

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

Edited by  
Ramón Espinasa-Pereña and John Pint

ISV XII, Mexico, 2006



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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



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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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**XII INTERNATIONAL SYMPOSIUM**

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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 miscellaneous or theoretical papers.

All this information has been arranged into four different Sessions: México, Rest of the world, Biology and Theoretical.

**México Session, Chairman C. Lloyd:** 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.

**Rest of the World Session, Chairmen K. S. Woo, João C. Nunes and J. Pint:** 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).

**Biospeleology Session, Chairman Luis Espinasa:** 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.

**Theoretical Session, Chairman J. P. Bernal:** 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<sup>2</sup>. 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 ( $\text{SiO}_2 < 52\%$ , Figure 4) flowed south along very steep slopes (up to  $12^\circ$ ) until reaching the Sierra de Tepoztlán, a range of mountains made of Miocene volcanosedimentary 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  $0^\circ$  to  $6^\circ$  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  $5.7^\circ$ . 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  $25 \text{ km}^2$  covered by the flow, a volume of  $0.5 \text{ km}^3$  for the lava flow, plus  $0.076 \text{ km}^3$  for the tephra cone was calculated, giving a total of almost  $0.6 \text{ km}^3$  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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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 ( $\text{SiO}_2 < 52\%$ ) flowed south along very steep slopes (up to  $12^\circ$ ) until reaching the Sierra de Tepoztlán, a range of mountains made of Miocene volcanosedimentary 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  $0^\circ$  to  $6^\circ$  to the north. Numerous E-W and N-S fractures and small faults cut these rocks. The Sierra Tepoztlán is 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  $5.7^\circ$ . 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 difference 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 elucidate 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.

Additionally, 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  $2,835 \pm 75$  and  $4,690 \pm 90$  years before present (ybP), and made morphological comparisons between it and the nearby Chichinautzin volcano, dated at  $1,835 \pm 55$  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 typicalropy 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.

Reference:

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  $0.56 \pm 0.21$  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 N 19°38'13.099" W 96°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 photographic 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,  
 Jalisco, 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 Zozotz 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 Agglomerates**

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Tecolotlán cave, located near the town of Cuentepetec, 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 "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 Activity,  
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<sub>2</sub> and H<sub>2</sub>S 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 flow paths 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<sup>2</sup>. This value is very near to the value calculated as 43000 dyne/cm<sup>2</sup> 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 Geomunoreum 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, lava 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. Wind-blown 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<sup>2</sup>. 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 +cm. 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)**

Ed Waters

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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 Hellarannsóknafélgis 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**

John J. Pint

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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 September 2003, 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 16<sup>th</sup> and 19<sup>th</sup> 2005 by the authors. It is currently the longest reported from the Arabian Peninsula (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 to 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	1 to 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, 18<sup>th</sup>.

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 24<sup>th</sup> 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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João P. Constâncio<sup>3,5</sup>, Paulo Barcelos<sup>4,5</sup>,  
Paulo A. V. Borges<sup>2,4,5</sup>, Isabel R. Amorim<sup>6</sup>, Filipe Correia<sup>1</sup>,  
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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 Volcano-speleology (Pico Island, Azores, 2004).

Poster Presentation

**Catalogue of the Azorean Caves (Lava Tubes, Volcanic Pits, and Sea-Erosion Caves)**

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Manuel P. Costa<sup>2,4</sup>, João P. Constâncio<sup>2,5</sup>, João C. Nunes<sup>2,5,6</sup>,  
Paulo Barcelos<sup>1,2</sup>, Teófilo Braga<sup>5</sup>, Rosalina Gabriel<sup>3</sup>,  
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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 – Círculo 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<sup>1</sup> and Horst-Volker Henschel<sup>2</sup>  
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 9<sup>th</sup>, 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**

Stephan Kempe<sup>1</sup>, Horst-Volker Henschel<sup>2</sup>,  
Harry Shick, Jr.<sup>3</sup>, and Frank Trusdell<sup>4</sup>

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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 <sup>14</sup>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 ( $^{\circ}$ ) ( $\tan^{-1}$ (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 Petroglyph 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

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

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.

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 capped 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 ( $^{14}\text{C}$  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)**

Rosalina Gabriel<sup>1</sup>, Fernando Pereira<sup>1,2</sup>, Sandra Câmara<sup>1</sup>, Nídia Homem<sup>1</sup>, Eva Sousa<sup>1</sup>, and Maria Irene Henriques<sup>1</sup>

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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 *Streptomycetaceae*, 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 Tepoztlán**

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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 Tepoztlán, 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 (*Aneliptina* 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 speleal 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 speleal 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  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$ . 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 “WoMVOc—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, assigned 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 volcanioclastic deposits, mainly lahars and fluvial conglomerates and a few intercalated ash layers belonging to the Cuernavaca formation, which constitute the Buenavista volcanioclastic fan, which has its apex at the Sierra Zempoala volcanic complex and extends south to the limits with the state of Guerrero.

This volcanioclastic 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 agglomerates of andesitic nature. A recently mapped cave, developed in the Buenavista volcanioclastic 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 volcanioclastic fan

The Buenavista volcanioclastic 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.

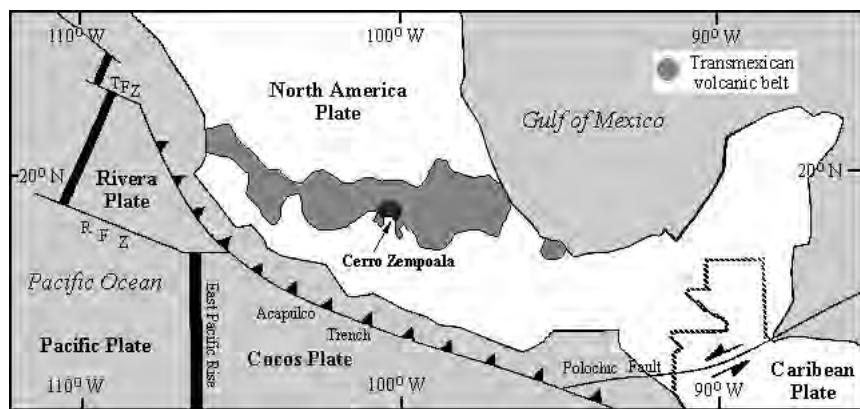


Figure 1. Map showing the tectonic setting and location of Volcan Zempoala, in the central portion of the Transmexican Volcanic Belt.

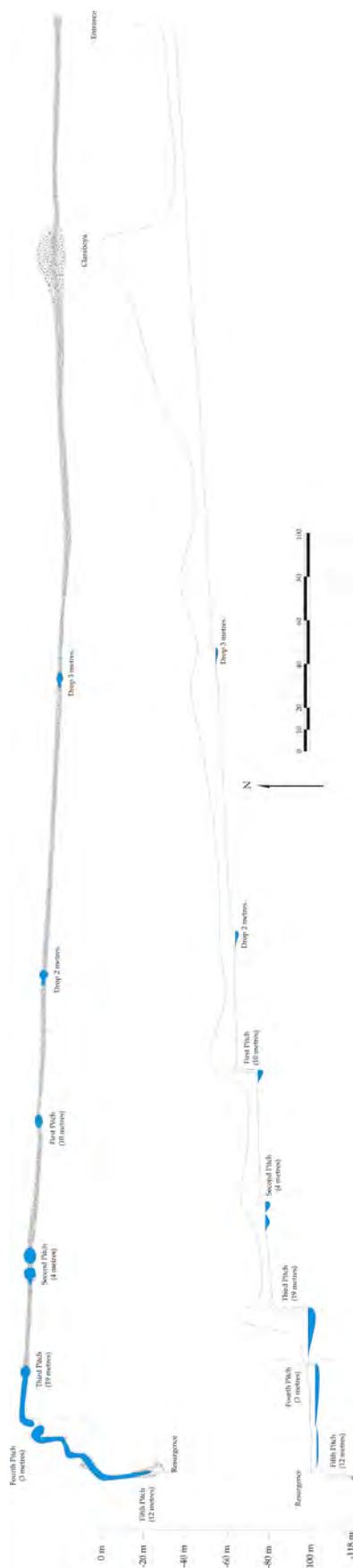


Figure 2. Plan and profile views of Cueva de Tecolotlán. A larger version of this map appears in the supplemental material on the CD.

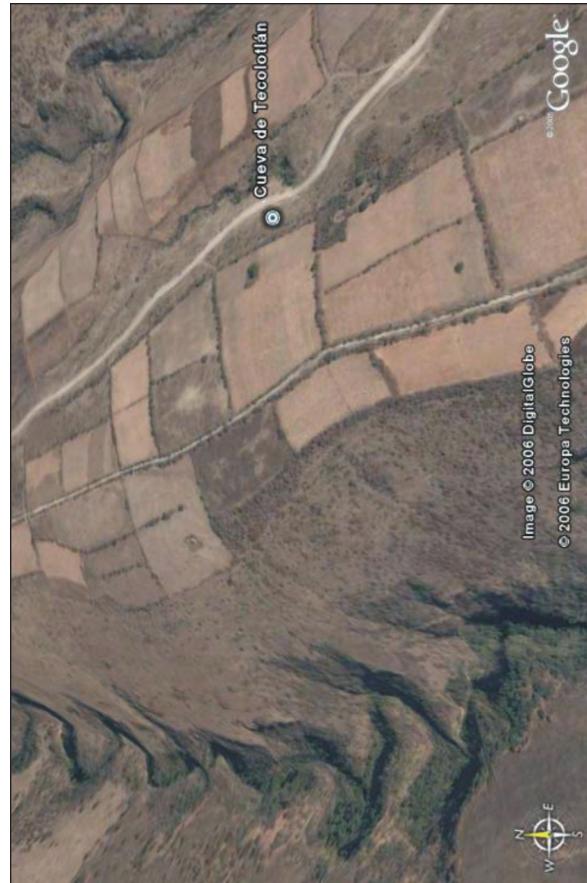


Figure 3. Upper portion of the Buenavista volcanoclastic fan, with the location of Cueva Tecolotlán. The Cerro Zempoala volcano can be seen at the apex of the fan. The canyon which drains it west slopes and then cuts through the fan is the Río Tembembe



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



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.

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

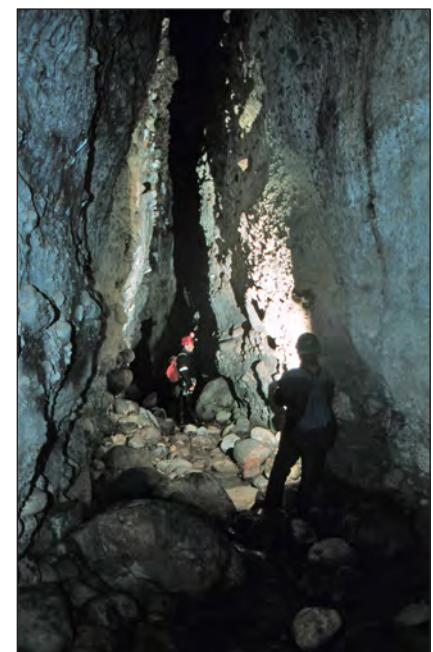


Figure 8. Most of the passage is a tall, canyon-shaped passage. The large andesitic subrounded blocks on the walls form part of the debris flow deposits in which the cave is excavated.



Figure 9. Plunge pool at bottom of third drop. The large andesitic subrounded boulders that form the host rock are perfectly visible.



Figure 11. Hourglass cross-section of the lower passage of the cave. Notice the entrenchment of the floor below the phreatic original passage.



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.



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 approaches 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.

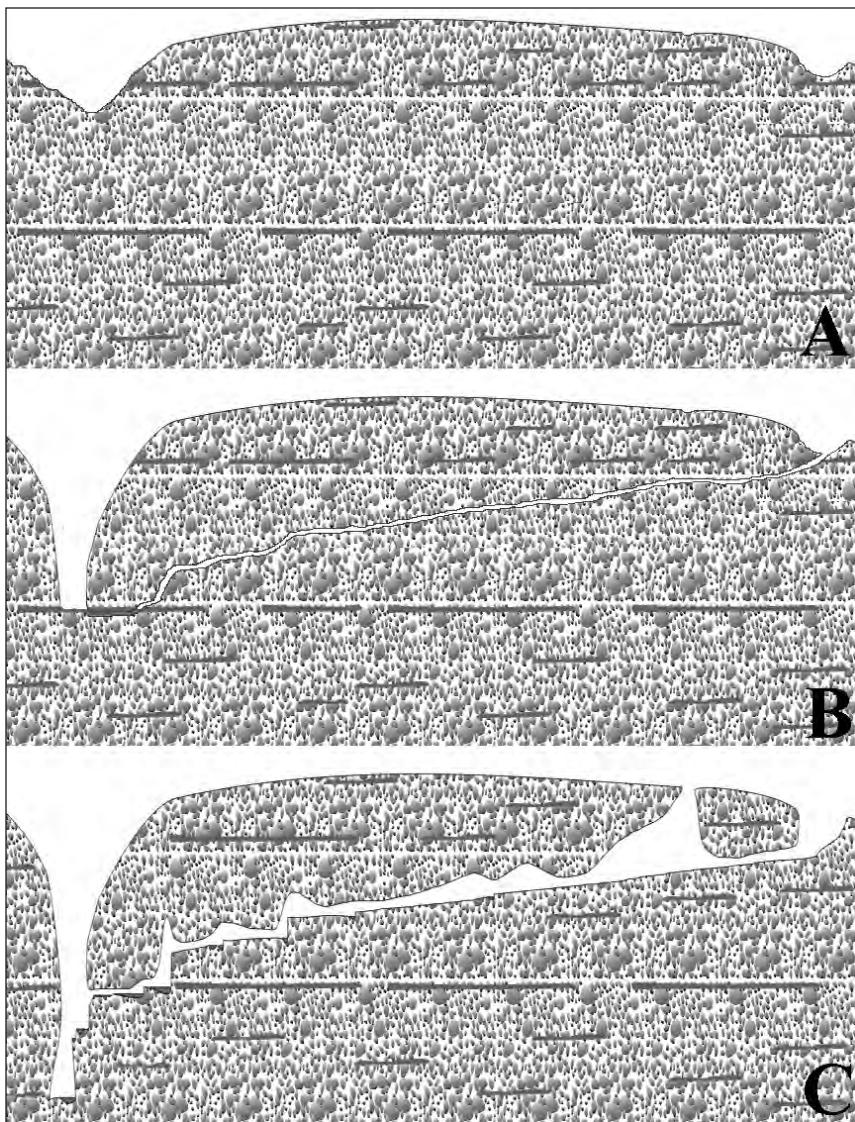


Figure 13. Geological cross-sections showing the development of Cueva Tecolotlán. The first stage would be the formation of the Tembembe valley almost to the level of the cave. When erosion first breached the ash layer between conglomerate deposits, it allowed water filling the fractures to start flowing 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 volcanoclastic 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, Taggart & Cross 1990, Jolley 1997, Bell & Jolley 1997). In this study we investigated a volcanoclastic 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 volcanoclastic series emerge underneath Quaternary volcanics (Fig. 1). In spite of the spectacular outcrops of these up to 800 m thick volcanoclastic 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 volcanoclastics. 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  $21.85 \pm 0.21$  Ma and  $15.83 \pm 1.31$  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.

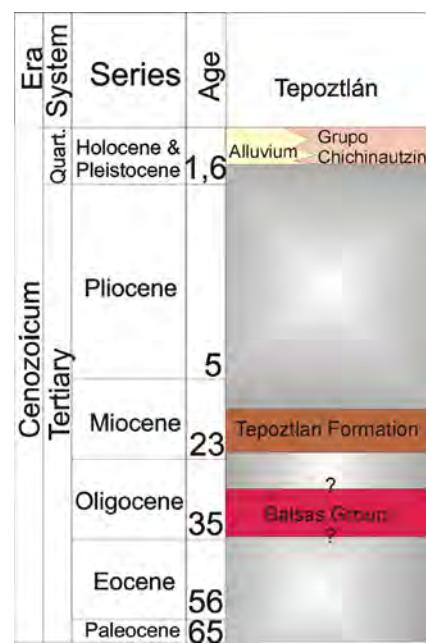


Figure 2. Stratigraphic succession in the study area.

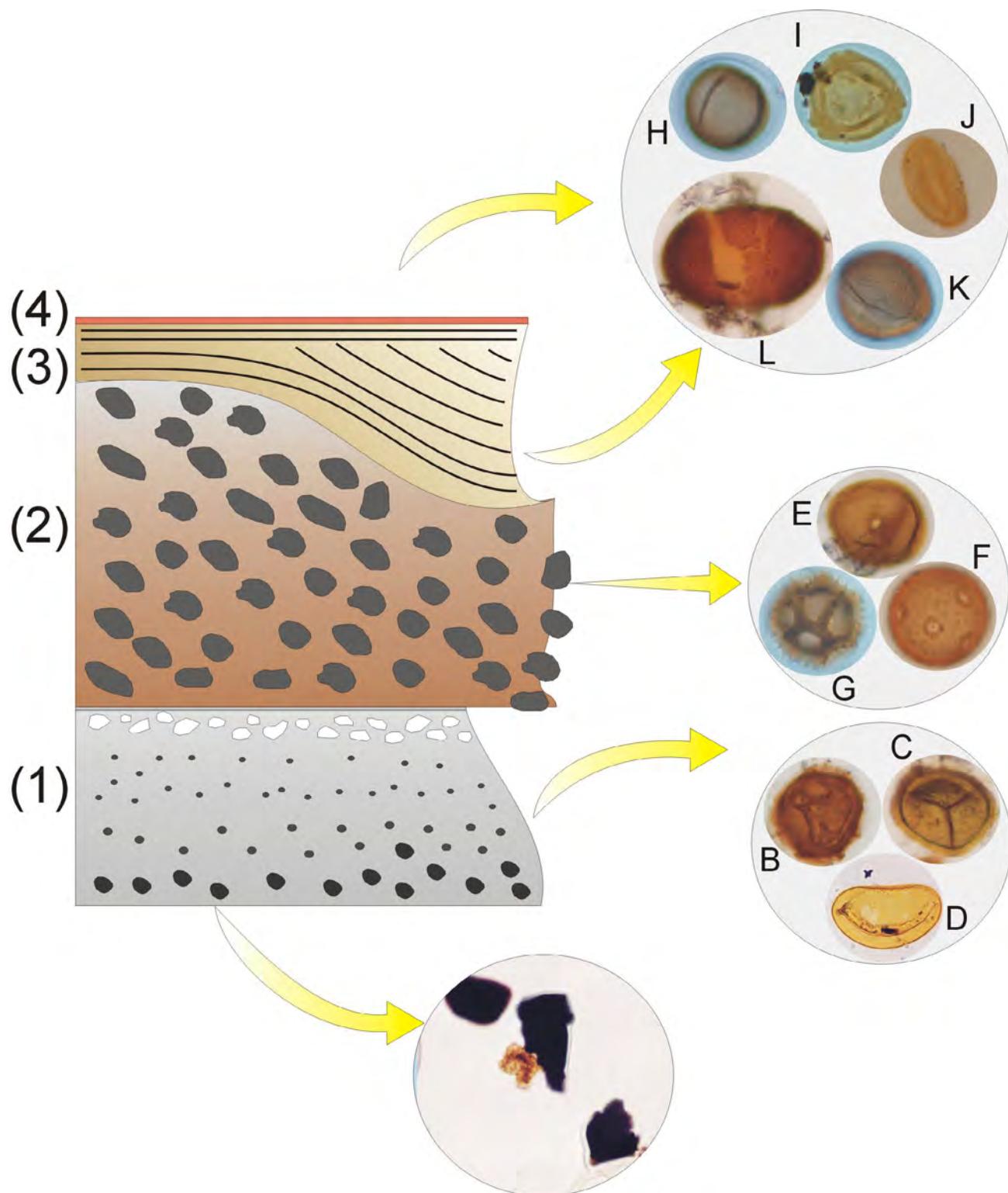


Figure 3. Ideal sedimentary succession of volcaniclastic sediments and characteristic sedimentary organic particles: (1) pyroclastic flow deposit, (2) lahar, (3) fluvial deposit, (4) lacustrine or waning-flood deposit.  
 A charcoal, B *Lycopodium* sp. (51 µm), C *Selaginella* sp. (42 µm), D Polypodiaceae (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  $11\ \mu m$  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 volcanioclastic 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 volcanioclastic 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.

## Acknowledgements

This study is part of a project on the Miocene development of the Transmexican Volcanic Belt in Central Mexico, supported by the German Science Foundation (DFG), Project No. HI 643/5-1.

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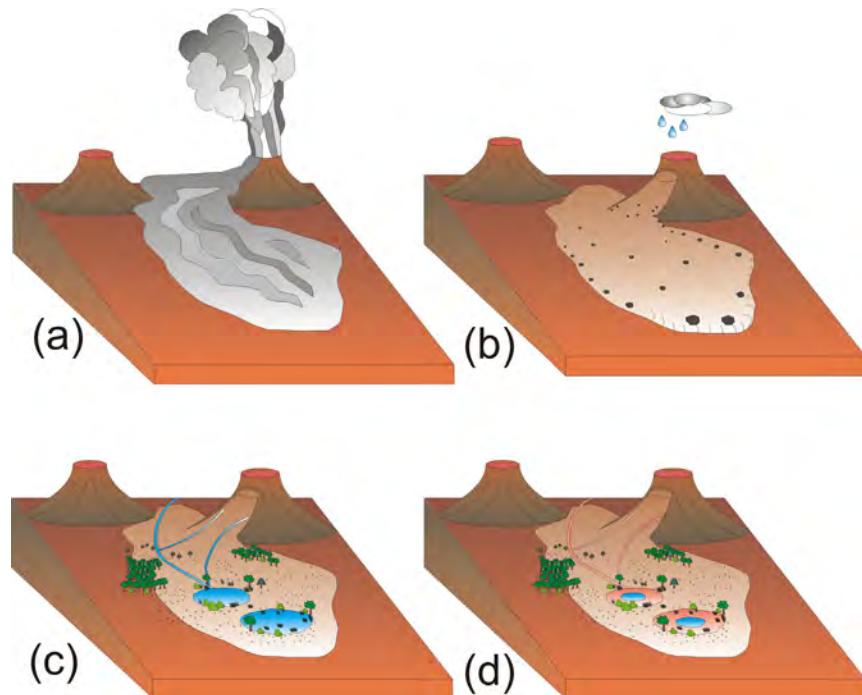


Figure 4. Changes in palaeoenvironment within time: a) ash flow, b) debris flow (lahar), c) fluvial reworking, d) waning stage.

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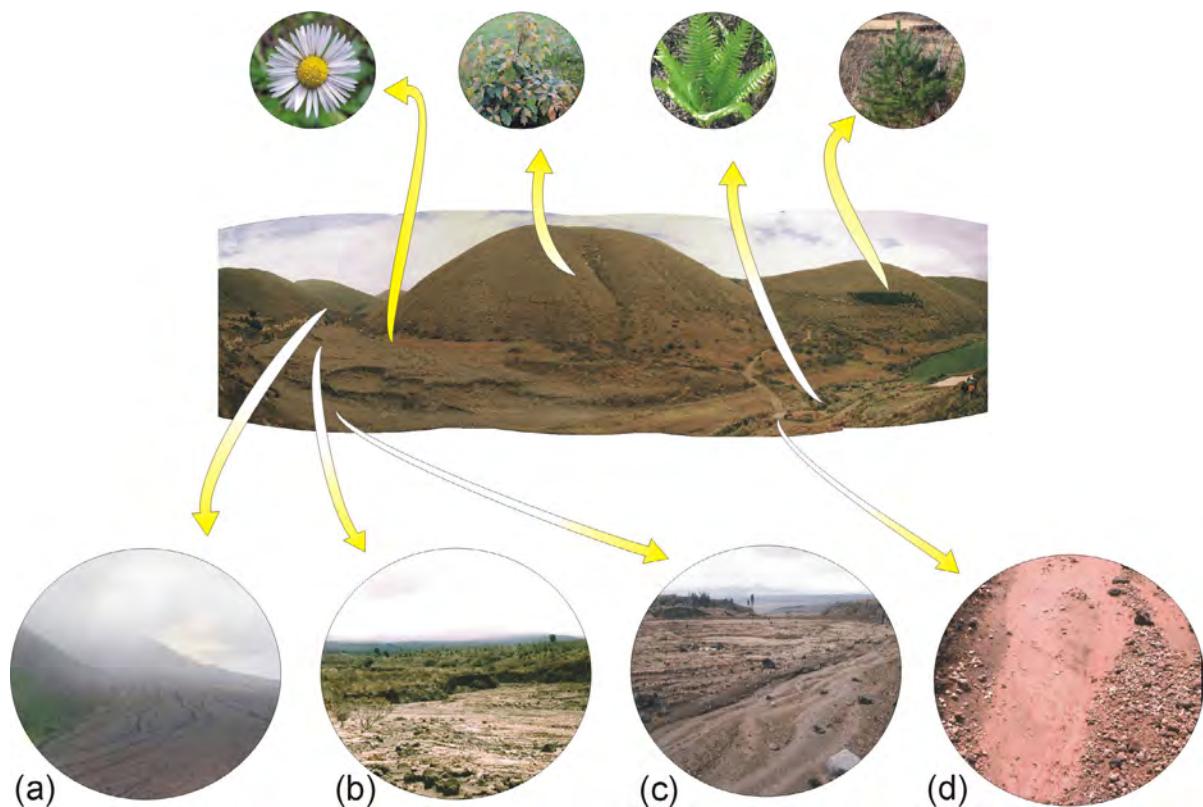


Figure 5. Modern analogue of the Tepoztlán Fm. (here with volcaniclastic deposits and their vegetation from the recent eruption of Cotopaxi, Ecuador, in 1877): a) pyroclastic-flow deposit, b) lahar, c) fluvial reworked deposits, d) waning-flood deposits.

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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  $2,835 \pm 75$  and  $4,690 \pm 90$  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 asropy 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 Ximantecatl (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<sup>2</sup> (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

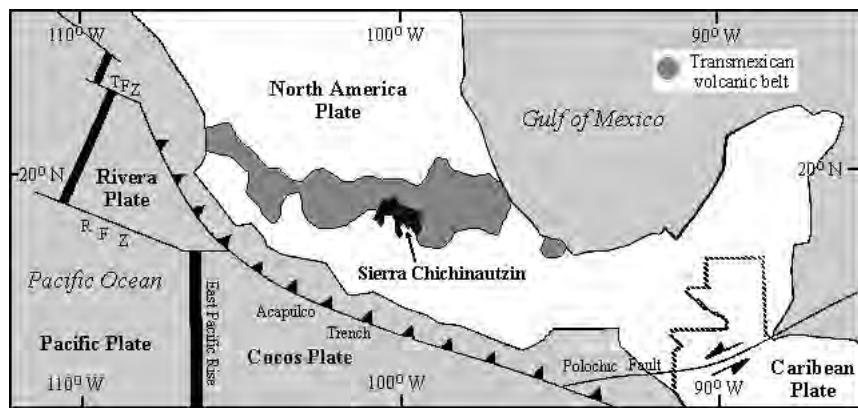


Figure 1. Location map of the Sierra Chichinautzin, showing the tectonic setting.

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 ( $9,620 \pm 160$  to  $10,900 \pm 280$  years B.P.), Guespalapa ( $2,835 \pm 75$  to  $4,690 \pm 90$  years B.P.), Chichinatzin ( $1,835 \pm 55$  years B.P.), and Xitle ( $1,670 \pm 35$  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”,

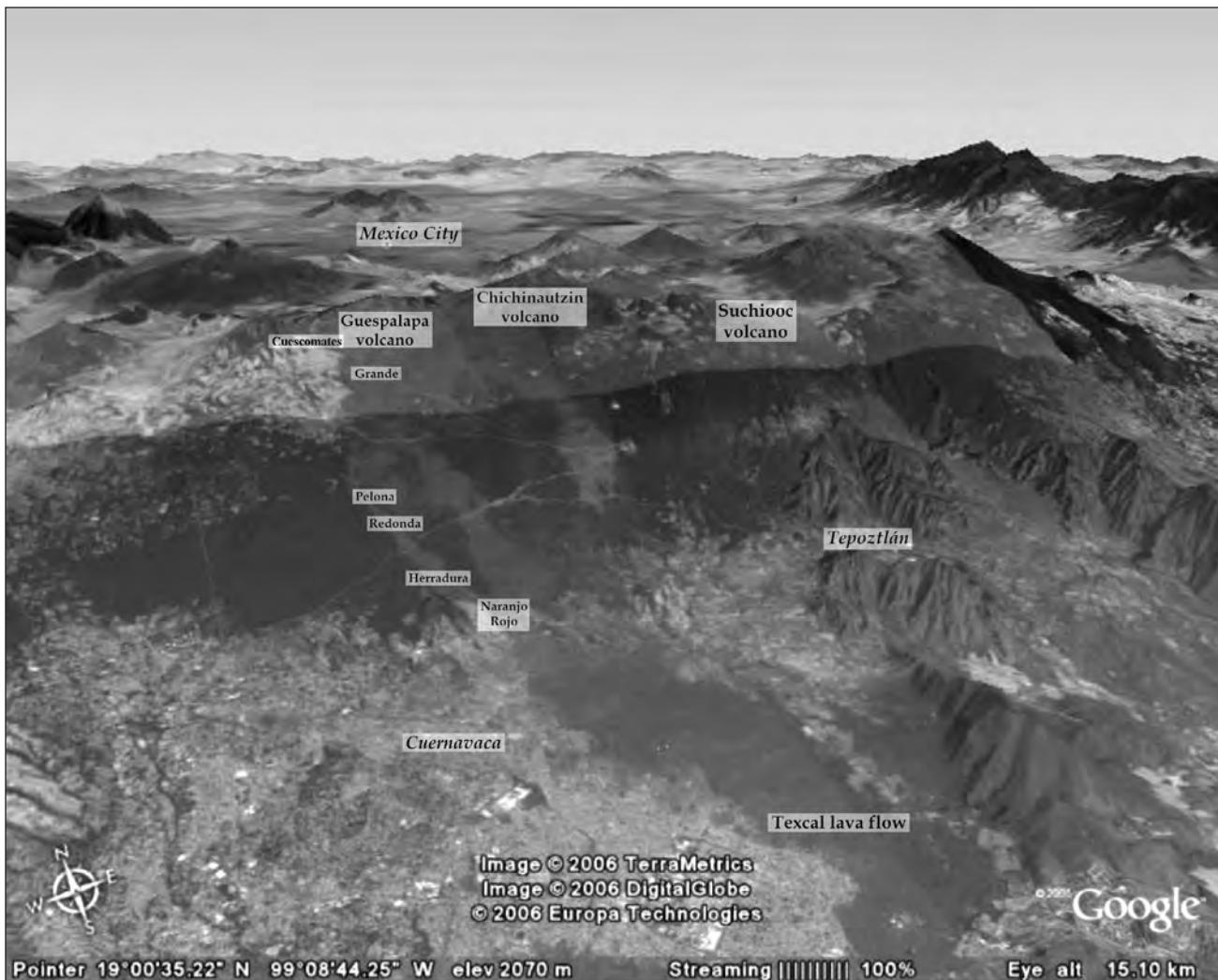


Figure 2. Image of the southern slopes of the Sierra Chichinatzin, with the location of the caves known along the upper slopes of the Texcal lava flow.

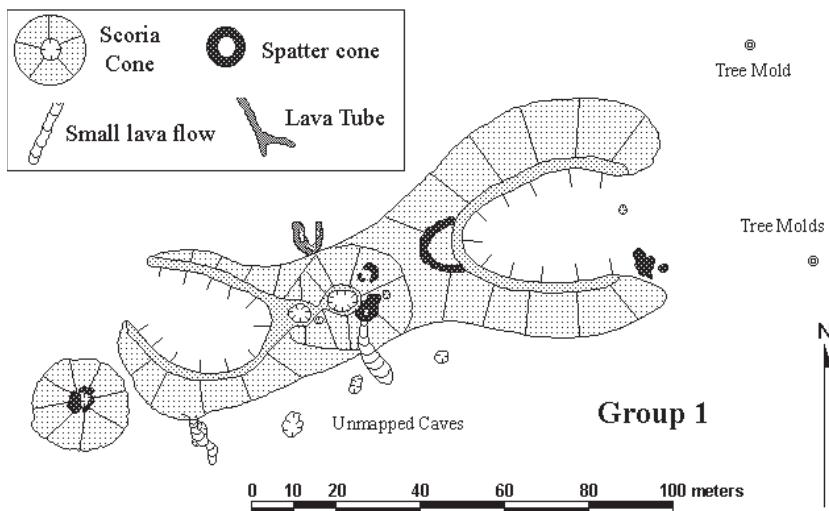


Figure 3. Plan of Cuescomates (Group 1).

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

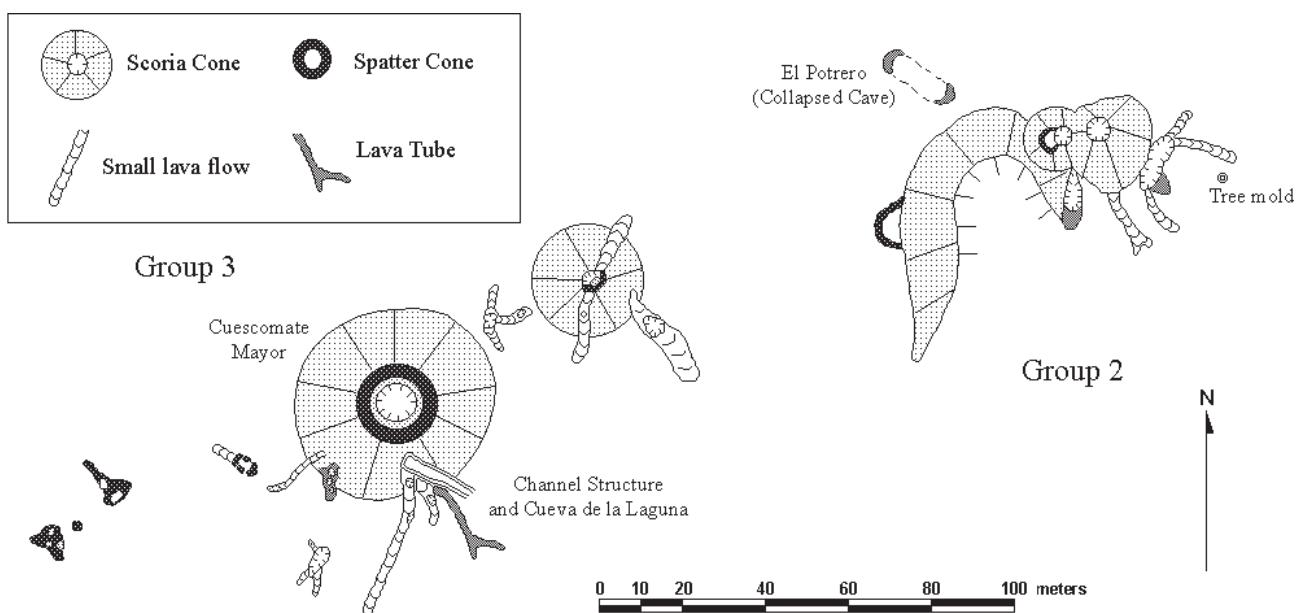


Figure 4. Plan of Cuescomates (Groups 2 & 3).



Figure 5. Los Cuescomates rootless vents are dwarfed by the surrounding 20 meters tall pine trees. Cuescomate Mayor is the one on the right.

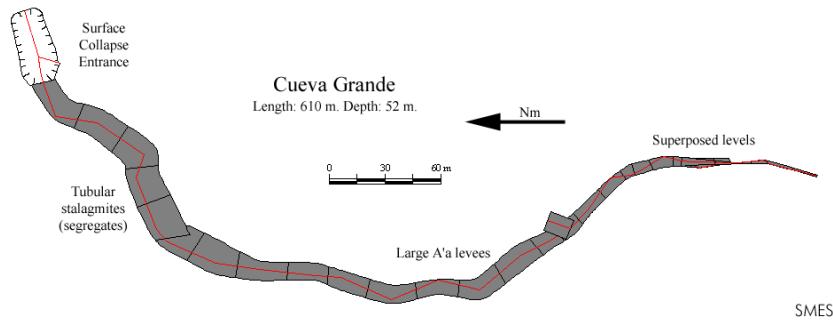


Figure 6. Map of Cueva Grande, a large master tube over 20 meters wide and high.



