6th International Symposium on Vulcanospeleology

Hilo, Hawaii
August 1991

G. Thomas Rea
Editor

National
Speleological
Society

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National Speleological Society
2813 Cave Avenue
Huntsville, Alabama 35810-4431
USA

6th International Symposium on Vulcanospeleology

Published by

National Speleological Society, Inc.
2813 Cave Avenue
Huntsville, Alabama 35810-4431
USA

Library of Congress Catalog Card No. 92-63229

ISBN 1-879-961-02-4

Cover photograph by H.J.L. Lamont, Associate of the Australian Institute of Professional Photographers, Associate of the Royal Photographic Society (London), James Cook University of North Queensland: *Barkers Cave, Undara Lava Tube System, North Queensland, Australia, 50 meters from its entrance.*

Printed in the United States of America

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Foreword

Held at the Hilo Seaside Hotel, Hilo, Hawaii, in August 1991, the 6^{th} International Symposium on Vulcanospeleology was co-sponsored by the National Speleological Society, the Western Speleological Survey, the Bishop and Lyman Museums, the University of Hawaii-Hilo Branch, and Hawaii Volcanoes National Park. A capacity crowd of about 60 attended the sessions, including the Mayor of Hawaii County and invited guests from the U.S. Geological Survey's Hawaiian Volcano Observatory and from Haleakala National Park. Participants attended from Australia, Iceland, Germany, Japan, Korea, the Netherlands, Portugal, Spain, and the United States. Principal host organization was the Hawaii Speleological Survey of the National Speleological Society.

Many parameters of lava tube caves and other volcanic cavities differ widely in different geographic settings. The formal and informal discussions during this series of international symposia bring together investigators on the cutting edge of this rapidly advancing field, with a great deal of obvious interdisciplinary cross-fertilization. But slowness of publication has limited their effectiveness. We are all indebted to Tom Rea, Executive Vice-President and member of the Special Publications Committee of the National Speleological Society, for the speed with which he has edited and produced this volume. Its organization differs slightly from that of the sessions. The text of the opening keynote address on Lava Tubes of the Solar System, by Ron Greeley, is found in the section on "Theoretical, Biological, Conservation, and Management Topics" instead of at the beginning. Papers presented during the mini-session of earthquake observations appear in the section on "Vulcanospeleology of Hawaii." Because Romania's Calin Fabian was unable to attend and did not submit a paper, the planned mini-session on lava tube remnants in ancient basalts was cancelled, and Yavor Shopov's paper was moved into the session on "Vulcanospeleology of the World." This new topic received other special consideration including Bruce Rogers' mention of a spacious, 8.2-million-year-old lava tube cave on Tol Island, Micronesia, (page 164) plus visits to three lava tube caves in basalt two million years old during the Oahu pre-symposium field excursion.

This volume contains the first vigorous attempt at standardization of vulcanospeleological terminology; Charlie Larson's paper is sure to draw argument. Receiving much more attention than in past symposia are open vertical volcanic conduits, considered in several papers and one poster exhibit. Obvious problems in translation should not be allowed to hinder due consideration of Ohsako's theoretical paper on vulcanospeleogenesis (page 262) which should be correlated with the explicatory paper by Nieuwenhuis (page 259). Anyone who has felt the impact of cylindrical tidal bores of water periodically emerging from "blue holes" in the Bahamas forming surface "boils" up to one meter high can postulate the possible existence of similar bores of lava within uncongealed beds. The question of cavitation, however, remains unresolved. And these are only a few of the wide-ranging, often controversial, topics considered in this proceedings.

Special thanks and acknowledgement are appropriate for many who assisted in the success of this symposium: the session chairmen (Jim Nieland, Tom Rea, Fred Stone, and John Holsinger), field excursion leaders and speakers (Kevin Kelly, Oahu; Jim Martin and Tom Wright, Hawaii Volcanoes National Park and U.S. Geological Survey Hawaii Volcano Observatory; Marlin Spike Werner, Puna; and Darrel Tanaka, Kauai), luncheon speaker Frank Howarth, U.S. Geological Survey speakers (Tom Wright, Christina Helicker, and Tari Moulds), Mayor Lorraine Inouye, registrars Lynn Scully and Marcia Halliday, and many staff people from the Bishop Museum and Lyman Museum, notably Anita Manning, Leon Bruno, and Paul Dahlquist. To all of you and all the others who worked so hard to make this symposium such a success, *aloha* and *mahalo*!

William R. Halliday
Symposium Chairman

Vulcanospeleology of Hawaii


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Hawaiian Use of Lava Tube Caves and Shelters

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Bishop Museum

Abstract

Due to the geological nature of the Hawaiian Islands, there are many lava tubes found throughout the islands. Some of the collapsed lava tubes provided ideal places for permanent or temporary shelters for the ancient Hawaiians.

The larger and longer lava tubes were utilized as places of refuge in time of war. Women, children, and elders hid there. The entrances to the caves were concealed by well constructed stone walls leaving a very narrow passage in which only one person could enter at a time. In these caves they had platforms for sleeping and cooking areas.

Except for refuge caves, other habitation areas are often found in and near the front portions of the opening. These are called shelters. Since these shelters were naturally well protected from the rain and winds, the place was occupied continuously or periodically over time. Since the layers of soil and artifacts are well preserved, by analysing such stratigraphy the archaeologist can determine the sequence of events that took place.

This paper presents several of the typical yet significantly important archaeological shelter sites and refuge caves on the Islands of Oahu and Hawaii.

Introduction

Because of the volcanic origins of the Hawaiian Islands, there are many lava tubes found throughout the islands. Ancient Hawaiians utilized lava tubes or collapsed lava tubes for many functions, especially as permanent or temporary habitation sites.

The terms caves and shelters have been used in Hawaiian archaeological literature rather loosely without any clear distinction. In this paper only the term shelter will be used. There appears to be two major types of such features in the Hawaiian Islands.

I. Lava tube shelter
  A. Short tube
  B. Long tube
    1. With vertical openings
    2. With horizontal openings
II. Overhang shelter

Lava Tube Shelter There are long and short lava tubes which have been utilized for dwelling, burial, refuge, and religious functions. Since it is difficult to determine what is a long or short tube, I set up criteria based on the utilized zone of the tubes, not the physical length of tubes. The short tubes are in most cases habitation sites. Long tubes, some of which are several miles long, are usually refuge shelters. Also, a long tube may have several separate habitation areas with separate openings.

The openings of lava tubes can be classified into the two following types:

1. Vertical openings. The breaks are usually from the top of tubes. In many cases, more than one entrance is present.
2. Horizontal openings. There are two types of horizontal openings.
   a. Some lava tubes were formed higher than the surrounding ground surface and have openings on the sides.
   b. Tube openings on cliffs usually have an overhang at the opening which provides shelter.

Overhang Shelter No tubes are associated with overhang shelters. Such shelters are usually formed by erosion on the base of a cliff or bluff.

The Use of Lava Tube Shelters

Habitation The collapsed tubes provided ideal places for permanent or temporary habitation. The overhang shelters were naturally well protected from the elements and suitable for habitation. The

deposition of cultural layers on the floors of tubes and shelters are deeper and better preserved compared with those of open sites. By analyzing such stratigraphy and associated artifacts, archaeologists can determine the sequence of events that took place.

Burials and Religious Functions Tube shelters were often used as burial places and the larger tubes were continuously used even into the protohistoric time. These burial tubes were maintained by either lineage groups or communities, and the burial tube entrances were well concealed. Unfortunately, some of those burials have been violated by pot hunters for years and are accessible to anyone today.

