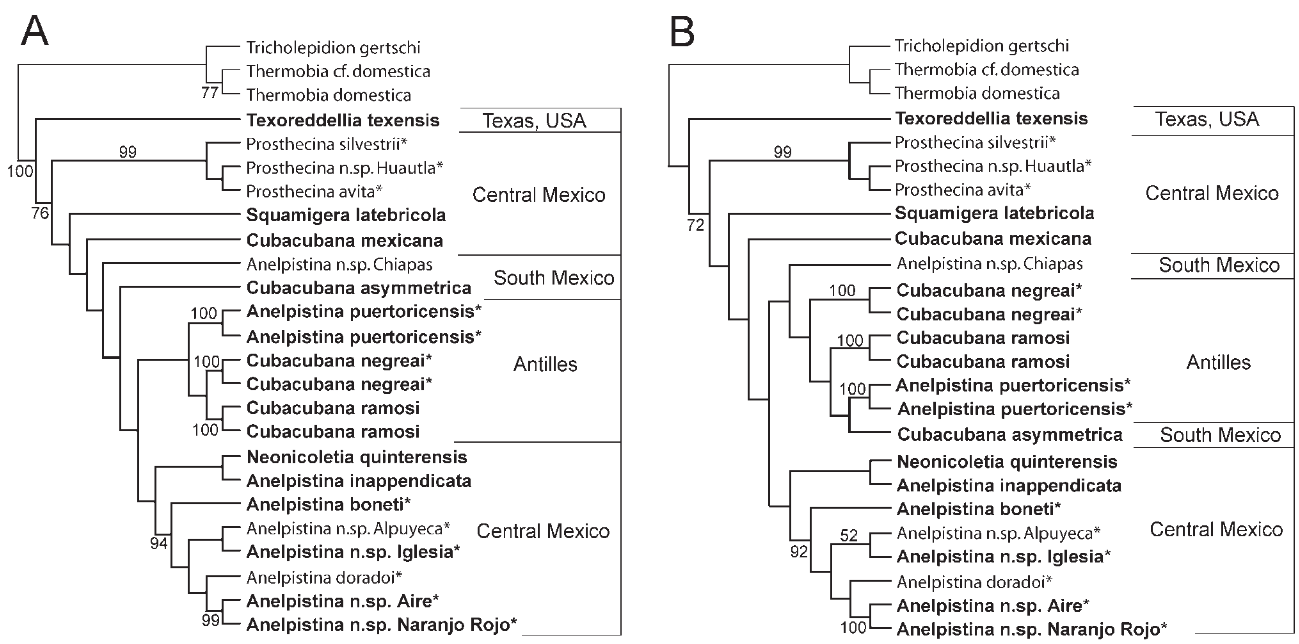

Figure 1. Figure taken from Espinasa et al. (In press). Two equally costly trees derived from the analysis of the combined analysis of sequence data from five loci and morphology. Bold species names indicate cavernicolous species. Asterisks denote species in which adult males have articulated submedian appendages on urosternite IV. Numbers on branches indicate jackknife support values. Notice that the specimen labeled *Anelpistina* n. sp. Iglesia is more closely related to *Anelpistina* n. sp. Iglesia than it is to both *Anelpistina* n. sp. Aire and *Anelpistina* n. sp. Naranjo Rojo.

Table 1. Samples studied, locality of collections, and references.

Samples	Locality of sample used	References
Anelpistina n.sp. Alpuyeca 1 individual	Alpuyeca, Morelos, Mexico (18º43' N, 99º15' W)	Google Earth
Anelpistina n.sp. Iglesia 6 individuals	Cueva de la Iglesia-Mina Superior, San Juan Tlacotenco, Morelos, Mexico (19º01' 02" N, 99º05' 29" W)	Espinasa, 1999; Espinasa-Pereña, 1999
Anelpistina n.sp. Aire *1 individual*	Cueva del Aire, Ajusco, DF, Mexico (19º13'30" N, 99º10'24" W)	Espinasa-Pereña, 1999
Anelpistina n.sp. Naranjo Rojo 4 individuals	Cueva del Naranjo Rojo, km 6.5 on the Cuernavaca-Tepoztlan highway, Morelos, Mexico (18º58' 46"N, 99º10' 54" W)	Tapie, 1987; Google Earth
Anelpistina n.sp. Herradura 1 individual	Cueva de la Herradura, km 6.5 on the Cuernavaca-Tepoztlan highway, Morelos, Mexico (18º59' N, 99º11')	Google Earth

reaction, with 1.25 units of AmpliTaq® DNA Polymerase (Perkin Elmer, Foster City, CA, USA), 200 μM of dNTPs, and 1 μM of each primer. The PCR program consisted of an initial denaturing step at 94 °C for 60 sec, 35 amplification cycles (94 °C for 15 sec, 49 °C for 15 sec, 72 °C for 15 sec), and a final step at 72 ºC for 6 min in a GeneAmp® PCR System 9700 (Perkin Elmer).

PCR amplified samples were purified with the AGTC® Gel Filtration Cartridges (Edge BioSystems, Gaithersburg, MD, USA), and directly sequenced using an automated ABI Prism® 3700 DNA analyzer. Cycle-sequencing with AmpliTaq® DNA polymerase, FS (Perkin-Elmer) using dye-labeled terminators (ABI PRISM™ BigDye™ Terminator Cycle Sequencing Ready Reaction Kit, Foster City, CA, USA) was performed in a GeneAmp® PCR System 9700 (Perkin Elmer). The sequencing reaction was carried out in a 10 μl volume reaction: 4 μl of Terminator Ready Reaction Mix, 10-30 ng/ml of PCR product, 5 pmoles of primer and dH_20 to 10 μl. The cycle-sequencing program consisted of an initial step at 94 °C for 3 min, 25 sequencing cycles (94 °C for 10 sec, 50 ºC for 5 sec, 60 °C for 4 min), and a rapid thermal ramp to 4 °C and hold. The BigDye-labeled PCR products were cleaned with AGTC® Gel Filtration Cartridges (Edge BioSystems). Chromatograms obtained from the automated sequencer were read and contigs made using the sequence editing software Sequencher™ 3.0. Complete sequences were edited in MacGDE (Linton, 2005), where they were split according to conserved secondary structure features. All external primers were excluded from the analyses.

Individuals whose sequence was different from other members of the same locality received a second DNA extraction and sequencing to verify that no contamination or human error had occurred.

Results and Discussion

Individuals from all localities belong to genus *Anelpistina* and are similar to *Anelpistina cuaxilotla* (Espinasa, 1999). Those of the cave localities were very similar in morphology, sharing troglobitic characters such as enlarged antennae, caudal appendages and legs. On the contrary, the Alpuyeca samples were easily differentiated by their comparatively smaller appendage/body ratio, as befits surface nicoletiids.

Table 2. Partial sequence alignment of mitochondrial 16S rRNA spanning nucleotides 298-354. In bold, specimens with a distinctive sequence corresponding to a species different to the majority of individuals of that cave locality. Dots = same nucleotide; lines = insertions or deletions; letters = nucleotides.

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Iglesia        TGACTAACCCTCTTGTAGGCAAGATTGTTTTATGGGCATG--TTGTTGATCCTTT-TATTAAGATTAATA
Iglesia        ......................................................................
Iglesia        .................................A....................................
Iglesia        ......................................................................
Iglesia        ......................................................................
Naranjo Rojo   ......................................................................
Aire           .A.C....--.......T...T.GG.TAC..T.AA.T...GT..A..........A...........T..
Heradura       .A.T....--.......T...T.GG.TAC..T.AA.T...GT..A..........A...........T..
Naranjo Rojo   .A.T....--.......T...T.GG.TAC..T.AA.T...GT..A..........A...........T..
Naranjo Rojo   .A.T....--.......T...T.GG.TAC..T.AA.T...GT..A..........A...........T..
Naranjo Rojo   .A.T....--.......T...T.GG.TAC..T.AA.T...GT..A..........A...........T..
Iglesia        .A.T....--.......T...T.GG.TAC..T.AA.T...GT..A..........A...........T..
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Sequence data from thirteen individuals were obtained. Length of fragment analyzed was of 499 nucleotides. Sequence analysis (Table 2) showed that individuals could be arranged into three distinct groups. The first group was composed of the individuals from Cueva del Aire, Cueva de la Herradura, three individuals from Cueva del Naranjo Rojo and one individual from Cueva de la Iglesia. Nucleotide differences among this group averaged 1.2 nucleotides, ranging from a minimum of zero to a maximum of four. The second group was composed of one individual from Naranjo Rojo and five individuals from Cueva de la Iglesia. Nucleotide differences among this second group averaged 2.1 nucleotides, ranging from a minimum of zero to a maximum of five. The last group was composed of the single individual from Alpuyeca. Members of group one against members of group two differed on 71 nucleotides on average, ranging from a minimum of 55 and a maximum of 78. Members of group one differed from the Alpuyeca individual by an average of also 71 nucleotides, spanning from 62-73 nucleotide differences. Members of group two differed from the Alpuyeca individual by an average of 54 nucleotides, spanning from 49-56 nucleotide differences.

Differences between individuals within a group are within the boundaries of members of a species for the Cubacubanininae, on the contrary, the differences among groups are those typically found across different species (Espinasa et al. in press). It appears that members of group one belong to an as of yet undescribed species, different from the also undescribed species of group two. This group two also appears to be more closely related to the surface species from Alpuyeca than they are to the troglobitic specimens of group one, which is in agreement with what was found by Espinasa et al. (In press) and shown in figure 1.

An interesting aspect of the two troglobitic species is that they can be found in several cave localities, regardless of the lava tube being formed from different lava flows. Members of group one species can be found along the entire Sierra de Chichinautzin in both the northern and southern lava tubes. This implies that these troglobites have the capability to disperse across lava flows, even in the absence of cave connections.

Another interesting aspect is that the two species appear to be sympatric in their geography. Both Naranjo Rojo and Iglesia cave were inhabited by members of both species. The competitive exclusion principle establishes that this is an ecological unstable situation, as two similar species can not occupy the same niche. The two species may have recently and independently colonized and adapted to the cave environment. Since the formation of these lava tubes is fairly recent (Holocene), with even Cueva de Naranjo Rojo and Cueva de la Herradura being formed less than 5,000 years B.P. (Siebe et al. 2004), it is likely that their dispersal has only recently put them in contact and we are in the remarkable position of witnessing a unique point in time and evolution where two sympatric species are in the process of a still unresolved competition for the same niche.

Conclusions

Cave Nicoletiids can disperse among lava flow systems.

The Sierra de Chichinautzin lava tube systems have independently been colonized by at least two different species of Nicoletiids.

The morphology of both species has converged as a result of troglobitic evolution.

Both species are sympatric (overlapping habitats), which represents an unstable ecological condition.

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2006 Field Trip Guidebook

Ramón Espinasa-Pereña

Introduction

The XII International Symposium on Vulcanospeleology is sponsored by the Sociedad Mexicana de Exploraciones Subterráneas (SMES), the Commission on Volcanic Caves of the International Union of Speleology (UIS), Grupo Espeleológico ZOTZ, Club de Exploraciones de México A.C., Veracruz Section (CEMAC), and the State of Morelos Section of the National Institute of Anthropology and History (INAH). It will be held in Tepoztlán, Morelos, México, in July of 2006. Several field trips will be carried out in the Sierra Chichinautzin, a Quaternary monogenetic volcanic field between the cities of México and Cuernavaca. The last field trip will visit lava tubes near the cities of Perote and Xalapa, in the eastern portion of the Transmexican volcanic belt, while obtaining views of some of the largest stratovolcanoes in México This guidebook will give the participants background information on the areas and caves to be visited.

The Sierra Chichinautzin Volcanic Field

Since most field trips will be held in the Sierra Chichinautzin Volcanic Field (SCVF), it will be described in detail. It is a volcanic highland elongated in an E-W direction, extending from the flanks of the Sierra Nevada, including Popocatepetl stratovolcano (presently active) in the east to the flanks of Xinantecatl (Nevado Toluca) stratovolcano in the west, in the central portion of the Transmexican Volcanic Belt (Martin del Pozzo, 1982).

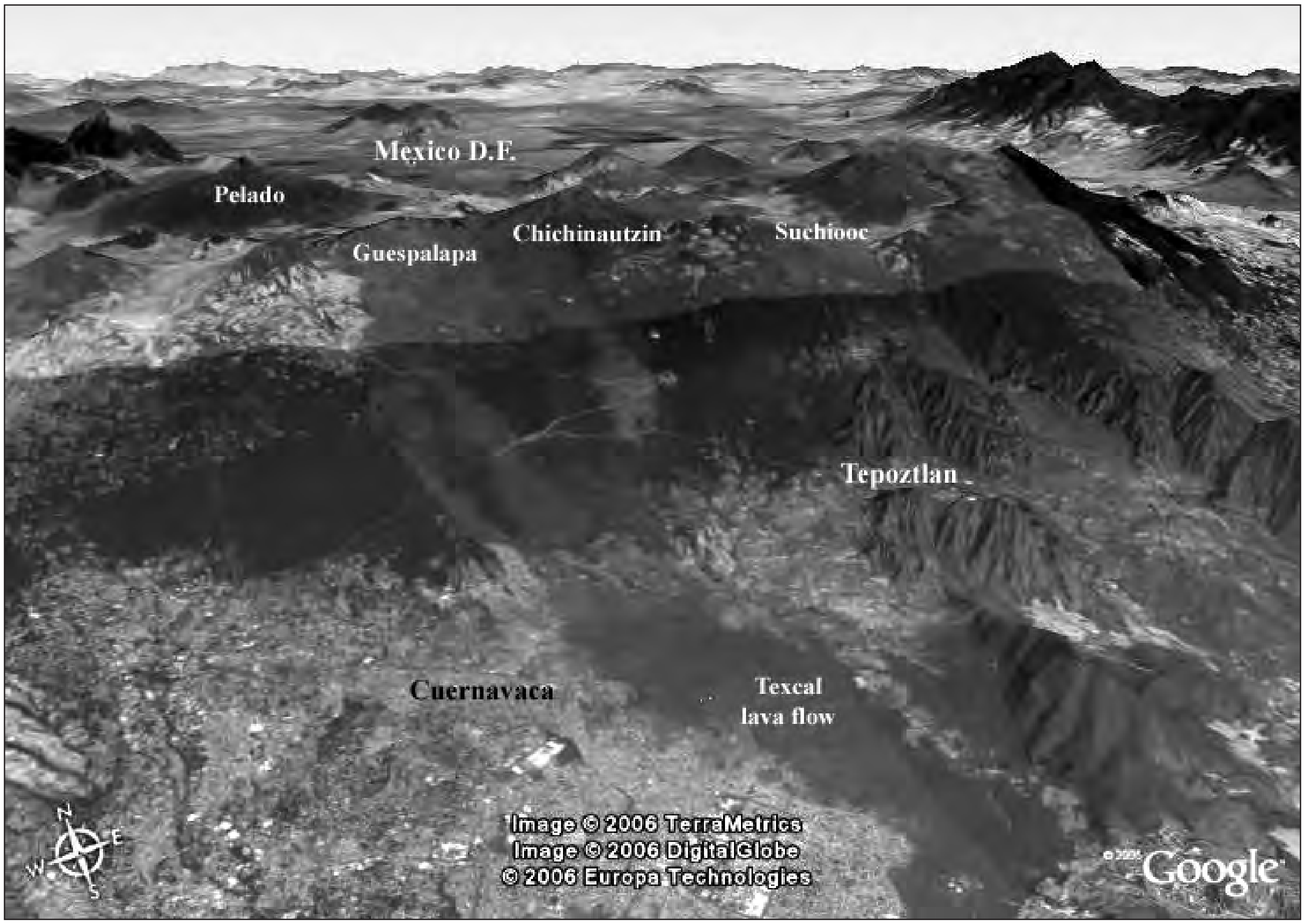
This volcanic field is made up by over 220 scoria cones and associated block, A’a or pahoehoe lava flows. SCVF forms the continental drainage divide that separates the closed basin of México, which artificially drains to the north, from the valleys of Cuernavaca and Cuautla which drain south, and from the Lerma River basin which flows west. According to Fries (1966), the Basin of México drained to the south before the Pleistocene. Since then, formation of the SCVF sealed the basin to the south (Mooser, 1963).

Lava flows in the SCVF vary considerably in their morphology. Most are compound andesite or basaltic andesite A’a flows, some of the thicker blocky lava flows are dacitic and a few are basaltic tube-fed pahoehoe flows. Lavas belong to the calc-alkaline suit, and are genetically linked to the subduction of the Cocos plate (Martin del Pozzo, 1982). The tephra cones, lava shields, associated lava flows, tephra sequences and intercalated alluvial sediments that make up the Sierra Chichinautzin cover an area of approximately 2,500 km^2 (Bloomfield, 1975; Martin del Pozzo, 1982; Lugo-Hubp, 1984). Paleomagnetic measurements indicate that most exposed rocks were produced during the normal Brunhes Chron and are therefore younger than 0.73-0.79 Ma (Urrutia and Martin del Pozzo, 1993), which is not surprising in view of the very young morphological features of most tephra cones and lava flows.

Recent studies by Siebe (2000) and Siebe et al. (2004, 2005) have published dates for some of the youngest volcanoes in the SCVF, several of which were emplaced at least partially by lava tubes: Teuhtli (>14,000 years B.P.), Pelado (9,620±160 to 10,900±280 years B.P.), Guespalapa (2,835±75 to 4,690±90 years B.P.), Chichinautzin (1,835±55 years B.P.), and Xitle (1,670±35 years B.P.). Other undated volcanoes whose lava flows were tube-emplaced, and which are morphologically very young include Yololica and Suchiooc. These and other

Tectonic setting of the Field Trip Sites in the Transmexican Volcanic Belt.

Sunset at the Sierra Chichinautzin.