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

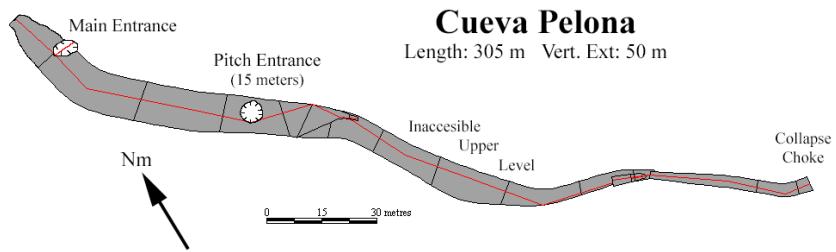


Figure 9. Plan view of Cueva Pelona. The outcrop of the Cuernavaca Fm. behind a lava lining is located between the two entrances.



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.

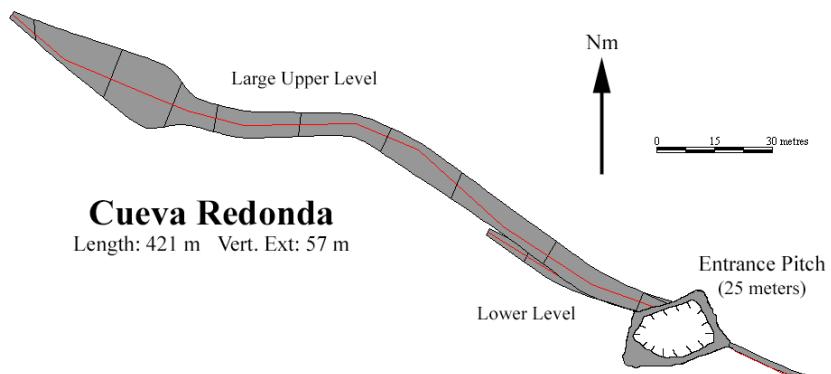


Figure 11. Plan map of Cueva Redonda. The entrance pitch of 25 meters was an open skylight during activity, as evidenced by primary features on its walls.

## Cueva de la Herradura

Length: 760 m Vert. Ext: 24 m

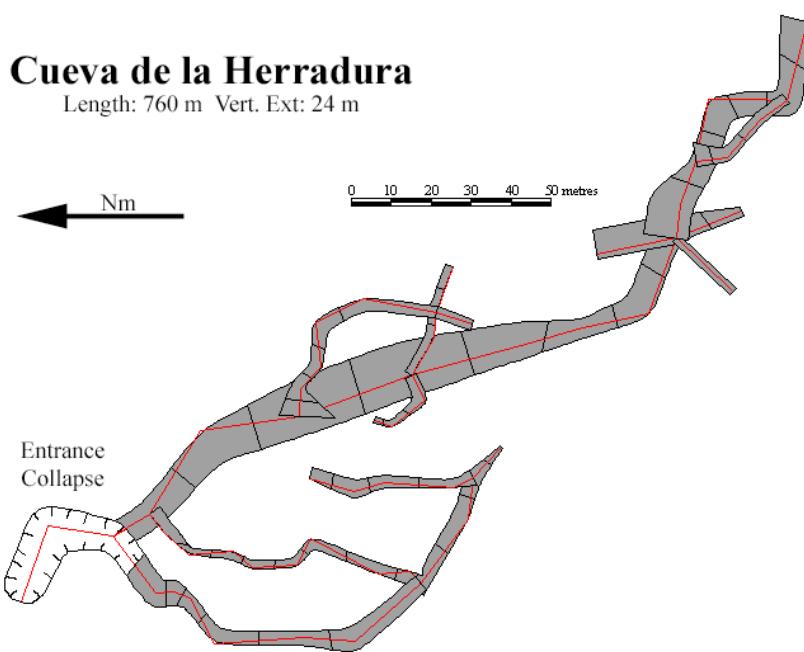


Figure 12. Plan map of Cueva de la Herradura, with a large main passage and upper level braided tunnels branching from it.

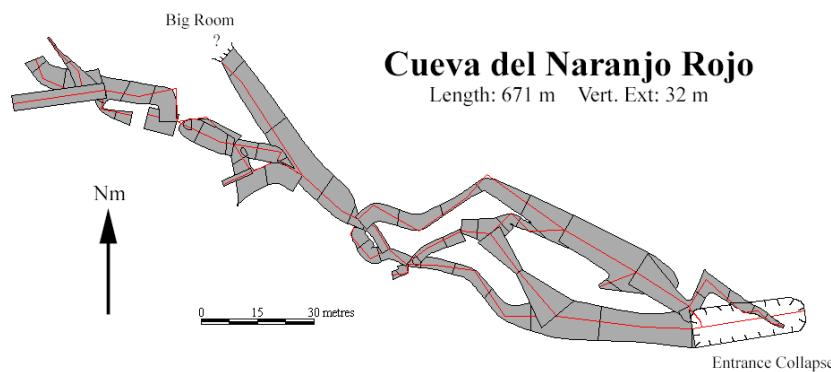


Figure 13. Plan map of Cueva del Naranjo Rojo, which contains a large multilevel master tube and upper level braided side passages, and is incompletely mapped.

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 Nayarit). The caves are situated in Cerro Tequilizinta, 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.

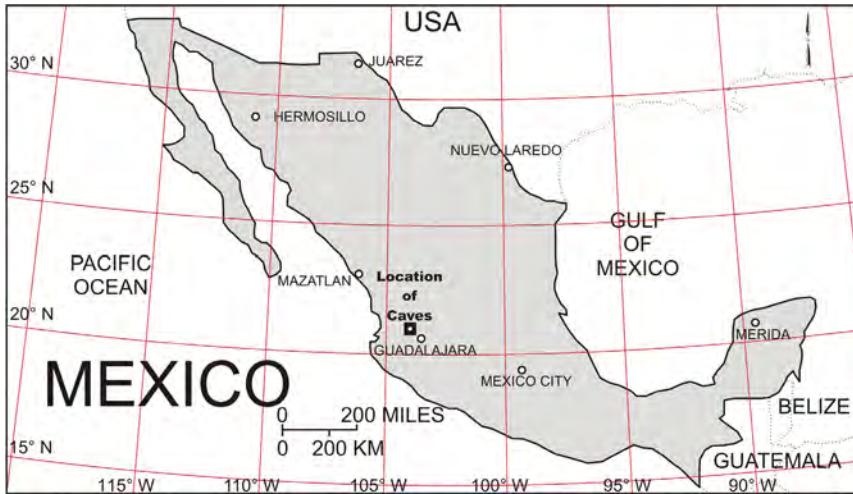


Figure 1. Location of Cuata and Madriguera de los Lobos Caves in Mexico.



Figure 2. Map of Cuata Cave.

### 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.

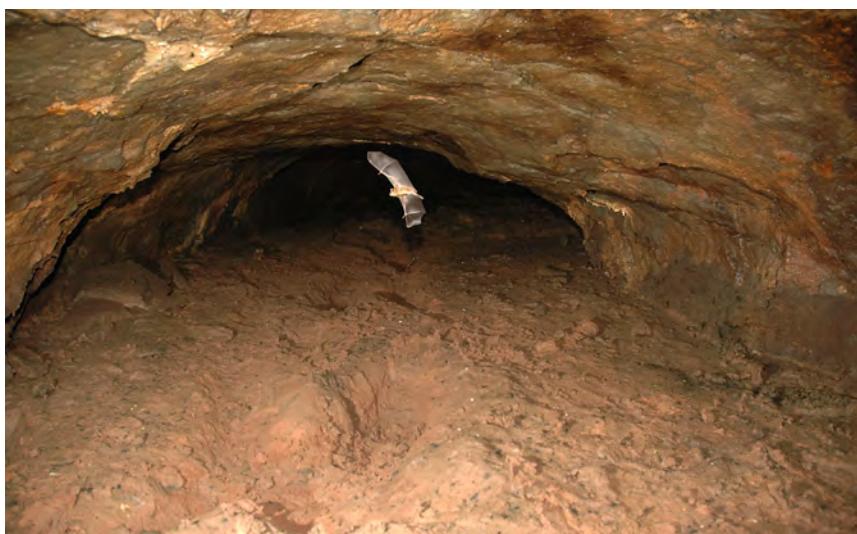
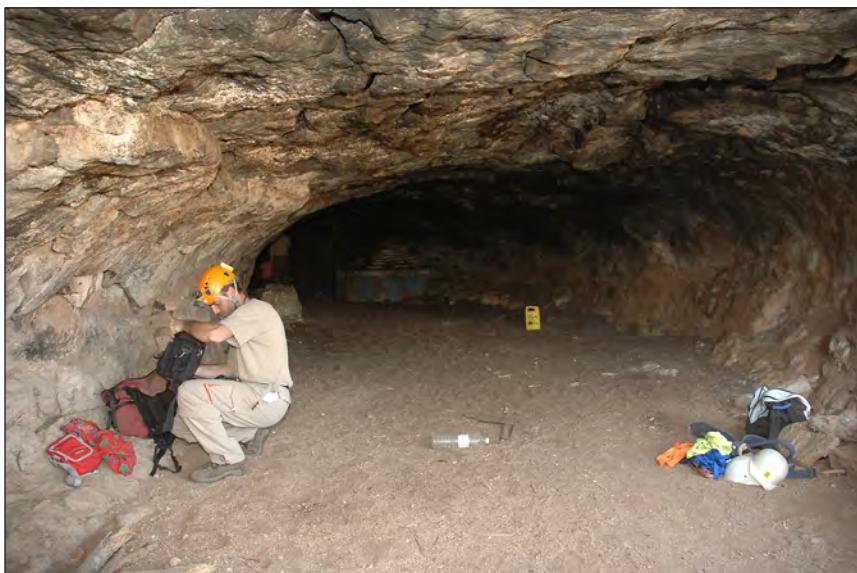
Members of Grupo Espeleológico Zott first investigated this cave in early 1990 and surveyed it during the same year. The cave can be reached via a paved road from Amatitán to the pueblo of Chome, after which dirt roads lead to a tequila distillery called La Taberna.

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 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 additional photographs for this article in the supplementary material on the CD.

MADRIGUERA DE LOS LOBOS  
TEQUILIZINTA, SANTA ROSA, JALISCO,  
MEXICO

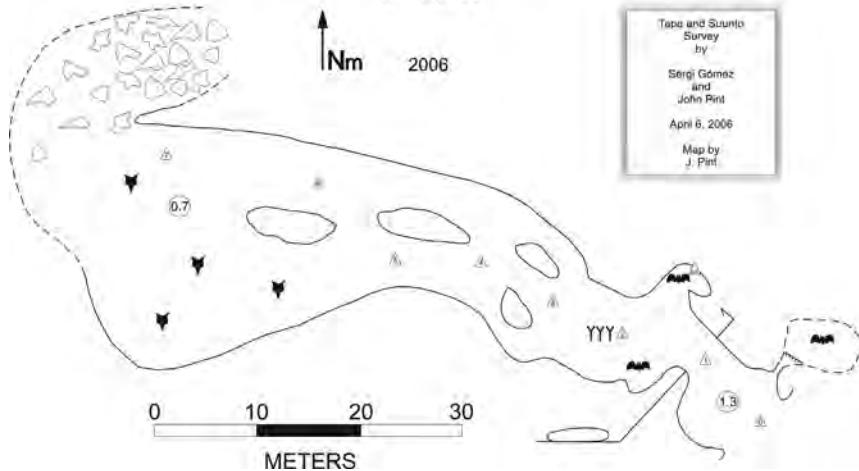


Figure 8. Map of La Madriguera de los Lobos Cave.



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 emitted 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<sup>3</sup> 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

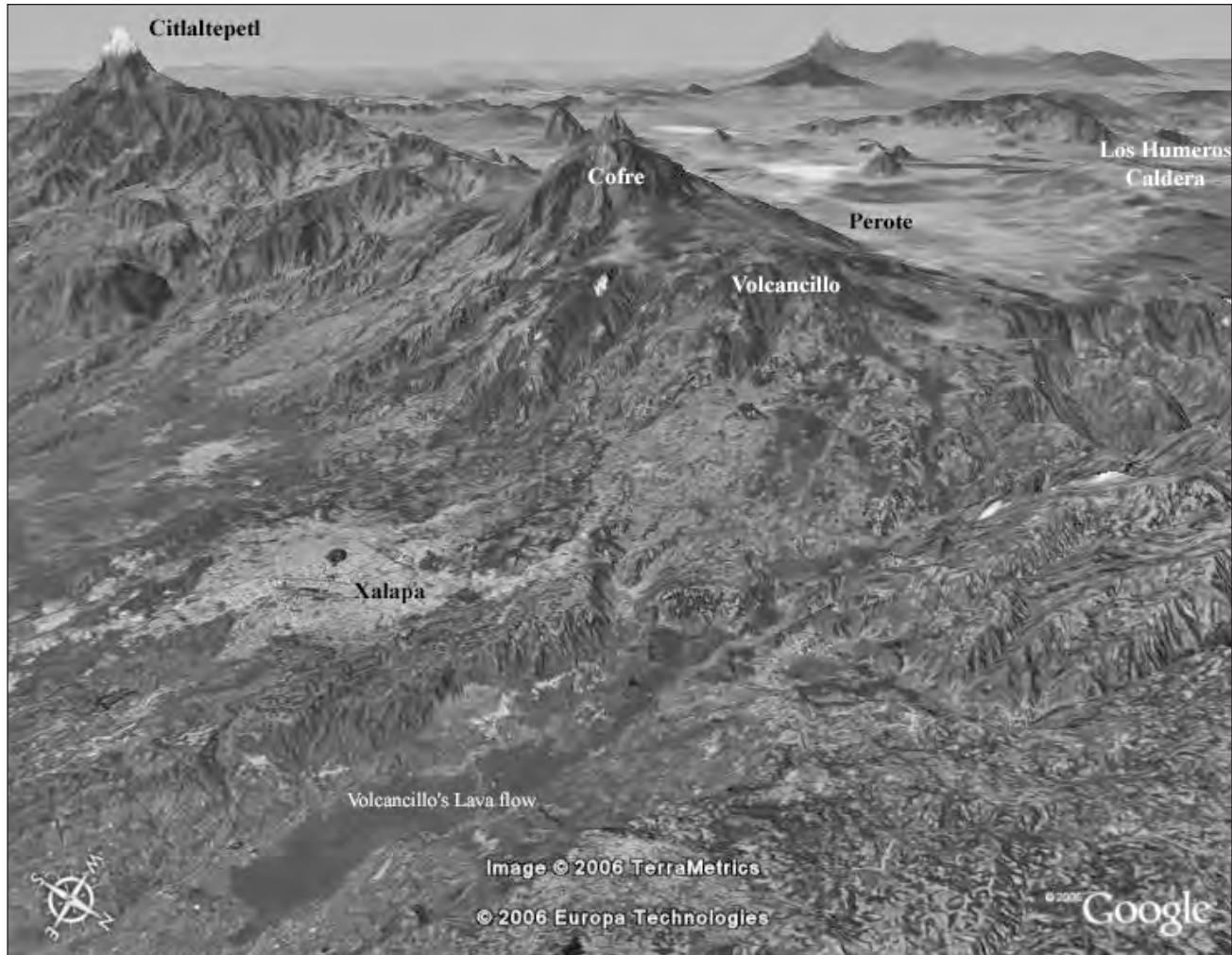


Figure 1. Las Cumbres volcanic complex and the Volcancillo lava flows.

Vigas which erupted  $870 \pm 30$  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

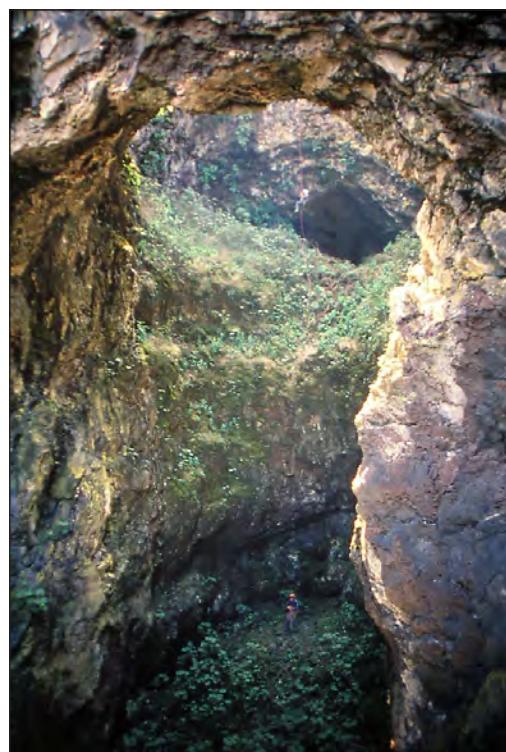
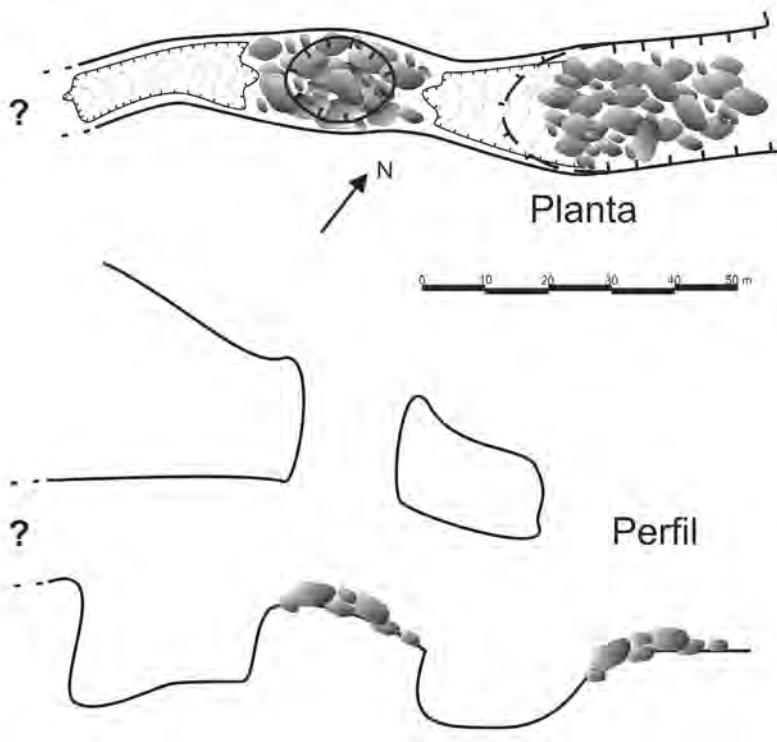


Figure 3. Cueva del Arco. Notice the two cavers, one on rope and the other at the bottom.

## Cueva del Arco Toxtlacoaya, Ver.

Topografiada con Suuntos y Cinta  
en marzo de 1994



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  $180^\circ$  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.

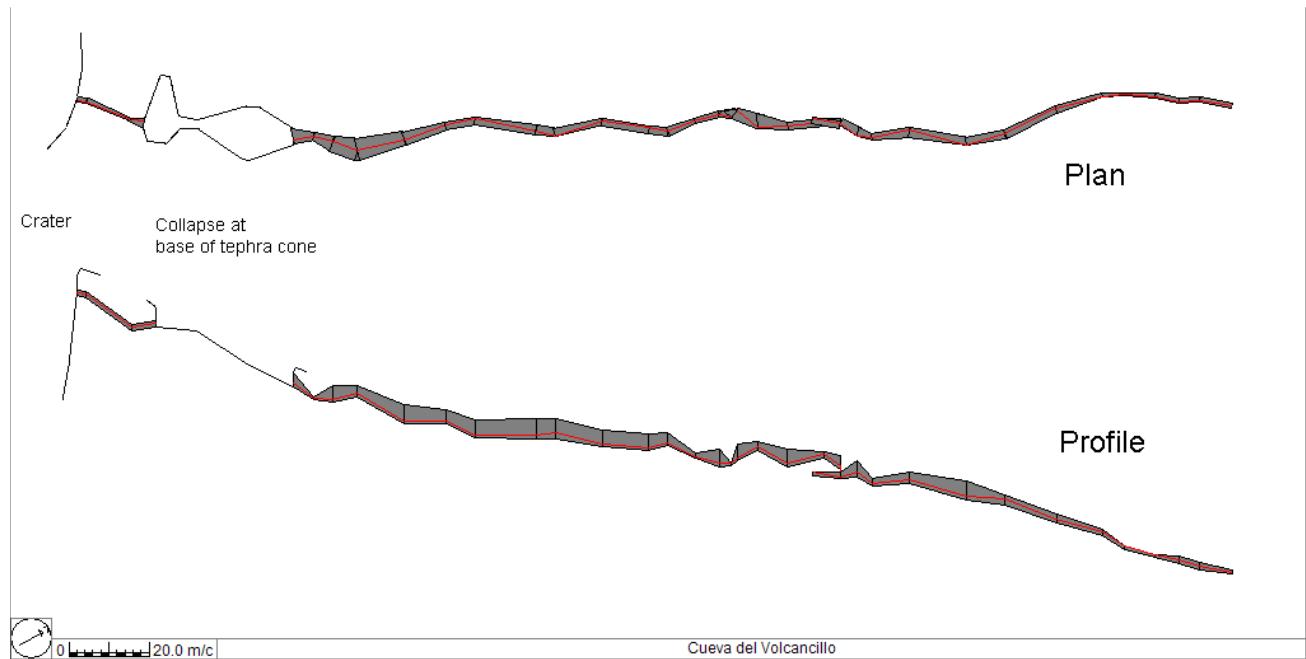


Figure 4. Plan map of Cueva del Volcancillo.

clefts andropy 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 Chichuasen 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 Tlalocula. It has been surveyed for 477 meters between two skylight entrances, but continues beyond in both directions (Figure 10). The upper portion contains two parallel 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

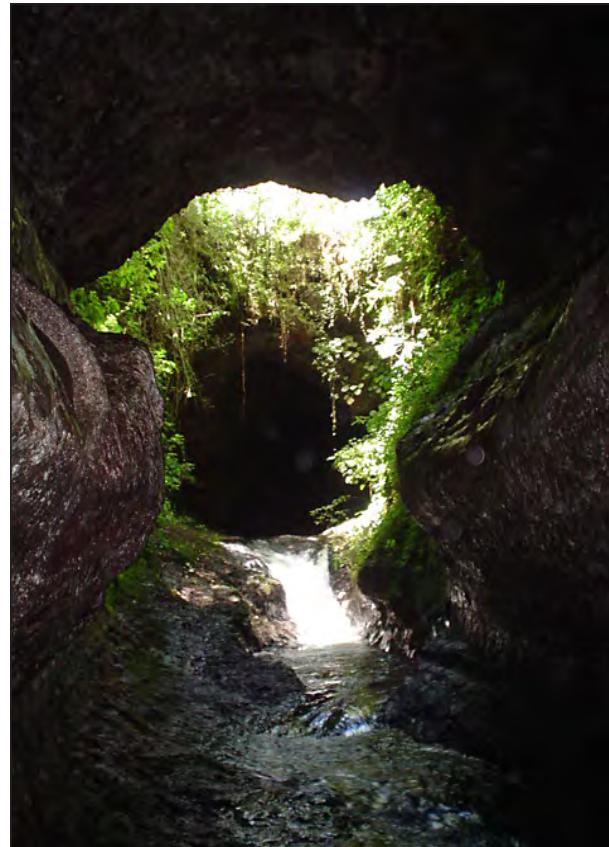


Figure 7. The Huichila River under one of the skylights in the cave.

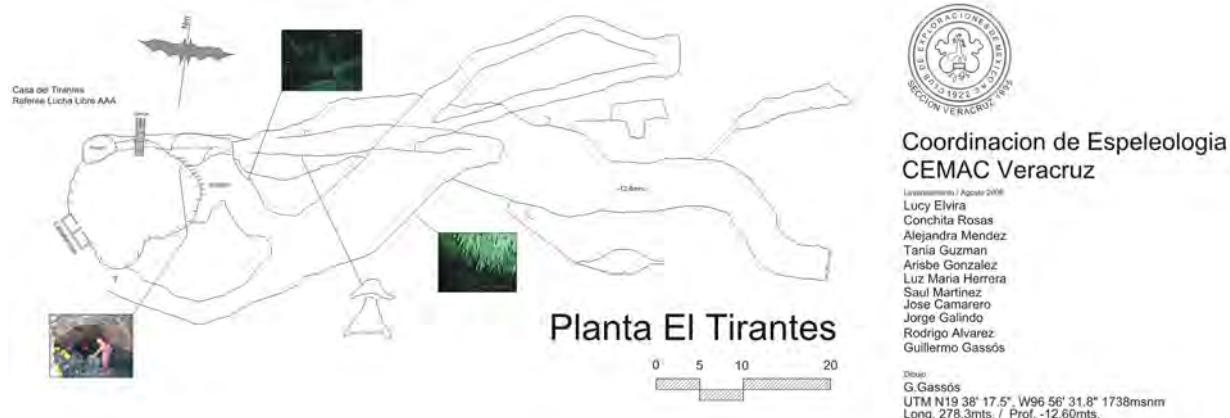


Figure 8. Plan and profile of Cueva de El Tirantes.



Figure 9. Plan and profile of Cueva de la Higuera.

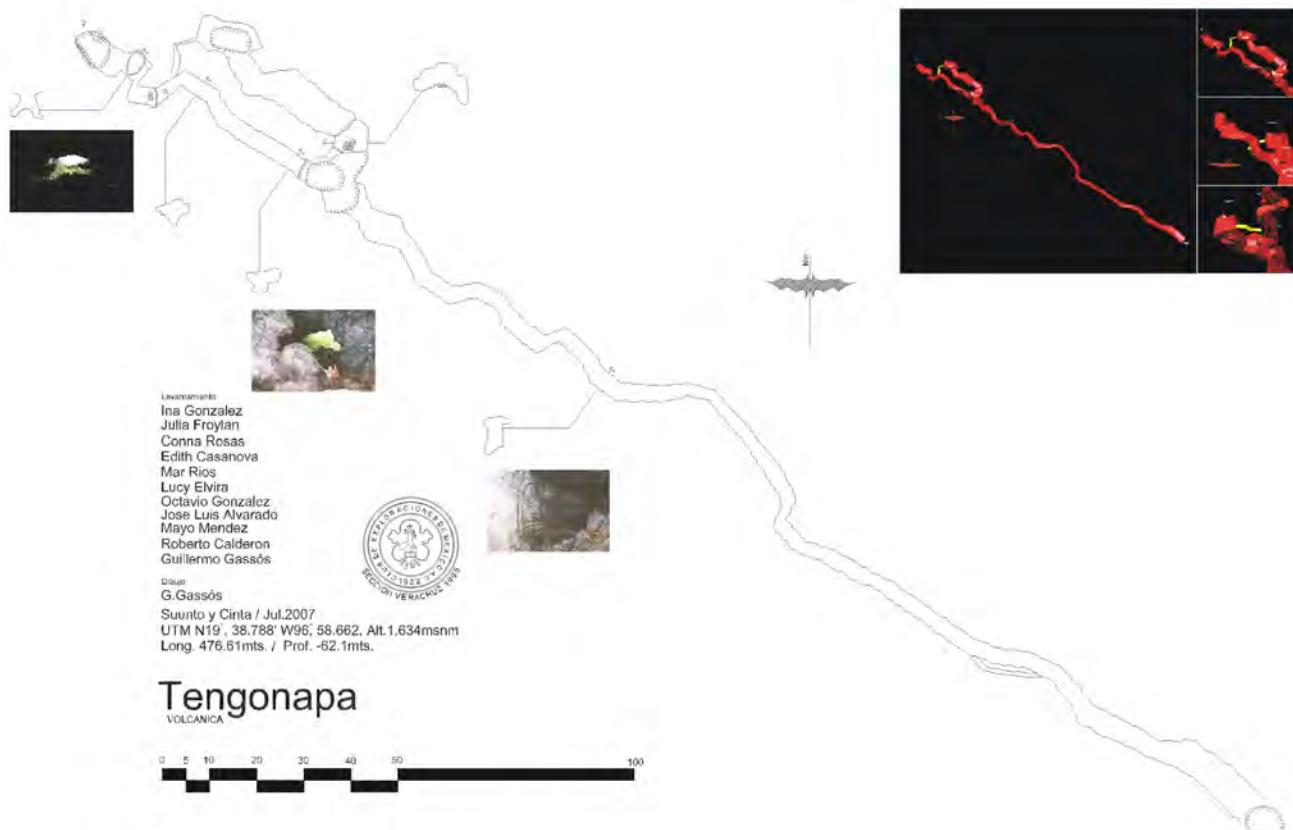


Figure 10. Plan and profile of Cueva de Tengonapa



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, sinistral 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 syn-depositional 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

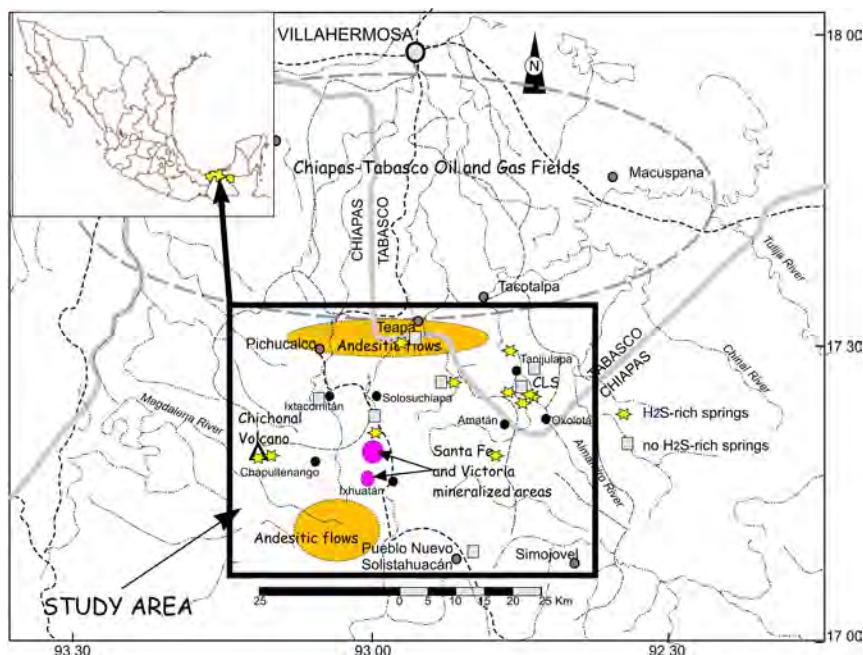


Figure 1. Location of the CLS (Cueva Las Sardinas or Villa Luz Cave) and Chichón Volcano (CV).  $H_2S$ -rich springs are presented by stars while no- $H_2S$  springs are presented by squares. The possible sulfur sources to the sulfur-rich springs in CLS are also shown.

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-  
sional 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

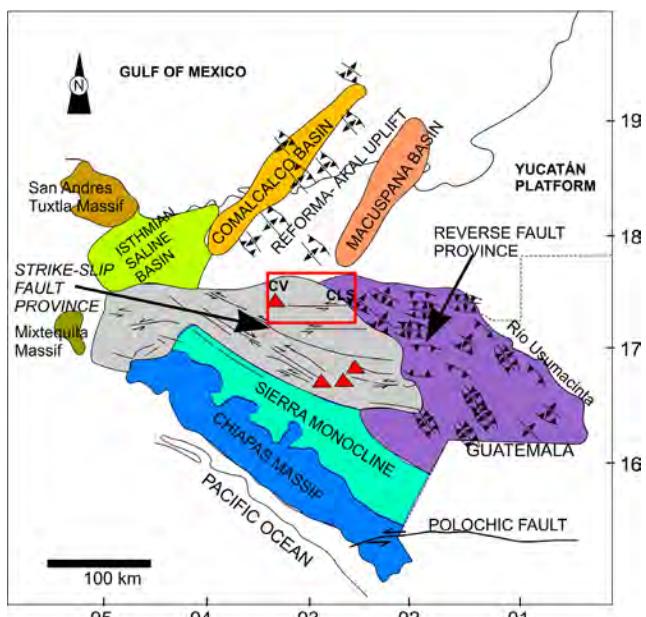


Figure 2. Structural provinces present in the study area. Chichón Volcano (CV) and Villa Luz Cave (CLS) are located in the Strike-Slip Faults Province. Volcanoes from the Chiapas Volcanic Belt or Arc in the area are shown as triangles (Modified from Meneses-Rocha [2001]).

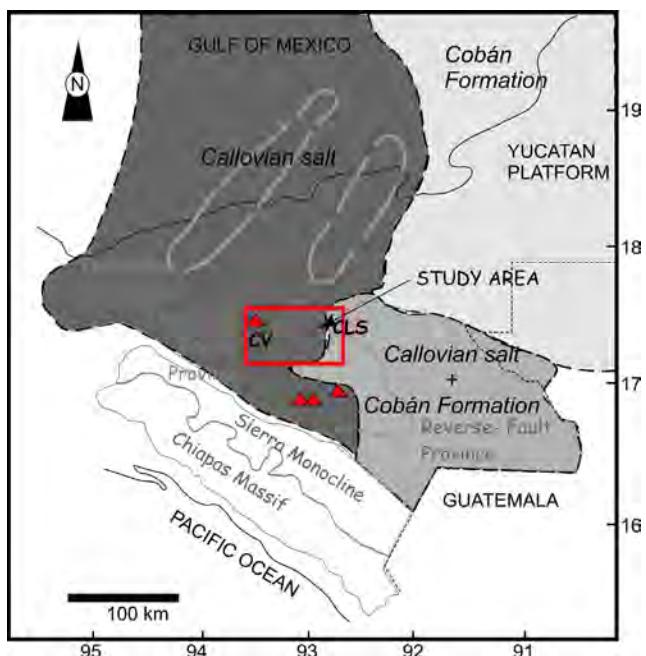


Figure 3. Type of evaporite deposit underlying the area (Callovian salt, halite or Cobán Formation, anhydrite). These deposits were one of the major controls on defining the structures present (modified from Meneses-Rocha [2001]).

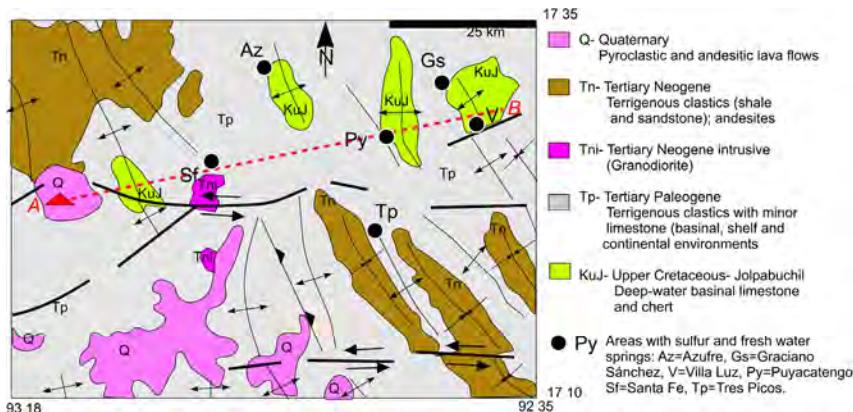


Figure 4. Generalized geologic map of the study area, showing the location of Chichón Volcano (CV) and Villa Luz Cave (CLS), as well as other sulfur spring areas. The orientation of the geologic section shown in Figure 5 is also shown (Modified from INEGI [1983] and Meneses-Rocha [2001]).

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].