Refuge Places The larger and longer lava tubes were used as places of refuge in times of war. Women, children, and elders hid there. The entrances to the tubes were well constructed by stone walls leaving a very narrow passage in which only one person could enter at a time. Thus it was effectively protected against enemy attack. In these tubes there are platforms for sleeping, cooking, and other activities.

Table 1

Number of Lava Tube and Overhang Shelters in the Hawaiian Islands (1991)*

Number of sites		Functions**		
		Habit.	Burial	Refuge
Hawaii	482	133	44	14
Maui	116	33	13	1
Lanai	18	14	4	-
Kahoolawe	5	4	-	-
Molokai	39	28	8	1
Oahu	84	23	35	2
Kauai	27	16	13	-
Total	771	251	117	18

* After Bishop Museum's site database.
** Functions determined for 386 sites.

The Current Record Of the circa 11,000 site records in the Bishop Museum, 771 sites are listed as caves and shelters. Unfortunately there is no clear distinction between tube shelters and overhang shelters. Table 1 shows that there are many unclassified sites, but it may still be possible to classify many of those sites if we go through the site records carefully. Another concern is that we know there are examples of lava tube shelters that were originally used for habitation and after abandonment became burial places. Such sites are not currently specified in the database.

The number of tubes and shelters on the Island of Hawaii is 482 compared with 116 on Maui, 84 on Oahu, and 27 on Kauai. Although dependent on the size of the island and its geomorphology, the number of recorded lava tube and overhang shelters most likely relates to the number of archaeological surveys conducted on each of the islands.

Hawaii Island Examples

Since the conference is being held on the Island of Hawaii, I would like to show examples of the typical sites in the different categories found on this island.

Lava Tube Shelter Waiahukini Site, #50-Ha-B21-6 (H8), located at Waiahukini near South Point, in Ka'u District.

This is one of the most important sites in the Hawaiian Islands. Fishhooks and other artifacts from the stratified deposit (Figure 1) provided an excellent typological sequence which eventually led to establishing a Hawaiian fishhook typology and chronology (Emory, Bonk, and Sinoto, 1959).

The site is a small fisherman's tube shelter approximately 67 meters from the foot of Pali-o-kulani cliff and about 200 meters inland from the shore. The tube shelter is a natural chamber for habitation. Entrances on two sides have been provided by natural breaks in the ceiling of the lava tube. The chamber has a floor space that is 6.7 by 8.3 meters and is dimly lit by the two openings.

The tube continues westward from the main living space but the area was not utilized for habitation except possibly for storage.

Three cultural layers in a total depth of 68 centimeters yielded nearly 1,200 fishhooks of many types. The type distribution of the hooks demonstrated a significant chronological sequence for certain types of hooks. This made it possible to place fishhooks from other sites in meaningful order and relationships (Emory *et al. i.b.*).

The subsequent excavations of other tube shelter sites in Waiahukini also showed very similar fishhook typological sequences (Sinoto and Kelly, 1970).

Lava Tube Shelter Hilina Pali Site, #50-Ha-B2-1, also listed as #50-HV-383, is located in Kalapala, Ka'u District. The tube-shelter is ori-

Figure 1 – Cultural deposits in Waiahukini lava tube shelter (HA-B21-6), Ka'u, Hawaii Island. Scale in inches (Bishop Museum photo).

ented north to south and a collapsed section of roof permits access from the surrounding plain into both the north and south portions of the tube. The south section, extending 145 meters from the collapse, shows little evidence of use. The north section contains abundant petroglyphs for a distance of about 17 meters from the collapsed area. The collapsed area is roughly circular and about 9.6 meters in diameter with a maximum depth of 2.7 meters. The tube-shelter has about 550 petroglyph units and has a platform with fire places.

The significance of the site is that the petroglyphs on the tube walls (Figure 2) were buried by cultural deposits. Usually, petroglyphs have been found on open lava fields and it has been difficult to establish a chronological sequence of petroglyph forms. The Hilina Pali tube shelter is the first site to provide clues for a typological sequence of Hawaiian petroglyphs. It is hypothesized that in illustrating anthropomorphic forms there was a style preference change from linear to triangular figures around A.D.1600 (Cleghorn, 1980).

Burial Tube Shelter Forty-four burial tube shelters on the Island of Hawaii are listed in the Bishop Museum database. I will describe one of nine burial tube shelters reported from Kalahuipua'a, Anaeho'omalu, and Lalamilo in the District of South Kohala (Kirch, 1979). Site #50-Ha-E2-56 is a large, apparently communal, burial tube shelter containing 30 individuals with three separate entrances. Burials were only found in the large central chamber. It measures about 20 by 15 meters, with a ceiling height of two to three meters. The burials are mostly found along the northeast wall, except for a central platform on which the scattered crania and infracranial materials of 13 individuals were located. One example of an extended burial lies in a canoe hull segment. There are two more canoe burials along the northeast and southwest walls. After the survey all the burial tube shelters in the area were sealed off to prevent any disturbance.

Refuge Tube Shelter There are 14 refuge tube shelters listed on the Big Island. I will describe one of them here: Hayes Tube Shelter #50-Ha-C19-1 (H51), located in South Kona District. In 1957 Dr. Kenneth P. Emory and I sketch mapped

Figure 2 – Petroglyphs on the wall of Hilina Pali lava tube shelter (HA-B2-1), Ka'u, Hawaii Island (Bishop Museum photo).

Figure 3—Part of bone fishhook cache found in refuge tube shelter known as Hayes Cave (HA-C19-1), South Kona, Hawaii Island (after Emory, Bonk, and Sinoto, 1959, Plate 4).

the tube shelter with the help of volunteers. The main tube has a narrow passage at the walled entrance and is at least 150 meters long. There are multiple branch tubes, two levels below and one above the main tube. One upper and one lower tube are each about 70 meters long. The tubes average 2.5 to 3.5 meters wide and 1.5 to 3 meters high. Chambers are six to eight meters wide with the ceilings two to six meters high.

Usually, artifacts found in the refuge tube shelters are much better in quality than those found from ordinary sites since refugees probably took with them their prized possessions. There is some evidence of the activities that took place in these refuge shelters, such as fishhook and ornament making.

In this shelter we found a most remarkable fishhook cache (Figure 3). They were buried under about ten centimeters of fine dust in a small area, and every scoop of my hands brought up several complete hooks. There were 19 unbroken one-piece hooks and 38 two-piece hook shanks and points. One of the one-piece hooks made from a human pelvis is to date the largest one-piece bone hook from an archaeological site in the Hawaiian Islands. There were also fine ornaments such as pendants, bracelets, and game stones found in the tubes and chambers of the site. There were also sleeping platforms and fire places. Inside the tube it is very dark and the candle nut (kukui) shells scattered throughout indicates that Hawaiians used them for a light source.

Archaeological evidence indicates that lava tubes and overhang shelters provided shelter for Hawaiians from the prehistoric to the early historic periods. Although houses and other surface structures were also commonly constructed and used, lava tubes and overhang shelters were convenient natural features that were fully utilized by Hawaiians.

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Recently Discovered Hawaiian Religious and Burial Caves

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Abstract

This is a brief report to accompany diagrams, maps, and overhead projections to illustrate the ancient Hawaiian use of the upper lands in the Puna and Wao Kele O Puna areas of the Big Island. This area has been extensively explored in recent years by me and by others, but the findings have not been published until now. I will present a personal, in-depth report concerning the findings of the exploration of these religious and burial caves.