The Sierra Chichinautzin forms a highland between the basins to its north and south. The dark horizontal shadow is an artifact due to the contact between two images, as are the apparent lava flows on the upper right corner.

previously published dates imply a recurrence interval during the Holocene for monogenetic eruptions in the SCVF of <1,250 years (Siebe et al., 2005).

During the XII International Symposium of Vulcanospeleology field trips 1, 2 and 3 and post-symposium field trips 1 and 2, the lava flows and/or lava tubes of Pelado, Guespalapa, Chichinautzin and especially Suchiooc volcanoes will be visited.

Pelado volcano (3,620 m.a.s.l.), is one of the most symmetrical cones of the whole SCVF. Its lava flows, 7 to 8 kilometers long, form a wide shield at the base of the cone. They are thick A'a or blocky flows of andesitic composition, so one would not expect lava tubes to develop. Despite this, a lava tube was explored and mapped recently at the beginning of the southeastern lava flows.

Guespalapa volcano (3,270 m.a.s.l.) is a series of small cinder cones aligned almost East-West, located just south of the drainage divide. They produced the most extensive lava flow in the SCVF, which flowed south far into the Cuernavaca plain. It reached 24 km from its source, creating the Texcal basalt lava flow, first mentioned by Ordoñez (1937). Siebe et al. (2004) conclude that this very long lava flow, which they consider to be A'a, must have necessarily been emplaced by a high-effusion rate eruption because they do not consider that tube-fed pahoehoe flows can reach very far in low to moderate-effusion rates (Peterson et al., 1994). Nevertheless, recent field work has uncovered five large lava tube caves, suggesting that the lava flow is mostly tube-fed pahoehoe. Near the vent area hornitos or rootless vents produced short lava flows which also developed small tubes.

Chichinautzin volcano (3,470 m.a.s.l.) gave its name to the entire volcanic field (Fries, 1966). The summit area is quite complex and several craters and aligned vents in an ENE-WSW direction can be identified both in the field and in aerial photographs. It produced extensive basaltic A'a lava flows in every direction. Although incipient tubes and inflation structures have been located, despite intensive search no true lava tubes have been found in this volcano.

Since most field trips will be held in lava tube caves of the Suchiooc volcano, a more extensive description will be made. Suchiooc volcano (3,300 m.a.s.l.) is the youngest of a cluster of tephra cones collectively known as Los Otates (Martin del Pozzo, 1982), roughly aligned in an ESE-WNW direction, and located south of the crest of the SCVF. Its tube-fed pahoehoe lavas flowed south along very steep slopes (up to 12°) until reaching the Sierra de Tepoztlán (ST).

The ST is an older range of mountains made of Miocene vulcanosedimentary deposits, which have been heavily eroded creating large pinnacles with very steep to vertical sides, often separated by very narrow, vertical sided ravines and gorges (Ordoñez, 1937). The ST rock unit has been named Tepoztlán Formation (Fries, 1966) and is a series of alternating layers of lahars, tuffs, fluvial sediments and volcanic breccias in layers that have a variable dip of 0° to 6° to the north (Haro et al., 1986). Numerous E-W and N-S fractures and small faults cut these rocks. The ST is considered the erosional remnant of a volcaniclastic fan (Ochoterena, 1977), and its age has been constrained by García-Palomo et al. (2000), who dated lava flows bounding it below and above at 21.6±1.0 and 7.5±0.4 Ma respectively.

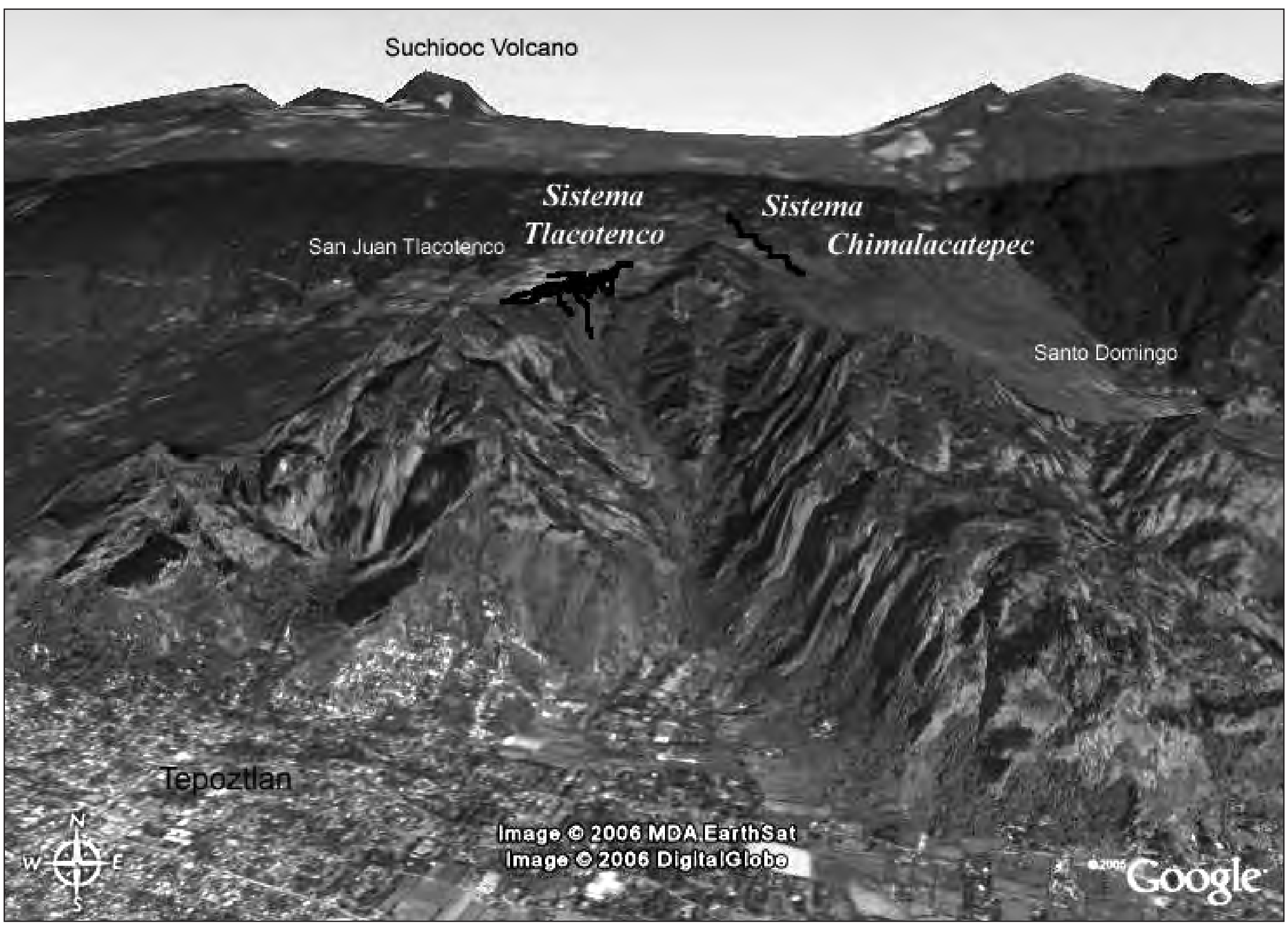
The Suchiooc lava flow separated into several branches among the ST pinnacles before continuing south towards the Oaxtepec plains. With over 18 km in length, it is one of the longest lava flows recognized in the SCVF. Over 26 kilometers of lava tube caves have been surveyed in this flow, and are described in detail by Espinasa-Pereña (1999, 2006).

At the northern base of the Suchiooc cone, between it and older lavas to the north, a series of levees mark the edges of a former lava lake about 600 meters long and 130 meters at its widest. This lava lake overflowed towards the east, creating a series of levee bounded channels that roofed up to form the caves of Sistema del Distribuidor. The channel-tube system fed at least three long, unitary lava flows to the south, which developed tubes from levee bounded channels. From east to west they are the Amatlán, Tepemecac and Chimalacatepec lava flows, named after the most important lava-tube caves en each of them.

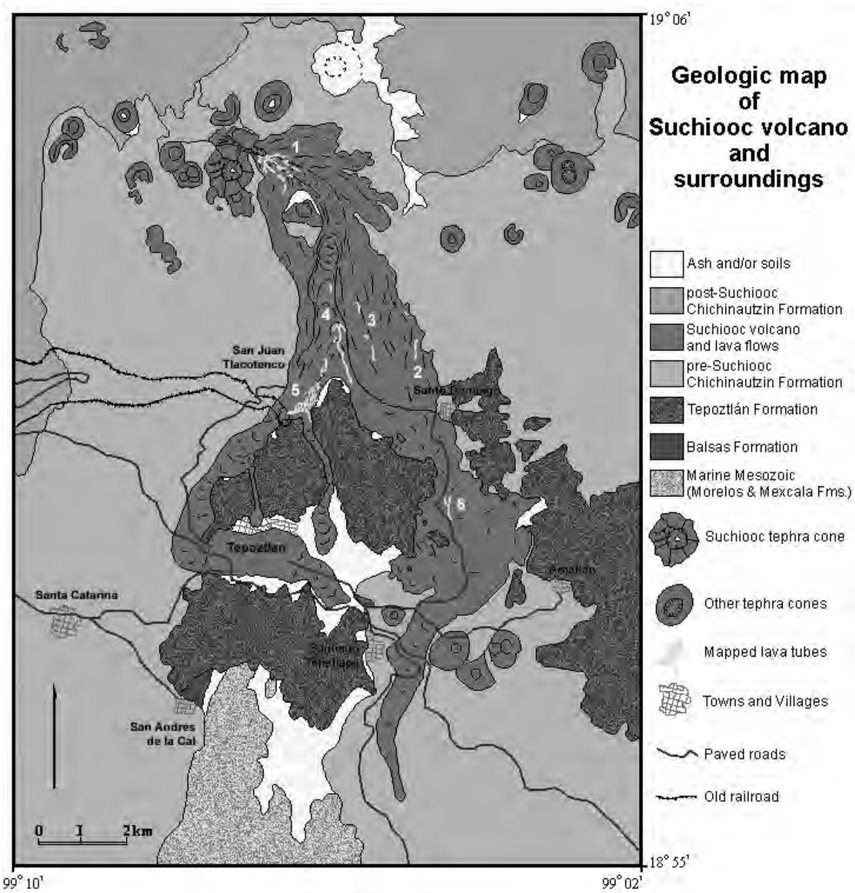
Lava flow was eventually concentrated on the western tube, developing by thermal erosion and internal levee growth a master tube, which can be seen in the caves of Árbol and Sistema Chimalacatepec. Overflows from hornitos or skylights above these tubes fed multiple or compound lava flows, which cover the unitary lavas mentioned above and form the majority of the flow south of the towns of San Juan Tlacotenco and Santo Domingo. Anastomosing lava tubes developed in this flows can be seen in Sistema Tlacotenco. Cueva del Diablo is a master tube with anastomosing side passages, in the lower portions of the flow.

Symposium Field Trip One, 3 July 2006. Overview of the Sierra Chichinautzin, Cuescomates and Cueva del Diablo

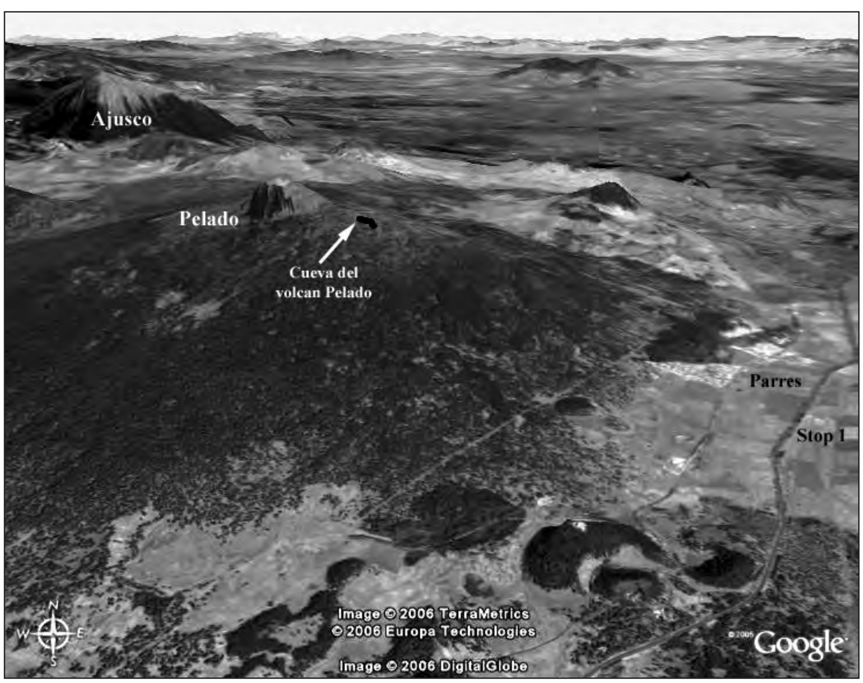
This day we will travel from the symposium site, Tepoztlán, along Highways 115 and 95 towards México City, until reaching the turnabout at kilometer post 41, near the town of Parres, where stop 1 will be made while the bus makes the U-turn.



The upper and middle portions of the Suchiooc lava flow. The dark horizontal shadow is an artifact due to the contact between two images.



Location of the major caves in the Suchiooc lava flow. (1) Sistema del Distribudor. (2) Amatlán lava flow. (3) Tepemecac lava flow. (4) Sistema Chimalacatepec (Field Trip 2). (5) Sistema Tlacotenco (Field Trip 3). (6) Cueva de Diablo (Field Trip 1).



Aerial view of Volcán Pelado and its lava shield.

Stop 1: Overview of the Sierra Chichinautzin Volcanic Field. Here we will get a view of the upper central portion of the Sierra Chichinautzin volcanic field. To the west the prominent tephra cone on top of a lava shield is Pelado volcano (3,620 m.a.s.l.), one of the highest summits of the SCVF. Its name is due to the lack of trees at its summit cone, which is caused by the altitude, close to the timberline. The andesite lava flows of Pelado flowed in every direction for about 7 to 8 kilometers, and are mostly A'a or blocky lavas with thick (5 to 25 m) flow fronts and few primary flow structures like channels and levees. Although completely unexpected due to the lava morphology and composition, a lava tube cave was explored and mapped near the eastern base of the cone. Cueva del Pelado, despite being only 69 meters long and containing almost no primary features of interest, with an altitude of 3,470 m.a.s.l. is the highest mapped cave of any kind in México and North America.

On the opposite side of the road an older cone, Acopiaxco volcano (3,310 m.a.s.l.), has a less perfect tephra cone and its lava flows have been covered by thick airfall tephra deposits from more recent eruptions. Among these layers, Siebe et al. (2004) identified a 14,000 year old marker layer, called the "tutti-frutti" pumice, which originated from Popocatepetl stratovolcano to the east. Beyond Acopiaxco, a low shield with an asymmetric tephra cone at its summit is Chichinautzin volcano (3,470 m.a.s.l.), one of the youngest in the SCVF at only 1,835±55 years B.P. Its name means "burning lord" in the prehispanic Nahuatl language, which indicates that local inhabitants must have witnessed the eruption. Although its lava flows reach up to 10 kilometers in length, it is mostly A'a, with easily identified superposed channel and levee structures. Although incipient tubes and inflation structures have been located, an intensive search produced no true lava tubes in this volcano's lava flows.

To the south the small cones (El Palomito and El Caballito) that make up Guespalapa volcano (3,270 m.a.s.l.) are visible beyond the western lava flow of Chichinautzin. Guespalapa produced the extensive Texcal lava flow to the south, mostly tube-fed pahoehoe, and many Hornitos and at least 5 extensive lava tubes are known in Guespalapa's lava flow. On our next stop we will visit the best preserved hornitos of this volcano, known as Los Cuescomates.

Board the bus to head back towards Cuernavaca on Highway 95. At kilometer post 48, right after the border between the Distrito Federal and the state of Morelos, and before a white bridge across the road, is a parking area for visitors to the Monument to José María Morelos, the XIX century Independence War hero whose name was given to the state where he fought. This is stop 2.

Stop 2: Los Cuescomates. After crossing the highway on the bridge, take the unpaved road heading north towards Guespalapa volcano on a slight upwards slope for about 15-20 minutes. After crossing the electric lines, take the first road that splits to the right (south) and follow it downwards for another 10-15 minutes. When you again reach the electric lines, get off the road along a path to the right, where you will find a series of small hornitos or rootless vents which form Group 1 of Los Cuescomates. In Nahuatl, Cuescomate means conical gourd or container.

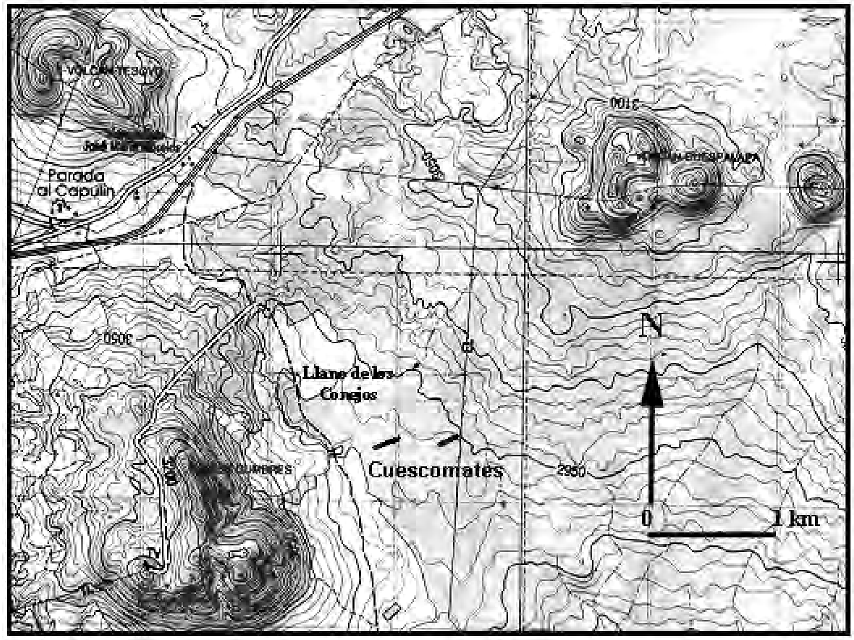
These rootless vents developed when the Guespalapa lava flow encountered a flat area, called "Llano de los Conejos", just north of the Tres Cumbres volcanic edifice. Thick ash and soil deposits, probably saturated with water, fill this ponded area and probably were in part responsible for the formation of the hornitos.