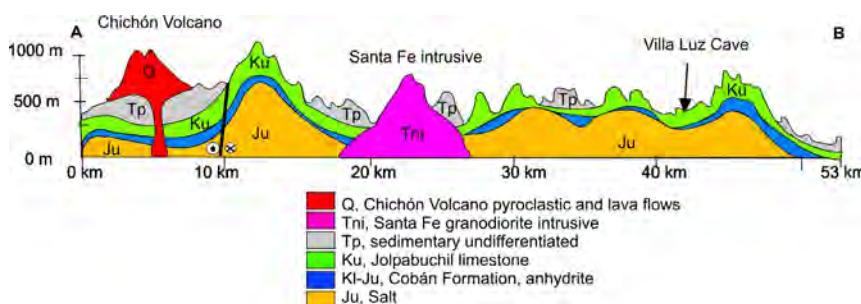


Figure 5. Geologic section of the study area showing a simplified interpretation of the geology (Figure 4, vertical thickness of the formations are not in scale). Ju=Upper Jurassic, Kl=Lower Cretaceous, Ku=Upper Cretaceous, Tp=Tertiary Paleogene, Tni=Tertiary Neogene intrusive, Q=Quaternary.

## 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  $2.2 \times 10^{13}$  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  $\text{H}_2\text{S}/\text{SO}_2 \approx 9$ . 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

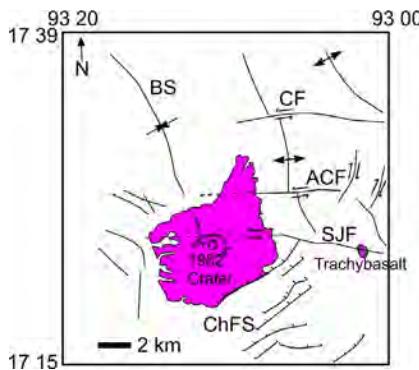


Figure 6. Plan view of Chichón Volcano (CV), showing the E-W lateral San Juan Fault (SJF) interpreted to control the magma-feeding system (modified from García-Palomo *et al.* [2004]) and which may serve as a groundwater flow-path for sulfur water from CV to Villa Luz Cave. Other major structures are: 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  $\text{H}_2\text{S}/\text{SO}_4$  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  $[\text{H}_2\text{S}] = 300\text{-}500\text{mg/l}$  and  $[\text{O}_2] < 0.1\text{mg/l}$ . 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  $[\text{H}_2\text{S}] < 0.1\text{mg/l}$  and  $[\text{O}_2] < 4.3\text{mg/l}$ . 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 ( $\text{pH}$ ,  $\text{P}_{\text{CO}_2}$  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  $\text{H}_2\text{S}$  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 Chichón Volcano crater lake from the west rim and sulfur deposits on the internal west crater wall associated to the fumaroles.

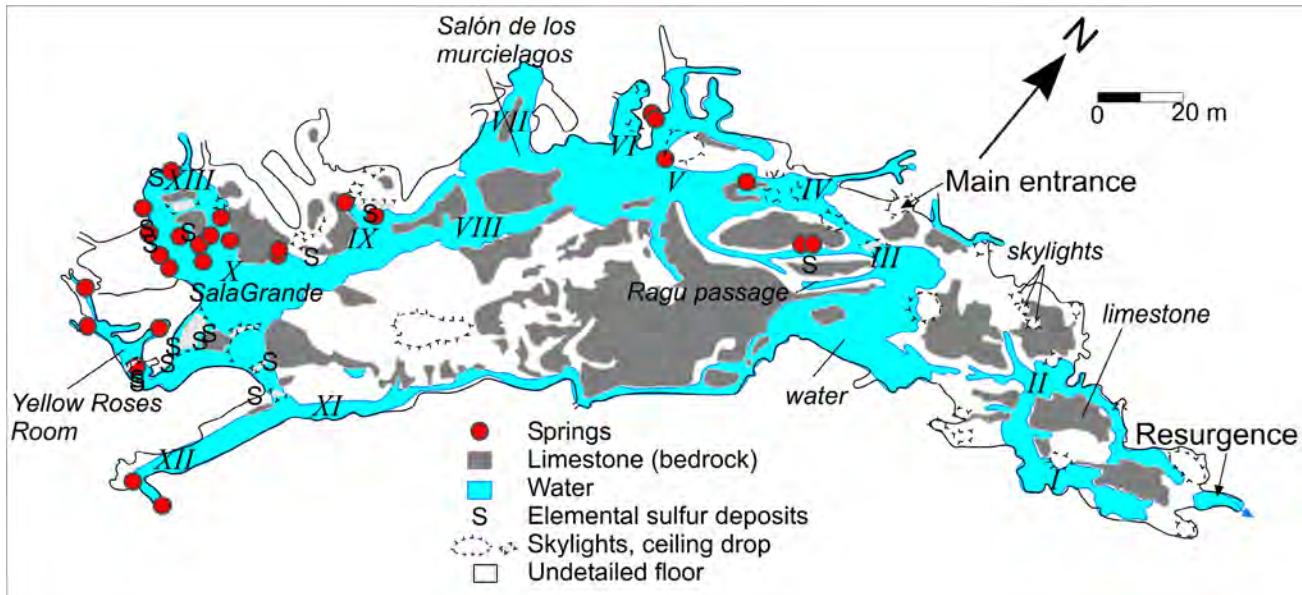


Figure 8. Simplified plain view of Villa Luz Cave (a.k.a. Cueva de las Sardinas, CLS) emphasizing the location of springs (red circles), streams skylights and limestone columns. The position of the main entrance, resurgence and areas with elemental sulfur is also included (Surveyed by Pisarowicz et al., [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.,

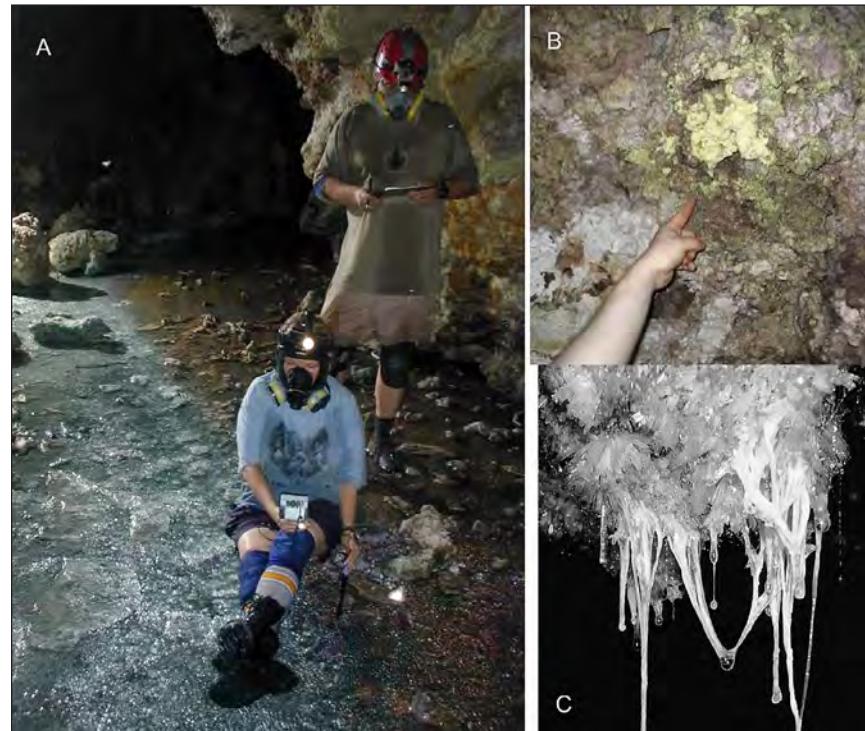


Figure 9. Photographs of Villa Luz Cave: A. End member springs,  $H_2S$ -rich in the left and  $H_2S$ - poor to the right [Hose et al., 2000], (Photograph by Kenneth Ingham); B. Sulfur deposits on the ceiling, associated to  $H_2S$ -rich springs; and C. Selenite deposits with biofilms (snottites) (Photograph 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

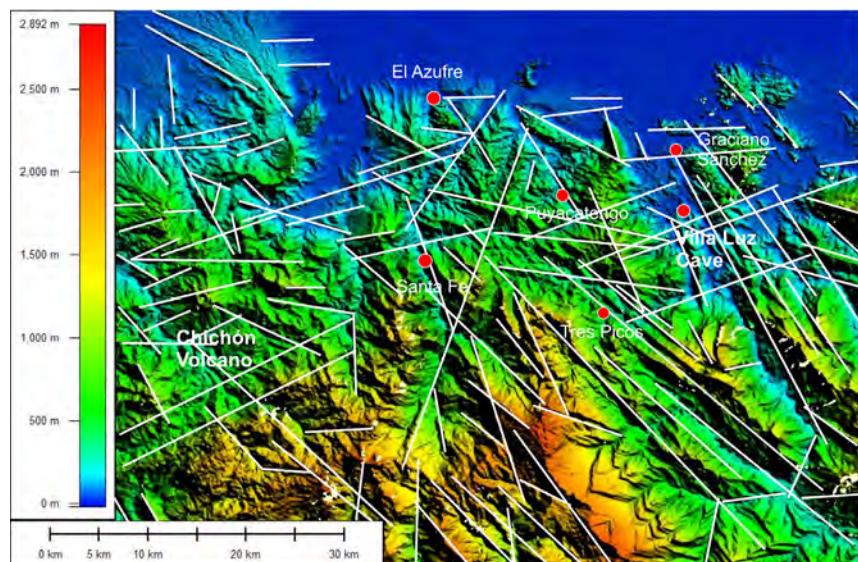


Figure 10. Major lineations on a radar image of the study area (white lines), showing the location of Chichón Volcano, Villa Luz Cave, and other sulfur springs regions (Santa Fe, Puyacatengo, El Azufre, and Graciano Sánchez sites). Darker color represents lower elevation above sea level (Radar image 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 ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) and anions ( $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ ,  $\text{F}^-$ ,  $\text{NO}_3^-$ ) [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  $\delta\text{D}$ -  $\delta^{18}\text{O}$ , 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 [Böttcher, 1999; DeCaritat, 2005; Rajchel, 2002].  $\delta^{34}\text{S}$  of both precipitates and  $\delta^{18}\text{O}$  of the sulfate precipitate will be determined, to compare the source and reactions occurring in the  $\text{H}_2\text{S}$  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  $\delta^{34}\text{S}$  [Hoefs, 2004] relative to CDT (Canyon Diablo Troilite Standard). Mantle  $\delta^{34}\text{S}$  is near 0‰, so Chichón 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 ( $\delta^{34}\text{S} \sim +17 \pm 2\text{‰}$ ) compared with the values spread in marine sulfides (-5 to -35‰) [Condie, 2005]. Since microorganisms strongly prefer the lighter isotope,  $^{32}\text{S}$ , sulfate reducing bacteria will produce negative  $\delta^{34}\text{S}$  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/connectedness 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

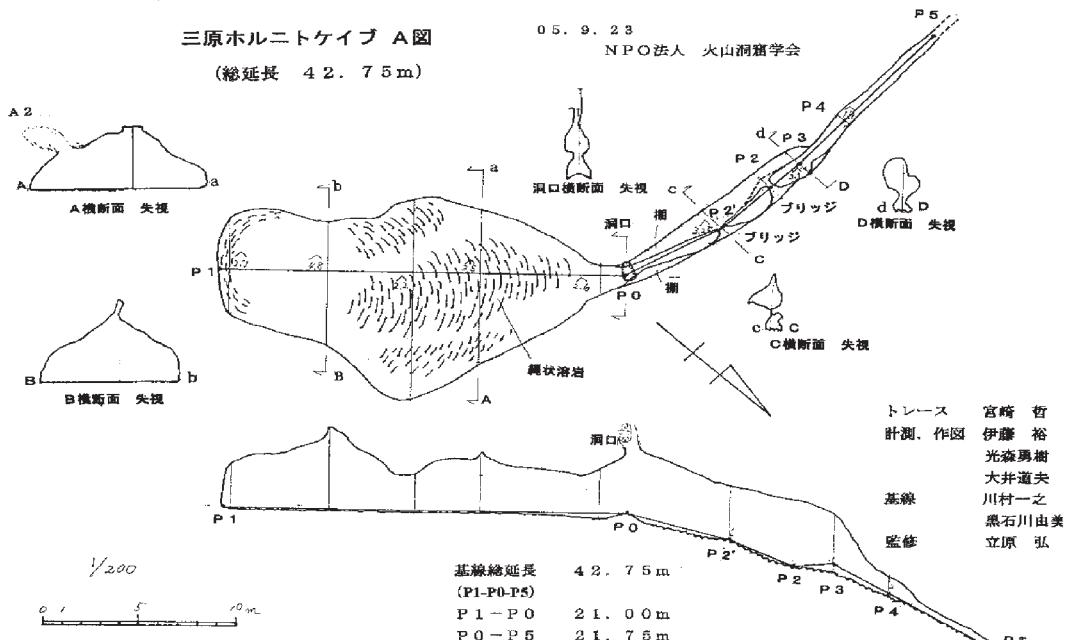
on Bingham characteristics of lava flow in the tube (T.Honda,2001) and from the height and slope angle of the lava tube on the sloped region, the yield strength of the lava can be obtained as 50000 dyne/cm<sup>2</sup>. This value is very near to the value calculated as 43000 dyne/cm<sup>2</sup> by G.Hulme(1974) 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.

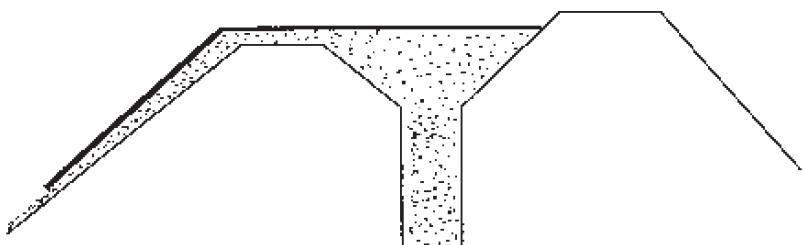
### Introduction

The hornito with lava tube cave is located on Izu-oshima island south of

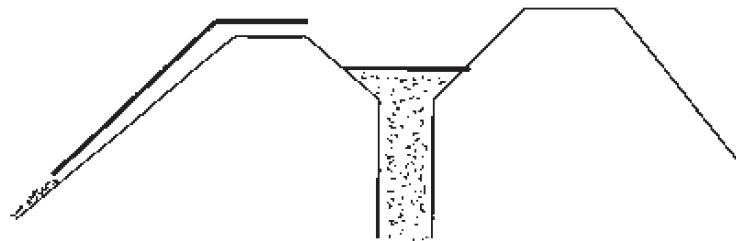
Tokyo in the Pacific Ocean. Izu-oshima island, located on the volcanic front of the izu-Ogasawara (Bonin) arc, consists of Mihara-yama which has large outer crater and small inner crater. This hornito and lava cave were formed inside of 1951 eruption lava flow deposited at the edge of inner crater of 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

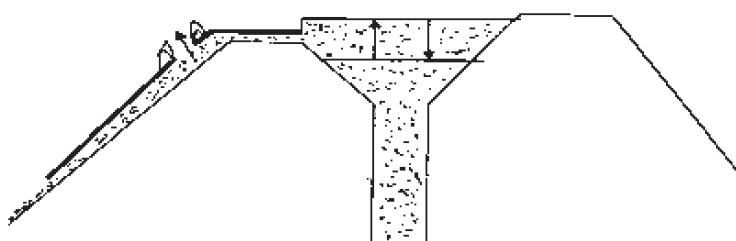




(A) 噴火口内の溶岩湖から溶岩が内輪山をこえてあふれ出し表面が固化し溶岩チューブが形成される



(B) 溶岩湖のレベルが下がり溶岩チューブから溶岩が抜け出して溶岩チューブ洞窟が形成される



(C) 溶岩湖のレベルが上昇し、溶岩チューブの内圧上昇により表面がわれ溶岩が溢れ出てホールを形成、その後溶岩レベルは下降

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 through 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. Based on this model, we can obtain the important physical property of lava: yield strength.

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 through 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( $\alpha$ )	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 <sub>2</sub> fraction of lava	Obtained yield strength	References
Mihara-yama	52~53%*	$5 \times 10^4$ dyne/cm <sup>2</sup> $4.3 \times 10^4$ dyne/cm <sup>2</sup> [7]	*T.Minakamil (1951)[1]
Mt.Fuji	49.09~51.3%*	$2.5 \sim 5.0 \times 10^4$ dyne/cm <sup>2</sup> [6]	*H.Tsuya(1971)[8]

was determined for the discharge parameters in which the yield strength plays a dominant role. The equation  $(Qg \sin\alpha)R/2 = f_B$  is the limiting condition to determine if the fluid in the tube can be drained out. Here,  $\alpha$  is angle of slope or inclination of tube,  $Q$  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,  $f_B = 5 \times 10^4$  dyne/cm<sup>2</sup> 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 ( $4.3 \times 10^4$  dyne/cm<sup>2</sup>) 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  $2\pi(\sigma/g\eta_L)^{1/2}$ , where  $\sigma$  is surface tension of liquid  $\eta_L$  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.

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Figure 3. Lava stalactite on the ceiling wall surface in the lava tube cave.

## 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 21<sup>st</sup> Anniversary Expedition to Raufarhóllshellir 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.

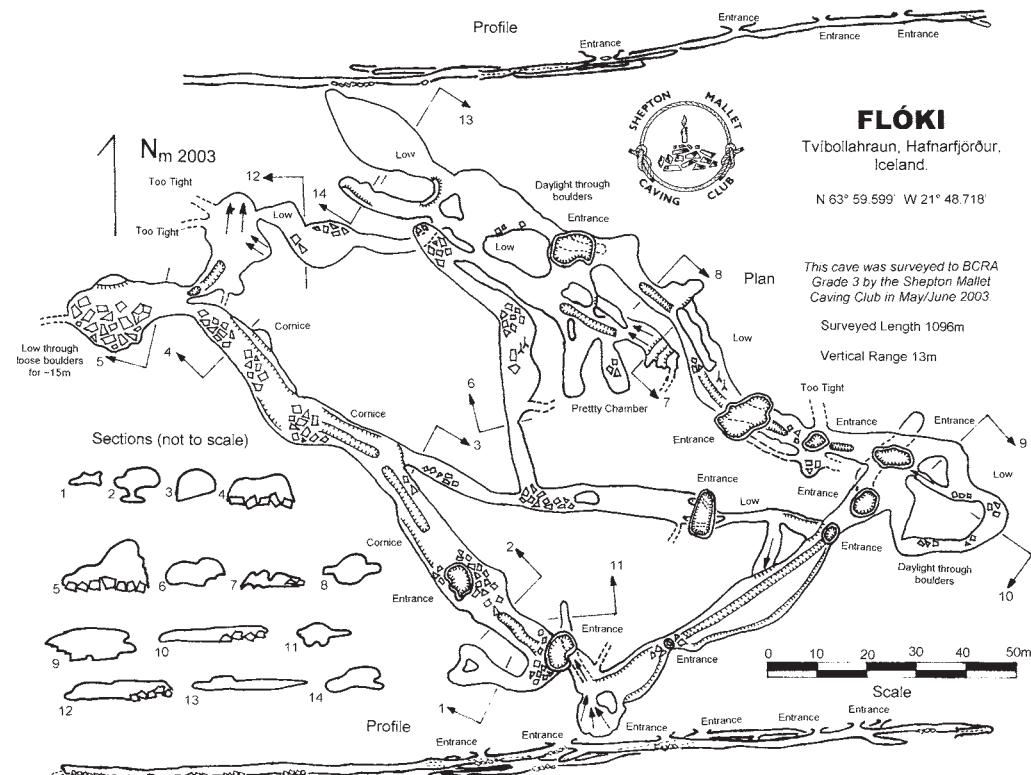
This paper describes the highlights of three visits to Iceland since the second Laki Underground Expedition. These visits were in May 2003, June 2005 and August 2005 and cover work on the Reykjanes Peninsula in southwest Iceland, and the Ódáðahraun lava fields in central Iceland.

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 Hafnarfjörður 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 8<sup>th</sup> 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 (Djúpikhellir) had received an accurate survey. During the 2003 expedition all the major caves were surveyed, and those surveys were tied together with a

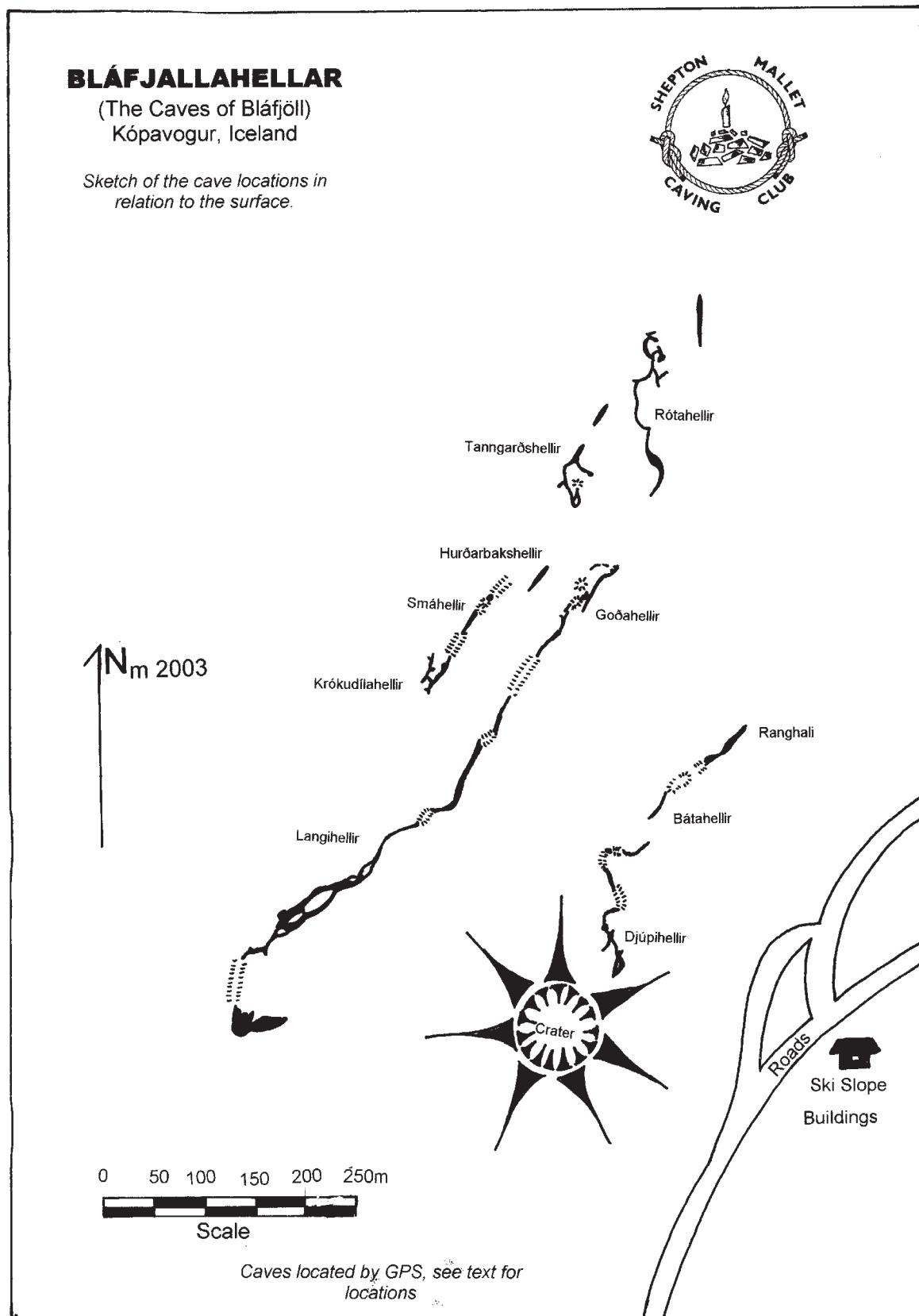
Top right: Unusual formations in Flóki(Terence Fitch).

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 its 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

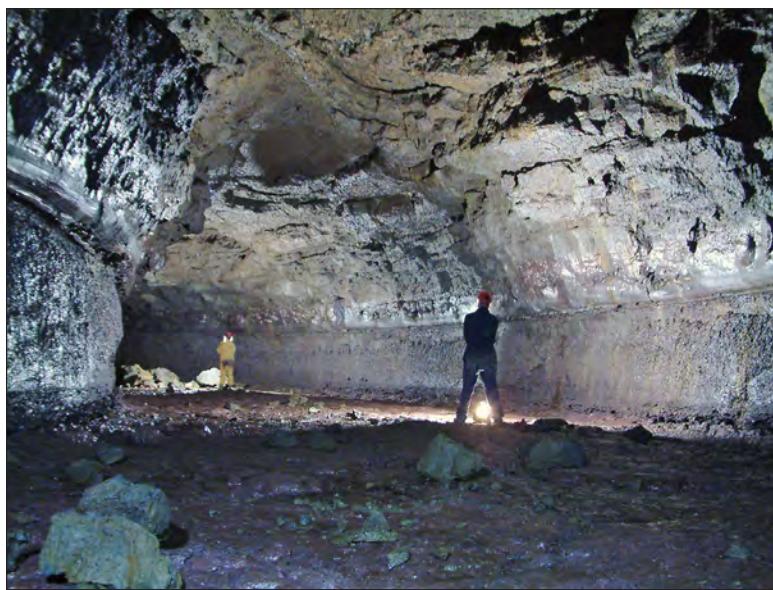
members were invited to survey the cave in June 2005. From this visit it was clear that Búri was part of a much larger system, including the well known caves of Arnahellir and Arnaker, and during a visit in August 2005 the other caves presumed to be part of the same system were also surveyed (except 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).

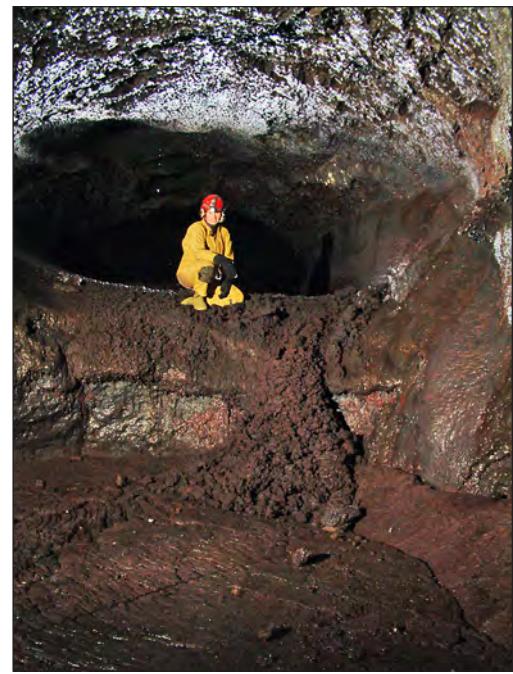
#### Ódáðahraun

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<sup>2</sup> 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.

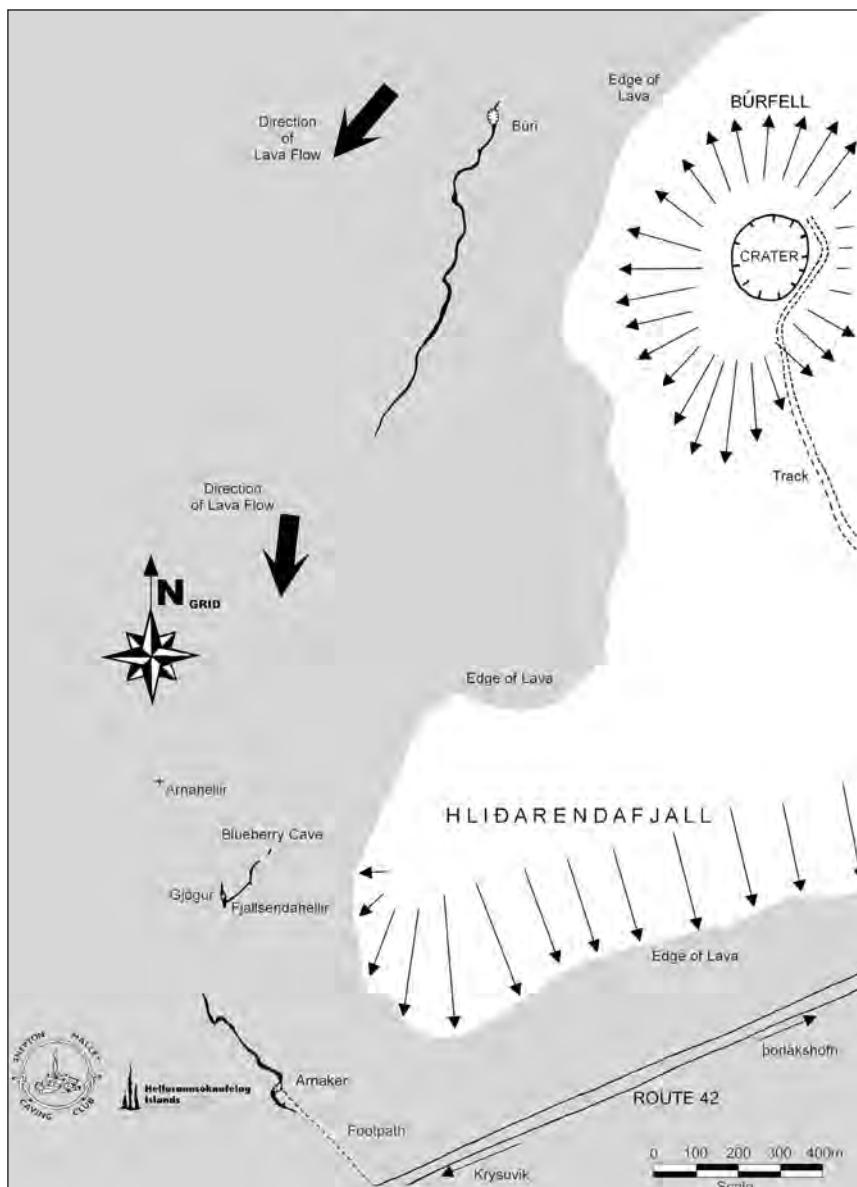
*Lofthellir.* Prior to our expedition



Main Passage in Búri (Ed Waters).



Lava Fall in Búri (Ed Waters).



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.

**Braðrafell.** Braðrafell is an ancient 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

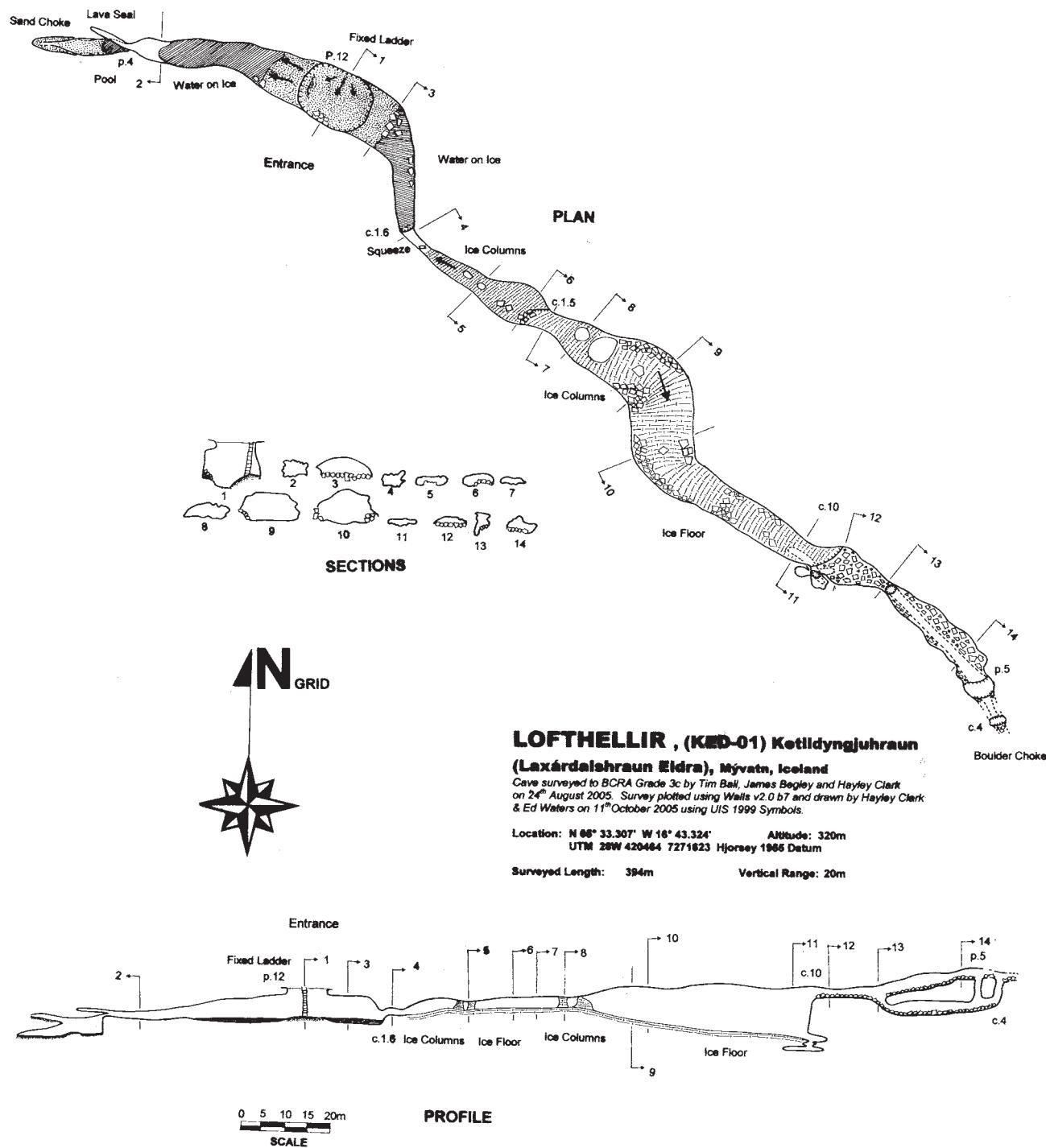
Map of the Leitahraun.



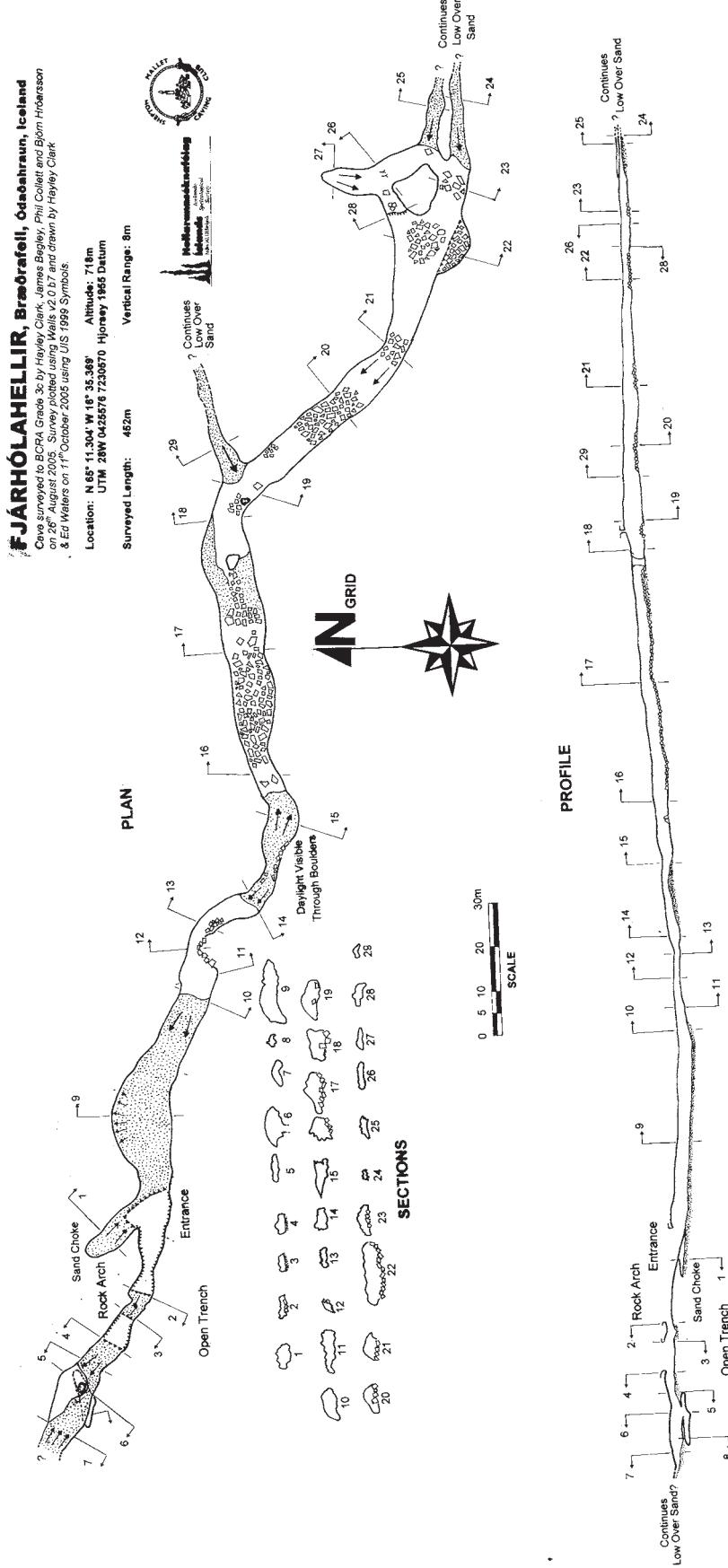
The large main passage of Lofthellir is decorated by fine ice formations (Keith Batten).