This is primarily a photographic presentation of an extensive cave system which runs for miles under the Puna forest reserve. The tropical rain forest here is one of the most beautiful in the world and is a unique example of the diverse fauna and biological microsystems that exist in Hawaii. The lush foliage and thick ohia forests make finding caves difficult and sometimes surprising.

This paper focuses on one of many caves located in this area. This particular cave has fascinated and inspired me. I have spent hundreds of hours exploring its many stone fortifications, crawl spaces, and miles of winding passage. I was amazed to find detailed rock work, seashells approximately eight miles from the seashore, torches, underground altars, burial chambers, and human remains in extensive sections of this lowland forest cave.

The cave's bedrock is primarily pahoehoe lava, with intrusions of red aa. It is part of a massive flow that swept northeast from the southeast rift of Kilauea volcano. My findings indicate that nearby areas in the higher elevations were used for crop production to balance the food needs of the coastal people. I am convinced that these people worked the land, and that this cave was used for religious purposes as well as a refuge site. Massive amounts of rock work in the form of fortified entrances, heiaus, altars, hidden artificial crawl spaces, and large quantities of seashells all reflect a sizeable work force and a cultured society. It is clear that the Hawaiians used and developed this area as an integral part of that society.

I firmly believe that this cave system should be protected and preserved. To accomplish this I have nominated it for national historic preservation.

As seen from the air, the topography of Wao Kele O Puna forest reserve is one of dense jungle surrounded by fields of orchids and wild grasses. Recent intrusions are drilling rigs used for exploratory drilling in the Geothermal Subzone.

One feature of this jungle is a sunken area with a well-laid set of stone steps leading down to a completely rock-filled round area (Figure 1). This sink is divided directionally, with stone walkways leading underground through fortified crawl

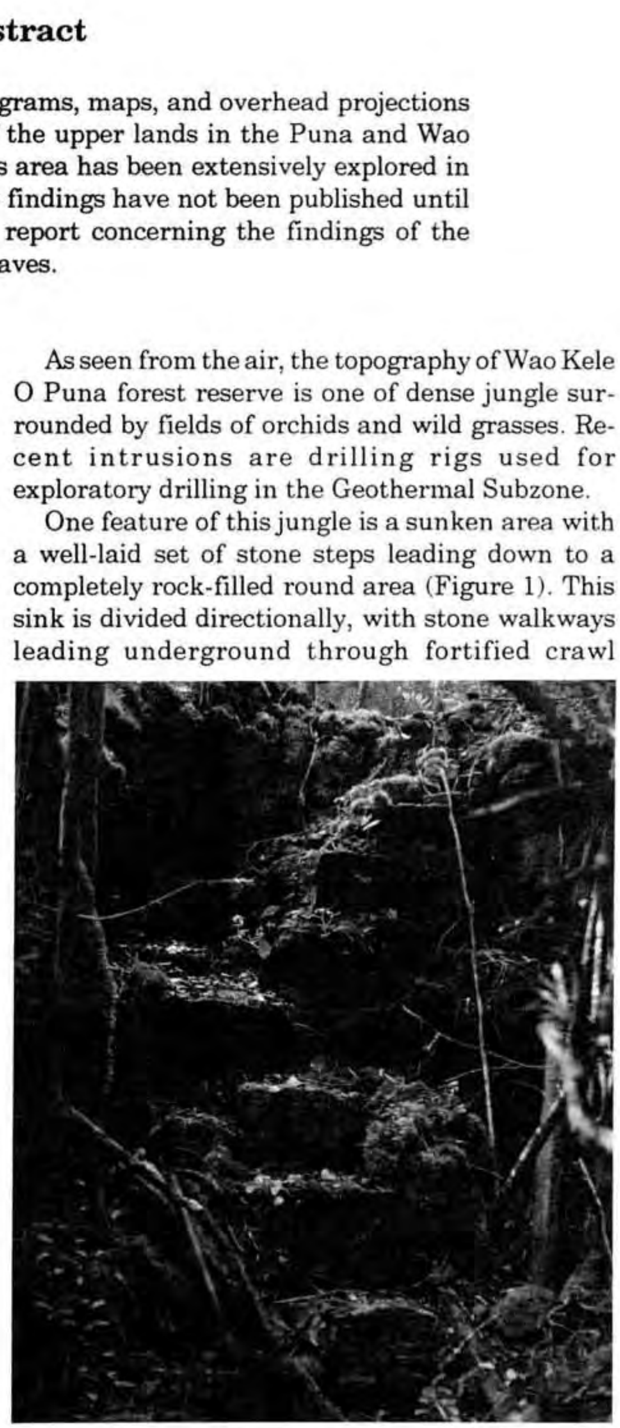

Figure 1 – Stone steps leading into the first sink (Photo by Brad Lewis and Tom Seal).

spaces. Well-fitted stone walls lead underground to a series of smaller stone walls, dividing underground chambers into possible living areas.

Farther uphill are many opihi shells strewn about the floor, the remains of many fires, and many different bones and teeth of various animals. Also seen are stacks of torches lining both sides of the cave. Careful inspection reveals teeth with holes drilled through the shank, used for jewelry.

Four hundred meters west is an underground altar four meters in diameter. On this altar are a pounder and stone bowl as well as additional seashells. In the center of the altar is a meter-long pit. The altar is constructed of red cinder and is situated in the center of the lava tube.

Farther uphill the cave is larger, with a high vaulted ceiling covered with stalactites and many patches of gold, silver, and crimson fungus-like material. High on a ledge in this large chamber is a crawl space that leads to a chamber where a torch four meters long lies burned, probably for religious purposes. I have found skeletal remains lying atop such burnt torches in other parts of this cave.

Still farther uphill is a large rock rubbed with seashells until white. Four giant cowry shells sit on this rock. Holes were drilled in these shells for fishing. This fishing technique is still used today in the harvesting of octopus.

One kilometer uphill is the first hidden crawl space. The Hawaiians who built these fortifications knew what they were about. Its entrance is well concealed by rubble from cave collapses in the area. From the cave the crawlway is invisible; this was

Figure 2—First fortified entrance (photo by Brad Lewis and Tom Seal).

Figure 3—Opihi shells and rock platform under three skylights (photo by Brad Lewis and Tom Seal).

accomplished in part by using a ledge that runs up the side of the tube. The rocks are fitted on each side of the passageway so that only one person at a time can fit into this narrow space. Travel must be single file through this passageway that is approximately 50 meters long. All loose rubble has been cleared to allow an easier passage.

Cold air flowing downhill leads the way uphill. At each opening out of the lava tube the sink areas are fortified (Figure 2). In the fourth of these areas are three natural skylights that illuminate another stone platform such as a heiau might have (figure 3). The platform area is divided directionally, similar to that first described.

This chamber is the most makai burial location in this cave. The skeletal remains of a small child are on a ledge adjacent to the platform area. Under what appears to be rubble is an adult burial chamber. There are skeletons of four adults, one much larger than the others.

Farther back in this area is another hidden crawl space. The same construction techniques were

used and great care was taken to conceal and camouflage the entrance.

The features of this cave system are still being discovered. Further studies will give better understanding of the people who did such an immense amount of work in fortifying and using this cave system in the Puna forest reserve. The cave runs through a Geothermal Subzone and may be harmed by further unregulated geothermal exploration.

I would like to thank Pele Defense Fund, Pali Kapu Dedman, Dr. Emit Aluli, CREADA, Brad Lewis, Tom Seal, the National Speleological Society, Sunny Seal La Plante, and Ryan and Jacob La Plante. And a special mahalo to all of the good people who work to preserve these endangered rain forests, caves, and the Hawaiian way of life.