Group 1 consists of 8 different vents aligned along a single ENE-WSW fracture. Four of them created small scoria cones, while the other four built spatter cones in which individual spatter blobs can be identified. The three middle vents have vertical-walled craters which can be entered with caving equipment and are connected through very tight fissures. Accreted lava lining covers the inner reaches of these rootless vents.

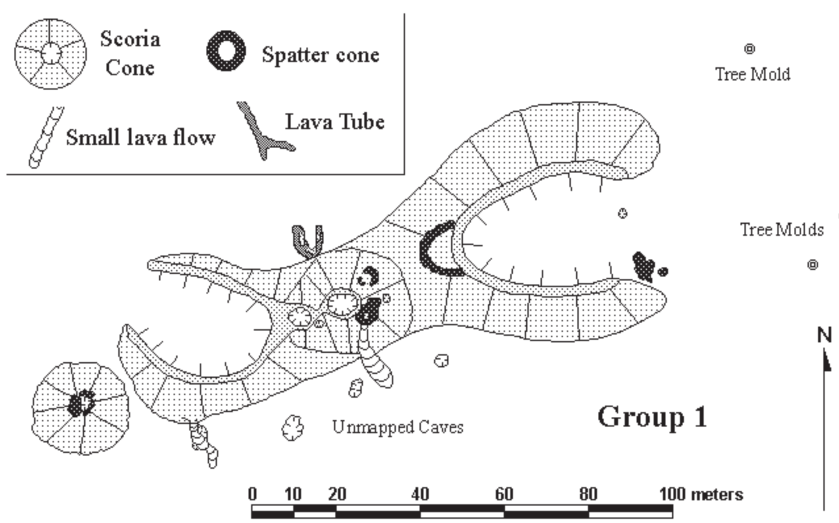
Small lava flows, issued by this group of "hornitos", formed several small lava tubes located to the NW and SE of the central vents. The area must have been covered by pine trees similar to the ones growing there today, as evidenced by several lava tree molds, up to 5 meters long, preserved to the east of the cones.

After visiting Los Cuescomates (Group 1), take a small path from their northern end, heading west, which surrounds the edge of the flows issued by them, and follow it towards the SW until reaching a small road heading south, which must be followed for less than 100 meters until reaching the northernmost of the group 2 Cuescomates. They are a group of 5 vents, three of which are tephra cones and the other two spatter cones. Only one of the vents, the easternmost, has a vertical-walled crater, which is connected through a tight fissure with a small hole on the northern base of the cone. A lava lining covers most of the inner walls of this vent, which is also lined with a large inner levee marking a former lava level inside the crater. Since this small cone is used as a quarry, its structure made of scoria fragments is easily seen. Lavas issued from this cone to the south generated well formed levee-bounded channels, and growth of the levees formed small caves. A collapsed cave to the north is used as an animal enclosure ("Potrero").

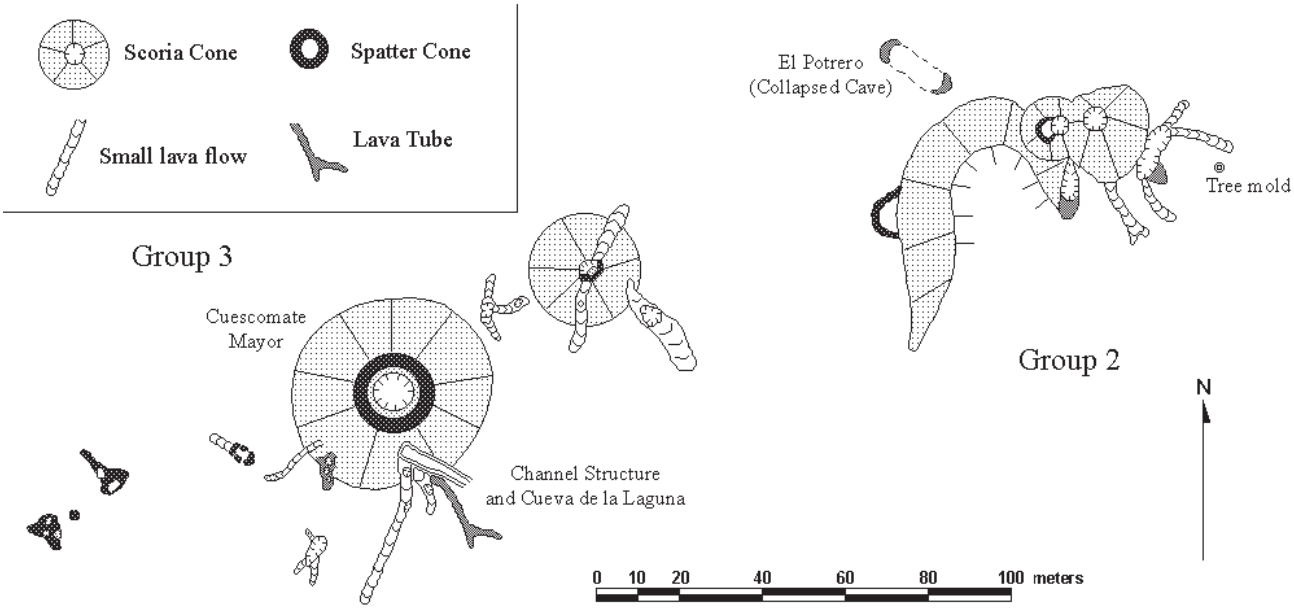
Walking west, less than 100 meters away is Group 3, which includes the largest of these small "hornitos". El



Map of the area of Stop 2.



Plan of Cuescomates (Group 1).



Plan of Cuescomates (Groups 2 & 3).

Cuescomate Mayor is 20 meters high and almost entirely made up of spatter. Avoid climbing its exterior walls except along the established trails on its eastern and western sides to prevent its destruction, as some of the spatter is not well consolidated. The crater is easily enterable, and still preserves part of a lava lining. At its southern base, a very interesting vent-channel structure is found, from which several different small lava flows were emitted, developing small lava tubes. One of them contains Cueva de la Laguna, with 62 meters of small passage and a little lake which gave it its name.

Further west, three other small vents produced small lava flows but no tephra or spatter, and are only recognizable by the presence of small caves or lava tubes. One of the vents has a crater about 15 centimeters wide but at least 3 meters deep, as sounded with a stick that didn't reach the bottom.

After visiting the Cuescomates, walk west until reaching the flat, soil-covered plain of Llano de los Conejos and cross it until finding an unpaved road. Follow it west, climbing slowly (remember you are at nearly 3,000 m.a.s.l.), until reaching the main Highway 95 at the Morelos monument. Lunch will be had at Restaurante Los Venados. Quesadillas (Fried corn "tortillas" filled with a variety of typical local ingredients like cheese, fungus, pumpkin flowers, etc.) are especially recommended.

Continue south along highway 95 towards Cuernavaca until kilometer post 64 where a parking lot is located.

Stop 3: Cuernavaca Valley Lookout. We are standing atop the southern flow of Chichinautzin volcano. Notice the difference in vegetation between this young (1,835±55 years B.P.) lava flow, consisting of small xerophyte plants, lichens and grasses, as compared with the vegetation of the surrounding, much older lava flows. Primary structures of the Chichinautzin lava flows indicate that it was emplaced along lava channels limited by levees, and the flow morphology is typical A'a. Many olivine crystals can be observed in samples of these basaltic lavas, and feldspar xenoliths are common.

To the south, a panoramic view of almost the entire state of Morelos can be seen. The lookout is almost precisely located along the surface trace of the La Pera normal fault system (Siebe et al., 2004) which essentially marks the

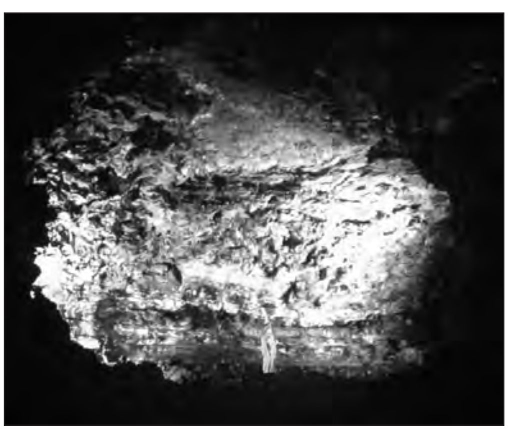
Los Cuescomates rootless vents are dwarfed by the surrounding 20 meters tall pine trees.

southern limit of the SCVF. The fault scarp is not visible, as it has been entirely covered by young lava flows, but seismic evidence shows that the fault system could still be active. The rounded hills across the valley are made up of Cretaceous limestone and shale. To the west, the Texcal lava flow, issued from Guespalapa volcano, can be seen as it is deflected by the Herradura volcano cone and then crosses the entire Cuernavaca valley before ponding against the limestone hills. The Texcal lava flow, between 2,835±75 to 4,690±90 years B.P. in age and 25 kilometers long, is the longest recognized lava flow in the entire SCVF. Both its morphology and vegetation cover indicate its extreme youth, comparable to Chichinautzin, so its age is most probably closer to the younger date. The Cuescomates "hornitos" seen in the morning are developed on this lava flow. Five large caves, remnants of a huge master tube, in places over 20 meters in diameter, have recently been mapped and are proof of its origin as a tube-fed pahoehoe flow.

To the east a series of rock pinnacles can be seen. They are the Sierra Tepoztlán, which is considered the remnants of a huge Miocene volcaniclastic fan. The city of Tepoztlán, the symposium site, is located in a depression developed among these pinnacles. The town above the pinnacles is San Juan Tlacotenco. Suchiooc volcano is just over the crest to the northwest, and its tube-fed pahoehoe flows branched among the Tepoztlán pinnacles. Underneath the town of San Juan are the twelve caves that together form Sistema Tlacotenco, which include the longest (and probably most complex) lava tubes known in Continental America.

Continue on highway 95 until reaching kilometer post 70. Take the branch to the right towards highway 115 which takes you towards Tepoztlán. After passing the toll booth, get out of the highway on the right and follow the signs towards the Cuernavaca-Tepoztlán federal road. Turn left and follow the road to the center of Tepoztlán. Turn right on main street and follow it down and out of town. Follow the road to a Y fork and take the small road to the left towards Santo Domingo Ocotitlán. After about 10 kilometers the bus will stop at a small parking area on the left. This is Stop 4. Walk across the field towards the cliff that limits it to the NW to visit an excellent outcrop of the Tepoztlán Formation, consisting of alternating layers of lahars, tuffs and volcanic breccias. Tube-fed basaltic lava from Suchiooc volcano surrounds the eroded pinnacles.

Stop 4: Cueva del Diablo. Walk across the road and cross a gate. Follow the path on the other side until reaching a bifurcation after about 200 meters. Take the right path, which leads straight into the main entrance. The cave is used as a maternity by Leptonycteris bats, so should be avoided in the winter months to prevent disturbing the colony. Being close to the road, it is the most frequently visited cave in the area, so the entrance area has many spray paints, and cord has been left in many passages in the cave by inexperienced visitors to find their way out. Extensive use of the map is recommended for first time visitors. During the symposium excursion, a through trip will be made to the smaller entrances. A total of 2,020 m of passages were surveyed in this tube. This cave is still used by local villagers for religious rituals to the devil, involving the sacrifice of chicken.



Large master tube in Cueva del Diablo.

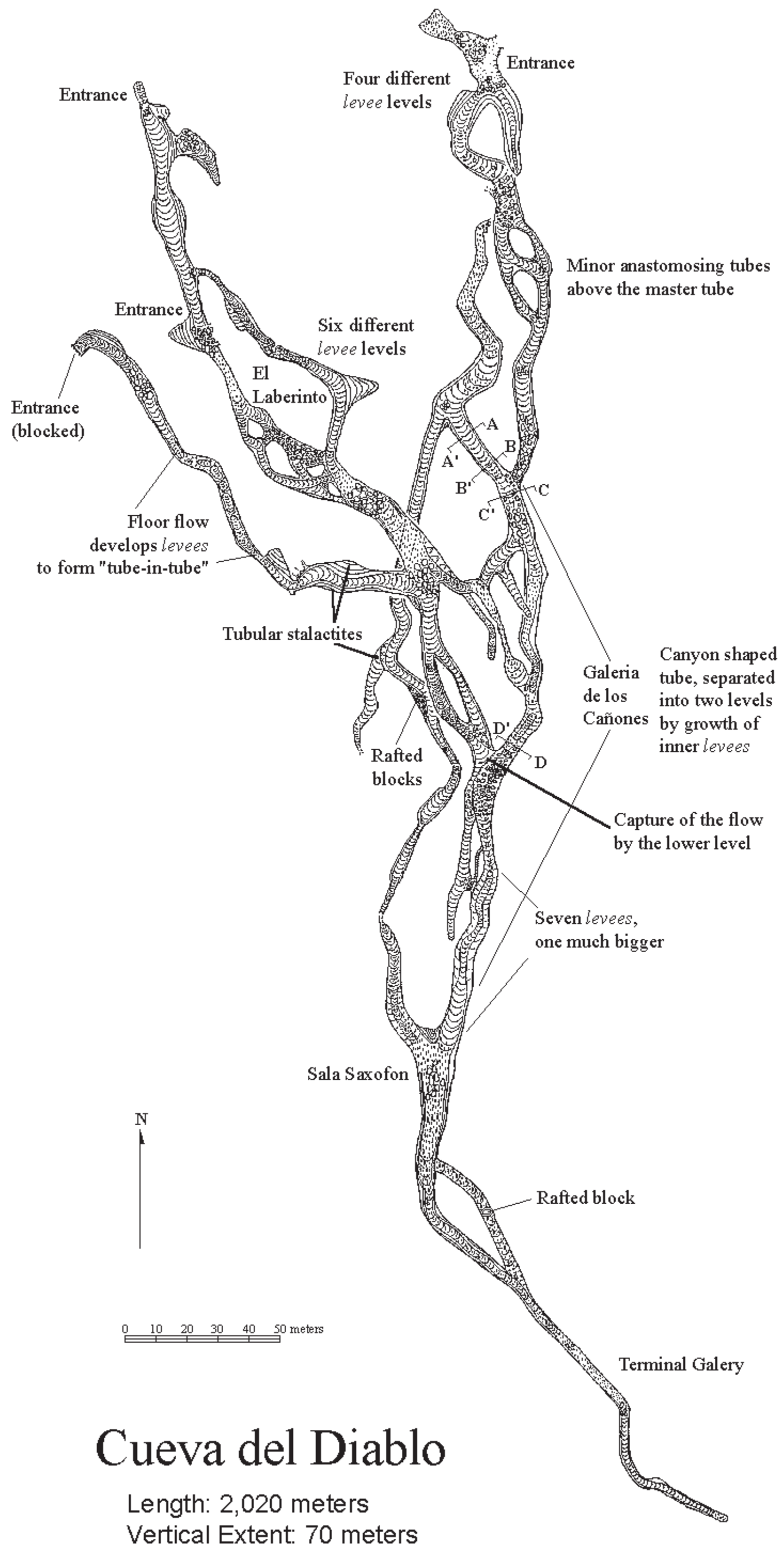
Cueva del Diablo consists of a large main passage, Galería de los Cañones, which is interpreted to be part of the master tube because of its size, canyon shape and the levees that split it into superposed passages. A complex series of upper level tributary passages join the main tube. In places the lining of the master tube collapsed during volcanic activity, so the multiple or compound lava flow containing the cave is clearly visible, made up of numerous small lava toes or tongues. Many tubular lava stalactites and stalagmites, made up of extruded segregates during early cooling of the lava tube, decorate the walls and many alcoves. Most of the smaller anastomosing tubes at a higher level still preserve their linings.

From the main entrance follow the left hand passage at every junction. Whenever you reach a bifurcation, follow the joining passage upwards for a while, but then return to the main or left hand branch. Eventually you will reach Sala Saxofón. Visiting the final portion of the cave, used by the bats, is not recommended. On the return trip, take the first large branch to the left and follow it to the Labyrinth. The right hand passage eventually goes to a crawlway after which the light from the two smaller entrances can be seen at both ends of a large tube. Exit from the furthest entrance and follow a path north back across the fence and road to the bus. The bus will return to the main square at Tepoztlán.

Symposium Field Trip Two, 5 July 2006. Sistema Chimalacatepec

Sistema Chimalacatepec. This cave is the main portion of the Suchiooc Master Tube. It is a large canyon shaped passage intersected by several skylight entrances, which were already open during activity as evidenced by the primary structures (levees, lava linings, etc.) in them. They are called, in a downflow direction, Cueva de Tatamasquío, Cueva de Chimalacatepec and Cueva de Iztaxiatla. With 201 meters in vertical extent and a total of 1,388 meters of surveyed passages, Sistema Chimalacatepec is the deepest lava tube explored in Continental America. Including Cueva del Árbol, another cave upflow from Chimalacatepec, the master tube can be traced over a total vertical extent of nearly 300 meters.