Entrance to Lofthellir.



Survey of Lofthellir. A larger version is included in the supplementary material on the CD.



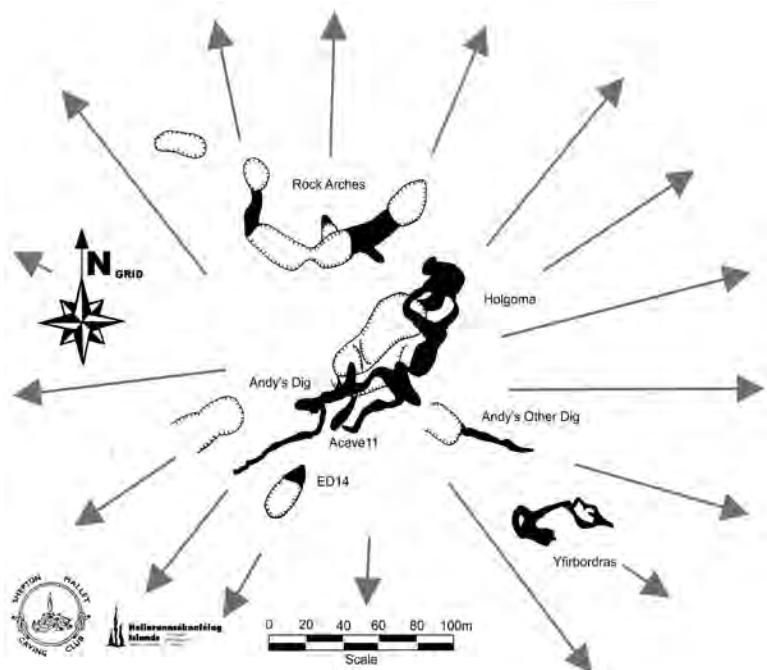
Survey of Fjárhólahellir. A larger version is included in the supplementary material on the CD.

Lava Formations in Hellingur  
(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 Litladýngja 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



Passage in Holgóma (Keith Batten).



Holgóma, Main Chamber (Keith Batten).



“Marmari Drottning” a large lava stalagmite encrusted with secondary minerals.

serious work is carried out by foreigners and only a couple of Icelanders.

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  $39^{\circ}$  and  $41^{\circ}$  longitude E and  $25^{\circ}$  and  $26^{\circ}$  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  $25^{\circ}56'N$ ,  $39^{\circ}54'E$ , 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 crawl spaces which may be connected. In September of 2003, it was found that dry sediment

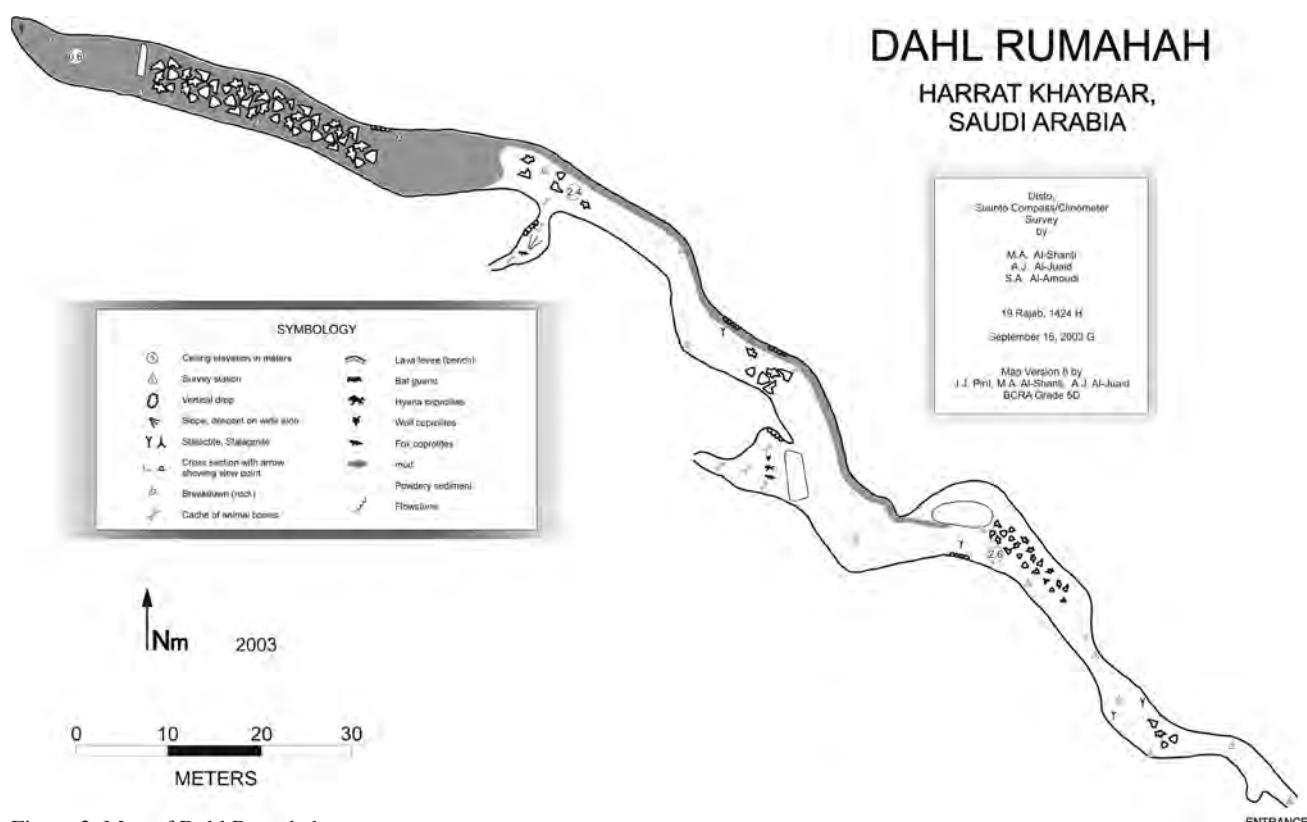


Figure 2. Map of Dahl Rumahah.

# MAJOR LAVA FLOWS (HARRATS) OF SAUDI ARABIA

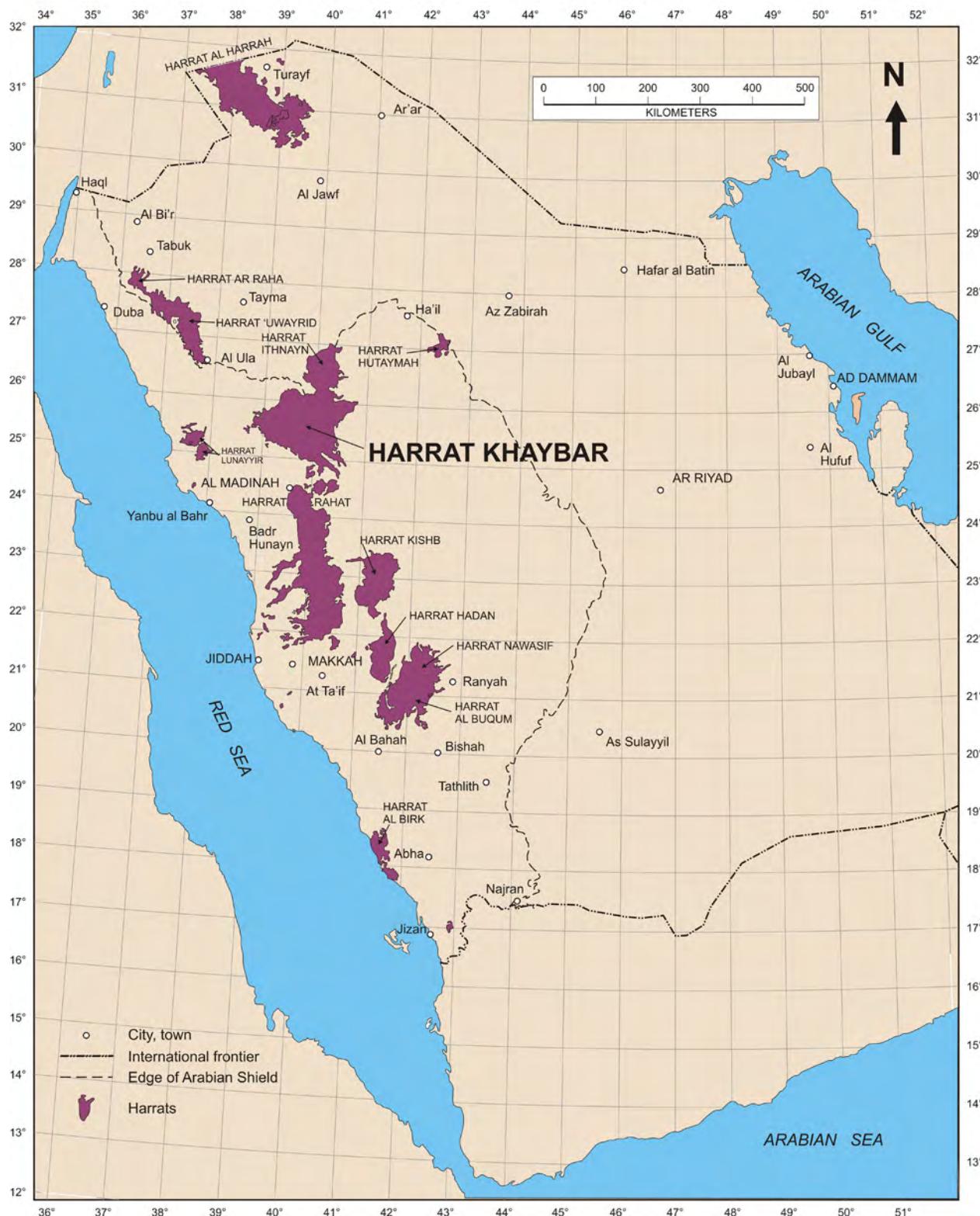


Figure 1. Location of Harrat Khaybar lava field in Saudi Arabia.

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 inter-continental 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 16<sup>th</sup> and 19<sup>th</sup> 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.

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 up-slope (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

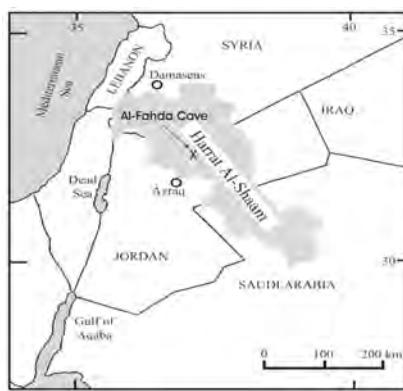


Figure 1. Location map of Al-Fahda cave and the extent of Harrat Al-Shaam (altered after Al-Malabeh, 1994).

and the existence of the benches prove that the passage existed when the lava was still actively flowing. It therefore appears that the 2<sup>nd</sup> 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 1<sup>st</sup> 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 2<sup>nd</sup> 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 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 it became too cool to keep lava flowing. It may also represent a later event that invaded the cave after it was

### Al-Fahda Cave sheet I

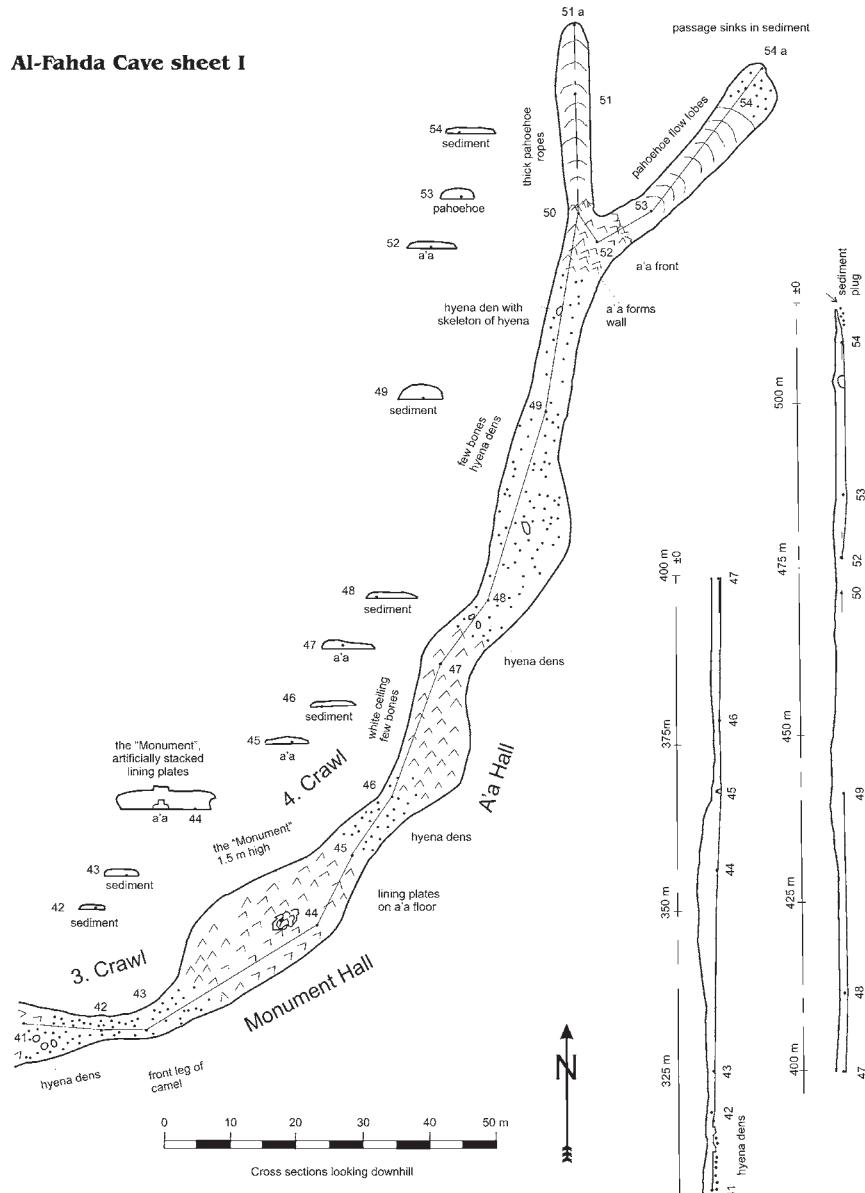


Figure 2. Map of Al-Fahda Cave (by the authors), sheet 1. The uphill and Mahmoud's passages. Larger versions of map figures 2–5 are in the supplementary material on the CD.

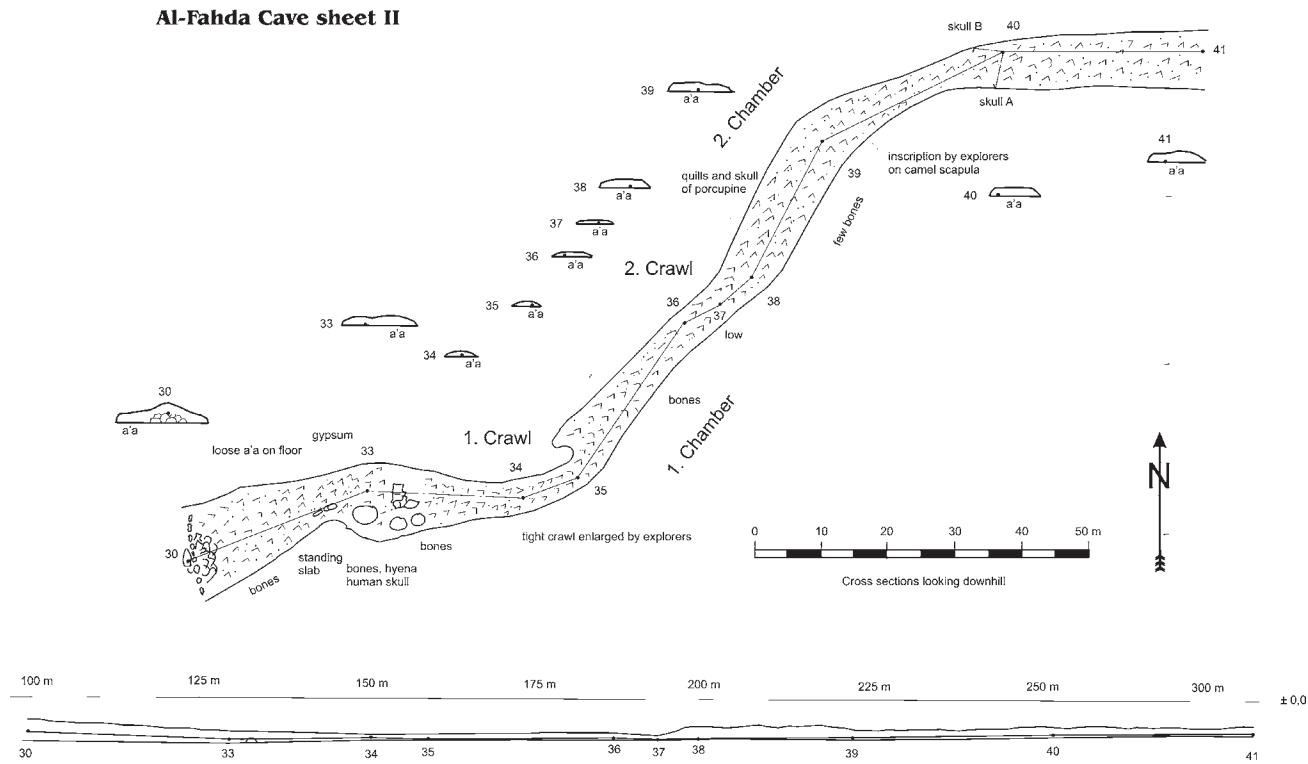


Figure 3. Map of Al-Fahda Cave (by the authors), sheet 2. The Mud, Large and A'a Halls. Also the both entrances.

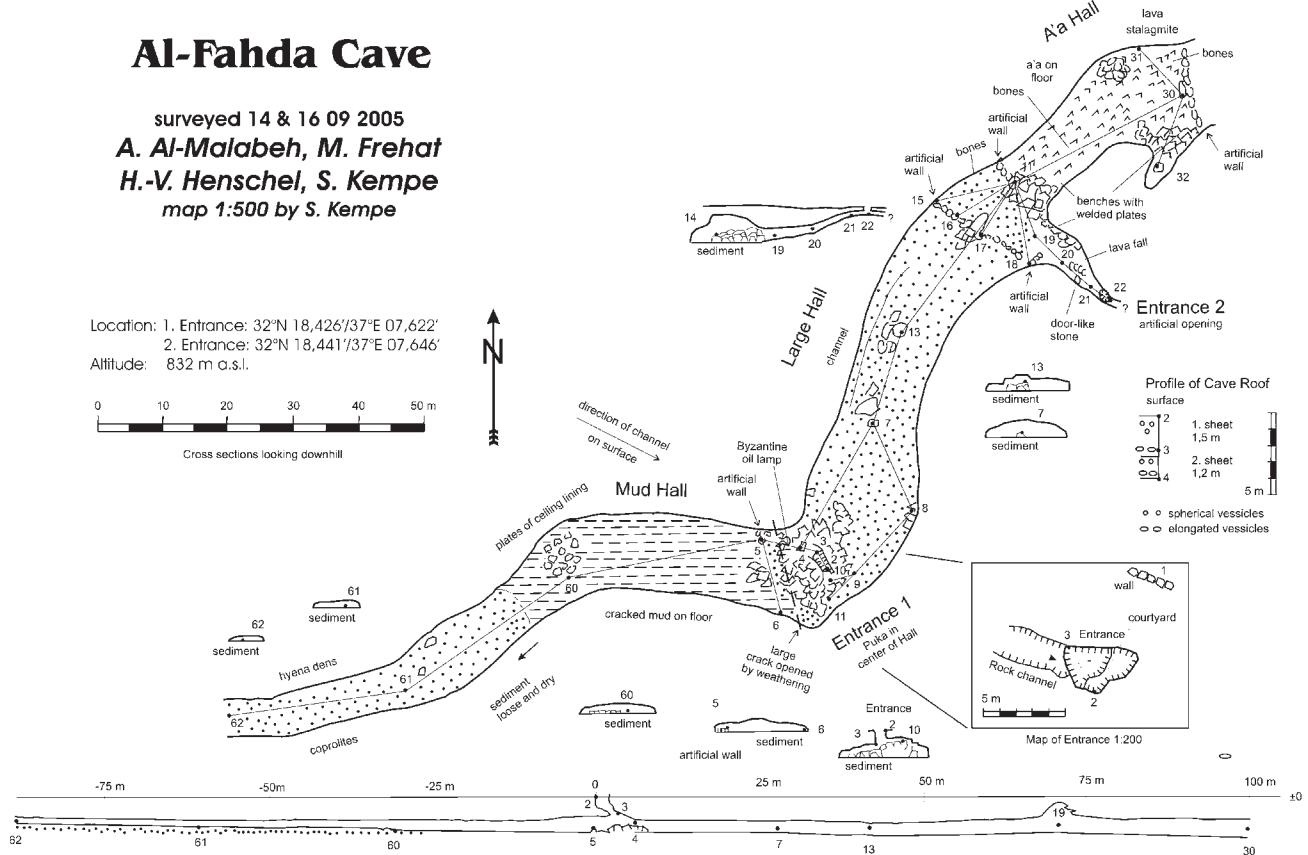


Figure 4. Map of Al-Fahda Cave (by the authors), sheet 3. The Crawl Halls.

**Al-Fahda Cave sheet III**

## Al-Fahda Cave sheet IV

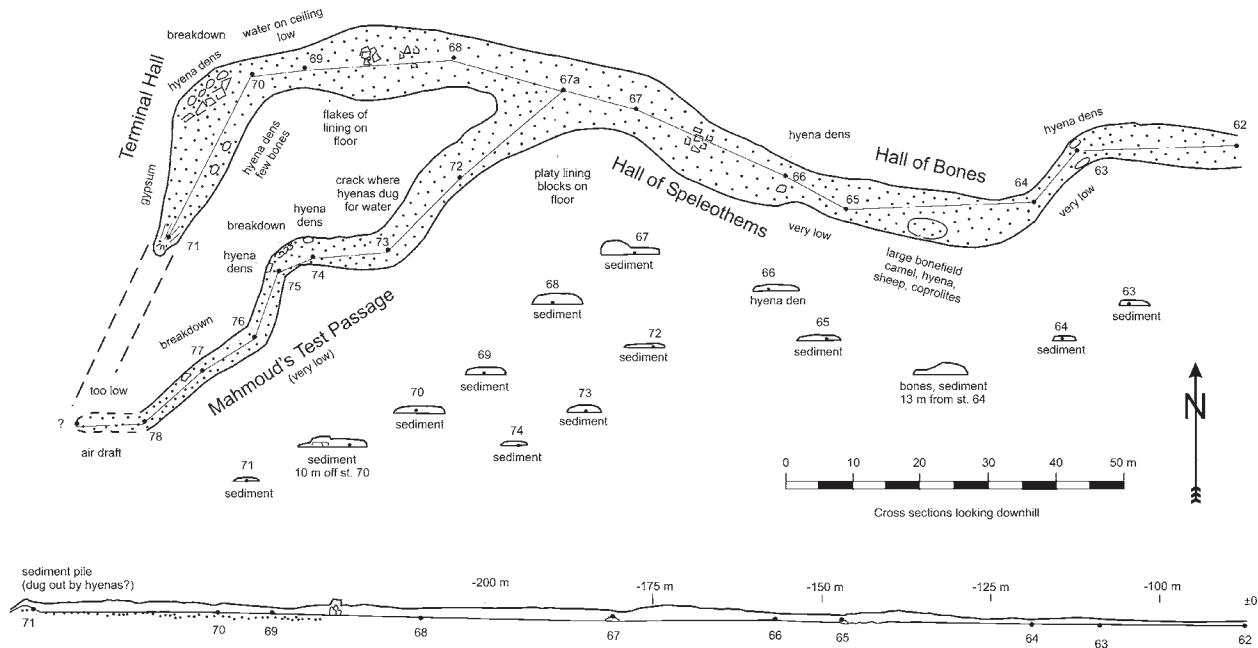


Figure 5. Map of Al-Fahda Cave (by the authors), sheet 4. Monument and, Pahoehoe and terminal Halls.



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
<b>Total</b>		<b>=SUM(ABOVE) 923.52</b>
	<b>Main Passage length</b>	
4-54a	Makai Passage	482.86
4-67a	Mauka Passage	187.10
67a-79	Mahmoud's Test Passage	101.07
<b>Total</b>		<b>771.03</b>
	<b>End-to-end (as the crow flies)</b>	<b>684.00</b>
	<b>Sinuosity (771.03/684)</b>	<b>1.13</b>
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	s l o p e (°) (tan <sup>-1</sup> (8.41/755.12)*	0.64°
Slope 2	slope (°) (tan <sup>-1</sup> (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

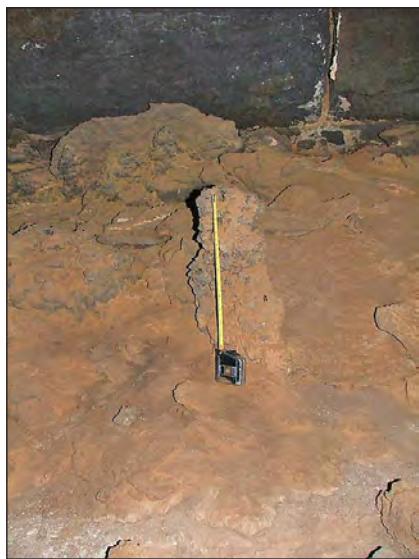
\* This is the slope of the path the primary flow followed over the terrain.



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 extends 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,

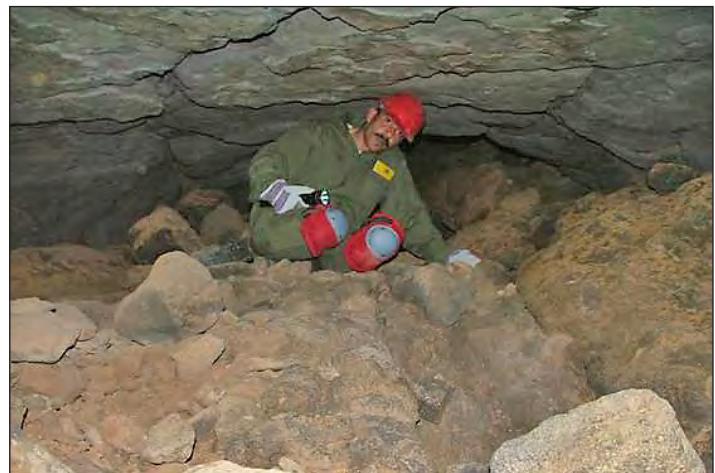


Figure 10. The second entrance passage resulted from the upward bending of the sheet in an axis more or less perpendicular to the flow.

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”

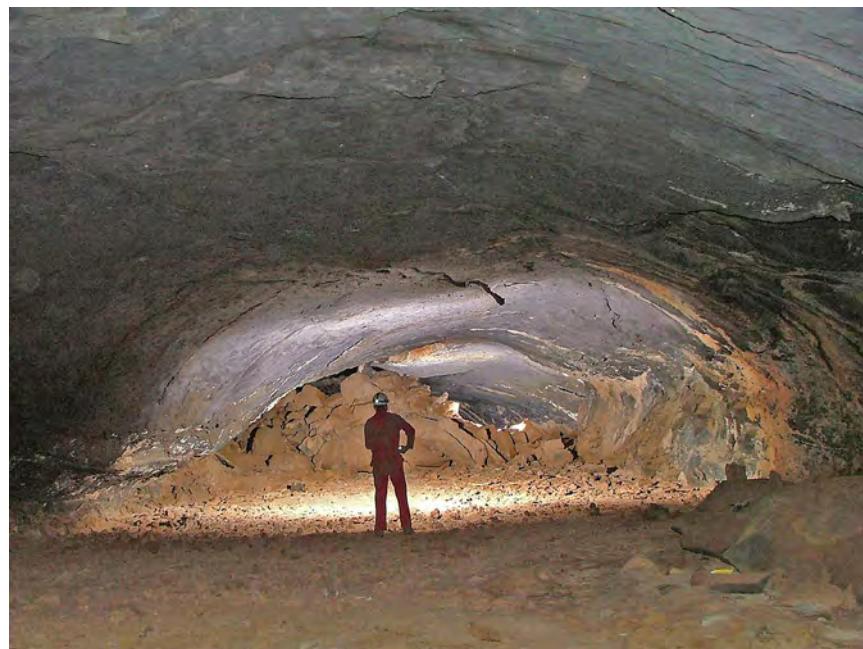


Figure 11. A small rubble stones cover the downhill section from wall to wall.



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.

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

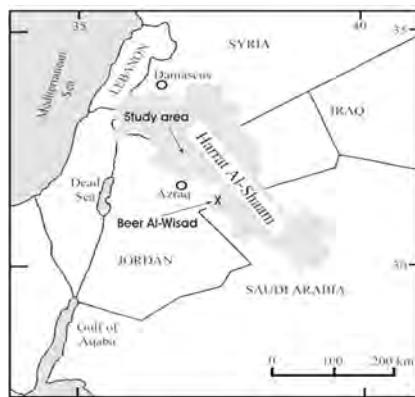


Figure 1. Study area and extent of Harrat Al-Shaam (altered after Al-Malabeh, 1994).

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 to 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	1 to 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					

## **Al-Badia Cave (Beer Al-Hamam)**

Location: 32°07.905'N/36°49.416'W (WGS 84)

surveyed 19.09.2003  
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drafting 1:500: S. Kempe  
Total length 440 m  
(358,5 m Station 6 - 22 + 80,5 m Station 6 - 32)  
type: lava tunnel

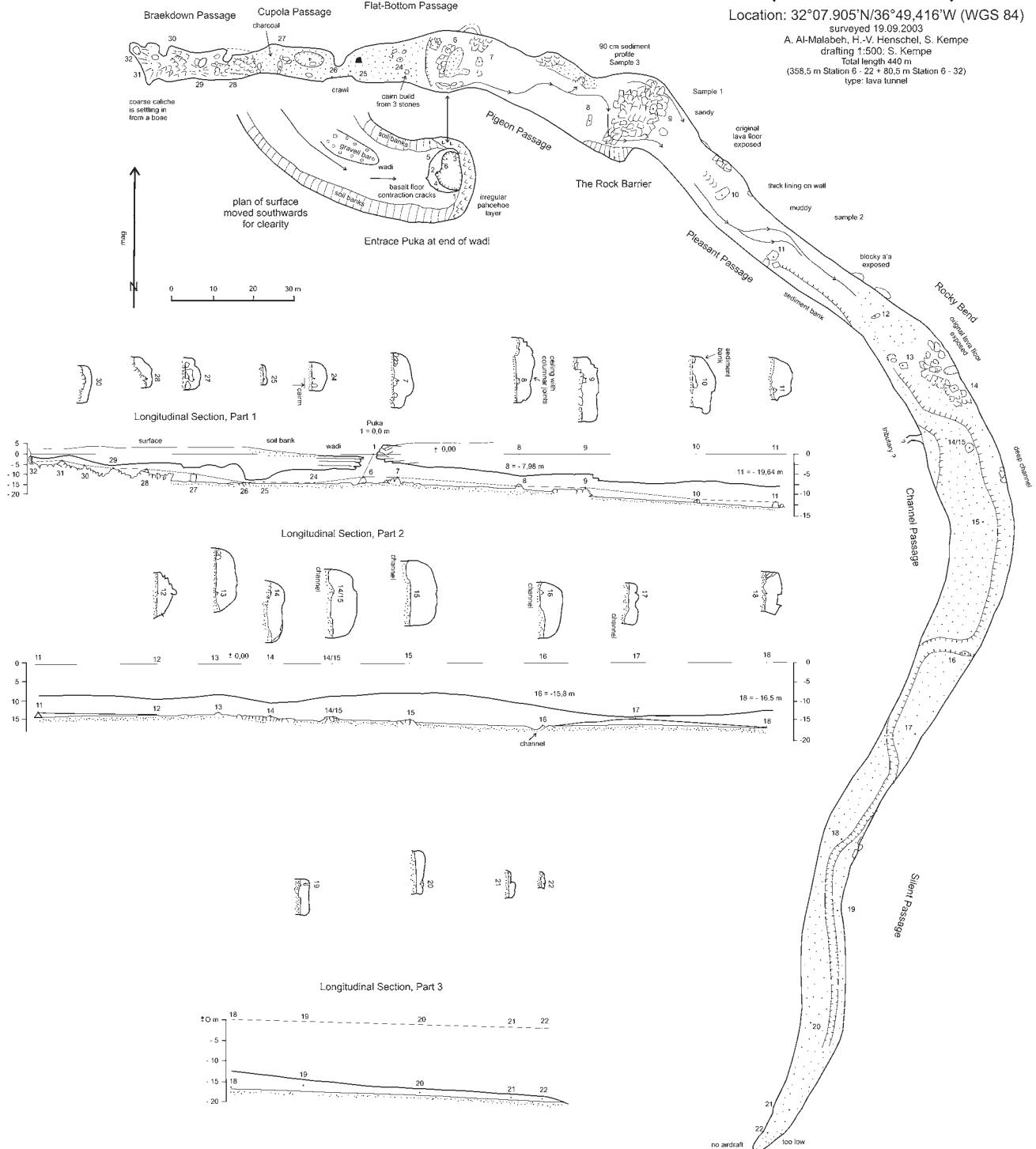
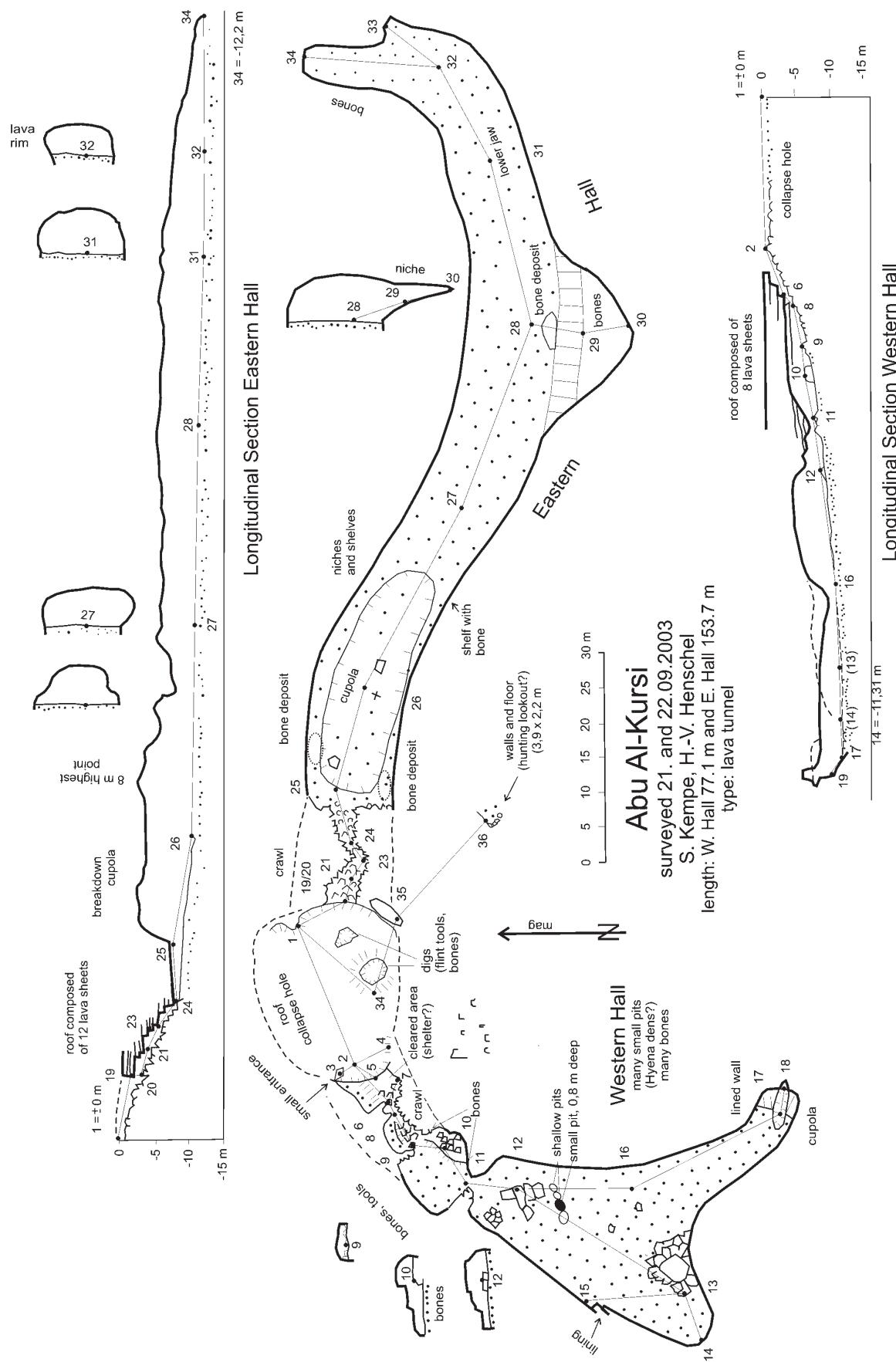


Figure 2. Map of Al-Badia Cave (by the authors). The cave is entered through a large breakdown hole, overhanging on all sides. This hole acts as a sink for a short wadi at times of heavy rains that has filled the cave with sediments.