Native Hawaiian Water Collection Systems in Lava Tubes (Caves) and Fault Cracks

Puna-Ka'u Districts, Hawaii

James F. Martin, Hawaii Volcanoes National Park,
National Park Service, U.S. Department of the Interior

Abstract

The coastal plains of the Puna and Ka'u Districts of the Island of Hawaii are a contradiction to the popular view that the Island of Hawaii is a lush tropical rain forest or a vegetated landscape with abundant water sources. This section of the island lies in the rain shadow of Mauna Loa and Kilauea Volcanoes and receives less than 30 inches of annual precipitation. When rain does come, it is in the form of sudden downpours, giving residents of the area little time to collect and conserve water. Due to the porous nature of the rock, there is no standing surface water.

In spite of these harsh climatic conditions, archaeological evidence indicates that an extensive agriculture complex existed not only along the coast, but into the most remote parts of what is called the Ka'u Desert. Passing through these agricultural areas are historic and pre-historic trail systems. These trail systems apparently played a significant supporting role for exchange between the ahupua'a (classic land divisions of Hawaii) and the geopolitical districts.

The question arises as to how could vast agricultural complexes and heavy foot travel over miles of arid land exist without dependable water sources? While planting-pits and mounds were designed to make the most efficient use of available water and conserve moisture (Carter, 1990:9), people involved in planting also needed potable water for survival. Most publications and research papers dealing with the early populations of this area make only oblique reference to springs and wells which the populations depended upon.

The Federal Cave Resource Protection Act (1988) has served as the impetus for the National Park Service to look closer at the lava tubes, caves, and fault cracks within Hawaii Volcanoes National Park. Past visitors to these underground areas found large volumes of standing water in fault cracks, and abundant drip areas within the lava tubes. Recent observers noted that in most cases, where the cracks and caves were located in the arid sections of the park, there has been extensive modification or utilization of these water sources by the early Hawaiians and others. The variety of western containers used for collection indicates that these water sources were used during historic times. William Ellis described similar water sources in his narrative of his trip around the island in 1823 (Ellis, 1979).

This report is directed at documenting recent observations and stimulating further research into early Hawaiian water collection systems. It also explores the implications that power and political influence of early chiefs in the arid portions of Hawaii could have been linked to the control of the water resources.

Historical Perspective

The area that now encompasses Hawaii Volcanoes National Park was divided into two major geopolitical districts, Ka'u and Puna. The district divisions extended from the coast, near Apua point, toward the uplands and the area of Kilauea caldera. Within these major land divisions there were numerous smaller divisions or ahupua'a. Ahupua'a were established to utilize resources from the sea to the mountains. This concept of land use provided villages with a variety of resources necessary for survival. The ahupua'a was at times divided into smaller divisions, but still keeping in mind the concept of sea to mountain resource utilization (Handy; Pukui, 1976:4). Travel between the land divisions was a regular occurrence. Prehistoric foot trails were used through the early 1900s. Foot travel gave way to horses, mules, and donkeys, resulting in well developed trail systems which crossed through different districts around the island.

It is difficult to visualize the extent of Native Hawaiian occupation of the Ka'u coast line in pre-contact days. The abundant archaeological features and pre-historic village sites indicate continuous use. During his visit, William Ellis noted that the Kealakomo village area, the remains of which are located just west of the Chain of Craters Road, was "populous, though desolate looking." While he did not record exact numbers of villagers, he estimated that 500 individuals attended religious services presented by the missionaries in the village (Ellis, 1979:188-189).

William Ellis was very aware of the lack of available water along the main trail systems in an area from South Kona to Kalapana. He noted that the first spring in 100 miles was encountered near what is now Pahala. He made a point of describing his guides' search for a cave located in the Ka'u desert where "clear water, filtered through the rocks, fell into calabashes placed there to receive it" (Ellis, 1979:170). Ellis continued to record how water was procured and its quality until he passed the village of Kealakomo (Ellis, 1979:188-189). Water continued to be a concern, even into recent times. In oral interviews with the kapuna (elders) of the Kalapana village area, reference is made to the lack of water and the need to procure it from sources in the mountains (Langlas, 1990).

Historical records and research indicate that water was a major concern. Observations were made in village sites in Ka'u that wells located near the ocean provided barely potable water (Kelly, 1969:24). The Ka'u Hawaiians placed a high value on the ability to locate potable water. The knowledge and skill needed to carry out this task was apparently so specialized that it was assigned to certain kahuna (experts in a specific practice) (Kelly, 1969:26).

The wells, caves, and cracks which have water in them seldom have trails to them. Occasionally they have fortified entrances with living spaces in the passages beyond the walls. This suggests that water was a controlled resource and its location was not offered as general knowledge.

Current Observations

There are very few documented references on Native Hawaiian water sources in the national park area. A few detailed descriptions were found in the reports of archaeological surveys of the coastal area of the park. These descriptions noted brackish water wells at village sites and an impressive crack that was located, prior to the 1989 lava flows, north of the Waha'ula Heiau. This crack contained a small lake of water approximately 12 meters long and three meters wide and between two and seven meters deep. Ala' or water worn stones had been placed at the water's edge (Carter, 1990:3).

One large cave, located in the Hilina Pali area of the park, is commonly referred to as Calabash Cave. In the early 1920s park visitors or employees found several wooden bowls or calabashes used for water collection. Located in this same area is the only other cave where detailed documentation of water collection has been made. Cleghorn and Cox (1976), in the process of describing the Hilina Pali Petroglyph Cave, gave a clear description of 50 gourd remains, a wooden bucket, and a wire bail. They recognized the significance of this site as a water collection area that was utilized into historic times. Cleghorn and Cox also conducted a small study to determine the productivity of collecting water from drip locations in caves. They found that they could collect over 630 milliliters of water a day from four drip locations. (Cleghorn and Cox, 1976).

In 1990, during field trips in designed to familiarize a select group of National Park Service managers to the diverse resources in park caves, the extent of water collection activity in the caves of the park became evident. Particular attention was given to point out subtle archaeological features which an untrained person may miss. While specif-

ically looking for manmade features in the cave, subtle rings of rock were noted along cave passages. Careful examination also disclosed remains of gourds within the rock rings, as well as an occasional shell stopper. These rings were cradles for water collection containers similar to those described by Cleghorn and Cox (1976), and were readily found in many passages. Once the staff became sensitized to this activity, water collection areas were found in virtually every cave they entered in the arid sections of the park.

The significance of water collection in caves became more evident as park employees started to explore the 'Ainahou cave system, currently the longest lava tube system known in the park. Segments of this cave system are believed to extend from the coast to the summit caldera. Over eight kilometers of these segments have been verified. A portion of the cave located below the Poli-o-Keawe Pali was described in the 1960s by a Native Hawaiian employee of the park (Hauanio, 1965-1969). He spoke of finding a cave with a walled passage and a small low entrance tunnel built through its base. He did not enter the cave.

In 1964, Colin D. Smart, while carrying out an extensive archaeological survey for the national park, described this same fortified entrance. His brief surface survey of the passage beyond the fortified entrance documented rows of rock, delineating work and living spaces, and assorted cultural items lying on the surface (Smart, 1965). His report, however, makes no mention of water collection sites.

Several National Park Service employees visited this same section of the 'Ainahou cave in 1990 after receiving a report of a vast amount of charcoal and other cultural features from visitors who had recently visited the cave. During this initial trip and subsequent visits, employees traversed over three kilometers of cave passage that had been intensely used throughout its length for water collection activities.