At the bottom of this cave, over half a kilometer from the nearest entrance, an archeological find was made, which included over 90 different ceramic and carved rock pieces, in excellent state of preservation, belonging to the Tlahuica culture (Vega Nova and Pelz Marín, 1994; Broda and Maldonado, 1994). The presence of a zoomorphic figurine representing a horse, and also of chicken

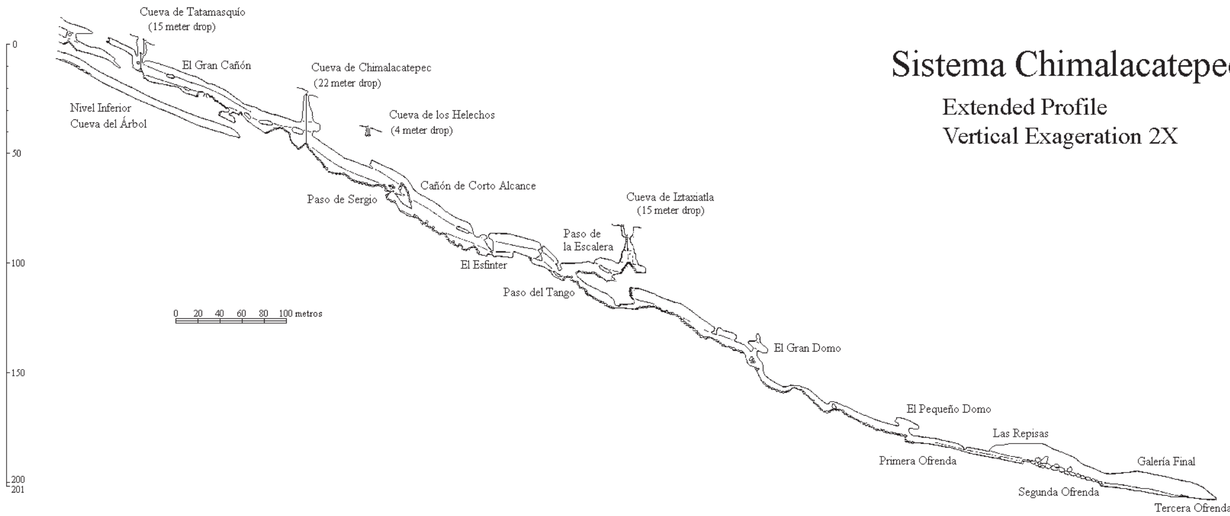


Plan view of Cueva del Diablo.

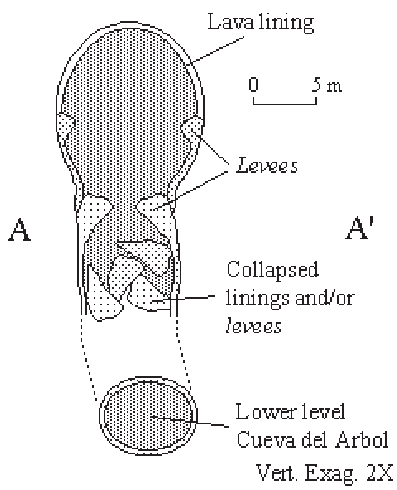
and pig bone fragments (animals introduced during the Conquest) seems to indicate a Colonial age for these offerings (Vieitez L., pers.com.). All the pieces were recovered by workers of the Instituto Nacional de Antropología e Historia (INAH), Morelos department, when they received our notification, and are presently in a specially adapted Site Museum in the town of San Juan Tlacotenco.

The bus will leave the main square at Tepoztlán and take the small road west towards the town of San Juan Tlacotenco. We will visit the site museum and then walk along the "Camino Real" path, climbing towards the northeast past several small houses until reaching a rock fence on the right. When the steep path flattens out, look for a break on the rock fence. A hundred meters below the fence, in the middle of a small ridge is the 15 meter entrance pitch known as Cueva de Iztaxiatla. This was an open skylight during activity, as shown by levees surrounding the whole pitch. A caving ladder (with safety rope) and/or an abseiling and climbing rope will be rigged for the field trip. Two other short climbs further into the cave also require rigging for intensive traffic. The plan map included is only of the portions of the cave accessible through Cueva de Iztaxiatla. After visiting the cave, the bus will return us to the main square at Tepoztlán.

The uppermost portion of the cave, which we will not visit, is accessible through the other two entrances. It is formed by at least three superposed levels, and the first hundred meters overlie the lowermost passages in Cueva del Árbol. Levees all around the entrance pitches, and a continuous lava lining all the way to the surface prove that these entrances were open skylights during activity. Progress is made along large terraces made up of wall levees, while most of the "floor" is made up of big breakdown blocks, mostly made up of collapsed levees and/or linings. This section of the cave ends at El Esfinter, where the wall linings on both sides of the passage join together, leaving only a very tight hole at floor level, less than 30 cm high and wide, floored with A'a lava, through which a howling wind is felt. This little hole is the connection with the upper passages of Cueva de Iztaxiatla.



Profile of Sistema Chimalacatepec showing skylight entrances and other features.



Cross section of El Gran Cañón, Sistema Chimalacatepec.

El Gran Cañón, upper passage of Sistema Chimalacatepec.

After descending the 15 meter entrance pitch of Cueva de Iztaxiatla, a passage can be followed upflow, soon reaching a balcony over a lower level. Either a 5 meter pitch or a short climb with the aid of a log takes us to another passage which we again follow upflow until reaching a final climb-down, Paso del Tango. This climb deposits us on the main or lower level of Sistema Chimalacatepec. All the above mentioned passages are superposed levels of a single canyon-shaped tube, separated by the growth of levees due to the cooling caused by the Iztaxiatla skylight. The downflow continuation of all this superposed levels is blocked and inaccessible.

Once on the lowermost level, a passage upflow with prominent wall levees, partially collapsed in places, reaches El Cañón Inferior, almost 20 meters high, but which soon ends against a high wall. At its base is the lower end of El Esfinter, the connection with the upper portion of Sistema Chimalacatepec.

Downflow from Paso del Tango on the lowermost level, after a tight spot between collapse blocks, an elliptic tunnel is reached, with prominent red A'a lava as a floor, where it is not covered by breakdown. Walls and ceiling are plastered by several lava linings, and pahoehoe wall levees and benches are also visible. After 130 meters, the passage goes underneath El Gran Domo, a possible skylight during activity, not open to the surface due to the development of a solid crust before the drainage of the tube.

Beyond El Gran Domo, the passage diminishes in height and widens, acquiring an elliptic cross-section. Walls, floor and ceiling are covered by a lining of easily broken scoriaceous red A'a lava. Further ahead the whole floor is covered by collapsed blocks of this lining. When the breakdown ends, the passage is elliptic on cross section, with pahoehoe wall levees, but the floor continues to be red A'a lava. The slope diminishes, as well as the passage size. Eventually, a crawl is reached.

Just beyond the crawl, the first archeological remains were found. Under the prominent wall levees were 3 incense burning pots with hollow handles and 16 earthenware bowls, while on top of the levees over 50 carved-rock figurines, mostly of jadeite were found.

One last segment of canyon passage of large dimensions with prominent balconies, called Las Repisas, follows. The floor is covered with large collapsed fragments of lava lining or collapsed wall levees. The scars of these collapses show several superposed linings, representing many episodes of successive emptying and refilling of the master tube.

The collapses end abruptly at the beginning of the terminal Gran Galería Final, which is 15 meters in diameter, partially filled by the red A'a lava on the floor. The levees disappear under this lava, which also has large contraction cracks. A bifurcation is reached, where three incense burning pots with hollow handles and 4 earthenware pots were found placed on the remains of a fireplace. The passage to the right

Incense burners, second offering, Sistema Chimalacatepec.

ends after only 20 meters, filled to the ceiling by the red A'a lava flow, while the main passage to the left continues for 50 meters in large dimensions to a large lava sump, where the ceiling and floor join. Two incense burning pots, with especially embroidered handles, and 10 earthenware pots, again placed over the remains of a fireplace, were found in the final chamber.

Symposium Field Trip Three, 7 July 2006. Cueva de la Iglesia-Mina Superior

Sistema Tlacotenco Group. Formed by 12 different caves developed inside a compound lava flow that was emitted by skylights above the Chimalacatepec master tube. These lavas flowed southwest along the eastern edge of San Juan Tlacotenco. The compound character of the flow can be observed in the railway cuts below town. As the lavas reached the prominent peaks of the Sierra de Tepoztlán, the flow subdivided into different tongues and entered narrow canyons eroded into the volcanic agglomerates. The tube system is a complex network of anastomosing passages, although in the upper portions a main tube, larger than the rest, is discernible and in places it is canyon shaped or has superposed levels (Cueva de Marcelo), but its character is quickly lost downflow as the tube subdivides into many smaller tubes (Cueva de la Iglesia). As the flow reaches Cerro Tepozteco it divides into two branches. The eastern branch is the steepest, and all the tubes heading towards it concentrated into a single, unbranched tube (Cueva de la Tubería), while the western branch remains with a moderate slope and continues to have many parallel and anastomosing tubes (as seen in Cueva del Ferrocarril and Cueva del Capulín). All the caves are genetically linked, but collapses, ash/soil fills and/or breakdown blockages have separated the tube system into the today known caves. A total of 16,032 m of passages have been surveyed in this system along a 301 m difference in height, mostly under constructions and streets of the town of San Juan Tlacotenco.

Many primary structures have been found inside this lava tube system. Most important in discerning the tubes history have been levee patterns both in walls and floor; rafted lava balls and lava ball dams; tubular lava stalactites, drip stalagmites and other segregated materials; shark tooth stalactites; flow marks; wall crusts, and late flows reoccupying an already empty tube. Additionally, secondary mineral deposits in the form of crusts, popcorn dripstone and flowstone are abundant in certain sections, particularly in the Segunda Axial passage of Cueva de la Iglesia.

Many junctions of tubes show evidence of formation of larger tubes by the accretion of smaller tubes, and there are many evidences of pirating of lava from an upper tube into a lower lying tube. It is important to stress that these underlying tubes are basically contemporaneous with the upper ones, and not the product of earlier flows. It was also found that those tubes which branch from the main one at a higher level show evidence of having been drained first, and on occasions to have been reoccupied by later flows which mainly refilled them and then solidified.

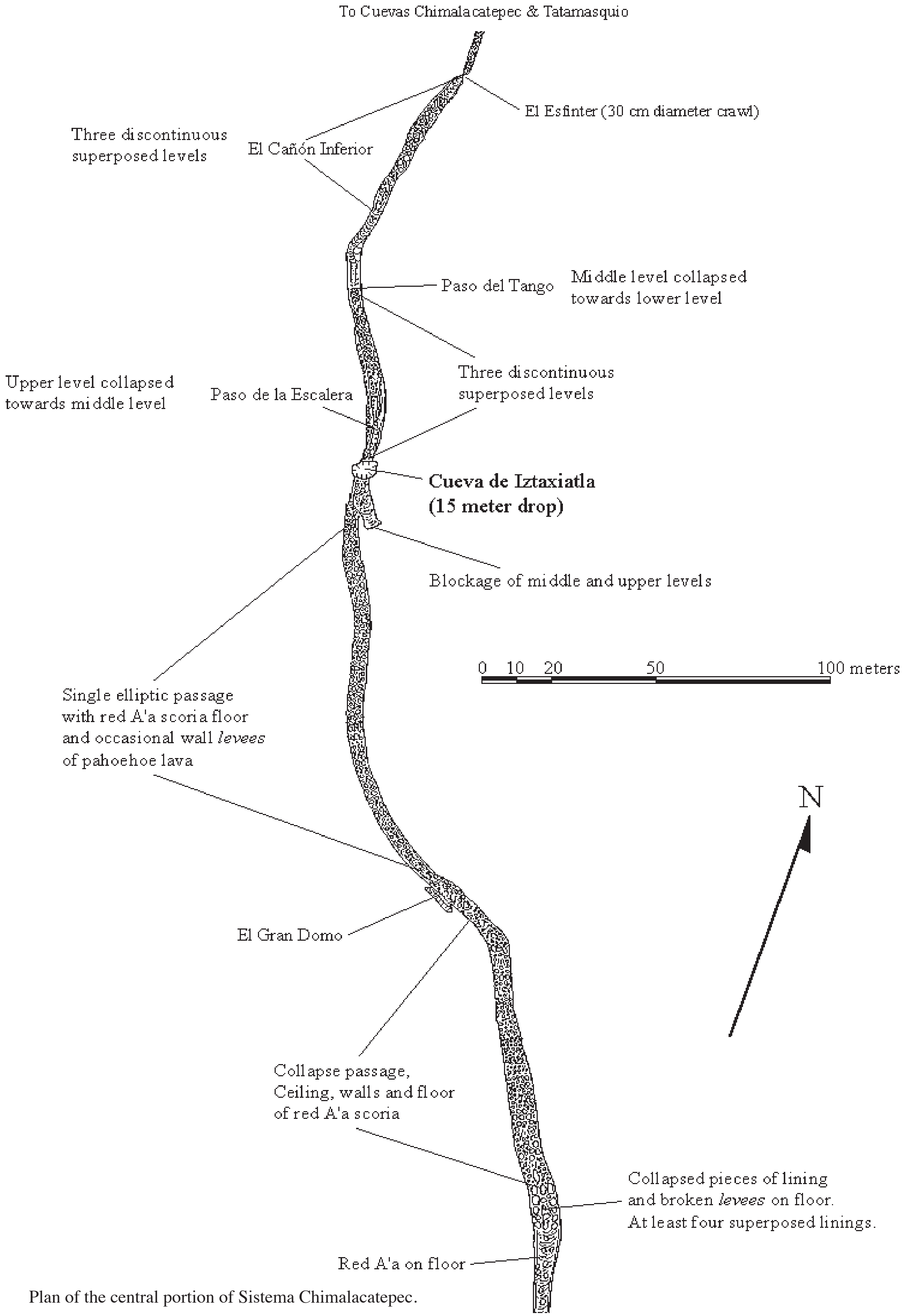
Although no evidence was found for erosion into the country rocks, many features record the modifications to the inner shapes of the tube made by the flowing lava eroding and/or remobilizing its walls and floor, including inward growth of levees, rafted blocks turned into lava balls, undercutting of the tube walls by lava that has been detoured by a wedged lava ball, undercutting of the base of lava falls behind lava ball dams, lava balls wedged at complex tube junctions and then transformed into tube walls, singenetic breakdown, etc.

No attempt will be made to describe every passage in this complex system, and details will only be given of the passages that will be visited. Intensive use of the map is recommended when visiting any of these caves, which should be checked at every junction. Directions are given with respect to an explorer entering the cave.

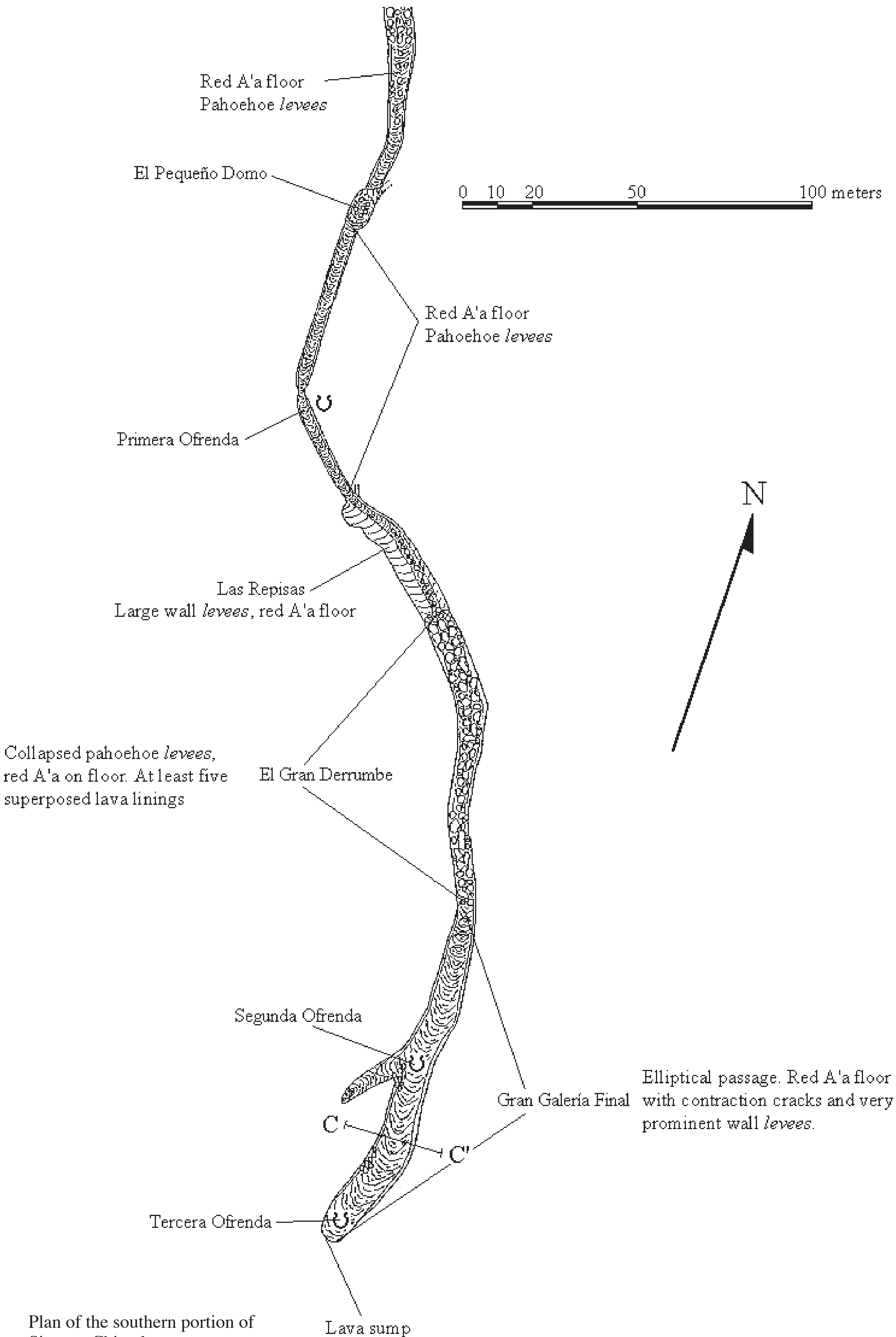
The bus will leave the main square at Tepoztlán and take the small road west towards San Juan Tlacotenco. After reaching the town, we will take the continuation of the main street and walk towards the only accessible entrance of Cueva de la Iglesia-Mina Superior, located at the extreme SE portion of town. It is a small crawlway slightly above the major collapse depression known locally as La Mina, behind a conspicuous white greenhouse.