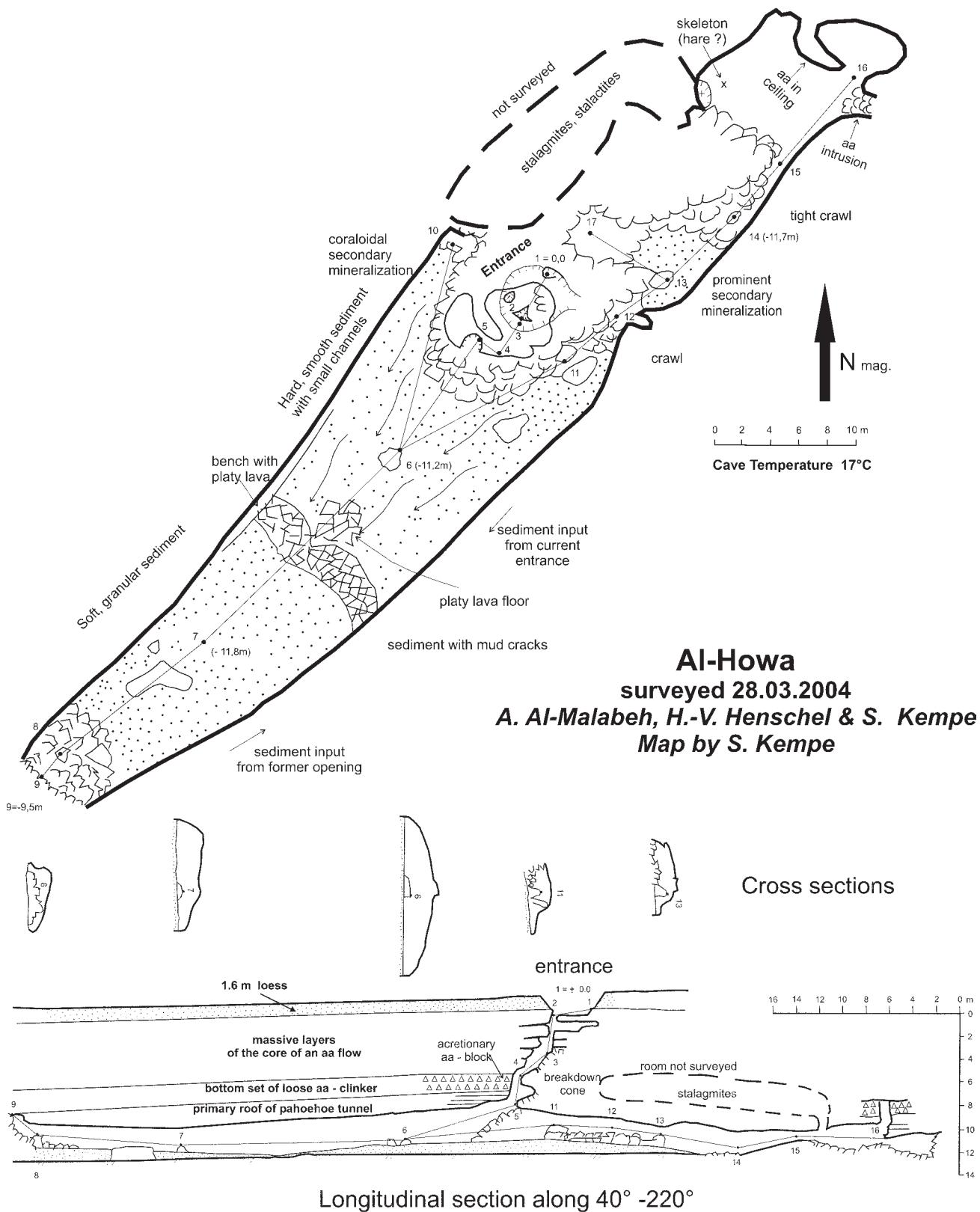




Figure 3. Entrance of Al-Badia Cave. It forms a sink in a small wadi. It is ca. 5 m deep and overhanging on all sides, exposing the uninterrupted lava sheets of the primary ceiling.



Figure 8. Panorama of Dabie Cave with prominent benches on both sides of the passage.

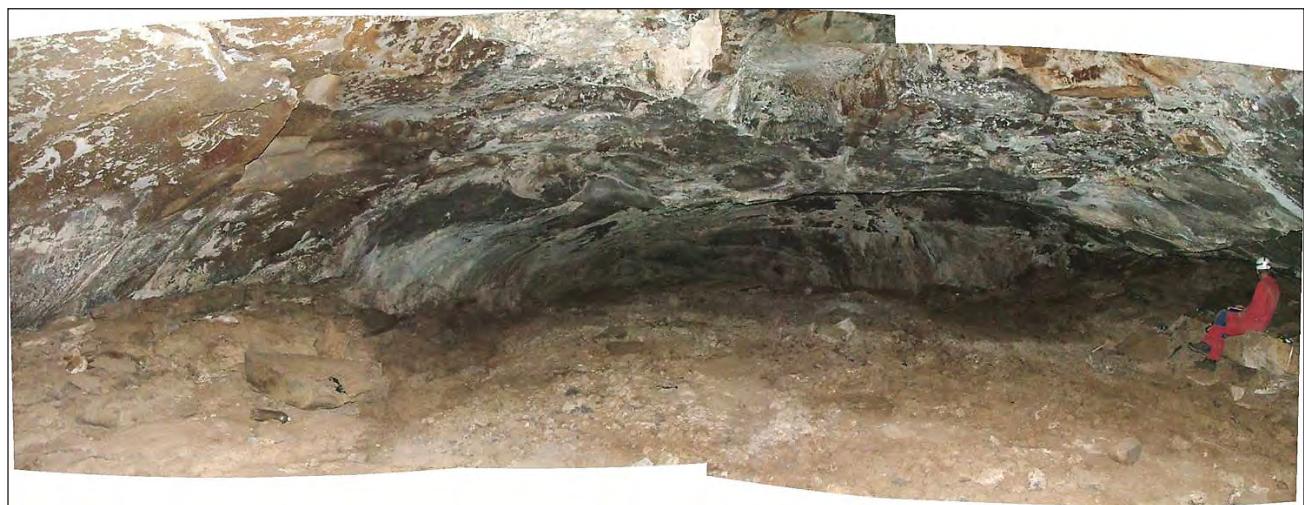


Figure 9. Panorama view of the terminal hall of Hashemite University Cave. The floor consists of thickropy pahoehoe.

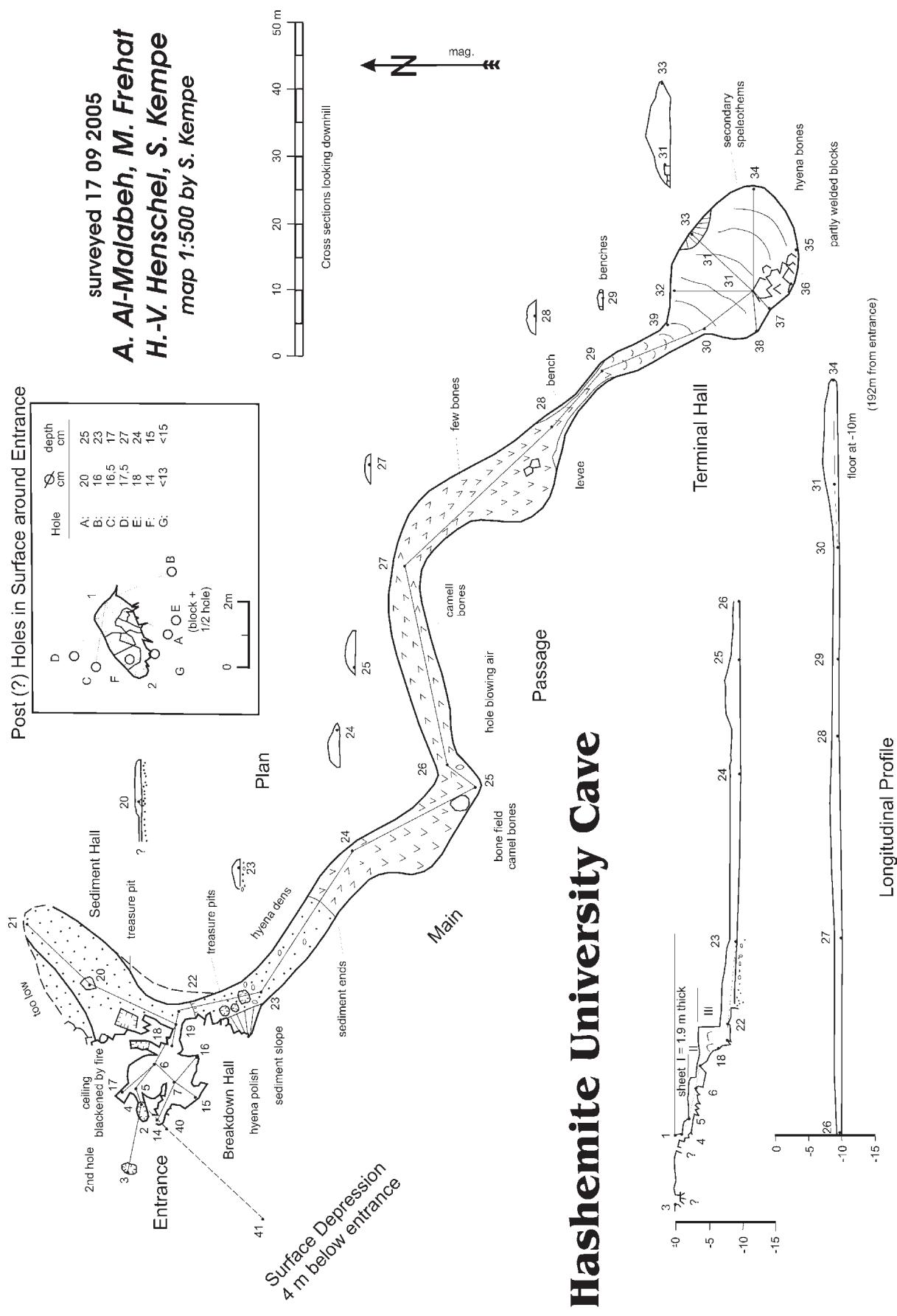


Figure 6. Map of Hashemite University Cave (by the authors). Entrance is through a breakdown hole.

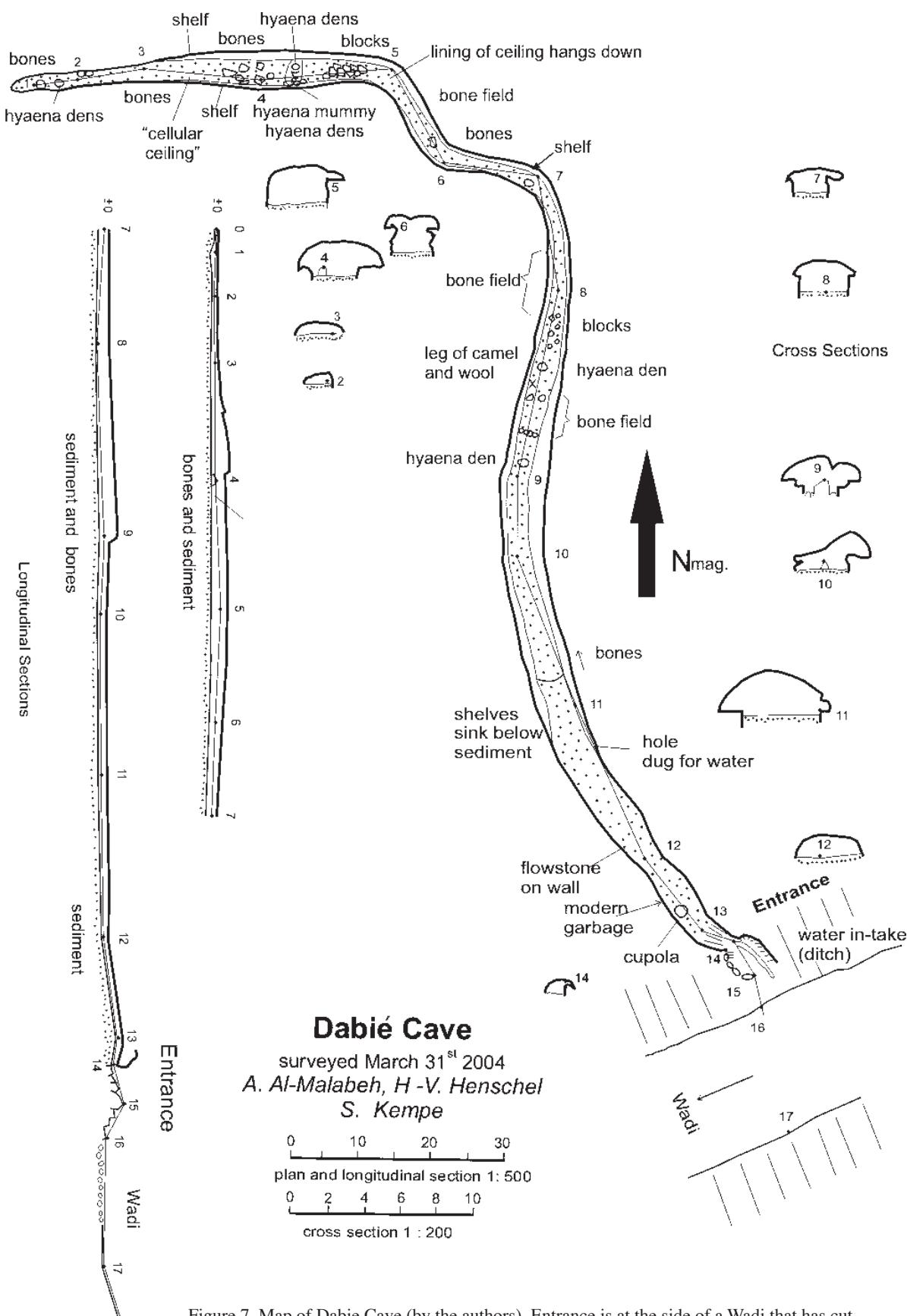


Figure 7. Map of Dabié Cave (by the authors). Entrance is at the side of a Wadi that has cut through the lava flow. A small channel used to divert water into the cave.

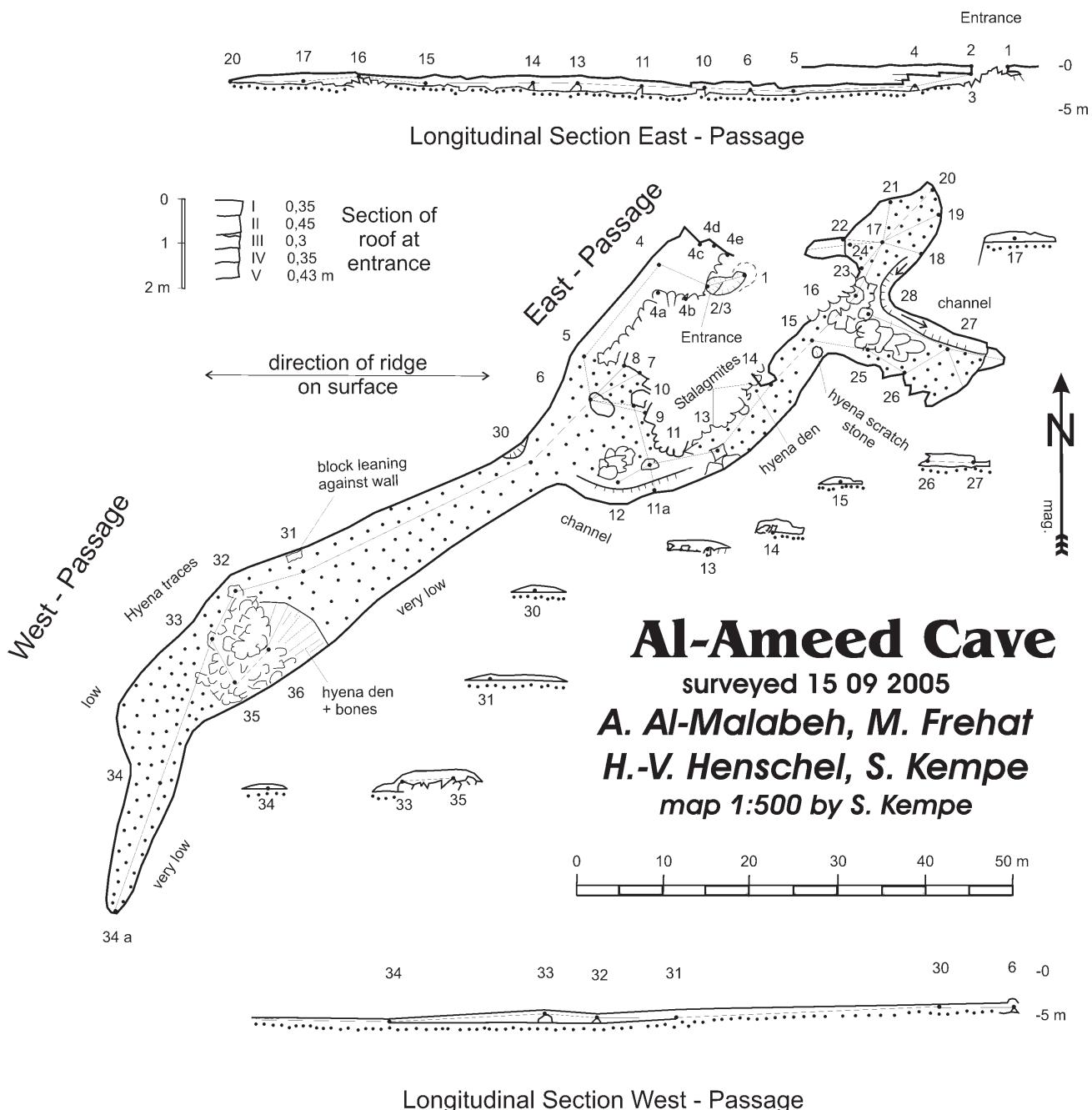


Figure 10. Map of Al-Ameed Cave (by the authors). Entrance is through centrally collapsed low and wide hall below up-domed lava sheets.

# Al-Hayya Cave

surveyed 18. 09. 2005

**A. Al-Malabeh, M. Frehat  
H.-V. Henschel, S. Kempe**  
map 1:500 by S. Kempe

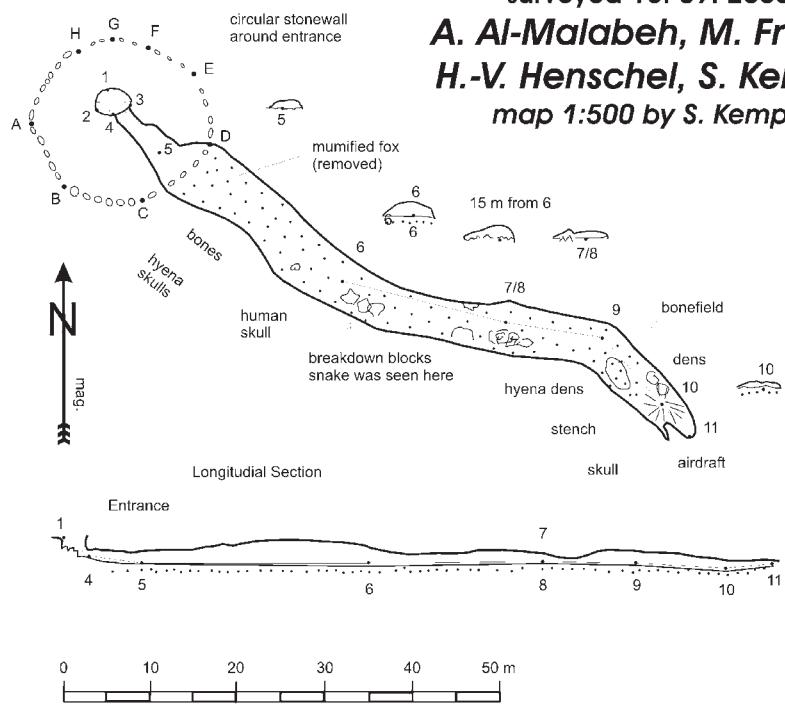


Figure 14. Pit of Beer Al-Wisad.

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.

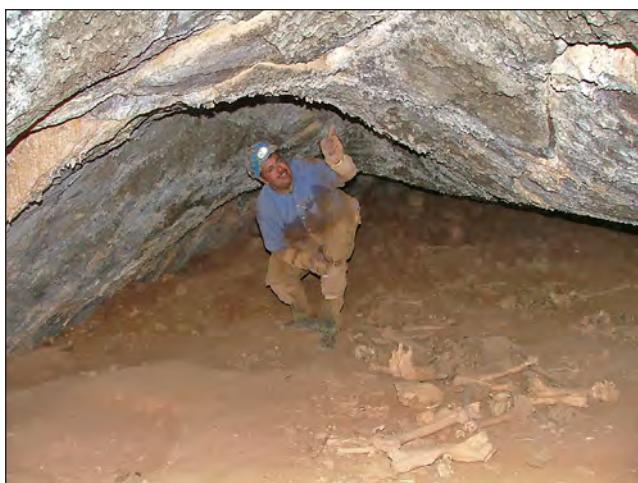


Fig 12. Passage view of Al-Hayya Cave. Bones (mostly from camel) in foreground are “left-overs” of hyenas.



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 three 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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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 9<sup>th</sup>, 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. . . .*”

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 it 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 3. Entrance of tourist section over a bridge that leads across part of an elongated collapse structure, called Kaluaiki.

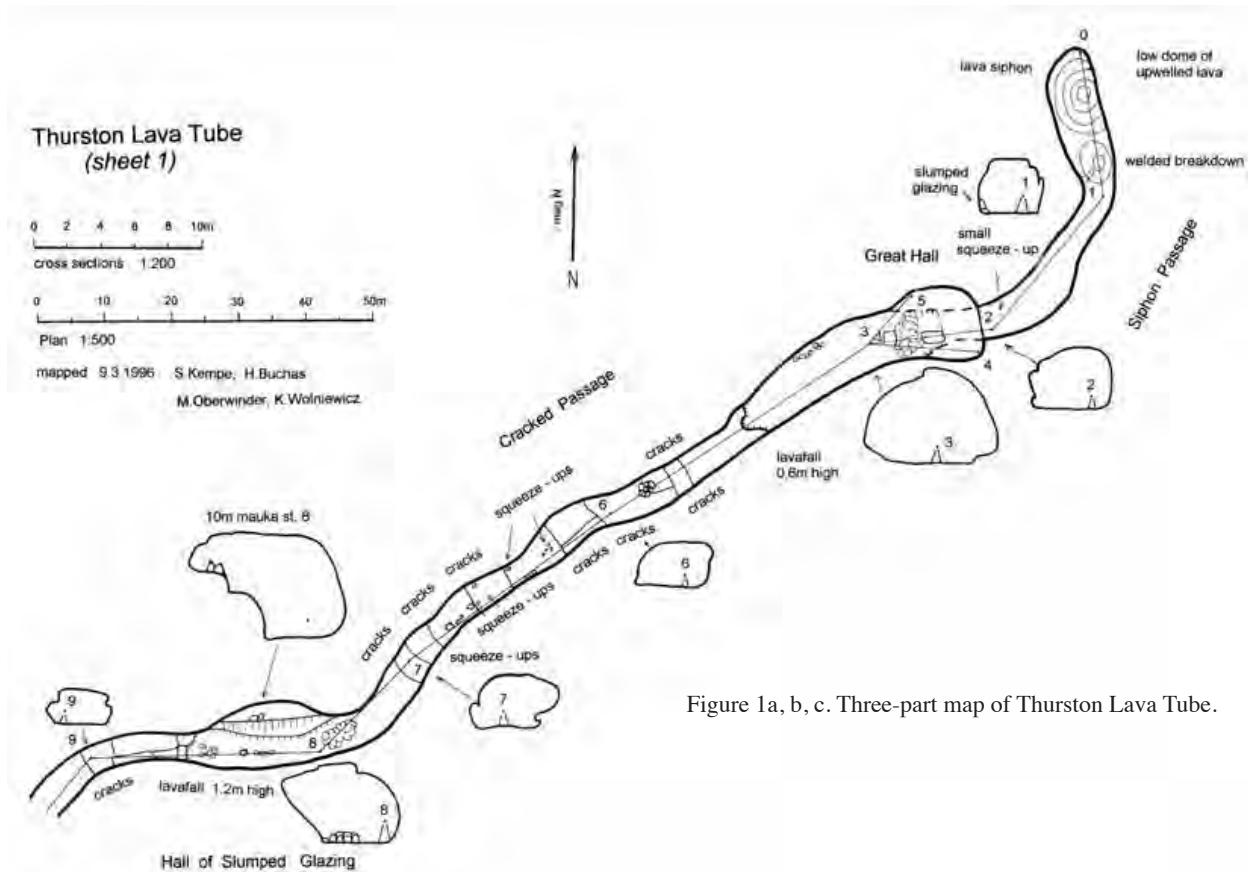
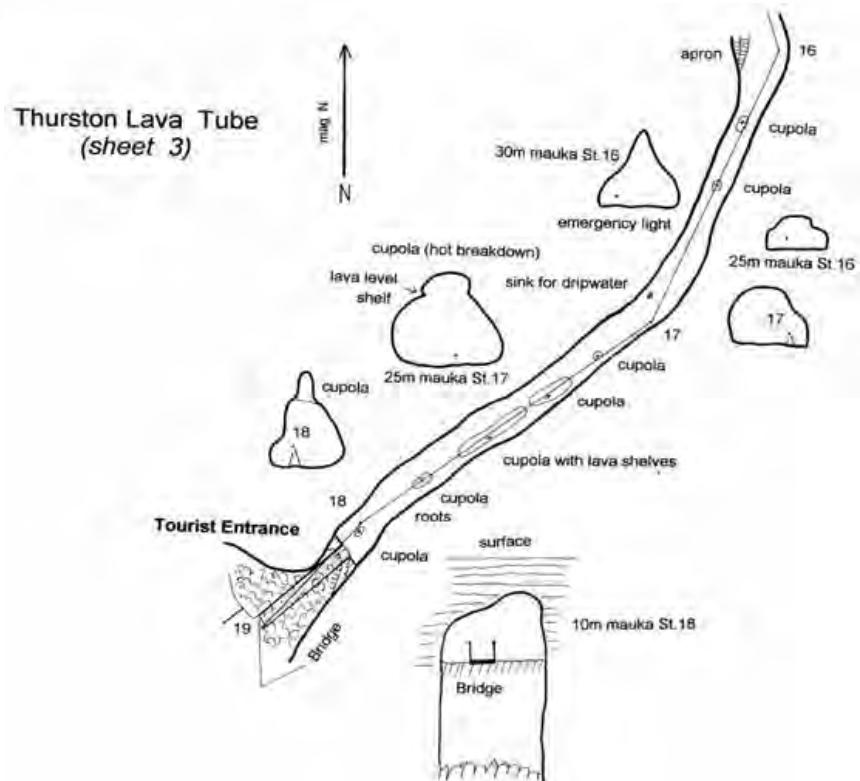


Figure 1a, b, c. Three-part map of Thurston Lava Tube.



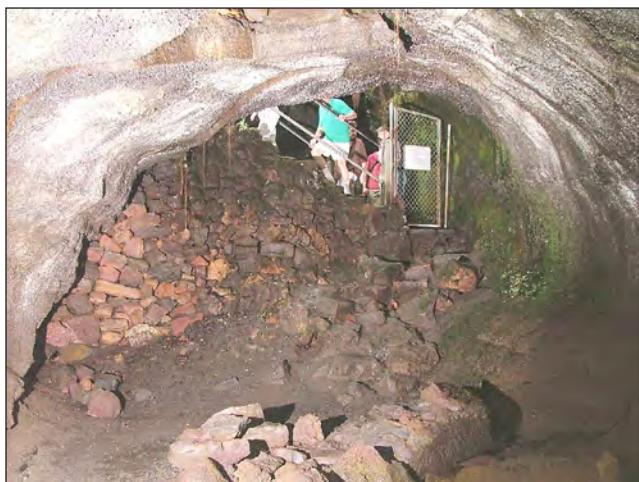
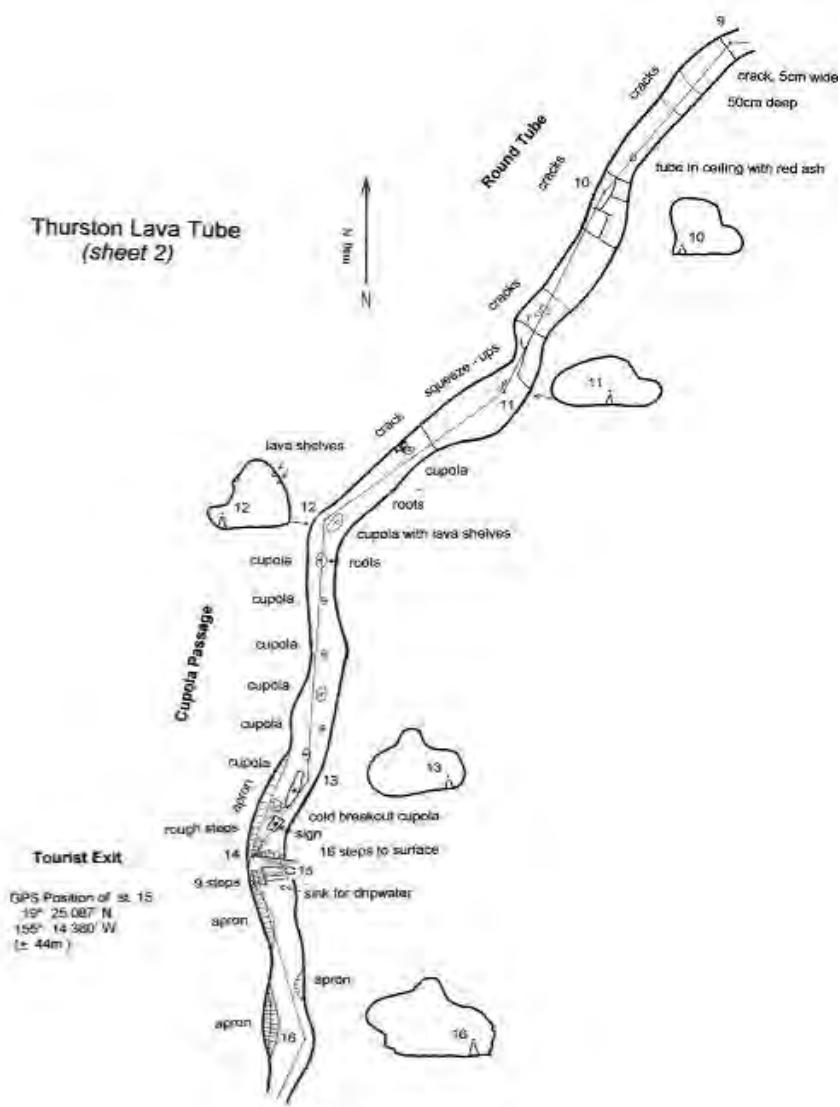


Figure 4. Exit with artificial staircase, looking mauka.

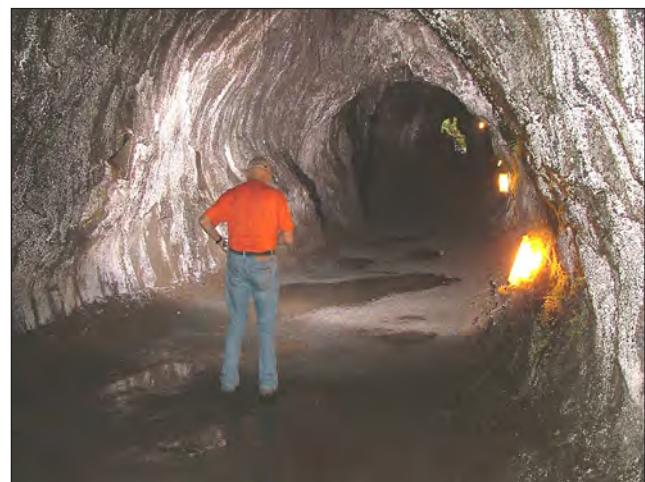


Figure 5. Tourist section looking makai.