This segment of the 'Ainahou cave, described by Hauanio and Smart, has been called the Puna-Ka'u Water Cave. Its entrance is a double collapsed skylight into the passage. The area of the skylight contains a variety of petroglyphs and platform structures. The upslope section of the passage is blocked by a constructed wall, which initially had a single tunnel opening near its center base. This opening was about one meter high framed by a one-meter long capstone. The original entrance passage enters the interior of the cave between two constructed platforms that must be crawled

Figure 1 – The author holding a large opihi shell used by native Hawaiians as a drinking cup at a natural water catchment basin in 'Ainahou Ranch Cave, Hawaii Volcanoes National Park, Hawaii. (photo by William R. Halliday)

through, producing a highly defensive entrance. Beyond the wall, the next 30 meters of passage contain a series of low rock alignments dividing work or living areas on each side, with a center rock lined trail containing abundant charcoal and midden. This first segment ends at another constructed wall over 10 feet high that blocks a second floor chamber.

At the base of the wall, a small pit connects to a lower section of the cave. For approximately the next 1.5 kilometers, the cave is a consistent tunnel of two to three meters wide and one to three meters high. At many points along the floor of this passage, where water is dripping, constructed rock rings were found that had been used as a cradle for a gourd or calabash. In many cases the decayed remains of the gourd could be seen, as well as several shell stoppers (Hiroa, 1964:57, fig. a). In one area, water had collected in a small depression in the rock floor. At the edge of the water, a large opihi (limpet) shell was found with a drilled hole at its edge. This suggests that some sort of a fiber cord may have been attached to the shell similar to those shells which are noted in Hiroa's *Arts and Crafts of Hawaii* (Hiroa, 1964:22, fig. 8). This and other occurrences of large opihi shells associated with natural water pockets indicates that standing water sources were used by Hawaiians on-site while in the cave passages.

Charcoal and torch fragments with burnt ends were also found near most of the water collection points. In areas where occasional running water had entered the passage, large amounts of charcoal several inches deep had been deposited. The abundance of charcoal suggests frequent and continuous use of this cave passage.

After about one kilometer, the passage passes under another skylight. This entrance area has numerous petroglyphs and historic Hawaiian names carved in calligraphic type script. The skylight was modified by enlargement and with the construction of stone steps. The cave continues beyond this skylight with frequent water collection points. In the rough breakdown areas of this segment, constructed stone paths were noted. This segment finally ends in a small collapsed skylight a short distance from the face of the Poli-o-Keawe Pali.

The 'Ainahou system continues from the upper face of the escarpment in several long segments to the 1,000 meter level of Kilauea. Throughout its length, it continues to follow the Puna-Ka'u district boundary. In these upper segments, the water collection activity becomes less frequent. The exception is one segment that is entered through a large collapsed skylight containing rock alignments and abundant ti plants, both associated with living areas. The segment above this living area contains stone trails and water collection devices ranging from gourd collection containers through five gallon cans with the tops cut off, coffee cans, and remains of wood barrels. The abundance and variety of water collection devices in this area suggests that this was a major water source well into the early 1900s when cattle ranching occurred in the area that is now the national park. These observations of water collection activities in the lower sections of the 'Ainahou cave system suggest that it provided Keauhou, one of the largest ahupua'a on the Island of Hawaii, with dependable water for its populations in the arid costal area.

As Handy and Pukui (1976) noted, the ahupua'a system of land use provided the Hawaiians a method of dividing control of an area or island while still providing the basic needs of subsistence for each group. Potable water, like fish and woodland products, was also a necessary resource for survival. This suggests that in arid sections of the island, the population and political strength of an ahupua'a could be strongly influenced by control of a dependable water source such as the 'Ainahou cave.

The Native Hawaiian water collection features in the 'Ainahou cave system represent just one of numerous culturally significant activities which have been associated with the cave. The passages also contain hearths, petroglyphs, and living areas which have not yet been examined. The abundance of the cultural features found in this cave, as well as the numerous biological and geological features, indicates that the cave systems in the national park may be untapped sources of knowledge of the biological, geological, and historic past of Hawaii. It is imperative that as the National Park Service proceeds to identify, map, and inventory these delicate resources, extreme care be taken by all to preserve these "time capsules" of the island of Hawaii and its people.

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Lava Tube Systems of the Hilina Pali Area, Ka'u District, Hawaii

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Hawaii Speleological Survey

Abstract

Two lava tube systems have been investigated in lavas of the Kilauea volcano in the Hilina Pali area, Ka'u Desert, Island of Hawaii. The longer one is the Charcoal Cave System, composed of four caves, with a total mapped length of over 1,500 meters. It is the central feeding tube of a clearly outlined flow lobe probably belonging to the Kalue flow group (500-750 yr BP). The Earthquake Cave System is a canyonlike tube, mapped for 338 meters, running perpendicular to the pali. It probably belongs to the lavas of the Kipuka Nene flow group (1,000-1,500 yr BP). It is not associated with a flow lobe and must have attained its large depth (six meters) by erosion into the underlying strata. This conclusion is substantiated by the fact that a soil layer is exposed in the walls of the cave. Both cave systems were modified not only by extensive breakdown, but also by aeolian and fluvial ash deposits which fill cave entrances and which clog passages.

Introduction

Lava tube caves are a common phenomenon within the pahoehoe lavas of the Mauna Loa and Kilauea volcanoes on the Island of Hawaii. The world-wide longest mapped tube system, Kazumura Cave (e.g., Wood, 1980), is developed in lavas which flowed from the Kilauea summit caldera eastwards, 350 to 550 years ago. Many other caves are known to rangers, residents, speleologists, geologists, biologists, and archaeologists, but apart from cave descriptions in the speleological literature little has been done to study their geology and speleogenesis systematically.

This paper deals with the tubes of the Hilina Pali area located within the Hawaii Volcanoes National Park. The area is situated in the center of the Ka'u Desert Quadrangle of the 7.5 minute series U.S. Geological Survey topographic map (*circa* 1918'N and 15519'W). The area is called Kipuka Keana Bihopa, i.e. the vegetation island (kipuka) of Bishops (a family name) Cave (keana). It is not quite clear whether the term keana designates one of the cave systems described later (Charcoal Cave System ?) or a cave system as yet undiscovered or one of the large breakout scars along the pali (where the term Keana Bihopa appears again in small print on the topographic map). The most important surface features of the study area are given in Figure 1. They are based on color aerial photographs taken 1988 and were made available to the authors by James F. Martin, chief ranger of the Hawaii Volcanoes National Park.

It should be noted that access to the described caves is regulated in order to protect them and they may be entered only with a valid caving permit from the National Park Service.