Cueva de la Iglesia-Mina Superior. With a surveyed length of 5,278 m, along a vertical extent of 60 meters, this cave is the second longest surveyed lava tube in continental America. It comes within 20 meters of surveyed passages in Cueva de Doña Macaria (420 m), and within 10 meters from passages in Cueva del Ferrocarril-Mina Inferior (6,538 m), from which it is segmented by a 20 m long surface trench. Cueva del Castillo (455 m) actually passes above and then below passages in Iglesia, but is still unconnected.

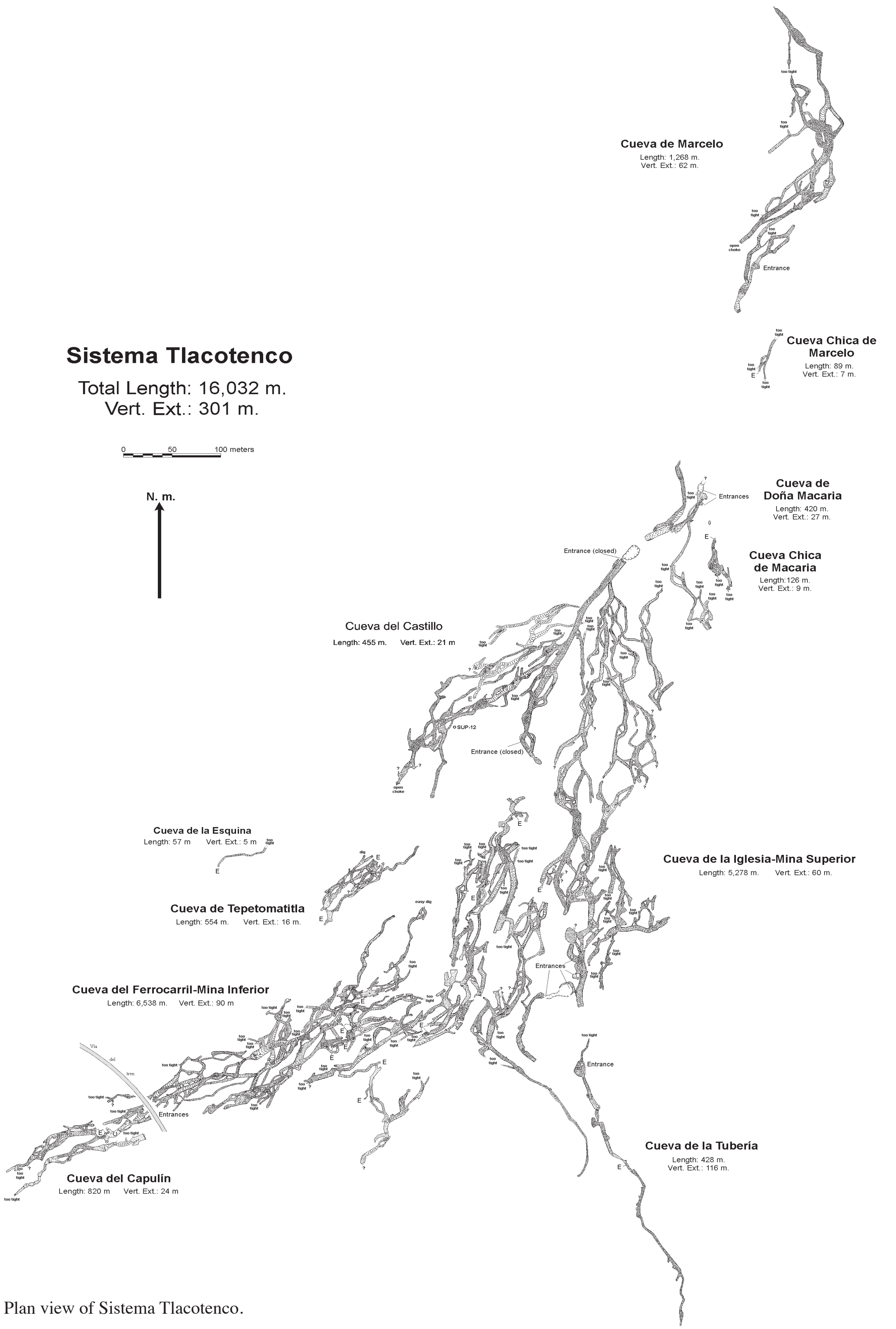
Its entire development is under the eastern edge of the town of San



Plan of the central portion of Sistema Chimalacatepec.



Plan of the southern portion of Sistema Chimalacatepec.



Plan view of Sistema Tlacotenco.

Juan Tlacotenco. There are six known entrances, three of which have been blocked by the owners of the property. One of them, unfortunately, saw fit to build a sewer drainage while blocking the topmost entrance. Of the remaining three entrances, very close together, the only accessible one actually enter what is known as Cueva Mina Superior, at the upflow edge of the trench separating it from Cueva Mina Inferior, the easternmost entrance of Cueva del Ferrocarril-Mina Inferior.

From the entrance crawlway a small climb, easily missed on the way back, takes us to a relatively large passage which leads downflow to the Mina Superior entrance (too tight to be of use) and upflow to the rest of the cave. Pottery fragments in this area and a treasure-hunt dig show that this portion of the cave was frequently visited. The main passage upflow is of crawling dimensions until reaching Salón de las Raíces, a spacious, mud floored side chamber with a large balcony overlook decorated by many tree roots. Following the mud floored passage upflow, again on hands and knees, one passes several side passages and slowly the main tube gains height at the base of a lava falls. A conspicuous lava ball hanging from the ceiling decorates this spot. Another crawlway ahead soon ends at a climb-down into a major junction of superposed levels, the connection chamber between Cueva Iglesia and Cueva Mina Superior.

Taking the passage on the opposite side of the main tube one soon reaches the Diaper Chamber, which is another complex junction. The main tube is followed upflow to a major breakdown chamber. Careful to note this spot as on the way back it is easy to take the wrong tunnel out of this collapse. Following the right wall, crossing the collapse is relatively easy. The breakdown soon ends at another complex junction of several tubes, the Labyrinth. Take the tube further west (left as you go in) and follow it upflow.

This is the Segunda Axial, the second major tube of the cave, and will be followed upflow until it joins the Galería Principal or main passage. Along its length, many junctions will be noted, some of which give access to other portions of the cave, while others are simple loop passages or superposed levels. Many interesting primary structures are developed along this tube, including levees, shark tooth stalactites, syngenetic breakdown covered partially by lava linings left by later flows reoccupying the tubes, etc.

After a few hundred meters, a crawlway is reached, after which the tube is decorated with abundant dripstone stalactites of opal, up to 20 centimeters long, with incipient stalagmites growing below. In places, flowstone with abundant microgours is developed on the floor or levees.

Finally, the Segunda Axial passage encounters a huge rafted lava ball which almost blocks the passage, but by crawling underneath one pops out in the upper reaches of the main Galería Principal. Notice that the conspicuous (from the downflow side) lava ball blocking the entrance to the Segunda Axial is completely invisible from the upflow side, having been eroded and/or covered by the lava from the main passage.

Do not follow the Galería Principal upflow, as it soon leads to the blocked entrance used as a sewer. Downflow, this tube is developed as a canyon with stacked upper levels. The floor is an A'a flow, but side benches of smooth pahoehoe decorate the walls, marking a high stand of the lava, and facilitate notably the traversing of this tube.

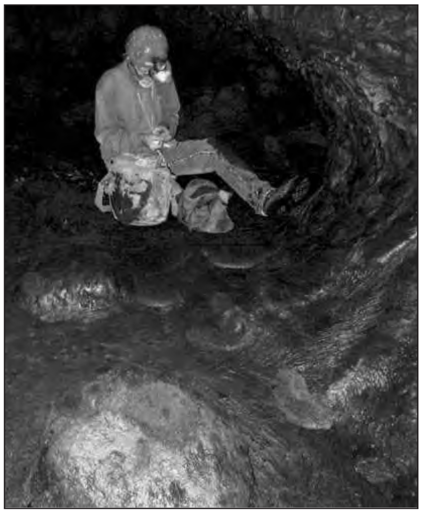
In the last couple hundred meters, with less gradient, the passage becomes lower and begins to anastomose, with some of the bifurcations obviously formed by huge lava balls. The lower entrance, caused by the fall of a tractor in the middle of a street, is now blocked by a concrete slab. Shortly afterwards the ceiling dips down and the floor becomes full of ash/soil. The terminus is only 30 meters from the huge rafted lava ball blockage that marks the topmost end of Cueva del Ferrocarril-Mina Inferior.

Several anastomosing side passages depart from the main passage. From upflow the first one on the east, 30 meters from the top entrance-sewer, gives access to the Segunda Axial, described above. The second one, also on the east side, is easily missed as it opens at floor level. It gives access to a hundred meter long tube with an A'a floor. The walls are made of clinkery pahoehoe, covered by a glazed lining only on the lower 1 meter of the passage walls.

The next side passage, this time to the west, is the entrance to Ramal de

Admiring Opal dripstone stalactites, Segunda Axial passage, Cueva de la Iglesia, Sistema Tlacotenco.

Galería Principal, Cueva de la Iglesia, Sistema Tlacotenco.



Admiring rafted blocks in Ramal de las Bolas, Cueva de la Iglesia, Sistema Tlacotenco.

las Bolas. This branch of the cave consists of three parallel tubes which start at a wide chamber, floored on its west side by a large amount of rafted blocks covered by a thin lining of pahoehoe. This blockage prevents direct access to the two westernmost tunnels, while the entrance to the eastern one is almost completely blocked by a large lava ball, which allows access by crawling underneath. The three passages present anastomosing development, with accessory branches and oxbows which complicate the plan even further. Many primary structures are present on all these tunnels. The three passages join at a complex intersection with abundant singenetic collapse blocks, from which two passages continue until they are blocked, by ash/soil the western one, and by a lava sump the eastern one.

Post-Symposium Field Trip One, 8 July 2006. Cueva del Ferrocarril-Mina Inferior

Cueva del Ferrocarril-Mina Inferior. This cave is the longest and most complex cave in the Suchiooc lava flows and the longest cave in the state of Morelos. It is the longest surveyed lava tube in continental America, with 6,538 meters of surveyed passages along a vertical extent of 90 meters. It has a total of 14 known entrances, located on the terrains to the south and east of the town of San Juan Tlacotenco. The most frequently used are in an artificial railroad cut at its western end. The remaining entrances are mostly

Lava stalagmite in Ramal de Luís, Cueva Ferrocarril-Mina Inferior.

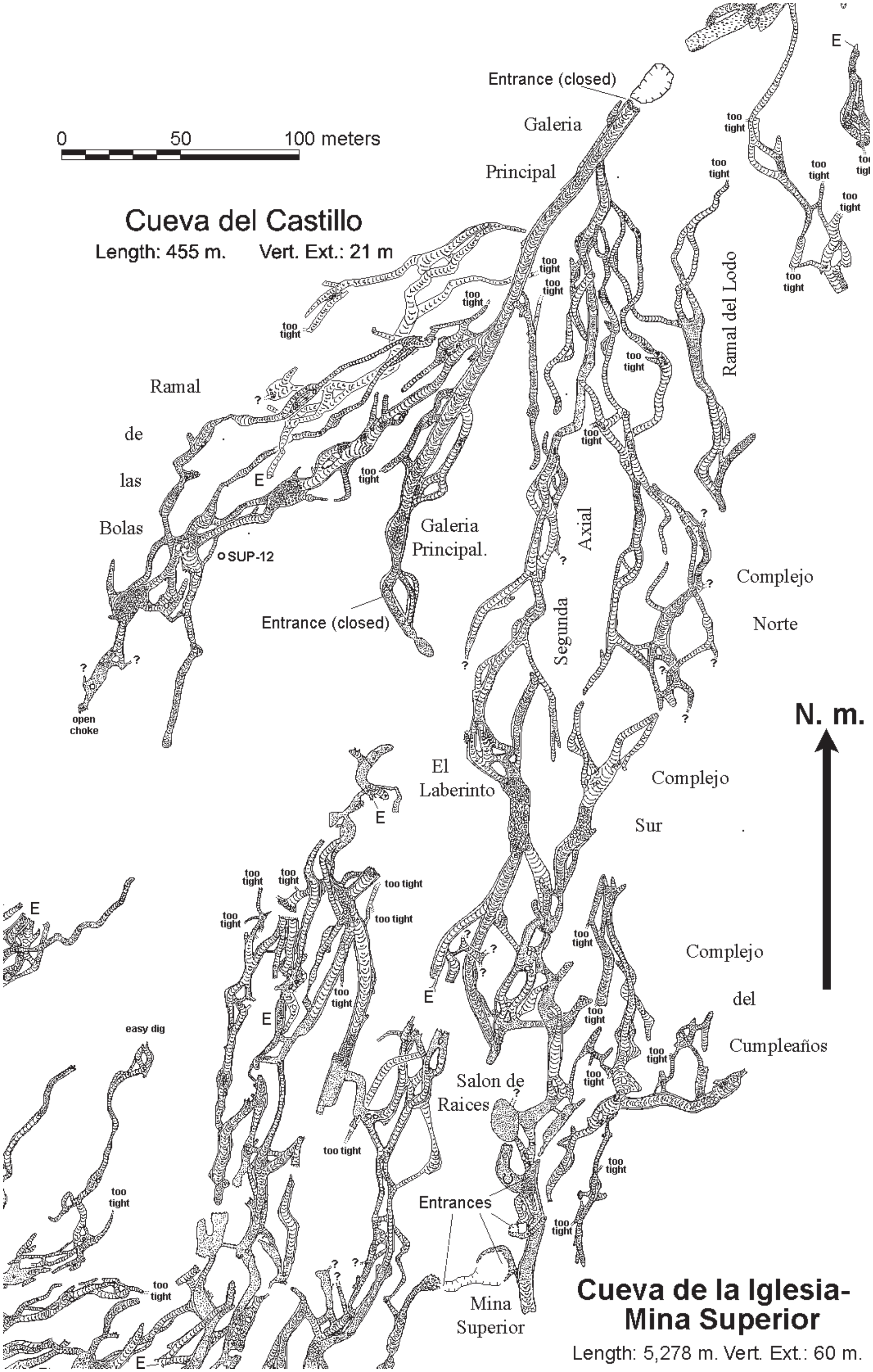
post-activity collapses although at least one, La Nopalera, may have been an open skylight during activity, as evidenced by the lack of breakdown at its base. Two of the known entrances have been blocked by the owners, and in one of them, unfortunately, a sewer drainage was built while blocking the entrance, while three of the remaining entrances have been used as garbage dumps. It comes within 20 meters of Cueva de la Iglesia-Mina Superior (5,278 m long), from which it is separated by the collapse trench known as La Mina. It is also only 15 meters from Cueva de la Tubería (428 m long) and is separated artificially from Cueva del Capulín (820 m long) by the railroad cut.

This cave is much more complex than Cueva Iglesia-Mina Superior. Except for the uppermost section (La Tubería), no master tube is present, and most passages are a very complex anastomosing labyrinth. It would be useless and very complicated to attempt to describe this entire cave, so only the major features will be described. Its complex character is further enhanced by the fact that the lava flow separated into two different branches as it reached the pinnacles and hills of the Tepoztlán Formation.

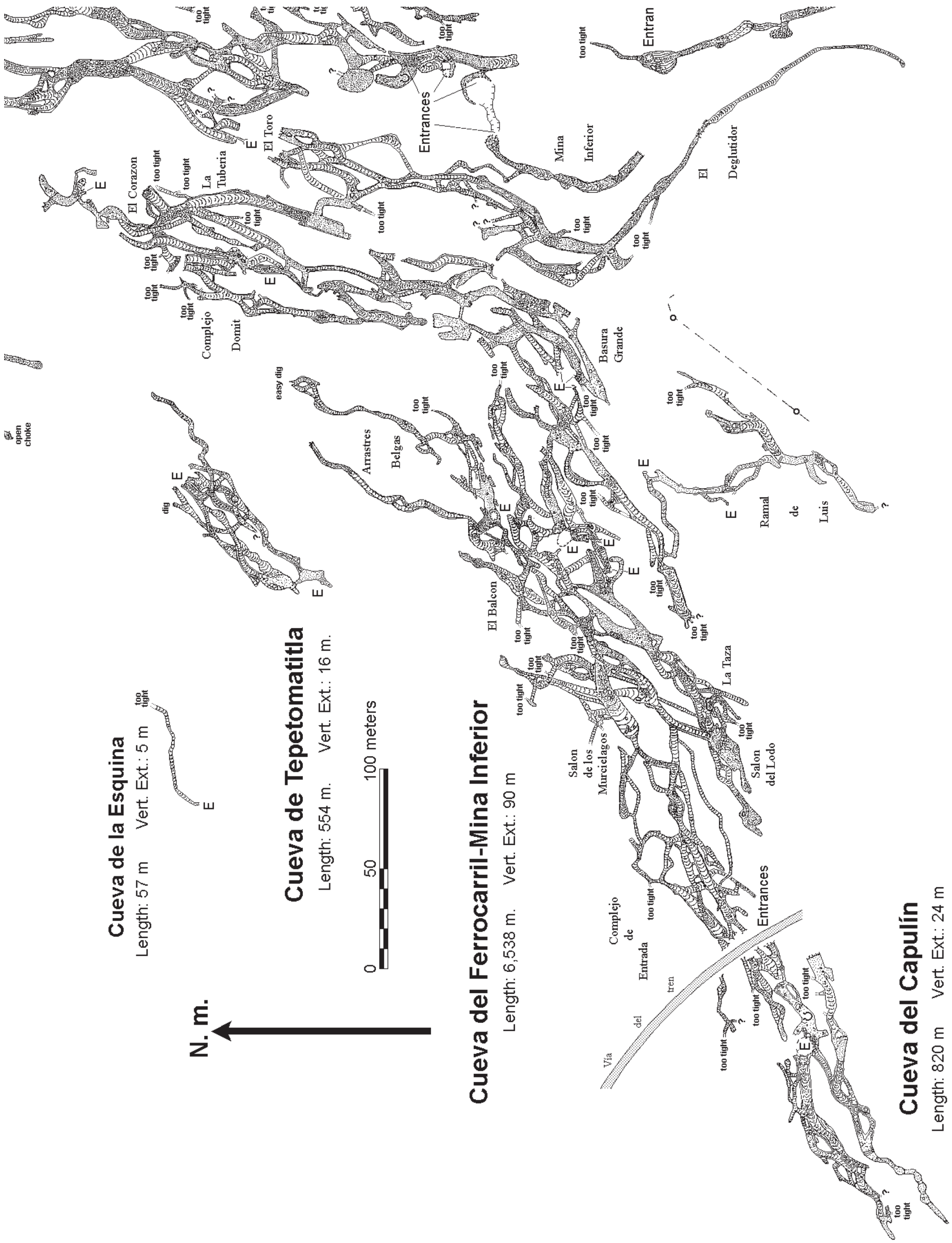
The upflow end of the cave is La Tubería, the continuation of the master tube in Cueva Iglesia-Mina Superior. It immediately starts to branch into several parallel tunnels of smaller dimensions, with abundant junctions between them. The easternmost branch collects the tubes which are a prolongation of the Segunda Axial and its tributaries in Iglesia-Mina Superior, and eventually begin to steepen as they reach the edge of the steep slope ending in Tepoztlán. All tubes in this branch coalesce into a single tube, named El Deglutidor, which after a steep descent ends in an ash/soil fill very close to Cueva de la Tubería.