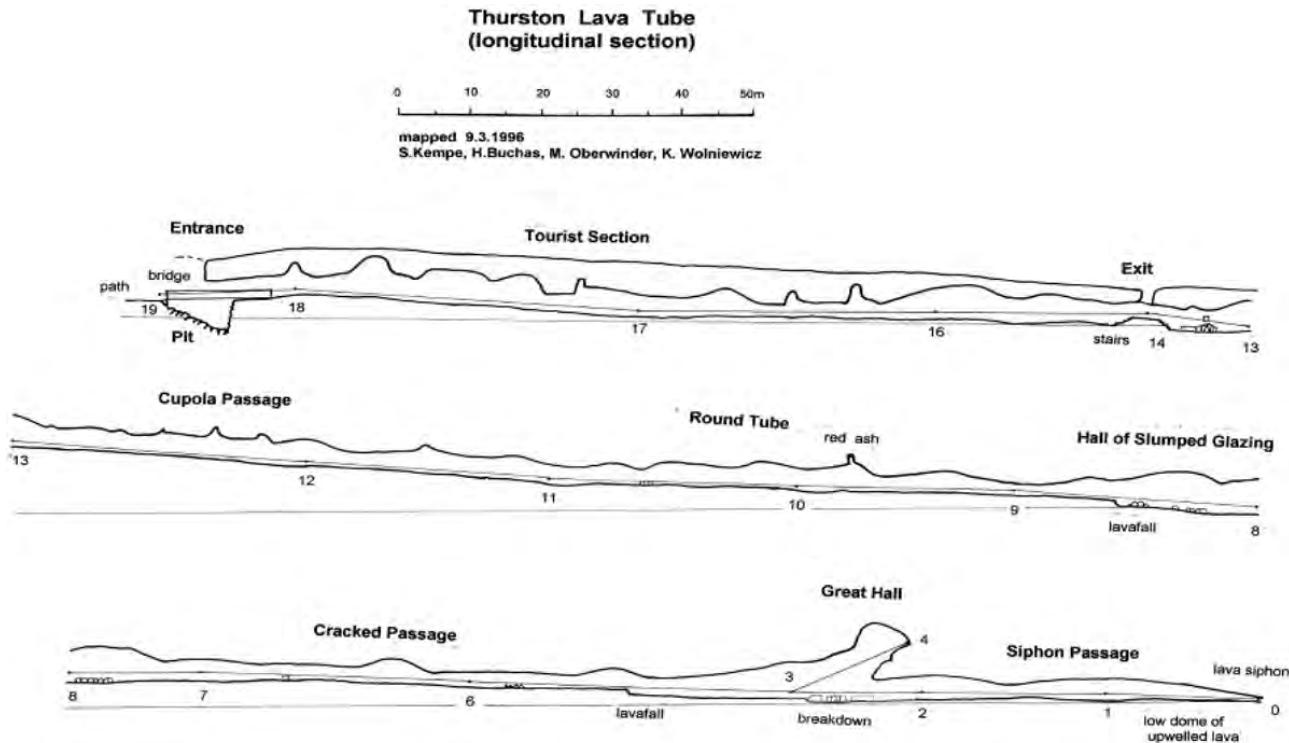
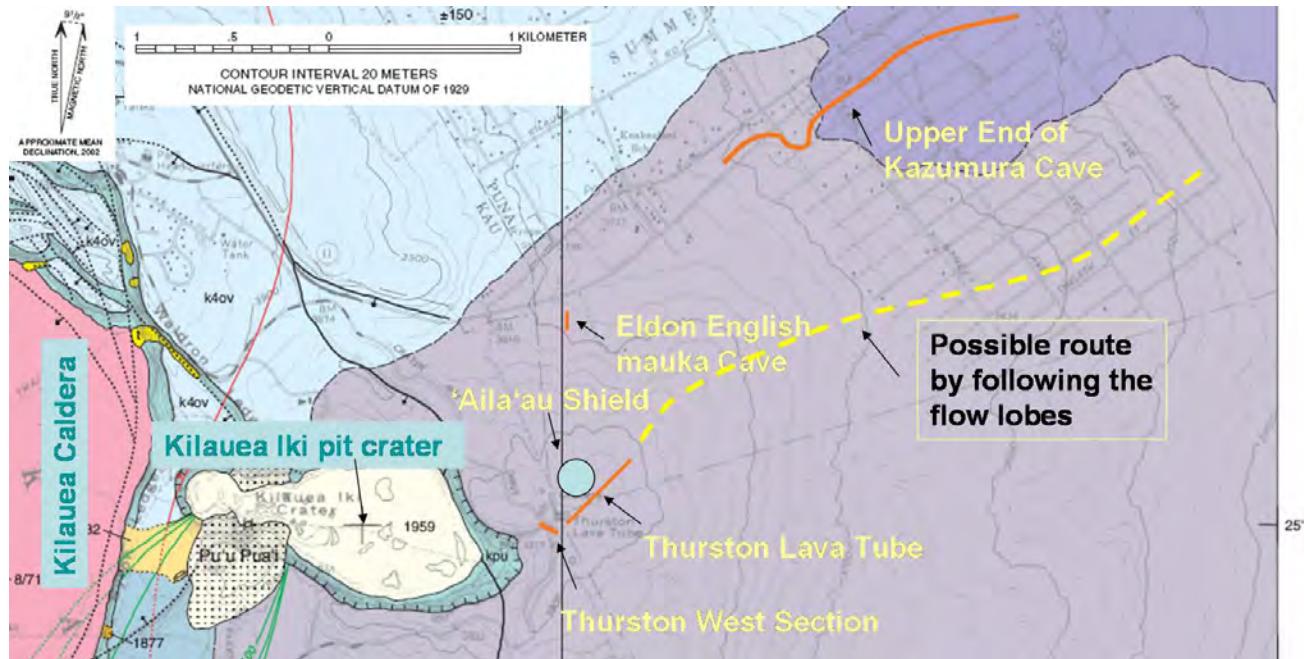


Figure 2. Longitudinal section of Thurston Lava Tube.



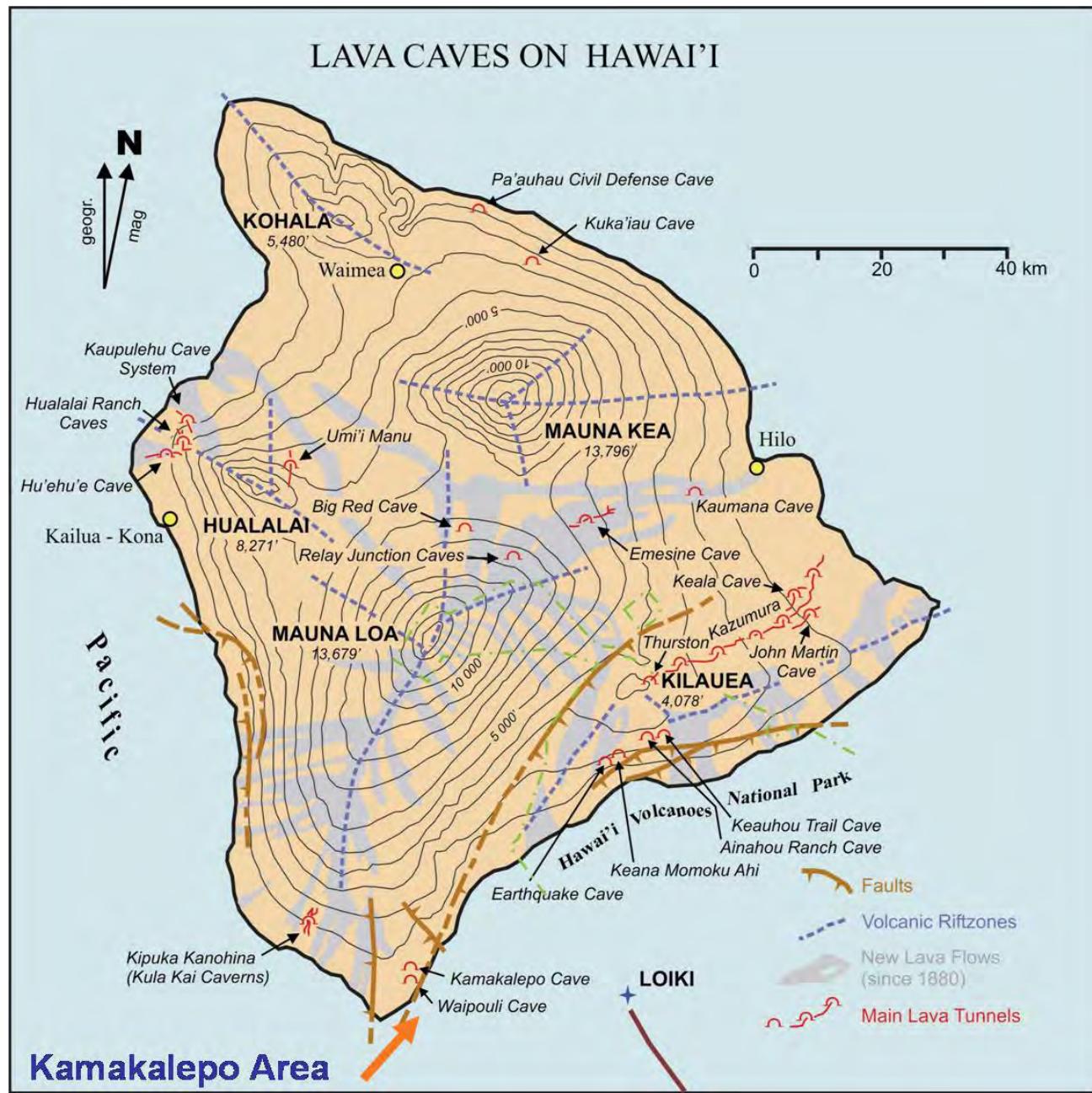


Figure 7. Map showing locations of some of the major lava caves on Hawaii.



Figure 8. Typical cross-section of Thurston Lava Tube.



Figure 9. Thurston Lava Tube ends in a Chamber, where 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 were 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 orropy 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 mauka 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-la'au flows.

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

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Figure 17. The surface of Thurston Lava Tube is quite irregular; the smooth glazing otherwise typical for Hawaiian lava tubes is largely missing.



Figure 18. This is an exceptionally “well decorated” section of Thurston Lava Tube which is otherwise devoid of spectacular stalactites.

<http://pubs.usgs.gov/imap/i2759/>  
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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<sub>2</sub>, 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 <sup>14</sup>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).

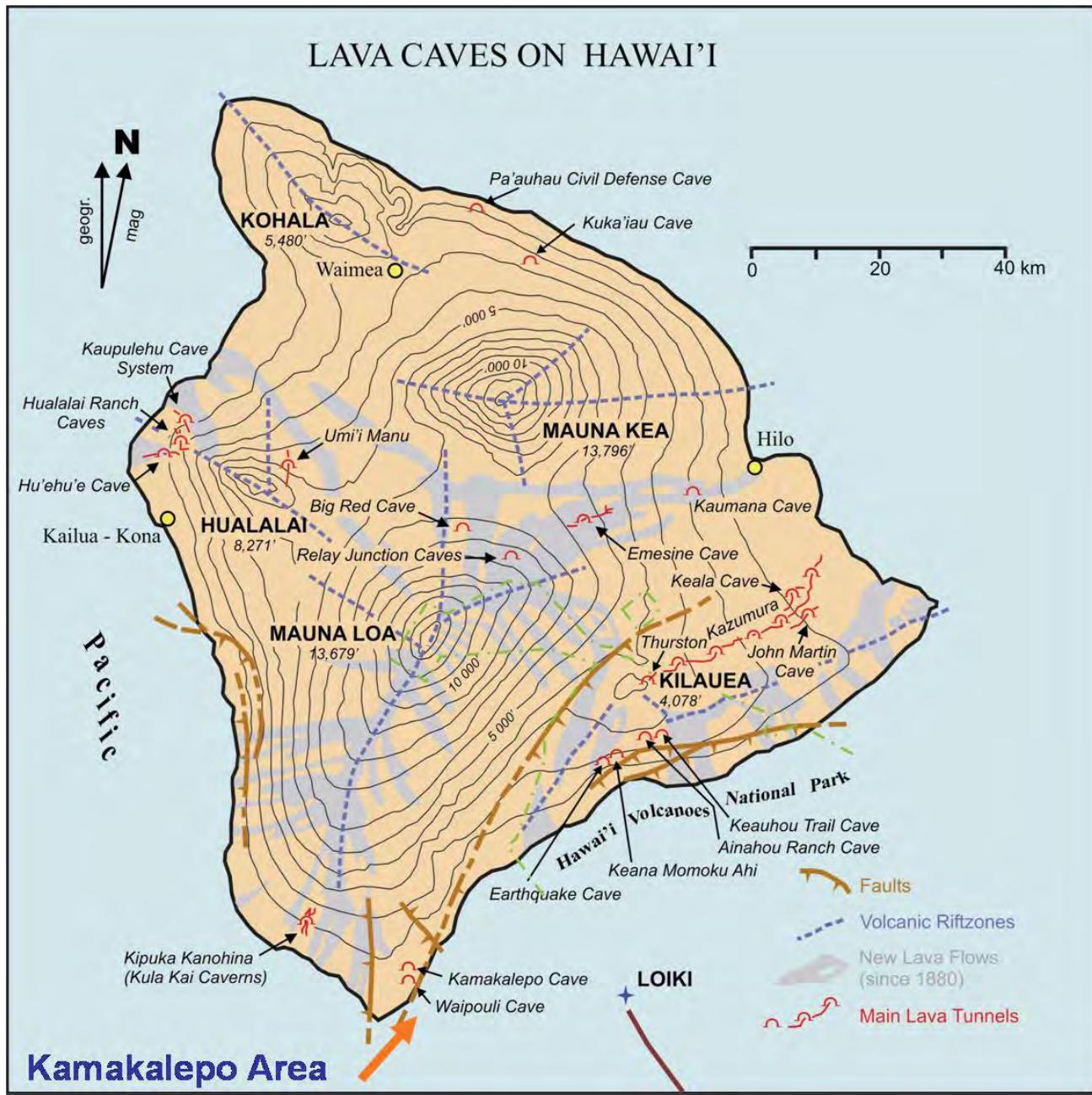


Figure 1. Map of Hawai'i with major cave systems.

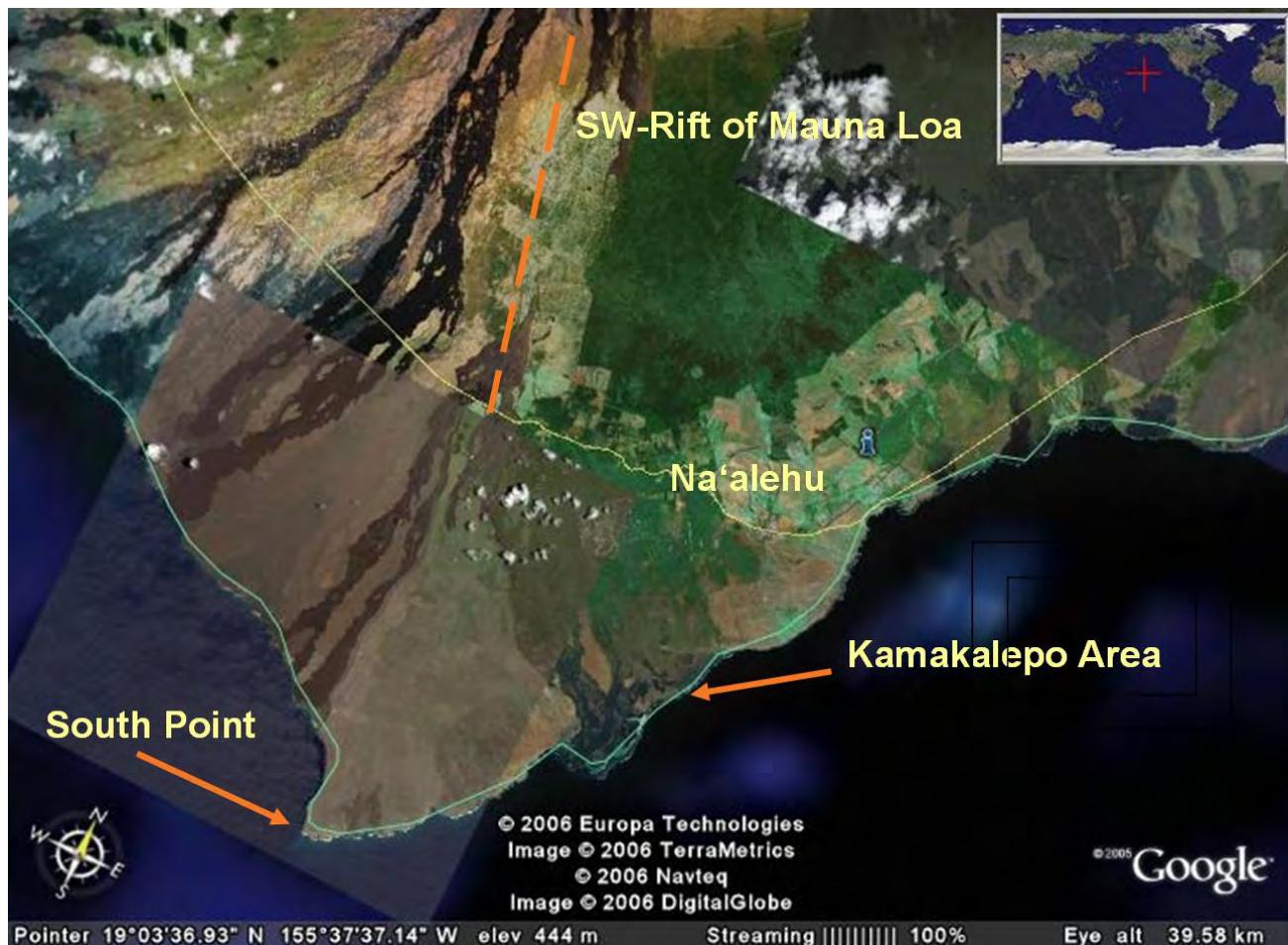


Figure 2. Google Earth picture of the southern tip of the Island of Hawai'i.

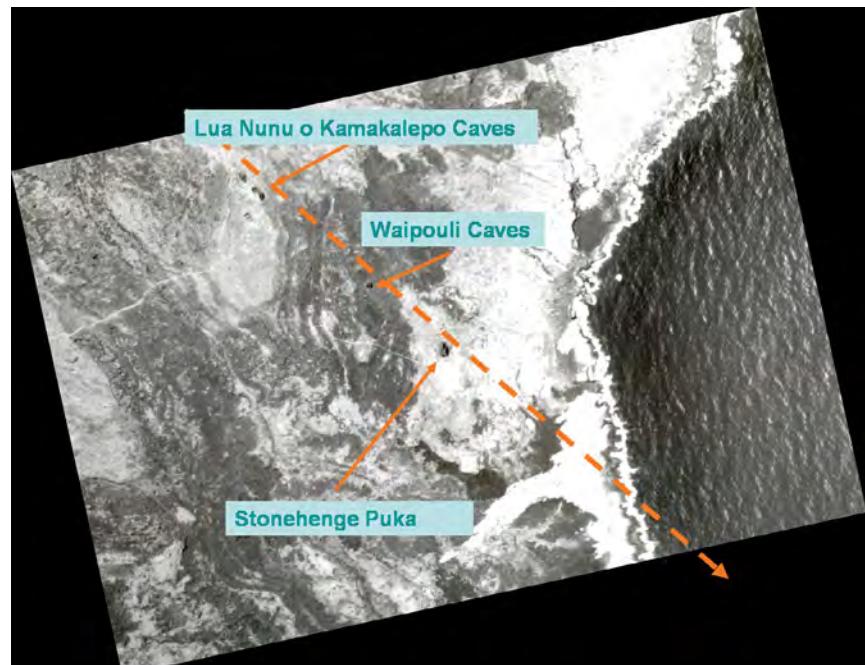


Figure 3. Aerial picture of Kamakalepo area. The light area is marks the grass-covered "Pahala Ash" outcrop.

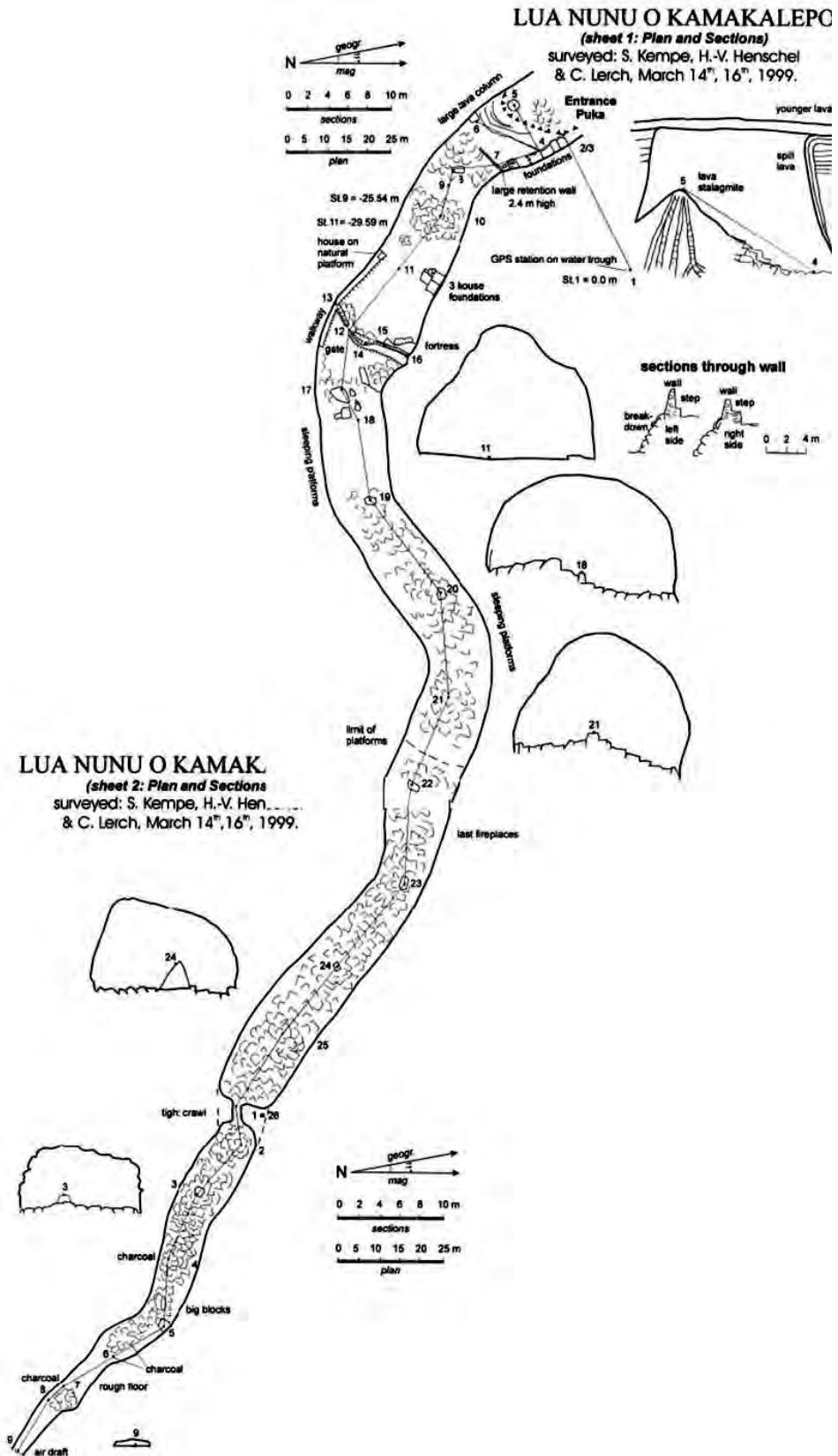


Figure 5 a. Map of Lua Nunu o Kamakalepo Mauka Cave.

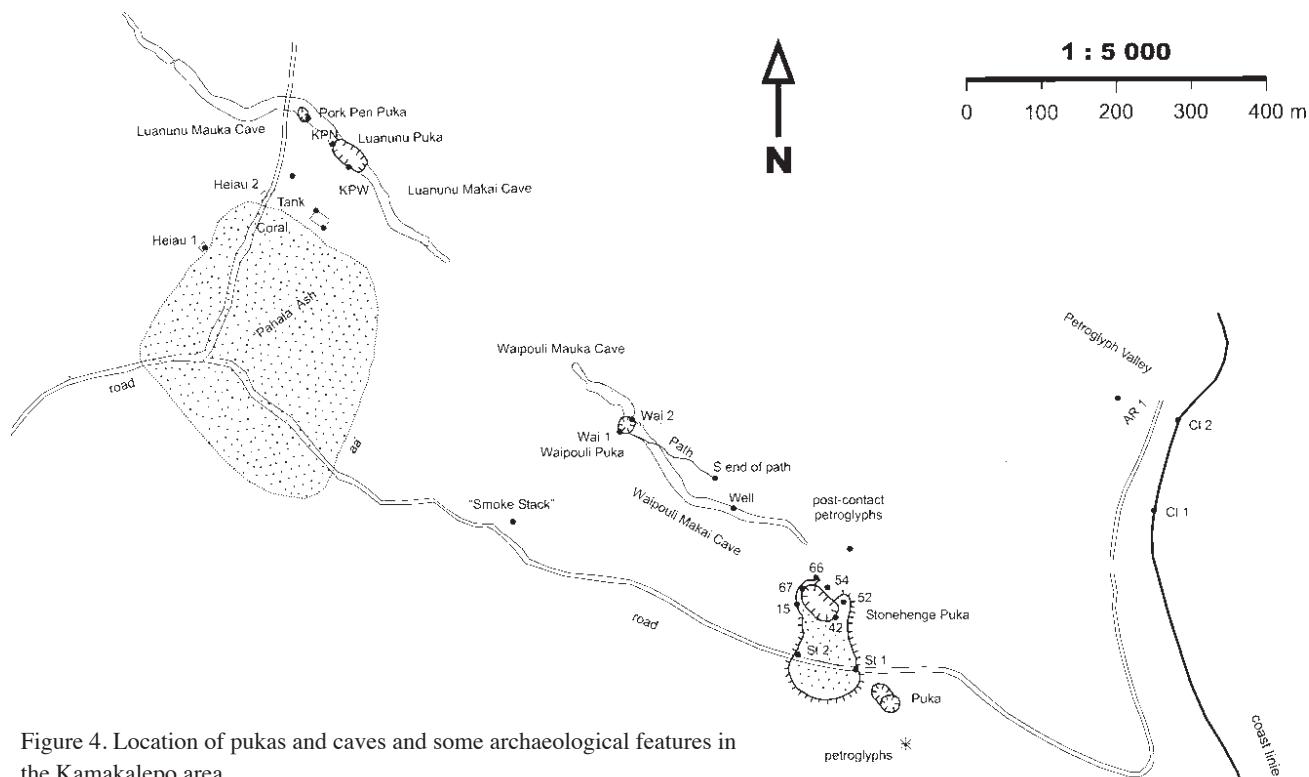


Figure 4. Location of pukas and caves and some archaeological features in the Kamakalepo area.

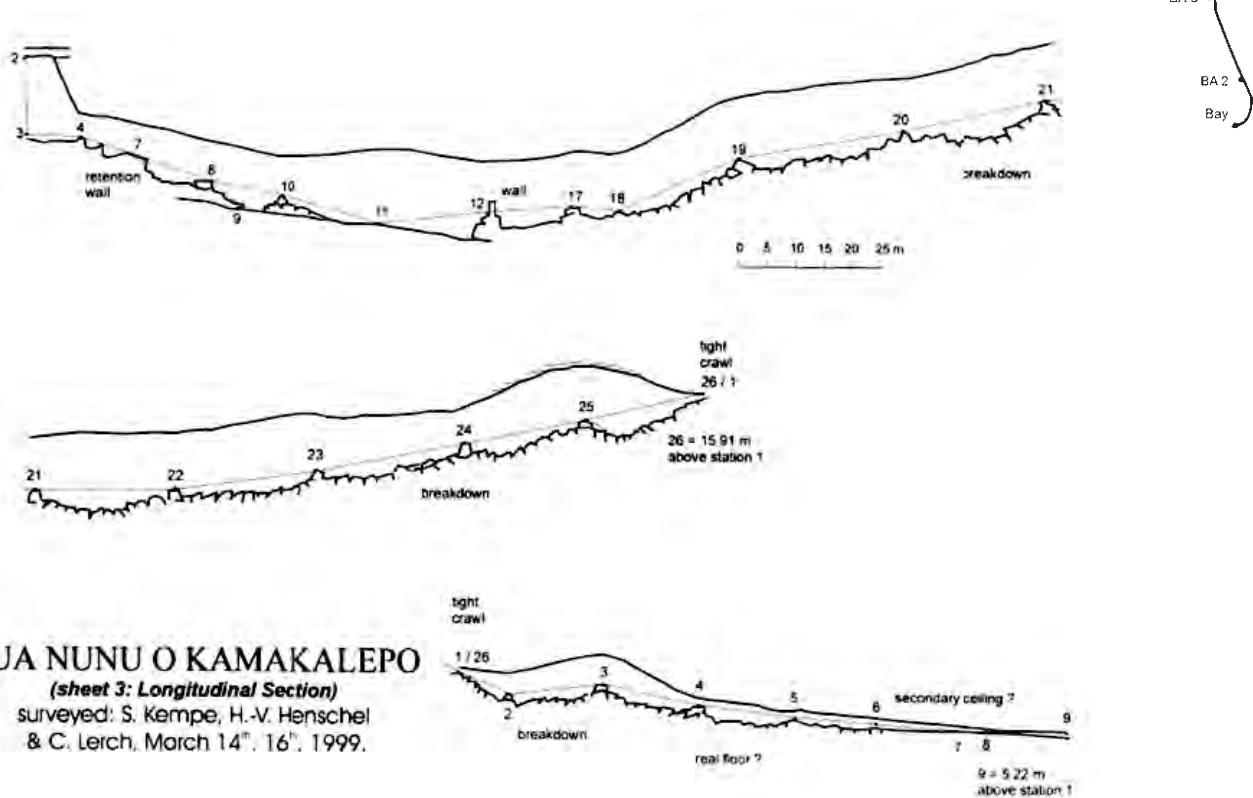


Figure 5 b. Longitudinal section of Luu Nunu o Kamakalepo Mauka Cave.

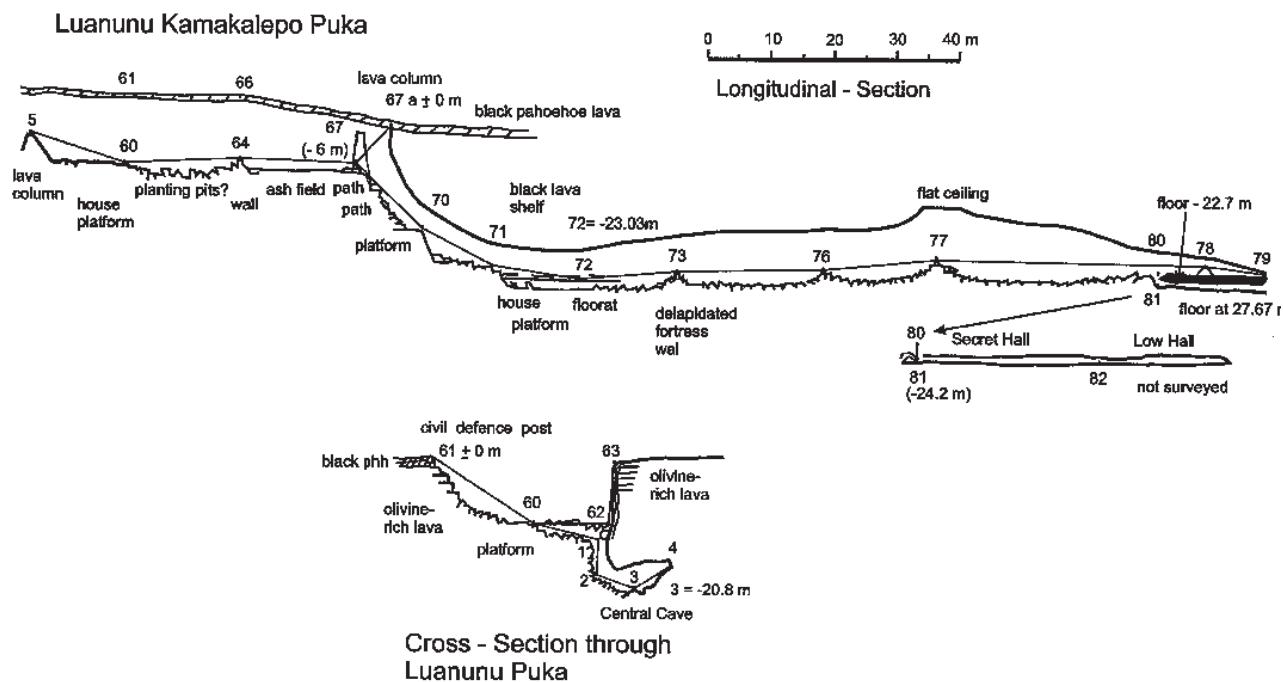
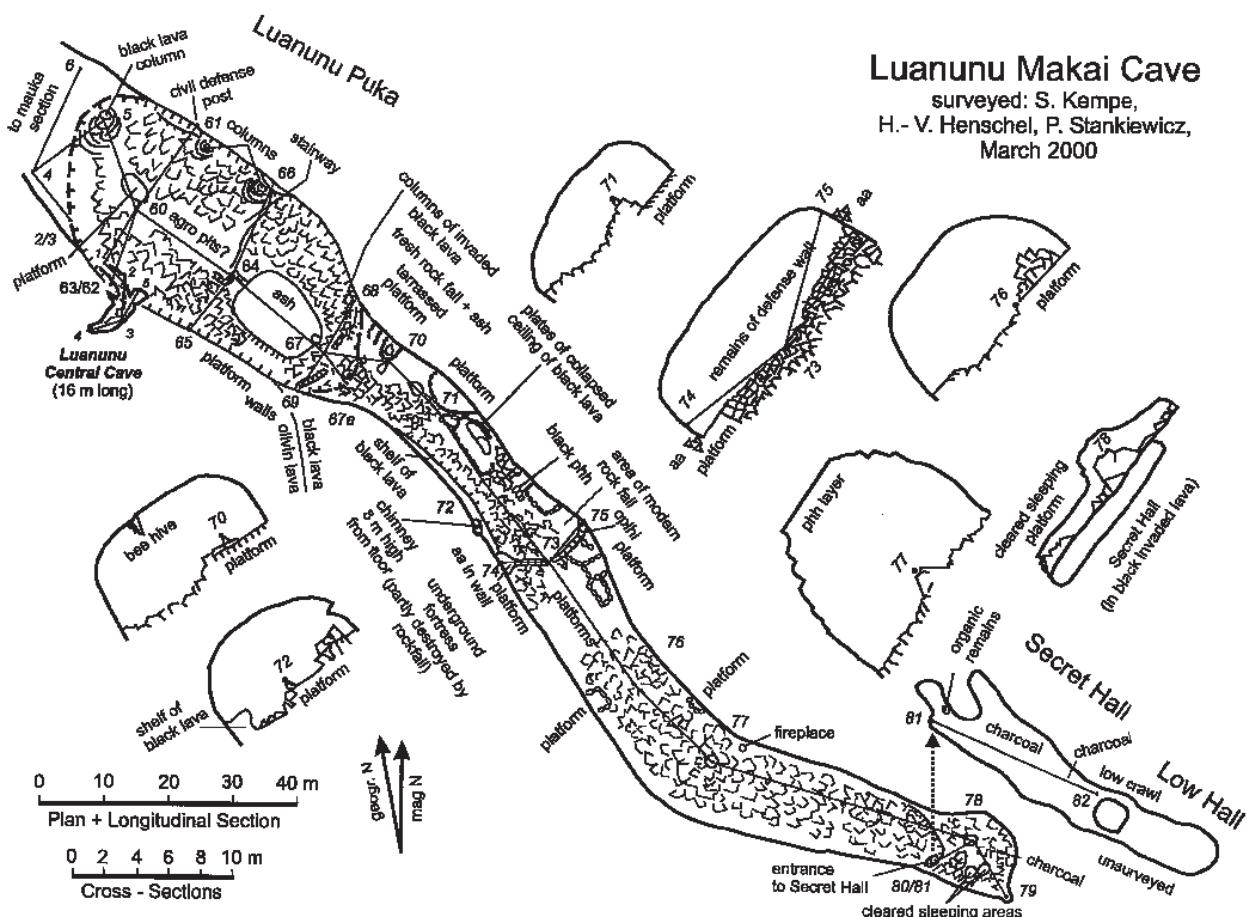


Figure 6. Map and longitudinal section of Lua Nunu o Kamakalepo Makai Cave.