Geological Setting of the Hilina Pali Area

The Hilina Pali is an escarpment which is a series of west-southwest to east-northeast striking, nearly vertical, high angle slip faults south of the Kilauea caldera. They are reached by the Hilina Pali road of the Hawaii Volcanoes National Park which ends at a shelter at 700 meters above sea level overlooking the faults (Figure 1, P at end of

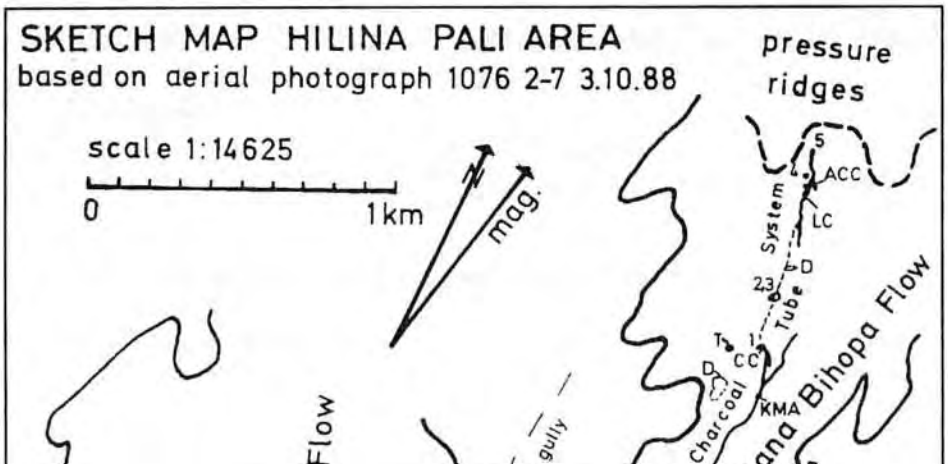


Figure 1—Sketch map of the Hilina Pali area giving flow lobe boundaries according to aerial photographs and lava tubes according to own surveys. Abbreviations: P = pullouts, D = dunes of Keanakakoi ash, T = tumulus, KMA = Entrance of Keana Momoku Ahi (Charcoal Cave), CC = Entrance of Calabash Cave, LC = Entrance of Ledge Cave, ACC = Entrance of Ash Crawl Cave, number 1-5: aeolian ash plugs sustaining kipukas, UEC = Upper Earthquake Cave, EC = Earthquake Cave, LEC = Lower Earthquake Cave.

road). Along the pali (the fault) the seaward block has subsided several hundred meters (maximum 550 meters) exposing the oldest accessible rocks of the Kilauea volcano edifice. Table 1 shows the local idealized stratigraphy as derived from the publications of Rubin *et al.*, 1987, Holcomb, 1987 and Easton, 1987. The lower sequence of caldera basalts (Hilina Basalt, 100 meters thick) is capped by the Pahala ash (nine meters thick) which must have been deposited before the major movements of the faults occurred. Radiocarbon dating shows that the ash was deposited between 11,000 and 25,000 years Before Present (yr BP). On top of the ash, thin members of the Holocene Puna Basalt series were deposited. These members are separated by soil and/or ash layers, 4,800, 3,500 and 1,130 (Uwekahuna ash) years old (Rubin *et al.*, 1987; Easton, 1987). The latest ash is covering the surface in the Hilina Pali area partially and belongs to the historic 1790 A.D. ash eruption of Kilauea (Keanakakoi member).

This seemingly simple stratigraphy becomes complicated as soon as one tries to assign dates to certain lava flows at the surface. In the paper of Holcomb (Figure 12.5 D), the Kipuka Nene flows and the surface of the lava at the end of the Hilina Pali road are grouped into different time slices (i.e. 1,000 to 1,500 yr BP versus 1,500 to 10,000 yr BP, respectively). Furthermore Holcomb puts the Uwekahuna ash into the latter time slice even though the ^{14}C date (W 3827, collector J. Lockwood; Rubin *et al.*, 1987) suggest an age of only 1,130±60 years as correctly cited in Easton's Figure 11.14. We therefore reinterpreted the stratigraphy using the published ^{14}C dates and suggest that the Kipuka Nene flows (dated with sample W5135 to 1,150±70 years, collector N.G. Banks; Rubin *et al.*, 1987) and the surface around the end of the Hilina Pali road belong to the same group of flows roughly 1,100

years old (not withstanding the fact, that older strata outcrop at the brink of the pali). To the north of the Hilina Pali shelter a large lobe (termed East Keana Bihopa Flow in Figure 1) transgresses the older flows. Holcomb groups this lobe with the Kalue flows which separate the Hilina Pali and the Kipuka Nene areas. The Kalue flow is not well dated and Holcomb suggests an age of 500 to 750 years. To the west of the Hilina Pali shelter another lobe extends almost to the brink of the Pali (termed West Keana Bihopa Flow in Figure 1). Holcomb groups it with the 250-350 years old Observatory Flows. However, Holcomb overlooks two ^{14}C dates which may indicate that this lobe is older, i.e. the samples W 5152 = 660±70 yr BP and W4402 = 700±70 yr BP (collector N.G. Banks; Rubin *et al.*, 1987, Figure 10. 5). The description of site W4402, (325 meters west of the Hilina Pali shelter) suggests that it may have been collected from under the eastern rim of the West Keana Bihopa Flow (Figure 1). The West Keana Bihopa Flow could therefore be also of the age of the Kalue flow group, i.e. 700 years old. The appearance of the east and west Keana Bihopa Flows on the aerial photographs is rather similar in color, surface structure and with regard to the thin rim of vegetation (which probably taps the water reservoir provided by the heat-cracked lava beneath the flow rims). They could therefore very well be of the same age.

Description of Tube Systems

Within the area three tube systems exist, two of which are accessible and have been mapped in detail. These are the caves within the East Keana Bihopa Flow collectively called Charcoal Cave System and the Earthquake Cave System east of the Hilina Pali shelter (Figure 1). A third system exists west of the West Keana Bihopa Flow. On the aerial photograph we noticed a breakdown hole (puka) shortly north of the Ka'u Desert Trail (Rain Puka, Figure 1). S. Werner and S. Kempe explored it July 13, 1991, but found that the underlying tube cannot be entered. The tube must be rather deeply seated and is buried in breakdown both upslope and downslope. On the aerial photographs no other pukas were noticed which could give access to this tube. Also in the center of the West Keana Bihopa Flow lobe no entrances were noted on the aerial photographs and none are known from surface excursions even though this lobe potentially contains a tube system.

Table 2 compares the speleological data of the two systems mapped. The Charcoal System is the longer of the two, but its gradient is less than that of the Earthquake System. The Charcoal Systems follows the center of the East Keana Bihopa Flow throughout most of the length of the lobe (Figure 1). Four caves and at least five ash-plugged breakdown holes (marked 1 to 5 in Figure 1) belong to the system. The presumed vertical section of the system is given in Figure 2. The ash-plugged pukas keep water in their thick ash deposits which therefore carry isolated stands of ohia trees and are visible as small kipukas on the aerial photographs. At least two dunes and the only large tumulus on the lobe also carry isolated stands of trees so that

Years BP	Member	Thickness (m)
1790 A.D.	Keanakakoi Ash	0 to > 2
700	Kalue Flows (including Keana Bihopa Lobe)	0 to 8
1,100	Kipuka Nene Flows (Including Earthquake Tube System)	2
1,130	Uwekahuna Ash	0.2
3,500	Puna Basalt	2
3,500	Soil	0.1 to 0.3
4,800	Puna Basalt	5
4,800	Ash on Top of Soil	1.5
10,700	Puna Basalt	4
11,000-25,000	Pahala Ash	9

Table 1: Stratigraphy of the Hilina Pali area (revised according to Holcomb, 1987 and Easton, 1987).