Cueva del Ferrocarril becomes especially complicated west of the connection with Mina Inferior. Essentially,

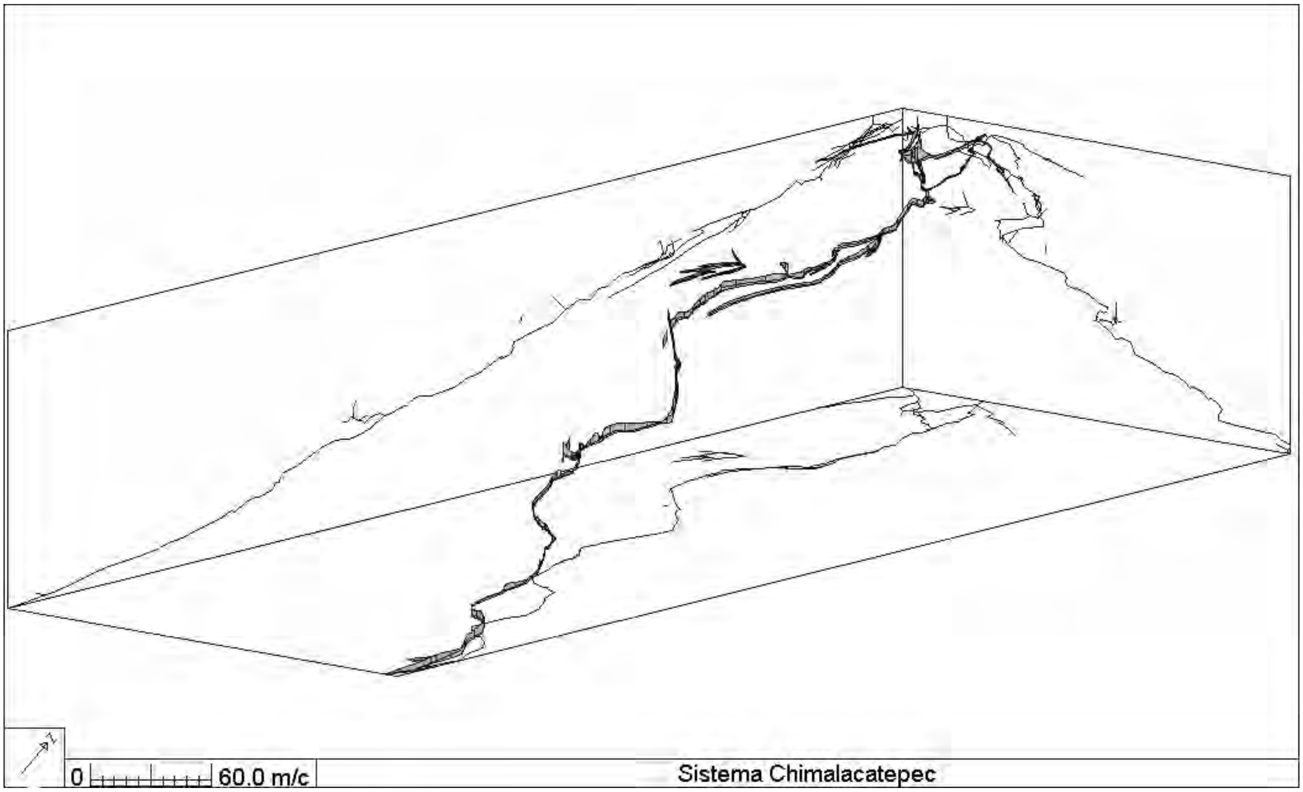
Lava cascade at junction of two levels, Cueva Ferrocarril-Mina Inferior.



Plan maps of Cuevas de la Iglesia-Mina Superior and Castillo, Sistema Tlacotenco.



Plan of Cueva del Ferrocarril-Mina Inferior.



Three-dimensional view of Cueva del Árbol, Sistema Chimalacatepec and Cueva del Potrero.

a lower anastomosing tube-fed flow, originating from the western tubes in La Tubería, was covered by the anastomosing lavas coming from Ramal de las Bolas in Cueva Iglesia-Mina Superior. In many places evidence can be found of the pirating of the flowing lava from the upper tubes by the lower ones due to collapse of the intervening ceiling/floor, and later modifications of the internal shape of the tubes due to the flow of lava can also be discerned.

At several complex junctions dams of rafted balls complicated the relationship of the overlying tubes even further by the formation of new tubes among the lava balls through undercutting. This is especially notable near La Taza and the Salón de los Murciélagos, but many smaller or less clear examples can be found throughout the cave. Levees, benches, shark-tooth stalactites and many other primary structures can be found on most tunnels.

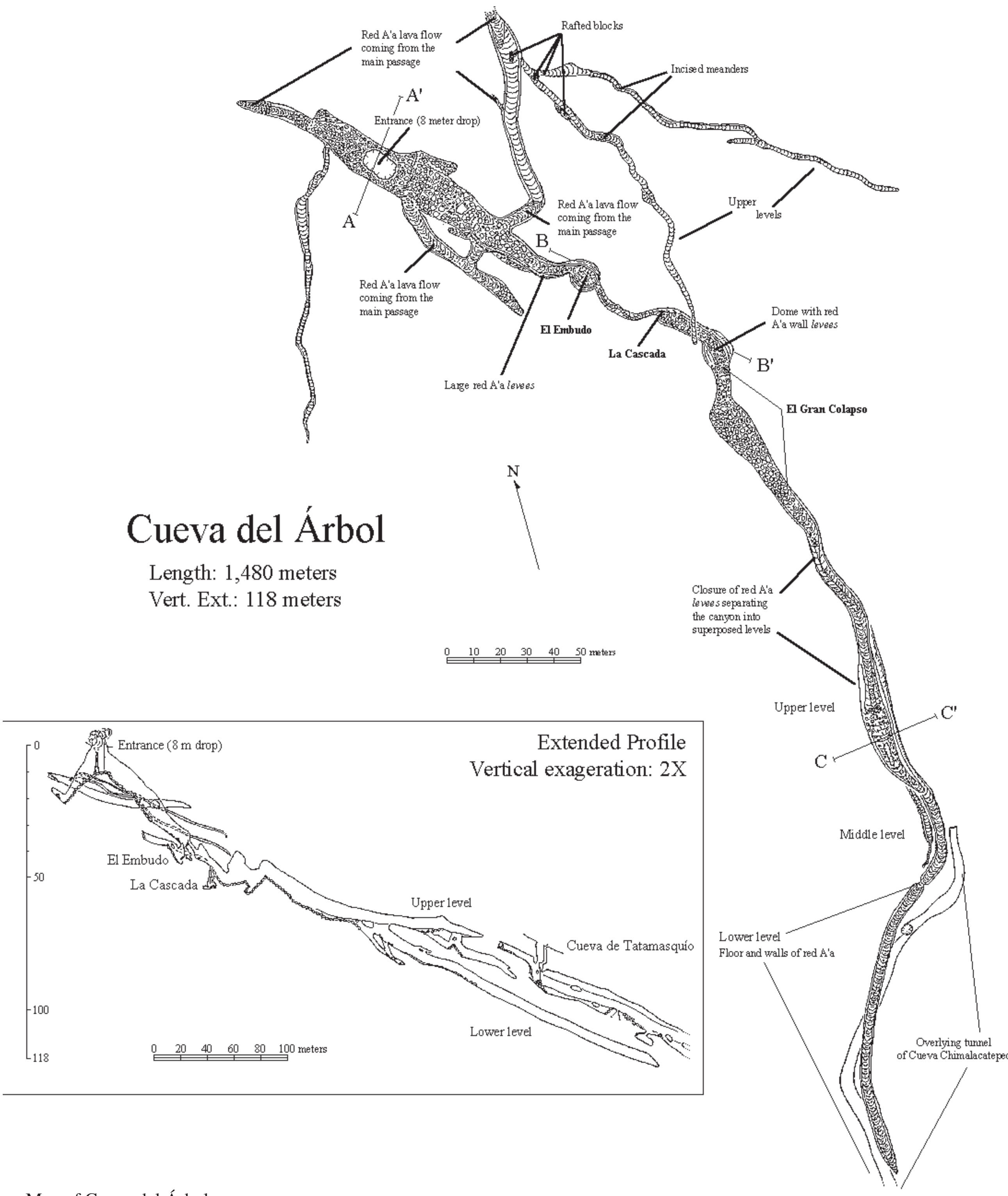
Eventually, the cave ends downflow where it has been cut by the railroad. In spite of the many parallel tubes just upflow from the road cut, only two small tubes were intersected, one of them forming the main entrance to the cave, while the other is too small to be of use.

The bus will leave the main square at Tepoztlán and take the small road west of town towards the town of San Juan Tlacotenco. After reaching the town, we will take the continuation of the main street and walk towards the main entrance of Cueva del Ferrocarril-Mina Inferior, located at the railroad cut to the south of town. It is a small crawlway above floor level on the NE side of the road, partly masked by the vegetation, and located opposite the conspicuous upper entrances of Cueva del Capulín on the SW side of the railroad, which are presently being used as a quarry site. A through trip will be done, depending on group size and fitness, or visitors can see the cave at their own leisure. Extensive use of the map is recommended, and you should locate yourself at every junction to avoid getting lost in this most extraordinarily complex cave.

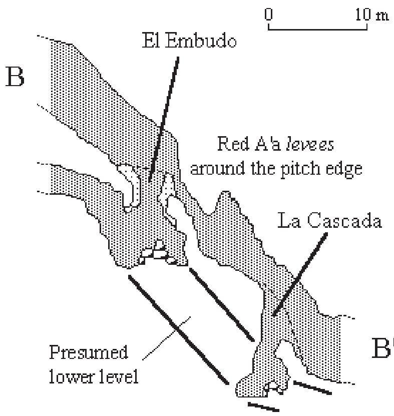
Post-Symposium Field Trip Two, 9 July 2006. Cueva del Árbol

In Cueva del Árbol and Sistema Chimalacatepec the master tube for the Suchiooc lava flow can be traced for almost 2 km along the steepest sections of the lava flow. Most of the master tube is up to 15 or 20 meters high in the canyon passages, but where the lowermost passage in Cueva del Árbol underlies the Gran Cañón passage in Sistema Chimalacatepec, the floor of the former is 35 meters below the ceiling of the latter. Most entrances functioned as hornitos or skylights during activity, as evidenced by the presence of levees surrounding the walls of the entrance pitches, wall linings up to the surface, and lack of breakdown blocks below the entrance. A total of 3,172 m of cave passages were surveyed in the Chimalacatepec lava flow, covering a 280 m vertical range. Cross sections of the tubes, and their general shape, suggest that an important element in the shaping of the tubes was downcutting, although only criterion 6 of Greeley et al. (1998) is satisfied.

Cueva del Árbol. The entrance to this cave is probably the most impressive in the Suchiooc lava flow. A 15 m wide collapse, 8 meters deep at the lowest point, gives access to a huge chamber-like passage 20 meters wide and over 50 meters long, covered in breakdown. Although it is possible that



Map of Cueva del Árbol.



Passage profile between El Embudo and La Cascada, Cueva del Árbol.

this entrance also functioned as an open skylight during activity, the collapse is too extensive for primary structures to remain. Nevertheless, this allows for observation of the enclosing rock, which is a series of up to 15 flow units mostly 1 m thick.

Upflow from the entrance and still within sight of it, the size of the passage diminishes to about ten meters wide, and two prominent wall levees appear under the breakdown only to disappear under a red A'a late flow which completely blocks the passage upflow.

Downflow from the entrance the main passage is huge, over 20 meters wide and ten to 15 meters high. Prominent wall levees form ledges along both sides, with a thermal erosion canyon between them. Large side tunnels lead away on both sides, soon blocked by the red A'a flow which invaded them from the main passage. After 70 meters, the red lava on the floor cascades into an impressive 10 meter deep pitch, El Embudo, lined with a large levee all around it. The pitch itself only gives access to a short segment of upflow tube which soon ends in breakdown under the entrance breakdown mountain and which is plugged downflow.

The way on after El Embudo is found by climbing around the edge of the pitch to the opposite side where, camouflaged behind the levee is a small upper level tube of small dimensions, 2 to 4 meters in diameter, which soon plunges into the main passage below forming La Cascada. A pitch just below it only gives access to a plugged section of a lower level, but the main passage continues on. Shortly after, a huge dome almost 15 meters high, with large levees of the red A'a late flow all around it, is encountered. The next 50 meters are floored by large collapse blocks, most of which are actually pieces of lava linings which have spalled off the walls, and the collapse never involves the encasing rock.

Shortly after, the floor flow of red A'a lava develops large levees that slowly grow outwards as one advances, until joining to form a separation between individual levels. This happens twice before the main or upper passage ends in a lava blockage, less than 20 meters from the continuation of this level in Sistema Chimalacatepec. The middle and lower levels, completely encased in linings of the red A'a flow, are accessible via downclimbs into the canyon floor before the closing up of the levees. The middle level is short and is blocked by rafted lava balls, but the lower level is much more extensive, underlying the main passage of Sistema Chimalacatepec for over 100 meters. Displacement of this various superposed levels is evidence of meander migration during the excavation, through thermal erosion, of the deep canyon, while the separation into different levels was caused by the growth of internal wall levees.

Cueva del Árbol was surveyed to a total length of 1,480 meters, and covers a vertical extent of 118 meters. Since it allows access to a master tube with clearly formed canyon shaped passages, separating into superposed levels, and also gives access to smaller anastomosing overflow tubelets, it is safe to say that it is one of the most instructive lava tubes of the area, at least from the geomorphologic and genetic point of view.

The bus will leave the main square at Tepoztlán and take the small road west of town towards the town of San Juan Tlacotenco. After reaching the town, take the "Camino Real" path northeast of the town of San Juan Tlacotenco, and follow it upwards past the turn-off towards Cueva Iztaxiatla. Take a series of small paths climbing steeply upwards, past the upper entrances of Sistema Chimalacatepec, past a fenced enclosure where the entrance to Cueva del Potrero is located, until reaching the large collapse entrance of Cueva del Árbol, marked by a conspicuous large tree which gives the cave its name. The entrance pitch will be rigged with a cable ladder (with safety line) and/or an abseiling and climbing rope for the

Upper level of main passage, Cueva del Árbol.

1995 eruption of Popocatepetl volcano.

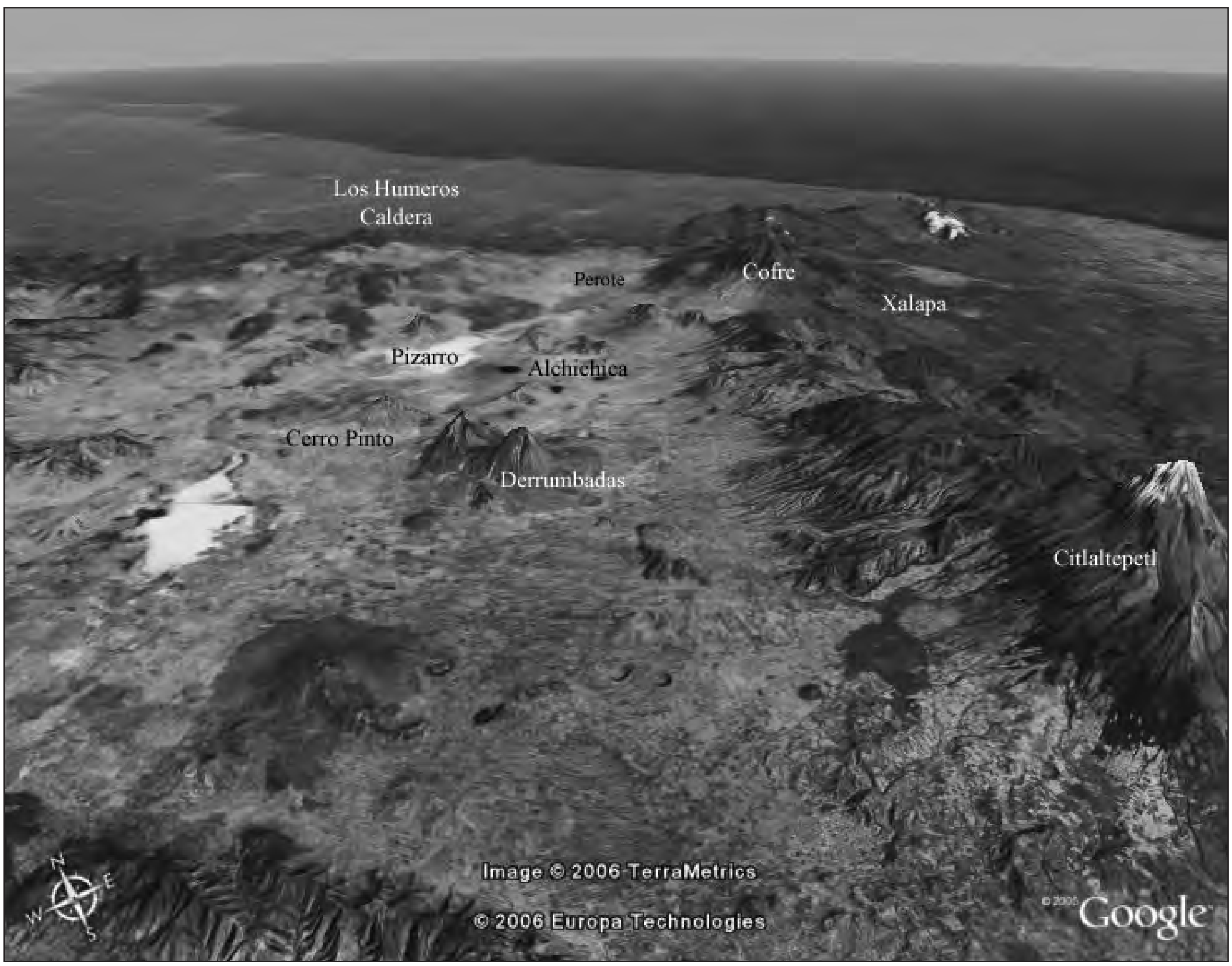
symposium field trip. Climbing aids will also be placed at la Cascada. Visit the cave at your leisure. Afterwards, return to the town of San Juan Tlacotenco, where the bus will take us back to the main square at Tepoztlán.