**WAIPOLI MAUKA CAVE**  
**(DARK WATER CAVE)**  
**(sheet 3)**

mapped: 2.7.1998

*W.R.Halliday, R.Hinsch, S.Kempe  
 P.Lockwood, T.Scheffler*

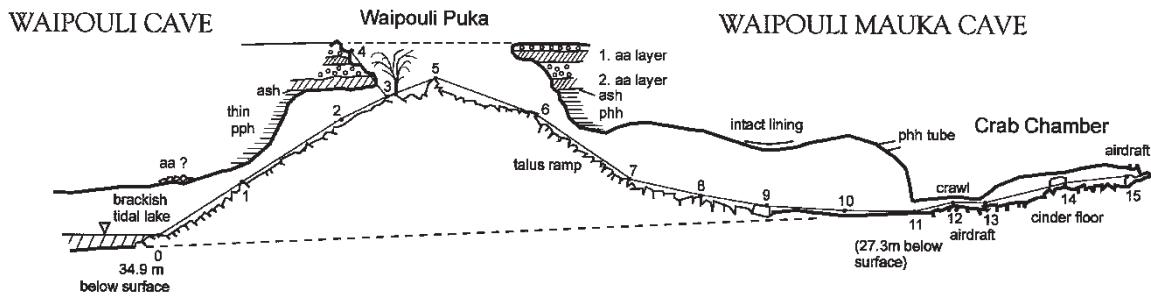
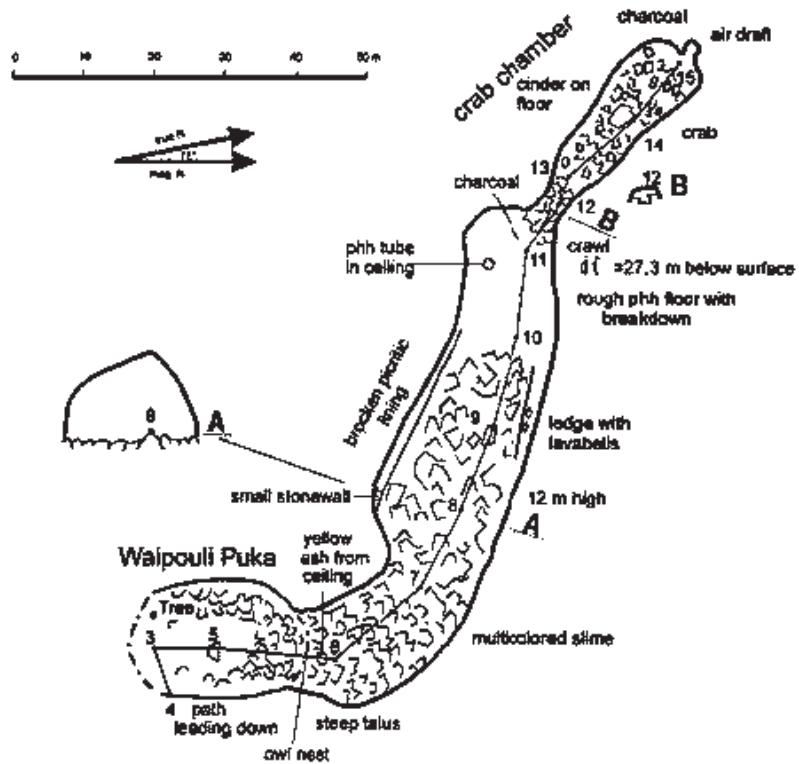


Figure 7. Map and longitudinal section of Waipoli Mauka Cave.

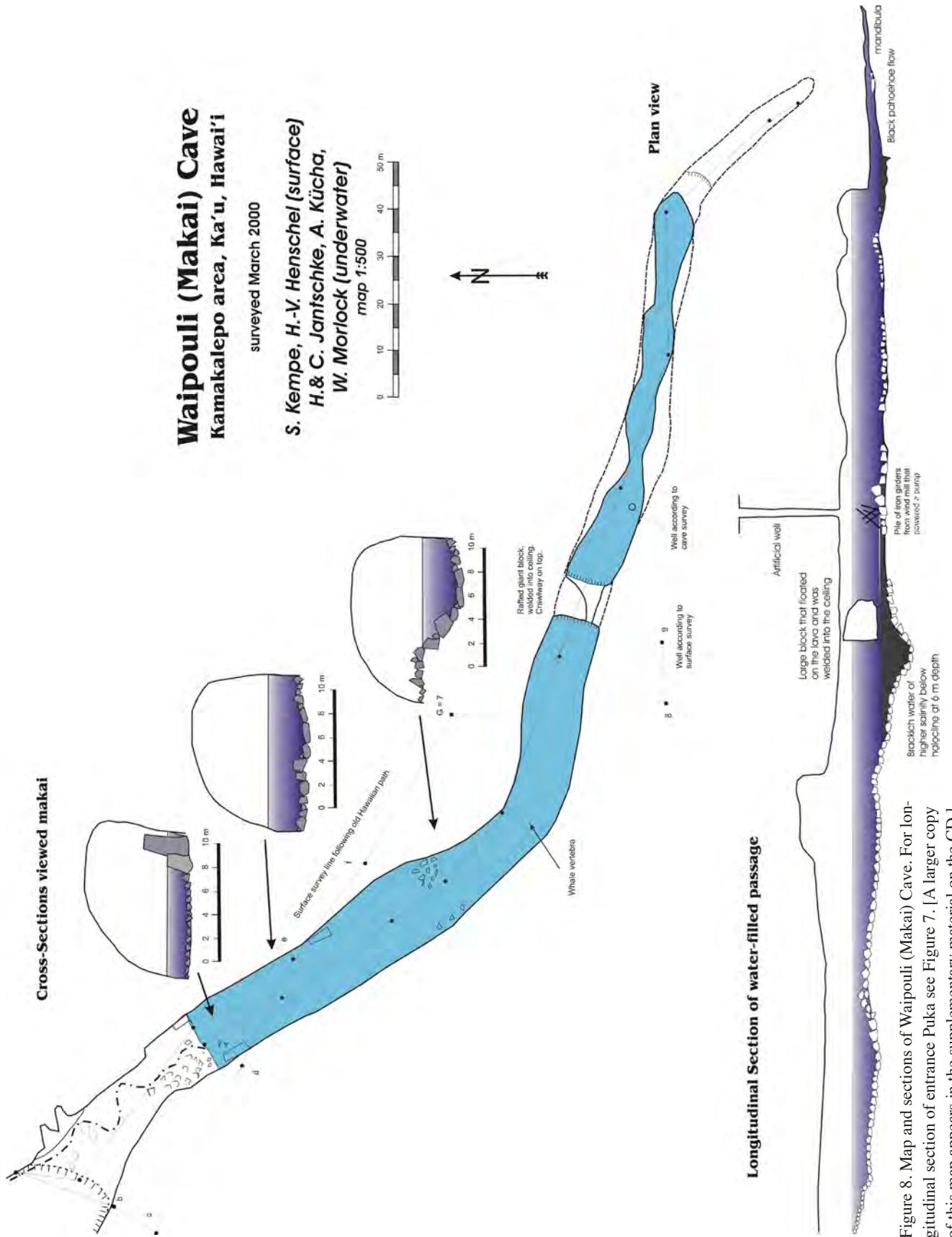


Figure 8. Map and sections of Waipouli (Makai) Cave. For longitudinal section of entrance Puka see Figure 7. [A larger copy of this map appears in the supplementary material on the CD.]

# Stonehenge Puka

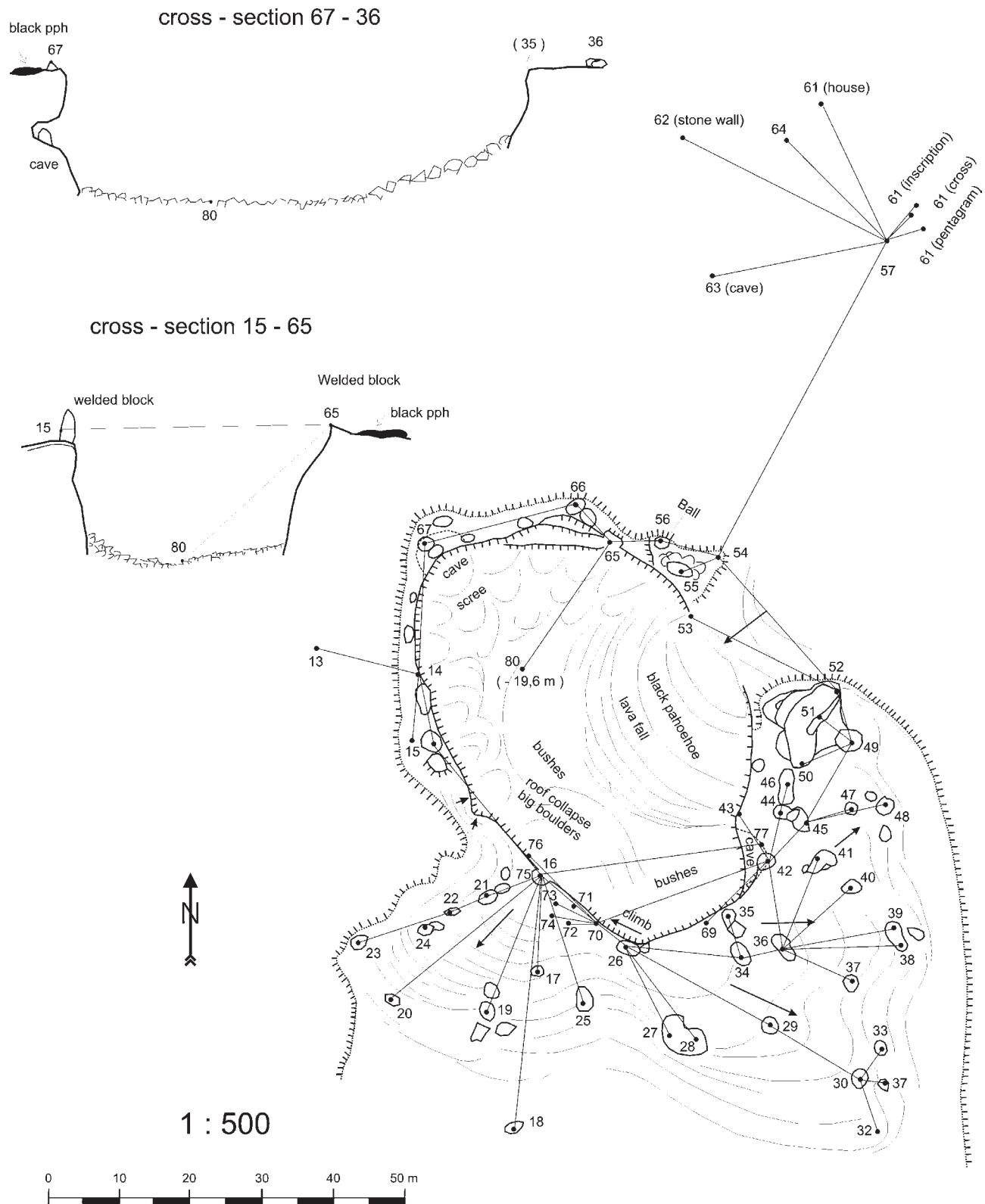


Figure 9. Map and cross-section of Stonehenge Puka.

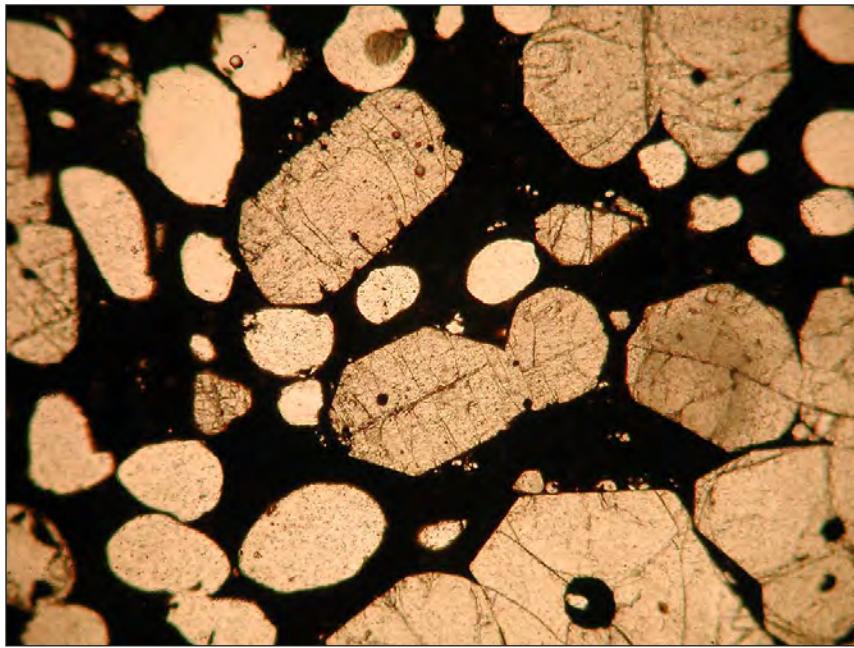


Figure 11. Petrographic thin section of the Kamakalepo-Waipouli-Stonehenge olivine vesicular picrite (plain light). The groundmass consists of opaque oxides; plagioclase is absent both as phenocrysts or in the groundmass; olivine is euhedral, forming a glomeroporphyritic texture with two generations 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 breach 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 it 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.

The evolving lava conduit therefore enlarged downward, until it was large enough to accommodate the flow,

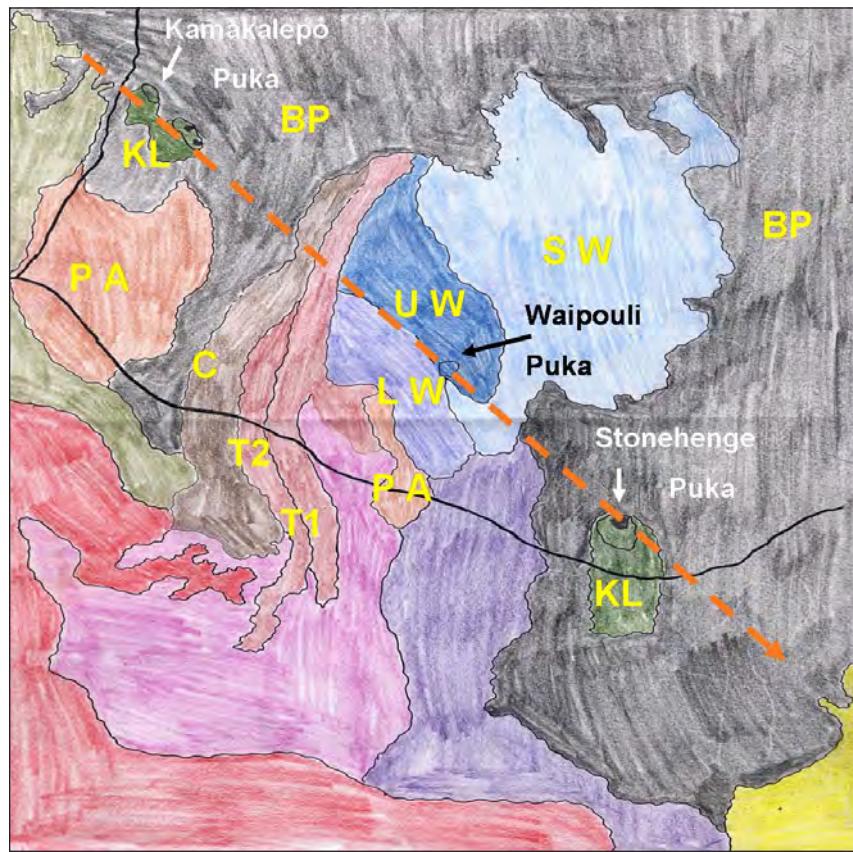
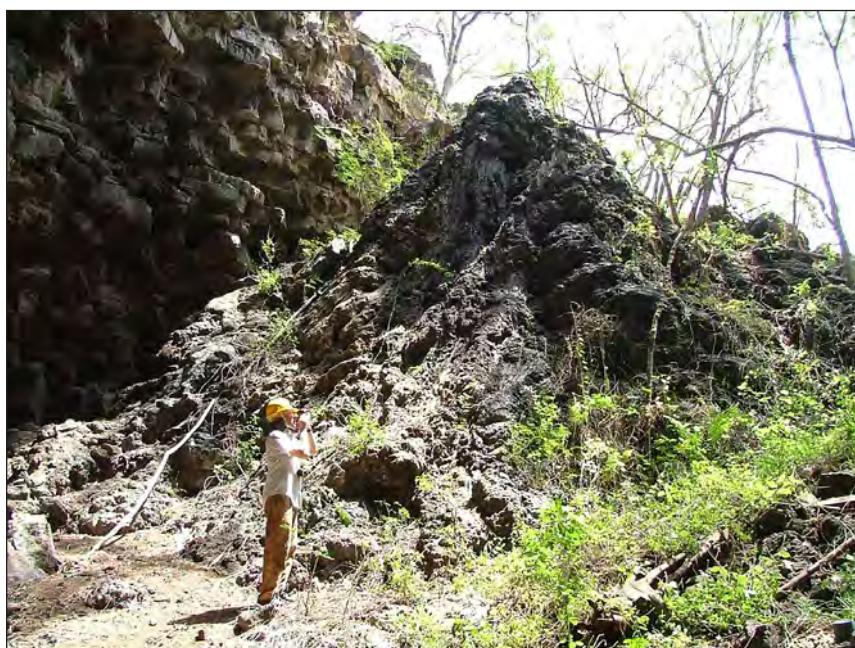


Figure 13. Geological map of the Kamakalepo area (by P. Stankiewicz, 2000, unpubl., University of Darmstadt). Stratigraphy (from top to bottom). Black Pahoehoe Flow (BP); Clover A'a Flow (C); Table-top A'a I and II flows (T1, T2); Upper Waipouli A'a Flow (UW); Lower Waipouli A'a Flow (LW); S Waipouli A'a Flow (SW); "Pahala" Ash (PA); Kamakalepo Lava ( $7360 \pm 60$  a BP) (KL). Further flows, younger than the Kamakalepo Lava but older than the Black Pahoehoe 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.]



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.

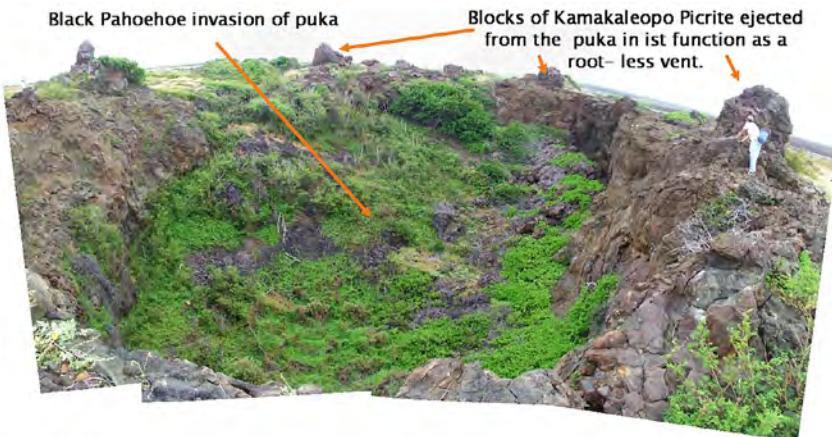


Figure 15. Panorama view (south) of the 60 m long and up to 20 m deep Stonehenge puka. Its rim is marked by large agglomerated lava boulders ejected from the puka when it served as a root-less vent when the Kamakalepo lava tunnel overflowed. From the SE the puka was later intruded by the black pahoehoe 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

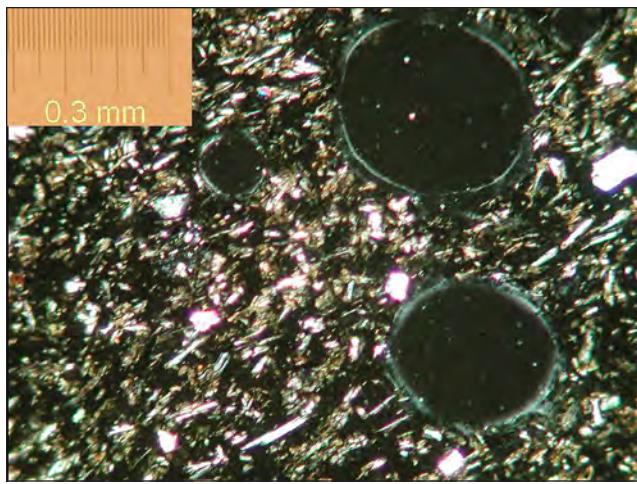


Figure 17. Petrographic thin section (polarized light) of Waipouli terminal black lava intrusion of olivine-plagioclase vesicular glassy basalt. Composition is about 40% glass, 40% vesicles, 15 % microlitic plagioclase and 5 % phenocrysts of euhedral olivine and plagioclase (no pyroxene phenocrysts). 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.

# Stratigraphic Profile at Luanunu Puka

taken at NE side, beginning at Civil Defense Post

S. Kempe & H. Schick, March 18th, 2005

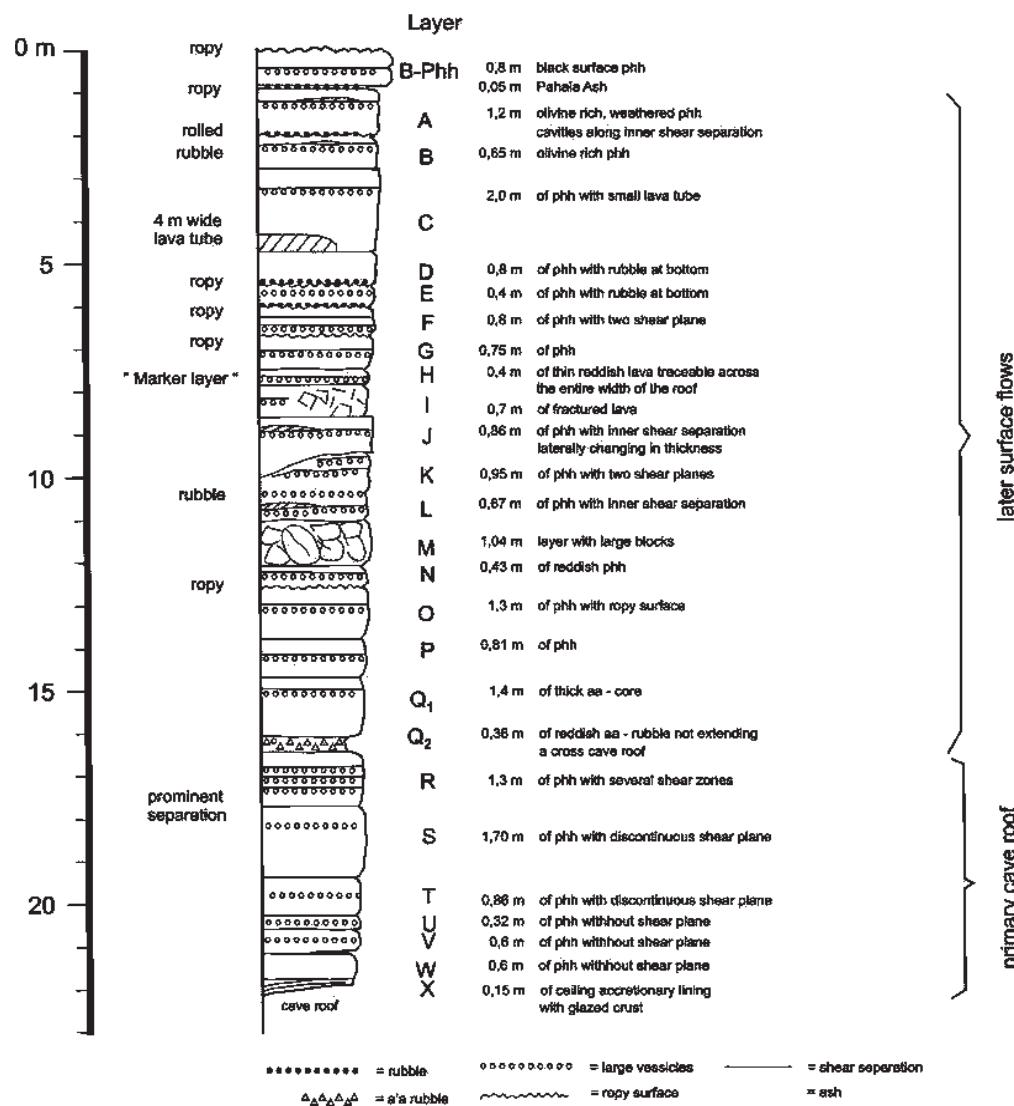


Figure 18. Stratigraphic profile of the Luanunu Puka at the mauka entrance.

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. 1 m	Palagonitized volcanic ash
1	Kamakalepo-Waipouli lava >25 m		Vesicular picrite (no plagioclase) with matrix of oxides. Olivine slightly iddingsitized.

# Waipouli Makai Cave

## geological section at entrance

### 15. 04. 2006 S. Kempe, H. Shick

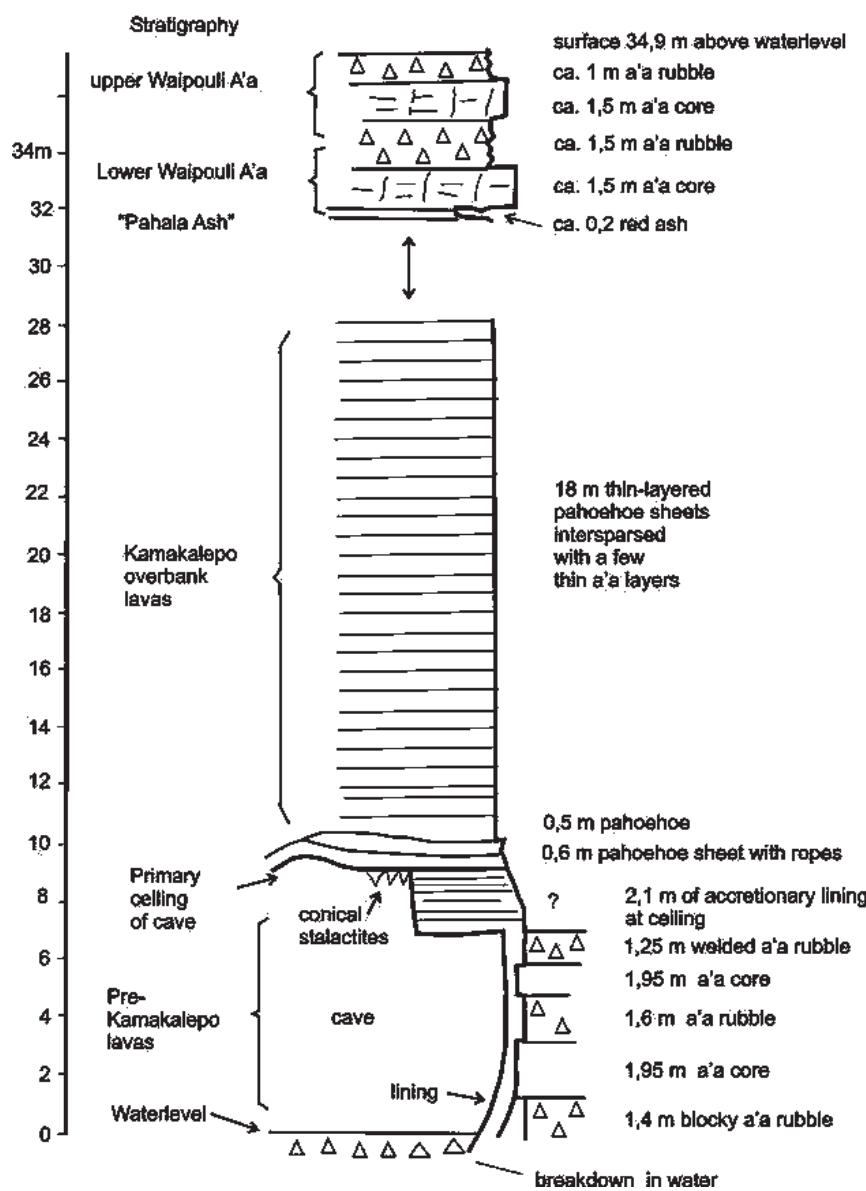


Figure 19. Stratigraphic profile of the Waipouli Puka at the makai entrance.

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.

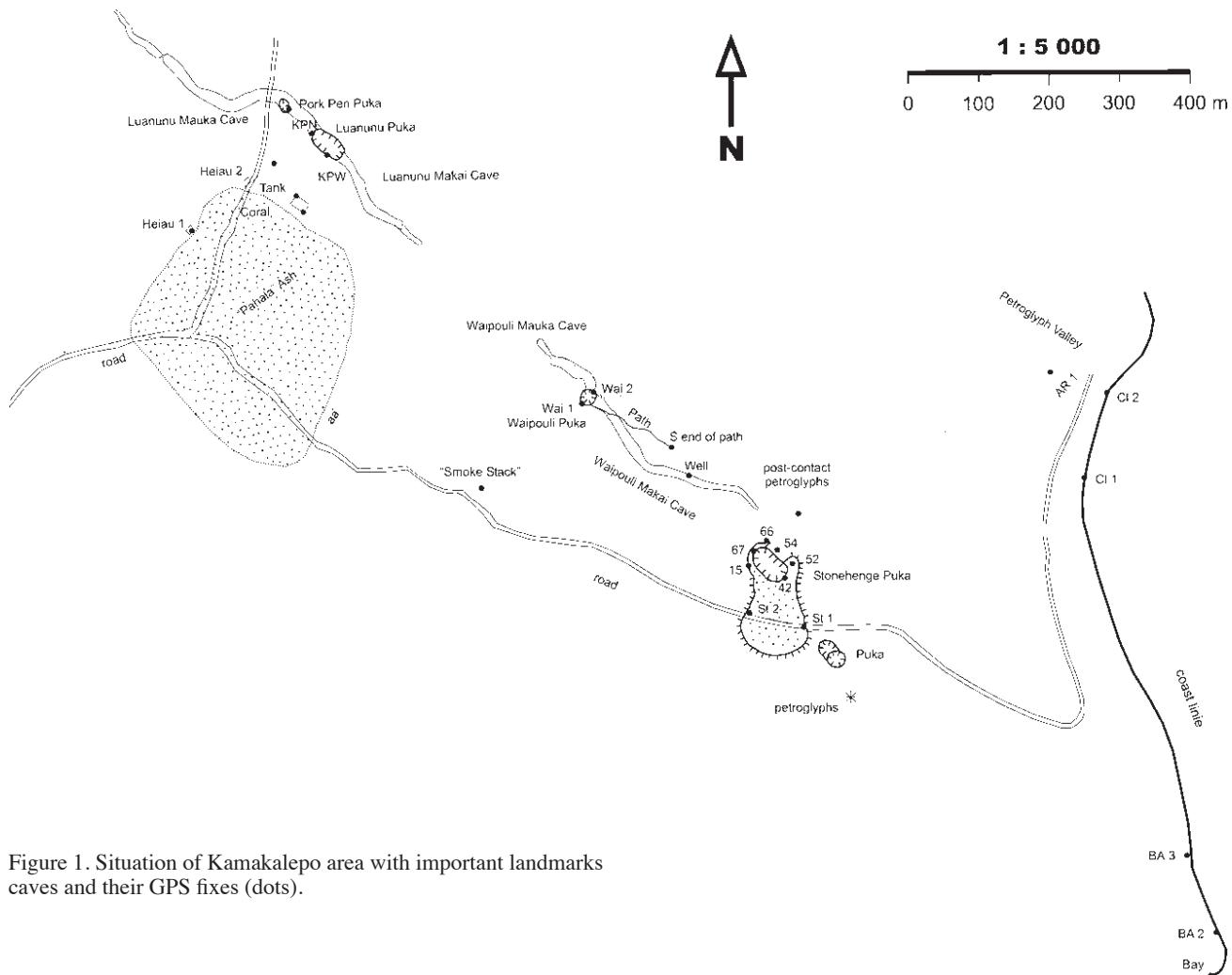


Figure 1. Situation of Kamakalepo area with important landmarks caves and their GPS fixes (dots).

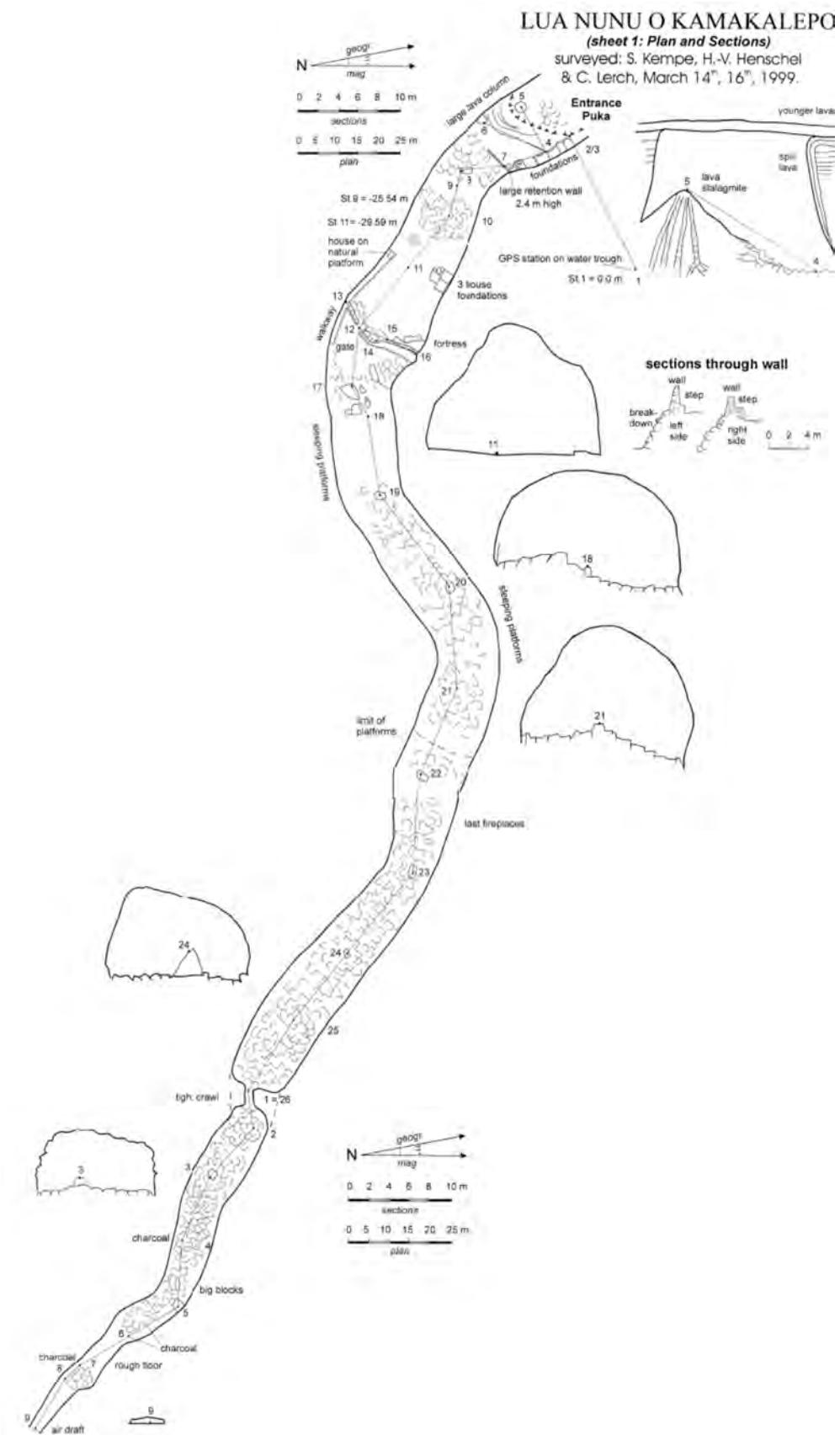


Figure 4. Map of Lua Nunu o Kamakalepo Mauka Cave. Note archeological details.