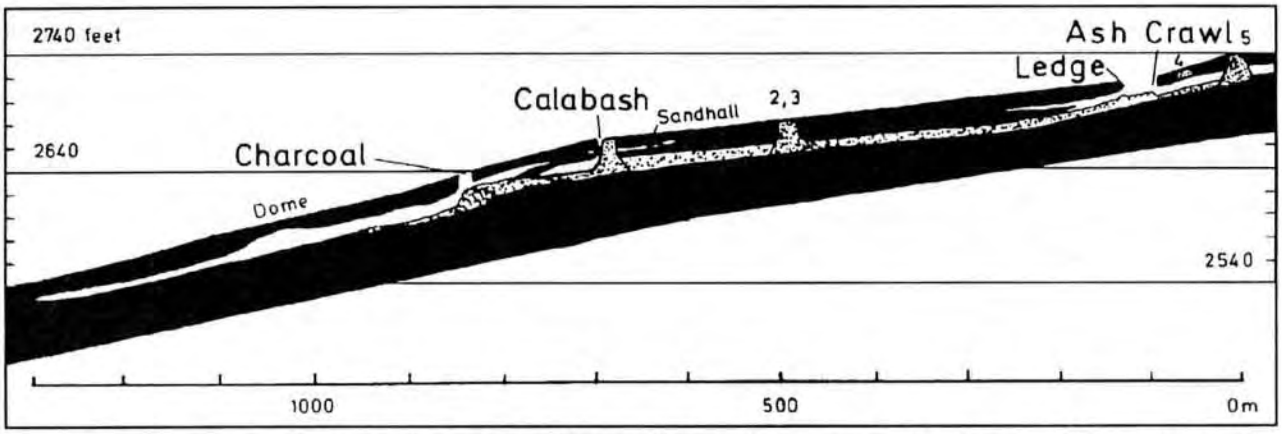


Figure 2—Longitudinal profile through the Charcoal Cave System in the East Keana Bihopa Flow lobe indicating entrances, main passages and ash deposits. Elevation of surface is according to topo map, sheet Ka'u Desert. Depth and size of caves are schematic only.

trees as such are not an infallible sign of buried tubes.

The East Keana Bihopa Flow is superimposed upslope by another flow lobe which is characterized by many large pressure ridges (tumuli). Shortly below, we encounter the first evidence of the East Keana Bihopa Flow tube system, an ash filled breakdown hole (No. 5, Figure 1). It is accessible underground in Ash Crawl Cave (Figure 3). The total mapped length of Ash Crawl Cave is 117 meters, with a horizontal extension of 100 meters. It is entered through the upslope opening of an elongated shallow breakdown feature. The crawl on ash leads to a passage which turns back (The Delta) and ends in a fluvial ash plug. Upslope the ash-floored passage encounters breakdown before the passage opens up to standing height (Dining Hall), the end of which is formed by the ash cone

Parameter	Charcoal Cave System	Earthquake Cave System
horizontal extension (m)	> 1,300	> 400
mapped (m)	1,500	338
elevation (feet)	2,740 to 2,540	2,300 to 2,200
vertical extension (m)	60	33
gradient	1⁄22 (2.6°)	1⁄12 (4.7°)
age of flow (years yr BP)	700 (?)	1,100 (?)
total number of caves	4 Charcoal C. Calabash C. Ledge C. Ash Crawl C.	3 Upper EC EC Lower EC
system	braided, tributary	single canyon
archaeological remains	stone settings charcoal	none
destruction	aeolian ash plugs, fluvial ash plugs, breakdown	fluvial ash plug, breakdown, ponds during floods

Table 2: Comparison of speleological data for the two tube systems mapped.

of plug 5. The cave must continue upslope beyond the obstruction.

Plug 4 is encountered north of the entrance breakdown hole illustrating that a passage (marked by plug 4 and the entrance sinkhole) parallel to Ash Crawl Cave must exist. It continues downslope as Ledge Cave (Figure 4) from the southern end of the elongated entrance sinkhole. Ledge Cave can be followed for 171 meters downslope and has a total length of 185 meters. The entrance is a low, wide crawl on fluvially deposited ash, then one has to squirm through breakdown before a walking size tube is encountered. The pahoehoe floor becomes visible under a shallow ash cover and ledges accompany the sides. In Ledge Room, the tube splits. The main passage is blocked by a fluvial ash plug, the side passage, a slightly elevated older overflow, is free of ash. The passage decreases in size and contains pahoehoe flow features, rafted blocks and magnificent lava formations. These stalagmites and stalactites show that hot gas flowed through the tube and could have caused partial melting at the ceiling of the tube, probably while the main passage still conducted lava (flowing at a level below the ledges). The side tube ends in loose breakdown, but an airdraft indicates that the cave continues. Bits of charcoal show that Polynesian explorers have visited this cave as far as Candle City. Torches have been cleaned on a block in Ledge Room. No charcoal was found in Ash Crawl Cave. However, recent fluvial ash layers may have covered any remains of prehistoric visitors.

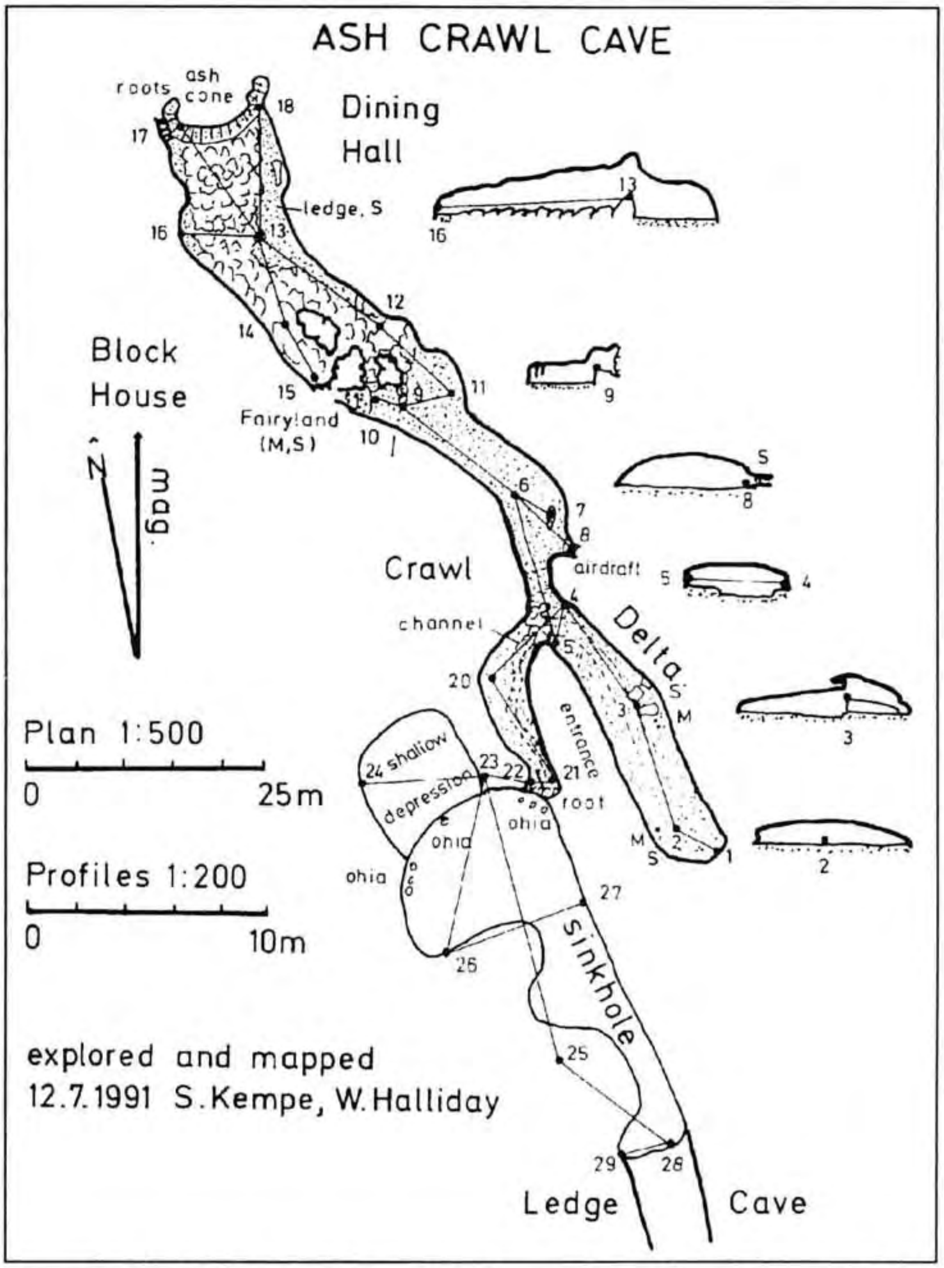


Figure 3—Map of Ash Crawl Cave, East Keana Bihopa Flow, Hilina Pali, Ka'u District, Island of Hawaii. M = lava stalagmites, S = lava stalactites.