Post-Symposium Field Trip Three, 10 to 13 July 2006: Lava tubes in the vicinity of Perote and Xalapa, states of Puebla and Veracruz

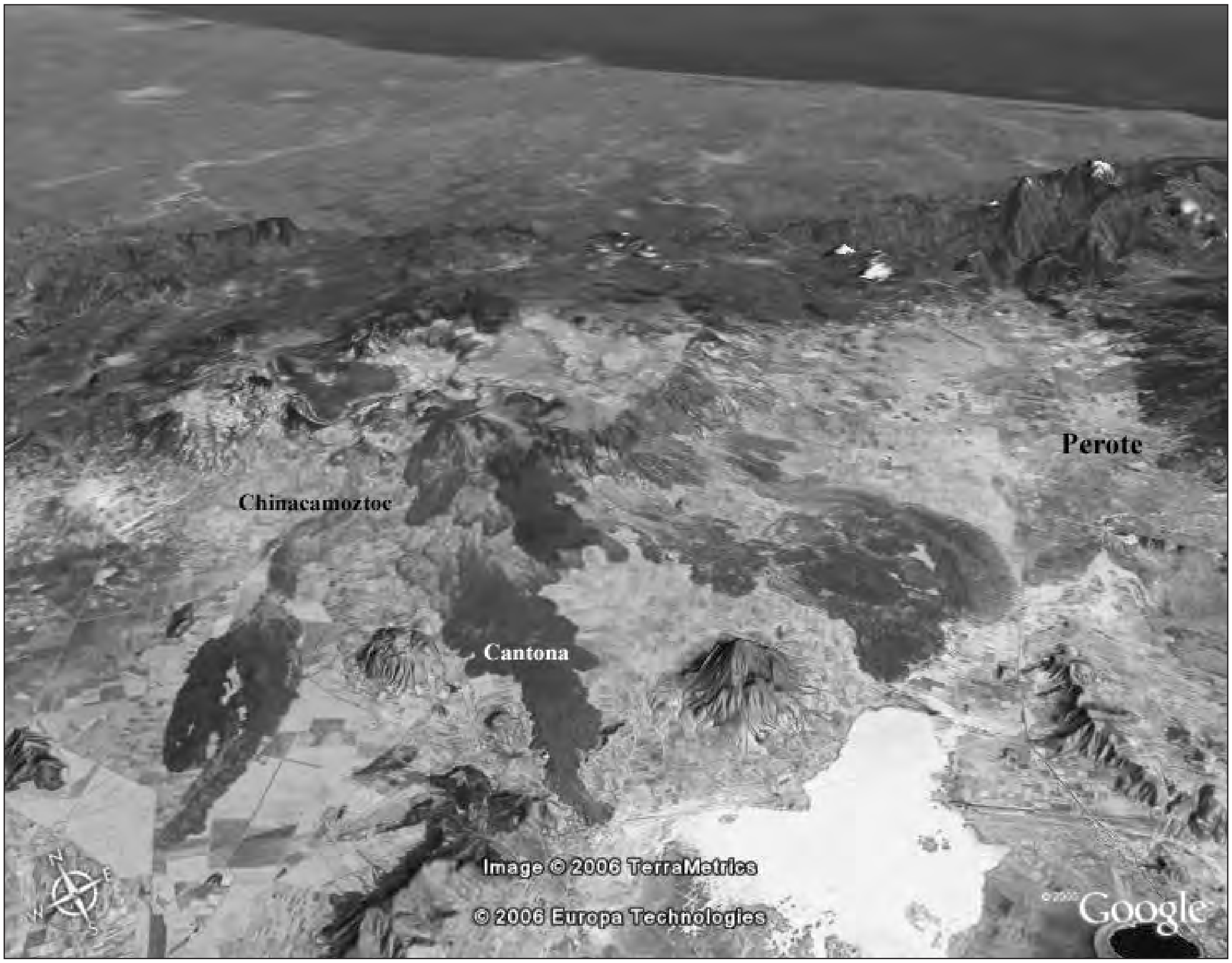
10 July 2006: This day we will travel from the symposium site, Tepoztlán, along highway 190 towards the city of Cuautla, and then take a new unnumbered highway towards Puebla, passing at the base of Popocatepetl volcano, where we will make Stop 1. From Puebla we will travel along highway 150 towards Orizaba; after the town of Acatzingo we will take highway 140 towards Perote, crossing the Libres-Oriental basin, where Stops 2 and 3 will be made. Finally we will visit the archaeological site of Cantona. We will spend the night in the town of Libres.

Popocatepetl volcano: Popocatepetl (5,450 m.a.s.l.) is Mexico's most famous stratovolcano. After many years of mild fumarolic activity, a series of phreatomagmatic explosions in December 1994 signaled its reactivation. Since then, activity has been restricted to the emplacement of successive domes inside the summit crater and their destruction during strombolian, vulcanian and/or subplinian explosions. These have produced numerous ash falls in the nearby cities of Puebla and México (Espinasa-Pereña and Martín-Del Pozzo, 2006). This renewed activity has reawakened interest in this volcano, as numerous recent papers have shown.

The present day cone of Popocatepetl is built atop the remains of at least two previous volcanoes, which were destroyed in large sector collapses of the volcanic edifice. Fries (1965) identified the resulting deposits in the valleys of Cuautla and Izucar de Matamoros and named them Tlayecac Formation. Robin and Boudal (1987) identified them as the products of Bezymianny or St Helens type eruptions. Siebe et al. (1995b) dated the youngest avalanche at 23,655 to 22,000 years B.P. Since then growth of the volcano has been characterized by the emission of numerous andesitic to dacitic lava flows from the main crater and from two sectors of lateral vents aligned in a NE-SW direction, interspersed with at least 10 plinian eruptions which deposited numerous airfall tephra layers, pyroclastic flow and lahar deposits in the valleys surrounding the volcano (Espinasa-Pereña and Martín-



The Libres-Oriental Basin forms the eastern end of the Transmexican Volcanic Belt.



Los Humeros Caldera and the lava flows on its southern rim.

Del Pozzo, 2006).

Stop 1: Popocatepetl volcano. At this stop we will visit an outcrop in which the two most recent avalanche deposits are visible. We will also see more recent pyroclastic flow deposits which underlie Atlixco, the largest city in the vicinity of the volcano.

The Eastern Portion of the Transmexican Volcanic Belt: It is a wide and flat closed basin, known in the literature as the Llanos de San Juan, Libres-Oriental Basin and Serdán-Oriental basin. It is limited on the west by the Malinche stratovolcano, and on the east by the Las Cumbres Volcanic Complex (Rodríguez, 2005), which includes México's highest volcano, historically active Citlaltepetl (5,690 m.a.s.l.), and the older Cofre de Perote (4,200 m.a.s.l.). To the northeast the basin is limited by the Los Humeros Caldera and to the northwest and south by older volcanic ranges.

Although the basin is surrounded by long lived stratovolcanoes, its interior is dominated by a variety of monogenetic volcanic structures such as rhyolite domes, tuff cones and rings, scoria cones and lava flows. The Las Derrumbadas, Cerro Pinto and Cerro Pizarro rhyolite domes are the most prominent volcanic structures in the interior of the basin, and the phreatomagmatic maar craters of Alchichica, Atexcac and La Preciosa rank among the most beautiful in the world (Reyes Cortés, 1979; Gasca Durán, 1981; Siebe et al., 1995a; Riggs and Carrasco-Nunez, 2004).

The Los Humeros Caldera was formed by the collapse of a pre-existing stratovolcano due to the eruption of very large pyroclastic flows which formed the Xaltipan Ignimbrite 0.56±0.21 Ma (Yañez García and García Durán, 1982; Ferriz and Mahood, 1984), distributed mostly to the north of the Caldera. Much later activity generated extensive basaltic lava flows emitted through the rim fractures on the southern side of the Caldera.

These lava flows are known from east to west as the El Limón, Tepeyahualco and Tenextepec lava flows. The archaeological site of Cantona is built on top of the Tepeyahualco lava flow, while the Tenextepec flow was emplaced through a large segmented master tube, Cueva de Chinacamoztoc, recognizable through at least 2 kilometers. It is possible that the other basaltic lava flows extruded from the caldera rim fractures were also emplaced through lava tubes, which would explain their lengths of up to 16 kilometers.

After Atlixco, continue along the road to Puebla, cross the city and take highway 150 towards Orizaba. Just past the town of Acatzingo take road 140 north towards Perote. After the town of Zacatepec continue right towards Perote. After the road turns into a highway, stop at any of the quarry entrances on the right of the road. This is Stop 2.

Stop 2, Las Derrumbadas Rhyolitic domes. Las Derrumbadas twin rhyolitic domes, with fumarolic activity and extensive rock alteration, are located in the middle of the Libres-Oriental basin and are the most prominent peaks of the area, both by their size and the many erosional gullies and collapse scars which give them their name.

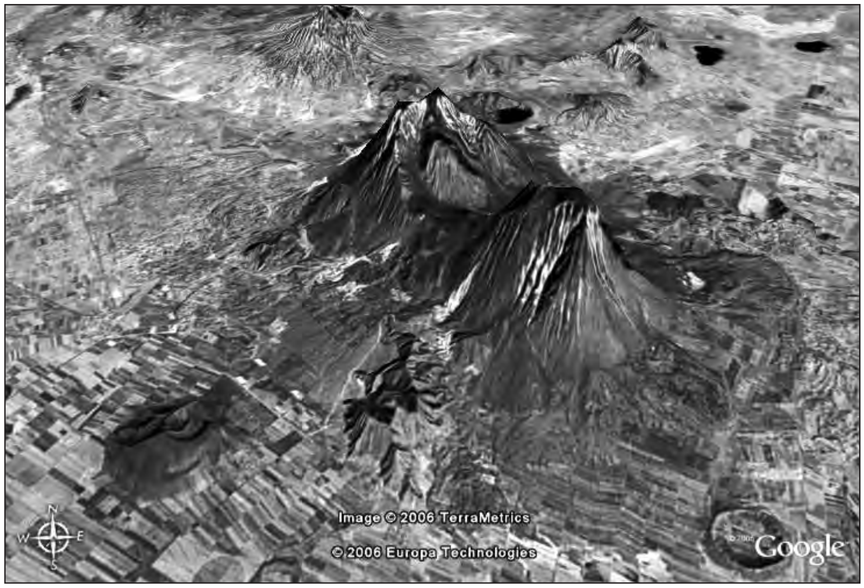
They were extensively studied by Siebe and Verma (1988) and Siebe et al. (1995a), who recognized at least two stages of dome collapse. The resulting debris-avalanche deposits consist of a chaotic mixture of blocks of faulted surge and pyroclastic flow deposits, as well as decameter-sized blocks of nonvolcanic origin such as Cretaceous limestone.

Continue northeast on road 140 until kilometer 24, where Alchichica lake is visible on the left of the road. Use any of several unpaved roads to descend into the crater lake. This is Stop 3.

Stop 3, Alchichica Maar. Alchichica is the largest maar crater in the Libres-Oriental basin. It was formed when a small amount of magma reacted explosively with phreatic waters in the lake deposits at the bottom of the basin. This generated a series of phreatomagmatic explosions which built a tuff cone around the vent. These explosions dissected a previous tephra cone, visible on the western crater rim. The juvenile components of the deposits consist of scoriaceous basalt or basaltic andesite. On your way into the crater, notice the numerous structures visible on the road cuts, including cross bedding, bomb structures, etc.

The Alchichica lake, although reputed to be bottomless, is only 60 meters deep in its almost 2 kilometers in diameter. The water is salty due to both evaporation and dissolved minerals. Notice that almost all the edges of the lake are rimmed by white caliche-like deposits. These are formed as stromatolites and are therefore representatives of some of the oldest known forms of life on Earth.

11 July 2006: From Perote drive back to El Limón at kilometer 35, where an unpaved road goes left towards Tepeyahualco for ten kilometers, passing



Google Earth image of the Las Derrumbadas twin domes. Notice the hummocky terrain on the northwest, formed by the first generation debris-flows, where Stop 2 will be made.

Debris-avalanche deposit forming hummocks at the base of Las Derrumbadas.

Tephra deposits at Alchichica maar. Notice bomb deformation on flat layers of ash.

Alchichica maar with Pico de Orizaba on the background. Notice the stromatolites on the shoreline.

Some of the buildings in Cantona.

by the base of Cerro Pizarro, another complex rhyolitic dome similar to Las Derrumbadas, recently studied by Riggs and Carrasco-Nunez (2004). When you reach Tepeyahualco, drive to the right on a paved road until reaching the parking lot of the Cantona Archaeological site. This is Stop 4. Visit the ruins at your leisure. We will meet at the bus for the drive to Chinacamoztoc cave, where we will spend the rest of the day.

Stop 4, Cantona Archaeological Site. Discovered in the middle of the 19^{th} century by Henri de Saussure (1855), this spectacular site was not excavated until recently. It is believed to be one of the largest urban centers yet discovered in Mesoamerica, and covers 12 square kilometers divided into three urban areas. They include a network of over 500 cobblestone roads, 3000 individual patios or residences, 24 ball courts and an elaborate acropolis with many ceremonial buildings and temples. These remarkable buildings were assembled by placing carved stones one atop the other, without any stucco covering or cement mortar being used in their construction. The buildings are adjusted to the topography of the thick lava flow where they were built, and take advantage of its steep slopes. They are evidently adapted for defense. Over time, Cantona turned into a fortress, since it developed in a period of social unrest. It was a contemporary civilization to the more famous Teotihuacan (A.D. 600 to 1000), which eventually dominated it. It was abandoned three hundred years before the conquest.

Take the small road east of Libres towards the town of Tepeyahualco. After 5 kilometers, take the small, unpaved road towards the town of Francisco I. Madero. Park the bus in the main square of town. This is Stop 6, the day's only stop.

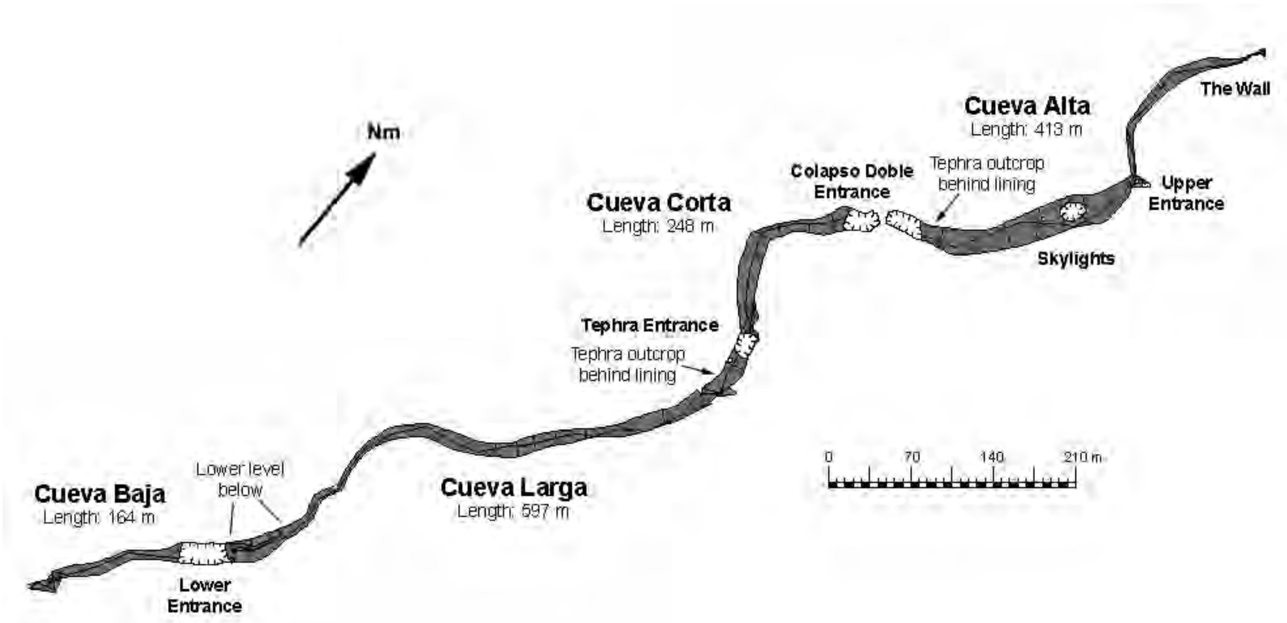
Stop 6, Cueva de Chinacamoztoc. The name of this cave means Cave of the Bats. It was first mentioned in the scientific literature by Virlet d'Aoust (1865). Later, in a study specifically dedicated to the cave, Haarmann (1910) calculated its length at about 500 meters. Finding stream deposits in the cave floor, he proposed that the cave had formed when the lava flow followed the course of a flowing stream, which evaporated and the gas pressure pushed the lava flow upwards leaving a void underneath. The portion of the cave visited by Haarmann is no longer accessible. Wittich (1921) in a study of the geology of the entire Llanos de San Juan area, describes the cave as being almost two kilometers long, and suggests that the stream deposits seen by Haarmann entered the cave after it solidified. He concludes that the cave formed by the solidification of the flow crust, but with liquid lava remaining inside. After the lava broke the crusted front, it flowed onwards, leaving a void behind.