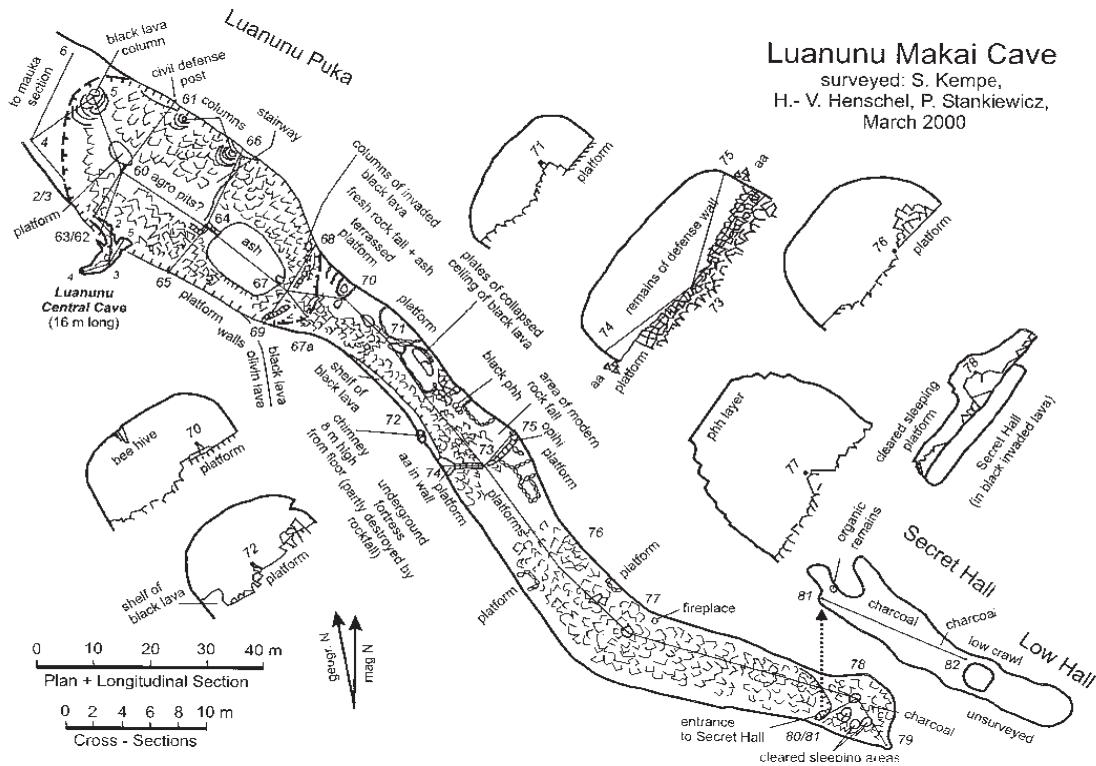


Figure 5. Map of Lua Nunu o Kamakalepo Makai Cave. Note archeological details.



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.

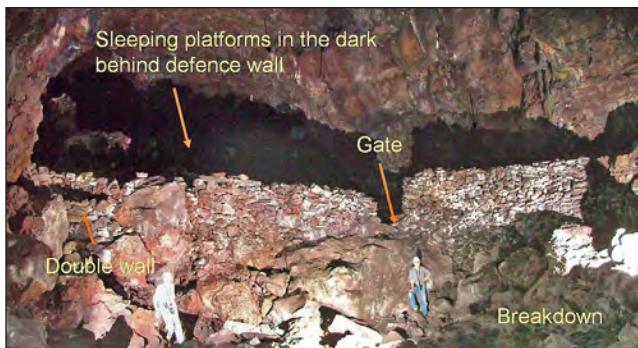


Figure 7. View mauka of the 25 m long defense wall in the Lua Nunu o Kamakalepo Mauka Cave. Note persons for scale and gate at the center of the wall.



Figure 8. View of the gate from the inside. Note the entrance of the cave 60 m away in the background.



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 petrolyphts, 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 "Secret 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 capped 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 ( $^{14}\text{C}$  dating in progress) (Fig. 11). The water was extensively used in the 20<sup>th</sup> 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 stickmen 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 poundmarks; 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 petroglyphs 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; $\Sigma=15$	2A2;2A3;1A4; 4A5; 1A6; 2A7; 2A10; $\Sigma=14$	1A3, 3A3; 1A6; 4A9 4A10; $\Sigma=13$
Simple stick man, one hand up	1A2; 2A7;1A10; $\Sigma=4$	1A5	
Stick man, legs spread	1A1; 2 A7	3A7; 3A10	
Triangular or square bodies		1A1; 2A2;1A3; 1A6; 1A8; $\Sigma=6$	
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 petroglyphs, 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 petroglyphs 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 20<sup>th</sup> 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.

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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.

## 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

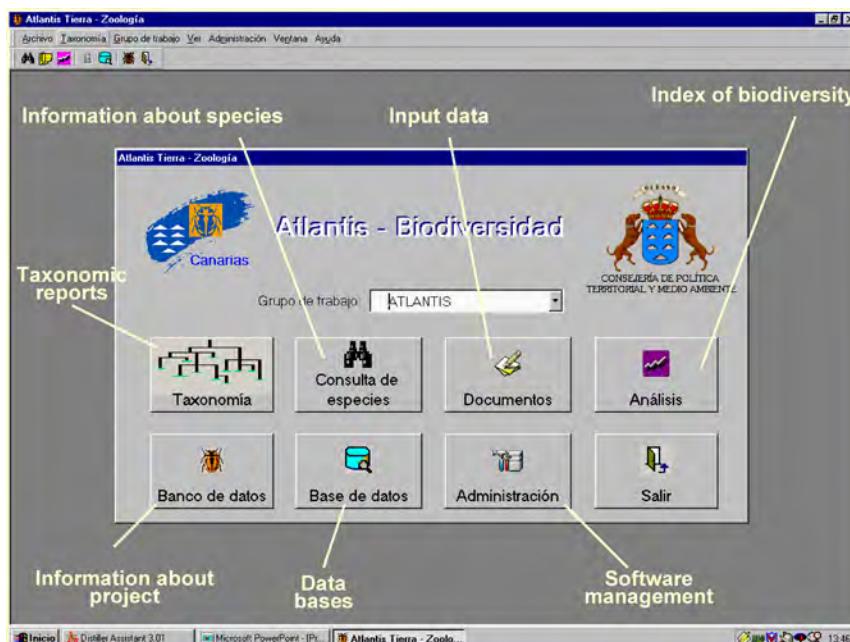


Figure 1. Entrance window of ATLANTIS Tierra 2.0, in which it is possible to observe eight possible entrance gateways, the most relevant being the taxonomic reports (“Taxonomía”), information about species (“Consulta de especies”) and data analysis (“Consulta de análisis”).

(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 conducting 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 especies”) 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: “How 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

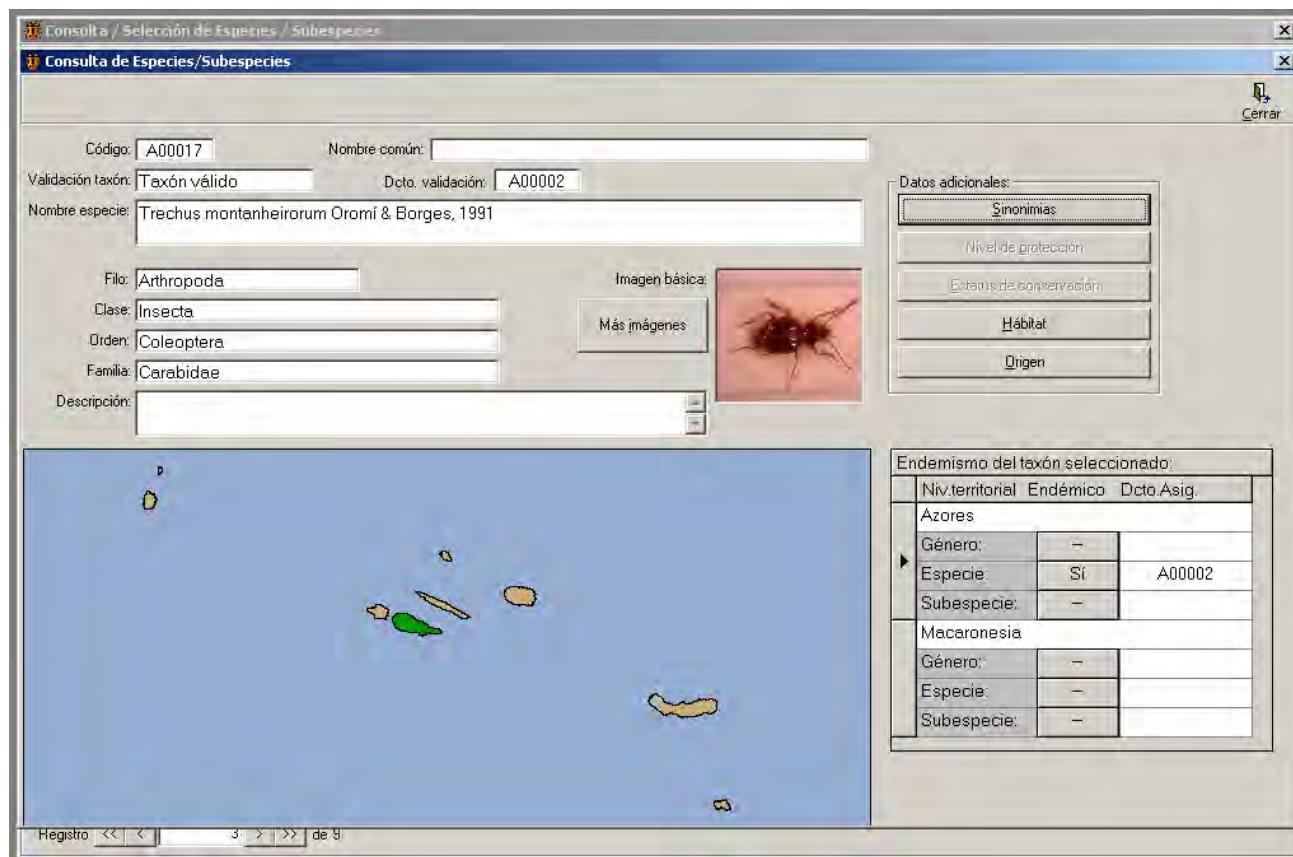


Figure 2. Species management window of ATLANTIS Tierra 2.0, in which it is possible to observe the nomenclature of the species, a picture, the distribution of the species in the archipelago (green island) and other relevant information concerning the habitats, conservation status, biogeographical origin, etc.

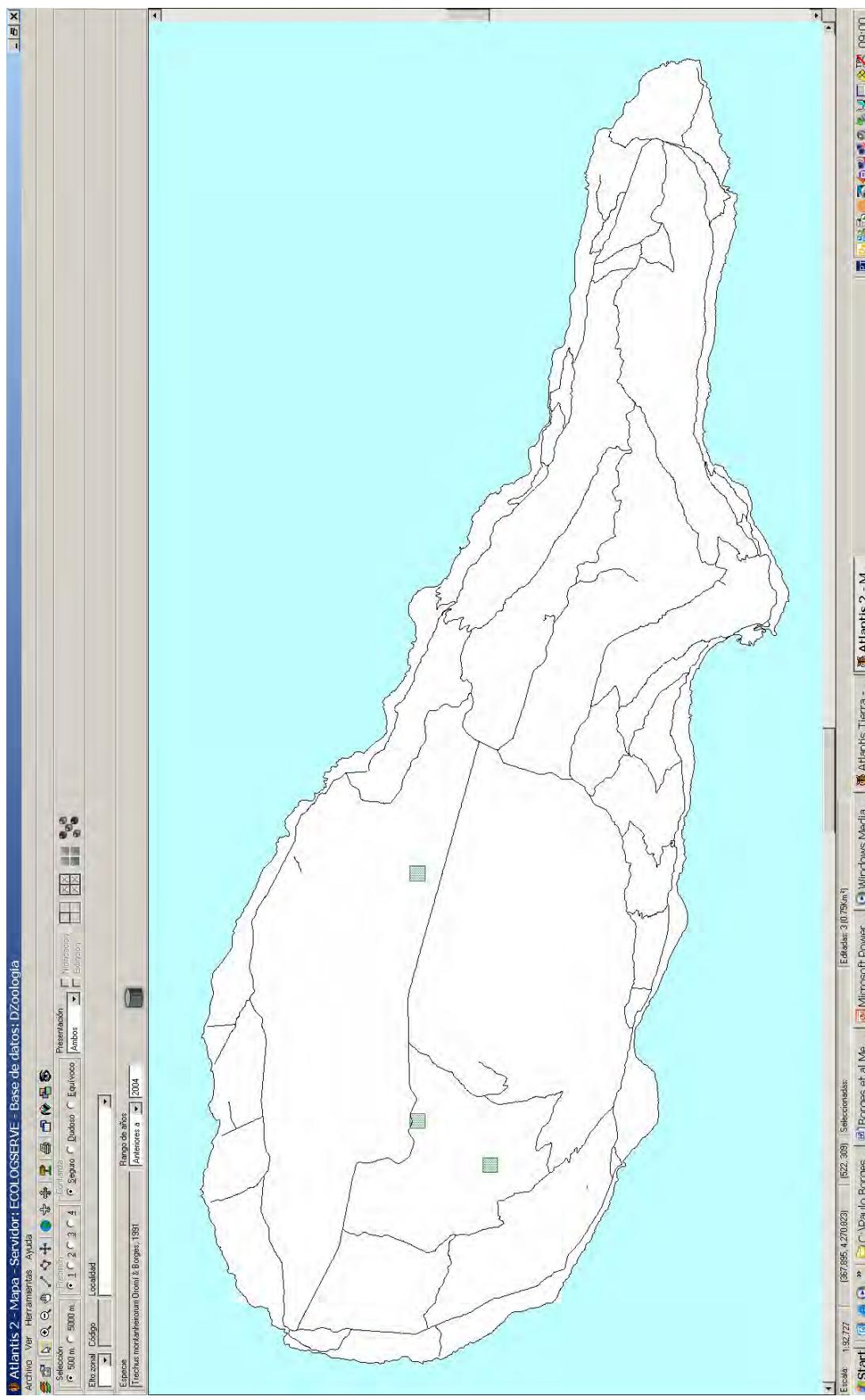


Figure 3. Species management window of ATLANTIS Tierra 2.0, in which it is possible to observe the detailed distribution of *Trechus montanheirorum* in the island of Pico (lines are main roads in the island).

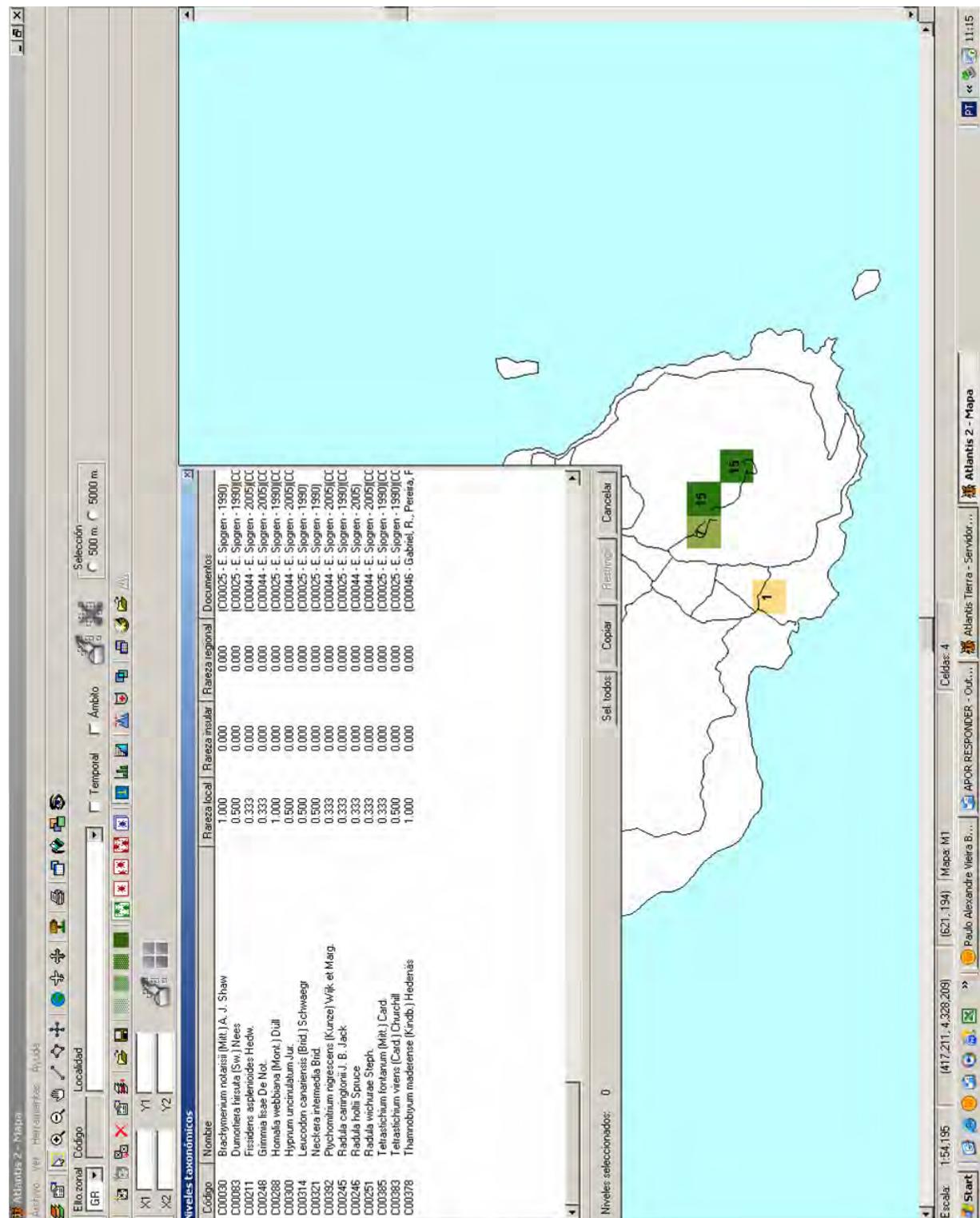


Figure 4. Data analysis window of ATLANTIS Tierra 2.0, in which it is possible to observe the number of bryophyte species in the European Red List present in caves from Graciosa Island (Azores). The list of species in the window corresponds to the grid cell with 15 species (Furna do Enxofre).

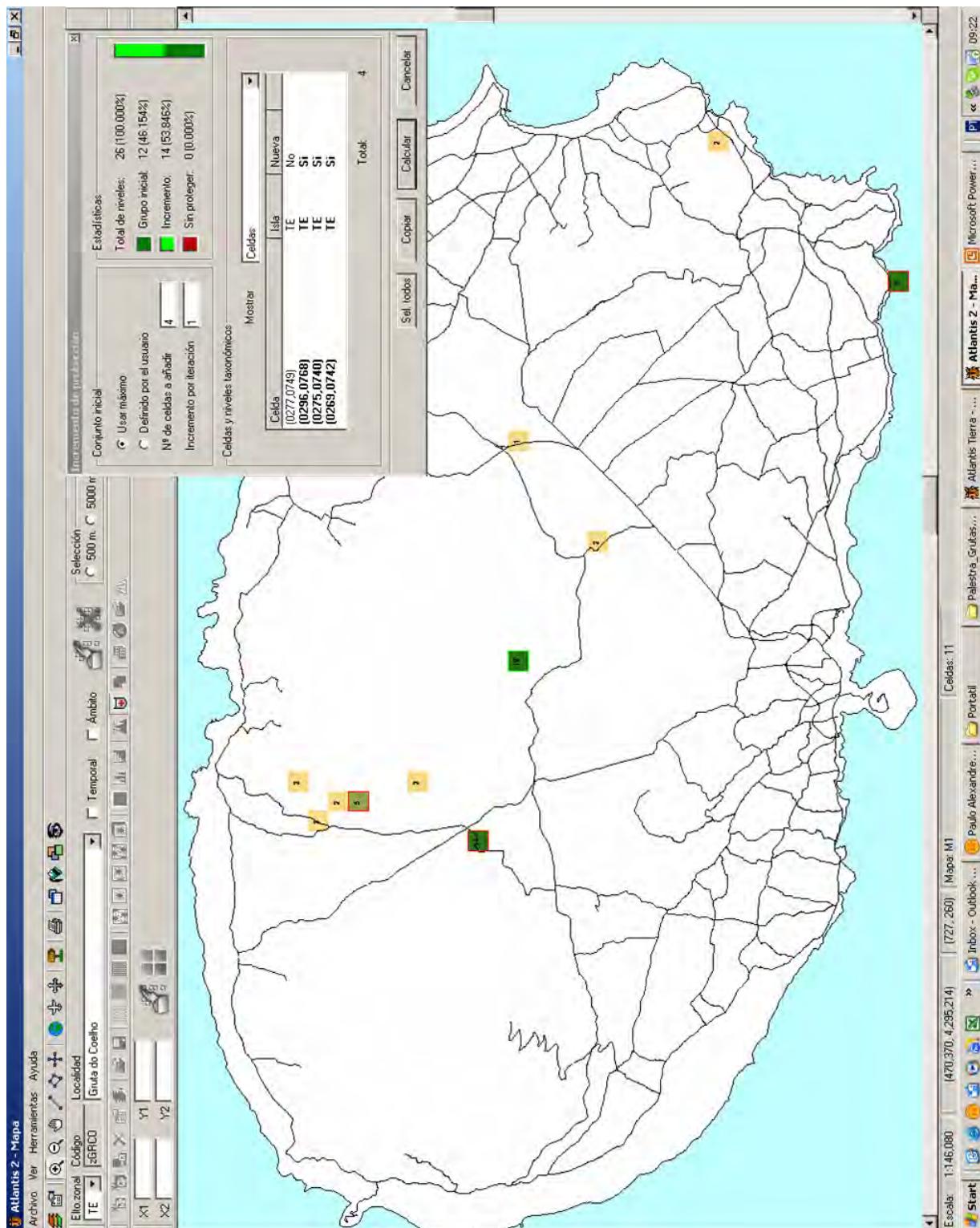


Figure 5. Data analysis window of ATLANTIS Tierra 2.0, in which it is possible to observe the four grid-cells that are necessary to include all the endemic arthropods occurring in caves from Terceira island (see text for further explanations).

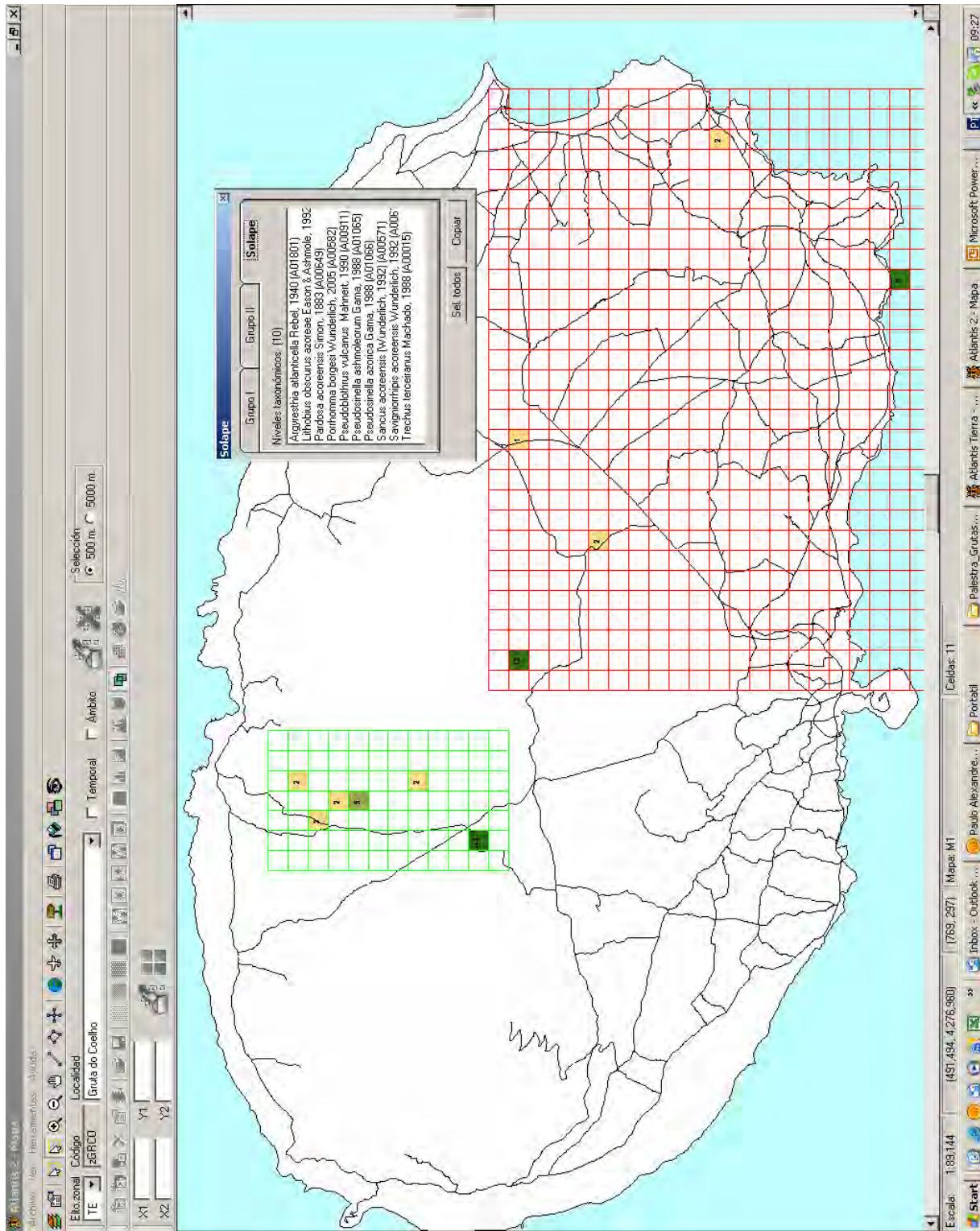


Figure 6. Data analysis window of ATLANTIS Tierra 2.0, in which it is possible to observe the list of endemic arthropods that occur in two distinct cave systems at Terceira island (see text for further explanations).

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 known 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 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?

### Acknowledgements

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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

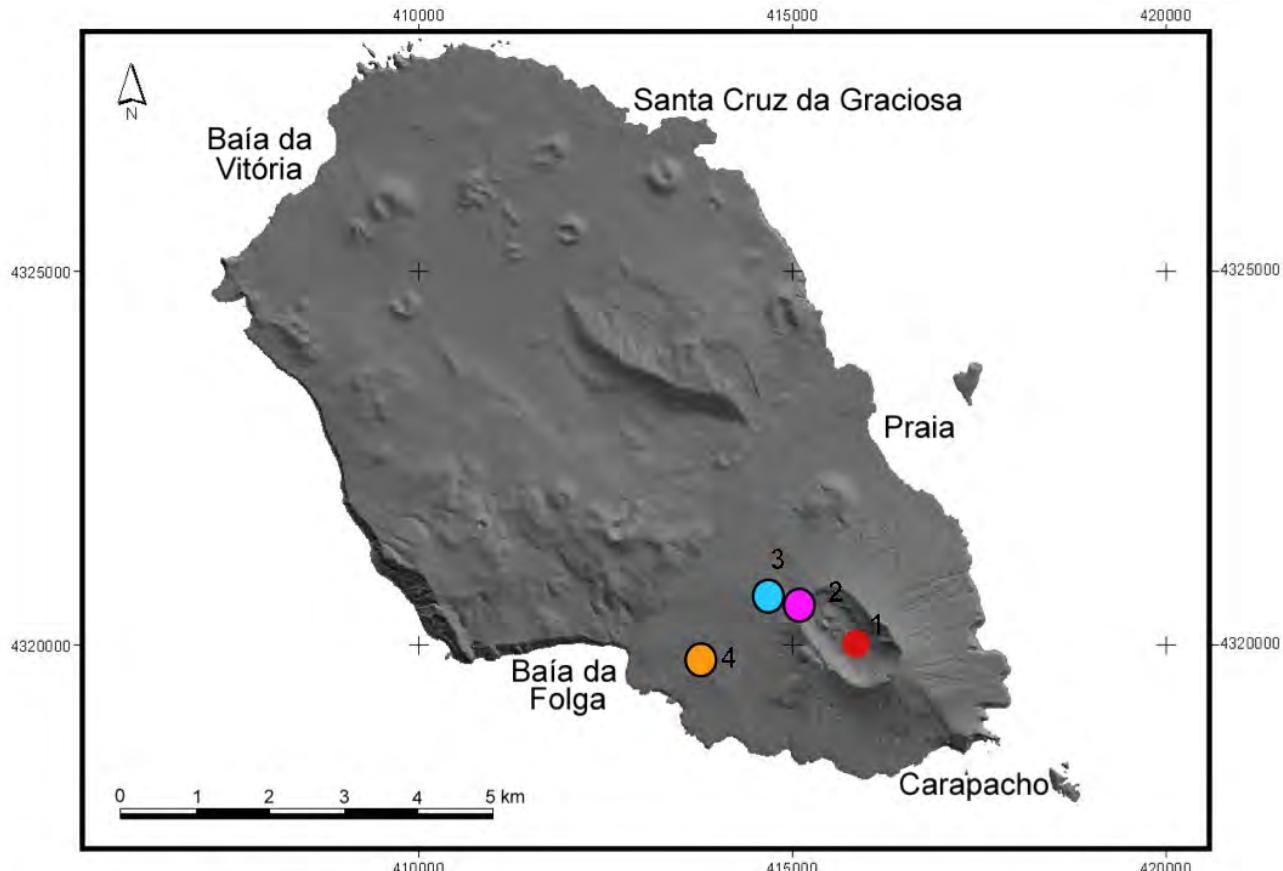


Figure 1. Sampled cave sites of Graciosa Island (Azores archipelago, Portugal). (1, Furna do Enxofre; 2, Furna da Maria Encantada; 3, Furna do Abel; 4, Galeria Forninho).

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 hyper-humid 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 (39°05'N, 28°00'W), and the second smallest of the Azores (61.7 km<sup>2</sup>). 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 luisieri Heterocladium wulfsbergii # Homalia webbiana Lejeunea lamacerina Leucobryum juniperoides 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	<i>Frullania azorica</i>
	Eur	<i>Frullania microphylla</i>
	Eur	<i>Homalia webbiana</i>
	Eur	<i>Marchesinia mackaii</i>
	Eur	<i>Myurium hochstetteri</i>
K	Mac	<i>Fissidens luisieri</i>
R	Eur	<i>Tetrastrichium fontanum</i>
	Mac	<i>Fissidens coacervatus</i>
	Mac	<i>Tetrastrichium virens</i>
V	Mac	<i>Radula wichurae</i>

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 Liège, 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 & Hernández-García (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, nearctic (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 in transporting 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 (SEMAR-NAT, 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<sub>2</sub>) (w) ig (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).

Tepoztlán 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 parnellii* (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. Geoffroy, 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 temperate 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)

After 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<sub>3</sub> 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 Tepoztlán, 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 murciélagos magueyero mayor Leptonycteris nivalis (Chiroptera: Phyllostomidae) en la Cueva del Diablo, Tepoztlán, Morelos* (Diet of the Mexican long-nosed bat *Leptonycteris nivalis* (Chiroptera: Phyllostomidae) in Cueva del Diablo, Tepoztlán, 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 *Ipomea 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 murciélagos* (Flowers for Lucía the bat) is the material which

had been being used in four schools of four communities in Tepoztlán. 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 made 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  $\mu$ l volume

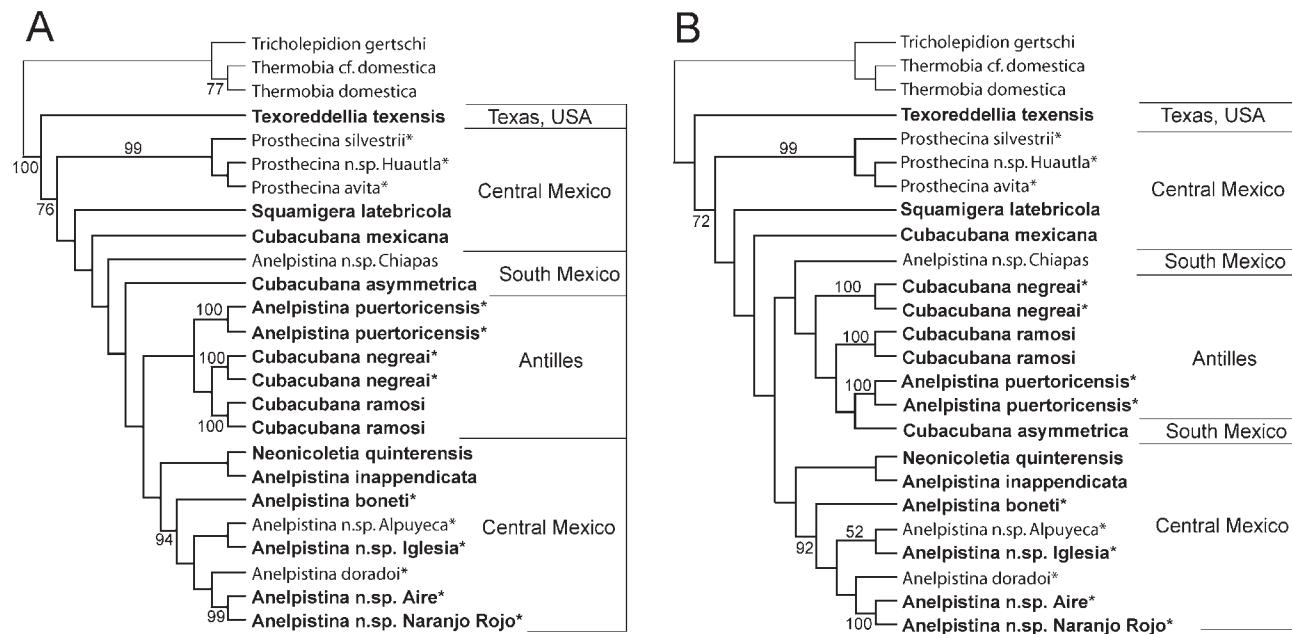


Figure 1. Figure taken from Espinasa et al. (In press). Two equally costly trees derived from the analysis of the combined analysis of sequence data from five loci and morphology. Bold species names indicate cavernicolous species. Asterisks denote species in which adult males have articulated submedian 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
<i>Anelpistina</i> n.sp. Alpuyeca 1 individual	Alpuyeca, Morelos, Mexico (18°43' N, 99°15' W)	Google Earth
<i>Anelpistina</i> n.sp. Iglesia 6 individuals	Cueva de la Iglesia-Mina Superior, San Juan Tlacotenco, Morelos, Mexico (19°01' 02" N, 99°05' 29" W)	Espinasa, 1999; Espinasa-Pereña, 1999
<i>Anelpistina</i> n.sp. Aire 1 individual	Cueva del Aire, Ajusco, DF, Mexico (19°13'30" N, 99°10'24" W)	Espinasa-Pereña, 1999
<i>Anelpistina</i> n.sp. Naranjo Rojo 4 individuals	Cueva del Naranjo Rojo, km 6.5 on the Cuernavaca-Tepoztlán highway, Morelos, Mexico (18°58' 46" N, 99°10' 54" W)	Tapie, 1987; Google Earth
<i>Anelpistina</i> n.sp. Herradura 1 individual	Cueva de la Herradura, km 6.5 on the Cuernavaca-Tepoztlán highway, Morelos, Mexico (18°59' N, 99°11' W)	Google Earth

reaction, with 1.25 units of AmpliTaq® DNA Polymerase (Perkin Elmer, Foster City, CA, USA), 200  $\mu$ M of dNTPs, and 1  $\mu$ M 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 °C 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  $\mu$ l volume reaction: 4  $\mu$ l of Terminator Ready Reaction Mix, 10-30 ng/ml of PCR product, 5 pmol of primer and dH<sub>2</sub>O to 10  $\mu$ l. The cycle-sequencing program consisted of an initial step at 94 °C for 3 min, 25 sequencing cycles (94 °C for 10 sec, 50 °C 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.

Iglesia	TGACTAACCTCTTGTAGGCAAGATTGTTTATGGCATG--TTGTTGATCCTT-TATTAAGATTAATA
Iglesia	.....
Iglesia	.....A.....
Iglesia	.....
Iglesia	.....
<b>Naranjo Rojo</b>	.....
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..
<b>Iglesia</b>	.A.T.....--.....T.....T.GG.TAC..T.AA.T...GT..A.....A.....T..

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 Cubacubaniniae, 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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