No other references have been found about this cave. In may 2006, in preparation of the symposium, members of Sociedad Mexicana de Exploraciones Subterráneas (SMES) and Club Exploraciones de México A.C. (CEMAC), Veracruz section, visited and surveyed the Chinacamoztoc lava tube. This survey is published here for the first time.

Chinacamoztoc cave is a large master tube 10 to 30 meters wide and >10 meters high in most places. The original entrance, as described by Haarmann, is now completely filled by stream deposits originated on the fields which partially cover the upper end of the lava flow. Haarmann describes the passage, now inaccessible, as being up to 10 meters wide and 15 meters high. He also mentions that the upper portion of the cave ends at an artificial wall built to prevent soil loss. The lower side of the wall was accessible through another, lower entrance (the Upper Entrance on the map), which is a small hole at the bottom of a 20 meter wide surface depression whose western wall is vertical. We believe this was an open skylight during activity. It gives access to a small shelf above the main canyon shaped passage.

Upflow, the passage is uninteresting and covered in sooth from torches. The floor is flat and mostly covered in sandy mud deposits. Eventually the lower side of the wall is found. Sometime in the last ten years, somebody dug a hole through the artificial wall, probably believing it hid a treasure, and the completely sediment-filled passage beyond is accessible through the dug tunnel for about 15 meters.

Downflow from the Upper Entrance the cave rapidly grows in dimensions, but traversing the passage is made more difficult by the abundant breakdown blocks on most of the tunnel. The intact sections are also not easily traversed, because the floor is made of very rough



Plan view of Cueva de Chinacamoztoc, Puebla.

A'a lavas.

A total of eight skylights break up the lava tube, of which three actually segment the 1,577 meters long tube into 4 caves 413, 248, 597 and 164 meters long (in a downflow direction). The skylight areas are used by large white owls as nesting sites, so please try to avoid disturbing them. On some of the skylights, the entrances to small anastomosing tubelets are visible high up the wall, near the ceiling level, and probably represent the original braided tubes from which the master tube evolved through thermal erosion.

Separation of the canyon passage into superposed levels is only visible in two sections close to skylights that might have been open during activity, but other skylights are probably post-activity collapses. The ceiling and walls of one of the lower levels is decorated with many small tubular stalactites. In contrast with tubular stalactites in the caves visited in the Sierra Chichinautzin, which always develop from behind lining breaks, here the segregates were extruded straight from the wall, which does not show lining breaks. In two other places, evidence of thermal erosion is seen where collapse of a lava lining exposes tephras and the Xaltipan ignimbrite. This is on a ledge still >10 meters above the cave floor.

After leaving the bus at the main square of Francisco I. Madero, we will walk for 2 kilometers along an unpaved road which leads to the Colapso Doble Entrance, from which we will walk along the surface to the Upper Entrance, where we will enter the cave. Follow the main passage downflow at your leisure and exit at any of the accessible skylights. The lower entrance requires a risky climb to get out, but will be equipped with a wire ladder and belay rope. Once out of the cave, walk in a general direction to the east until you exit the lava flow, and follow any of the many paths and unpaved roads back to the main square of town. At the end of the day, the bus will drive back to Perote where we will spend the night.

Las Lajas Cinder Cones and lava

The vegetation above the lava flow is made of Yucca palms and scarce pine trees. In the background is Cerro Pizarro and Citlaltepetl behind it.

The large Chinacamoztoc master tube at one of the skylights.

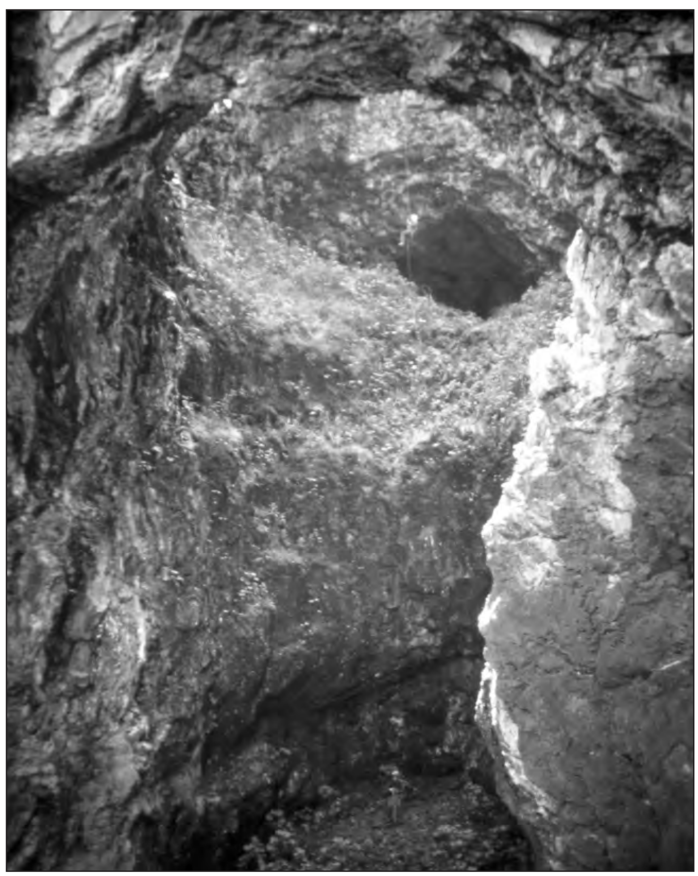
flows: North of Cofre de Perote a series of eruptive vents form what has been called the Las Lajas volcano, where over a dozen volcanic vents have been recognized and some of them have been dated (Siebert and Carrasco-Núñez, 2002). La Joya cinder cone complex is one of the oldest, and produced about 20 km^3 of basaltic flows that extend about 14 kilometers SE to underlie the city of Xalapa, capital of the state of Veracruz, about 42,000 years B.P. Cueva de la Orquídea might be located in one of these flows. Many younger volcanic vents and lava flows exist in the area.

The youngest lava flows dated by Siebert and Carrasco-Núñez (2002) originated from El Volcancillo (2,700 m.a.s.l.), a twin crater located 4 kilometers southeast of the town of Las Vigas which erupted 870±30 y.B.P. The cone complex straddles a sharp crested ridge between two valleys carved into the slope of Las Lajas volcano, a subsidiary cone of Cofre de Perote. It fed two lava flows that traveled down different drainages. The Toxtlacoaya A'a flow, originating from the southeastern crater, has a length of approximately 12 kilometers, while the Río Naolinco pahoehoe flow, which originated in the northwestern crater, traveled over 50 kilometers.

The eastern crater occupies the summit of a steep sided scoria cone that is breached in two places on its southern side. Large lava benches surround the inner crater and mark the highest stand of a former lava lake which overflowed the breach, generating a short lava flow which shortly stopped at the end of the first steep slope. We believe that most of the Toxtlacoaya lava flow issued from a pair of vents at the northeastern base of the cone, based on lava flow morphology. The lava flow crusted over forming a large lava tube with a big skylight, 25 meters in diameter, which overflowed frequently forming a small shield. Quarrying of a lower entrance and the building of an Oleoduct collapsed most of the cave, leaving a semi-natural rock arch giving the cave its name, Cueva del Arco.

Siebert and Carrasco-Núñez (2002) claim that the 35 meter thick lava pile visible on the walls of Cueva del Arco represent the minimum thickness of the lava flow, and do not consider that the tube could have been originally much

Tephra layers behind lining, evidence of thermal erosion.



Cueva del Arco. Notice the two cavers, one on rope and the other at the bottom.

smaller, and the present height be caused by thermal erosion, as suggested by the passage cross section.

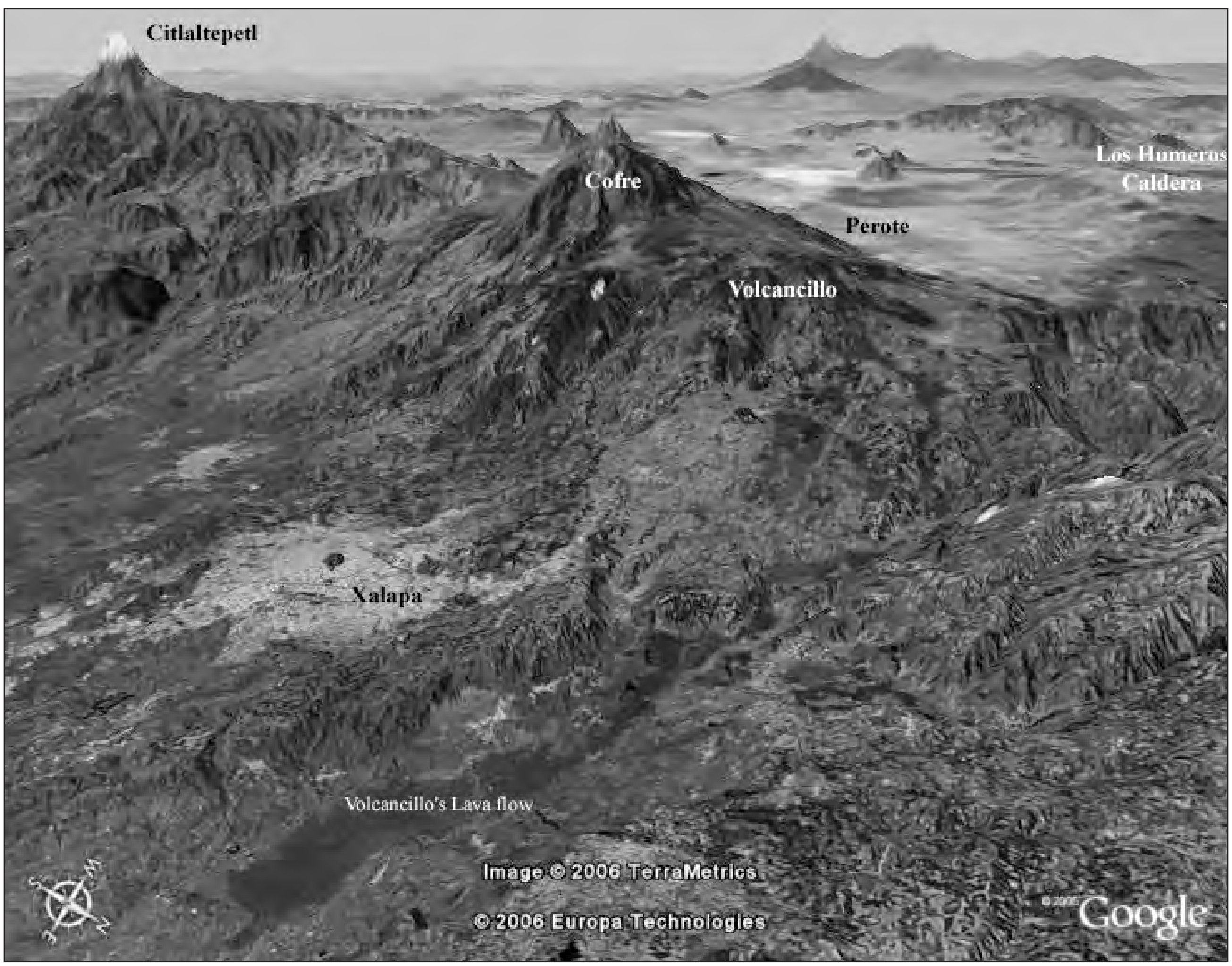
The western or main crater, 200 meters wide and 90 meters deep, partially truncates the eastern scoria cone and was produced by collapse of a small lava lake that overflowed the western scoria cone. In both craters we find the same sequence of events: building of a scoria cone by lava fountaining, followed by the emission of lava which formed a lava lake. In the western crater, the scoria cone was overtopped over an arc of 180° by pahoehoe sheet flows, which were truncated by the crater collapse. The uppermost entrance to Cueva del Volcancillo is exposed in the upper northern wall, and marks the main outflow of the Río Naolinco lava flow.

The whole of the Río Naolinco lavas were fed through lava tubes, as evidenced by numerous primary inflation structures such as tumuli, pressure ridges, inflation clefts and ropy textures throughout. To date, the only surveyed cave is Cueva del Volcancillo, located near the crater. Only two other caves are known in the entire flow, but neither has been explored or surveyed. After 15 kilometers, a steep fall near the town of Tlacolulan, the lavas entered the deep valley of the Naolinco river (which today does not flow on the surface) and followed it for nearly 35 kilometers. The lava flow ends at a narrow canyon west of the town of Chicuasen at an altitude of 360 meters, immediately beyond the popular Descabezadero Cascades, the birthplace of the Actopan river, which comes out at the contact of the lava flow with underlying conglomerates.

12 July 2006: The bus will drive towards Xalapa, the capital of the state of Veracruz, along highway 140, four kilometers past the town of Las Vigas de Ramirez, to the town of Toxtlacuaya, where we will make Stop 7, which will last all day.

Stop 7, El Volcancillo and its lava tubes. After leaving the vehicle at Toxtlacuaya, we will walk uphill to the entrance to Cueva del Arco (Outcrop 1). Walk into the collapsed and quarried lower channel, underneath the arch that gives the cave its name. Notice the canyon-shaped cross section of the tube, which suggests that the present shape was achieved through thermal erosion.

Return to the Oleoduct and climb above the channel to reach the rim of the skylight. Careful when approaching the edge, as it is a 35 meter pitch to the bottom. Notice the overflow structures which are evidence that this skylight



Las Cumbres volcanic complex and the Volcancillo lava flows.

Crater of El Volcancillo as seen from the summit.

overflowed numerous times during activity, building a small shield.

Above Cueva del Arco, follow a small path upwards past the front of the small SE flow. Climb it and reach the southern side of the Eastern Crater (Outcrop 2), where we will observe numerous flow structures and the lava benches inside the crater.

Continue climbing uphill along the southern base of the tephra cone. Notice along the way the alluvial sediments deposited at the point where El Volcancillo blocked the drainage of one of the several ravines that come down the upper slopes of Las Lajas volcano (Outcrop 3). When we finish surrounding the main tephra cone, take the southern ridge and follow it to the summit of El Volcancillo, from where a panoramic view of the crater can be obtained (Outcrop 4).

Continue surrounding the crater towards the north until reaching the edge of the former lava lake, where the edges of the main channel overflow can be studied. Descending slightly to the north we will reach the main entrance collapse of Cueva del Volcancillo (Outcrop 5)

Cueva del Volcancillo, 540 meters long, consists of two segments: the upper one goes for less than 50 meters between the crater wall and a surface collapse, after which the entrance to the main cave is encountered. It is a beautiful master tube with up to three superposed levels separated by the growth of wall levees. In those sections where the levees do not join, their surface texture is especially beautiful. After nearly 350 meters, a small skylight entrance is encountered, below which is a seven meter pitch which can be rigged with a wire ladder and a safety rope. Shortly afterwards the cave ends in breakdown.

The beautiful wall levees in Cueva del Volcancillo.

After visiting the cave, continue walking around the crater to the east, noticing the shelly pahoehoe flows that constitute this portion of the lava flow (Outcrop 6). As we start going down, notice how the lava flow was covered by an even younger mudflow coming from Las Lajas volcano. The mudflow (Outcrop 7) includes individual andesite blocks up to several meters in diameter and completely covers the SW lava flows from Volcancillo.

As we continue the descent along the eastern edge of El Volcancillo's lava flows, notice numerous outcrops where the lavas cover tephra layers from the same eruption, which in turn cover paleosoils developed on the Las Lajas volcano slopes (Outcrop 8). Charcoal from one of these was used to determine the age of the eruption.

When we reach the Oleoduct, we will follow it back to the east to return to the bus, which will then continue on highway 140 to Xalapa, where we will spend the night.

Free evening, we recommend visiting the historical center of the Colonial city of Xalapa.

13 July 2006: El Descabezadero, Xalapa, Veracruz: The city of Xalapa, capital of the state of Veracruz, is famous for its Colonial buildings, its cultural life and its many parks. It is built atop lava flows from the La Joya volcanic cluster, near El Volcancillo, which were dated by Siebert and Carrasco-Núñez (2002) at over 24,000 y.B.P. through stratigraphic criteria. Although no volcanic risk assessment has been carried out, it is clear that a new eruption in the area could represent a serious risk for the city and its environs.

Stop 8, El Descabezadero. Beautiful spring and cascades which give birth to the Actopan river. These springs bring back to the surface the waters of the entire Río Naolinco basin, which have

Plan of El Volcancillo with marked outcrops.

been filtered by the Río Naolinco lava flow coming from El Volcancillo. The spring is at the contact between the lavas and underlying conglomerates. This is also the put-in for the descent of the upper Río Actopan, one of the most popular commercial river-rafting trips in México.

Return to the bus and continue for 1.5 kilometers to the beginning of an unpaved road on the right. Follow it for a hundred meters, past a bridge over the Actopan river and reach El Tranchete, a popular restaurant, where a refreshing swim and a good meal will finish the field trip activities. Hope you've enjoyed the trip.

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