The tubes in the upper part of the East Keana Bihopa Flow are all near the surface, the roof is not more than one or two meters thick, the size of the passages is moderate, wider than high and often trapezoid or rectangular in cross-section. Several passages appear to have developed parallel to each other.

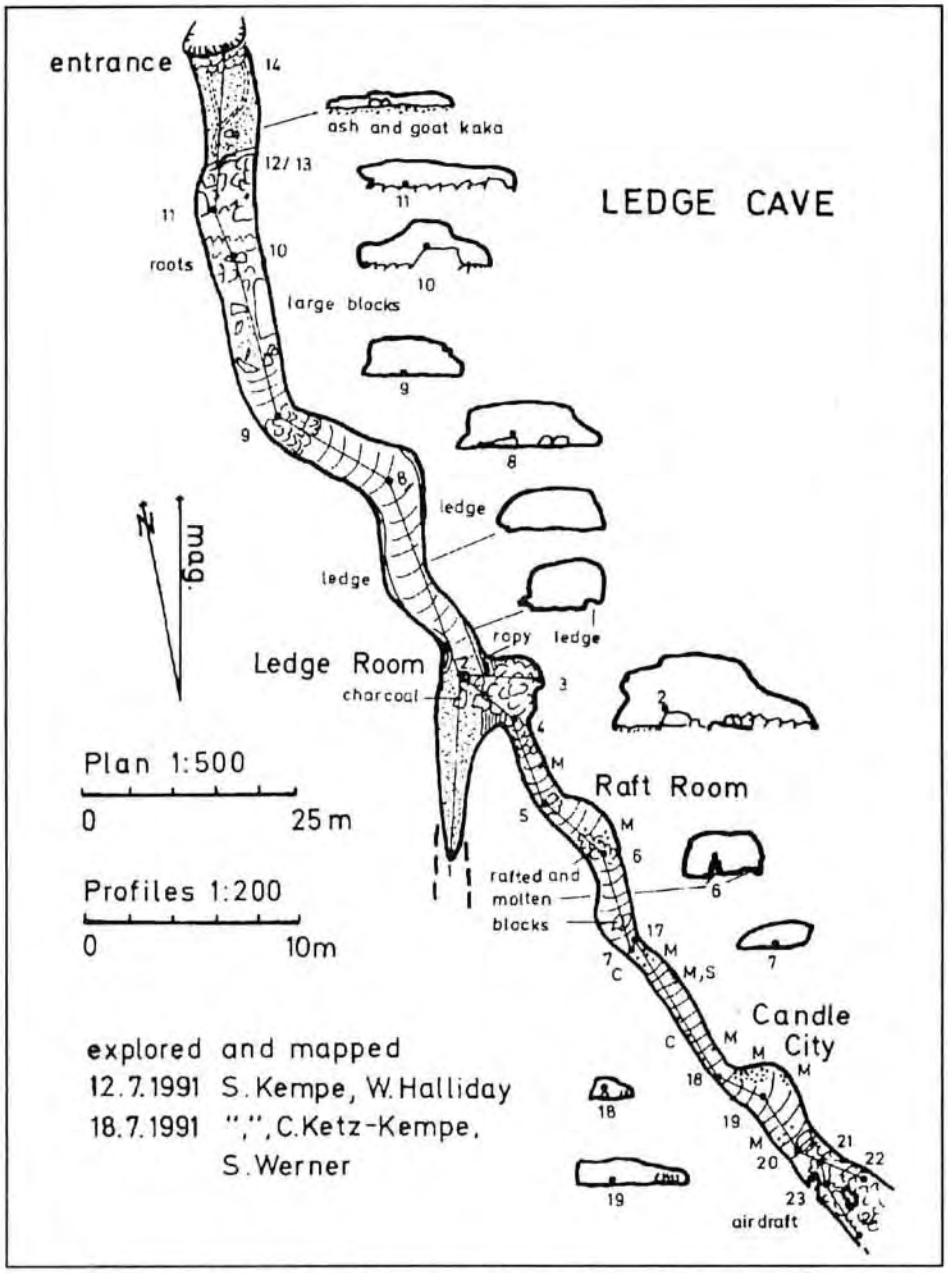


Figure 4—Map of Ledge Cave, East Keana Bihopa Flow, Hilina Pali, Ka'u District, Island of Hawaii. M = lava stalagmites, S = lava stalactites, C = charcoal.

The next few hundred meters of the tube system cannot be followed underground, but the ash-plugged twin breakdown holes 2 and 3 show that the cave continues with a wide passage. The next ash-plugged breakdown hole (No. 1) downslope has partly been eroded and provides access to Calabash Cave, the beginning of the Charcoal Cave System (Kempe and Ketz-Kempe, 1979). Here we encounter a huge passage which, after 80 meters, is clogged by fluvial ash (Figure 6). On an elevated and ash-free loop, stone settings were found which were used to hold drip water collecting calabashes. A few piled-up stones served as stepping stones up the ledge. In the ceiling a very narrow near-surface tube is intersected, a nasty belly crawl interconnecting with the Charcoal Cave (Keana Momoku Ahi) proper. The cave system has been mapped (1978) by the authors and was described in detail already. The map published here does however include the L-series passage below Junction Hall mapped December 9, 1988, by S. Kempe and G. Landmann.

The entrance hole of the Keana Momoku Ahi is planted with ti (a Polynesian plant with large leaves which spreads only by planting), shaded by a few ohia trees and offers the most spectacular entrance setting in the area. Downslope it gives access to the same large tube as in Calabash Cave. Upslope however, the fluvial ash is ponded behind the breakdown pile clogging the main passage completely. The breakdown occurred at a place where three tubes met, (i) the large trunk passage, now filled with ash, (ii) the belly crawl connecting from Calabash Cave and (iii) a small tributary upslope tube. This tube can be followed for more than 250 meters upslope before it ends in breakdown. In Sand Hall a small ash cone enters through an inconspicuous hole, showing that this tube runs near the surface. It may be the same tube as encountered in the Candle City passage in Ledge Cave, but actual proof for this hypothesis cannot be offered. Below

the Keana Momoku Ahi entrance the tube is six meters high and four meters wide and gives the impression of a gently meandering canyon. Washed-in ash covers the floor. Throughout the next 300 meters the trunk tube is accompanied mostly by narrow side tubes. The trunk opens up into the enormous Dome of Darkness which is 50 meters long, 12 meters wide and 6 meters high and is littered with large breakdown blocks. Beyond the dome the pahoehoe floor becomes accessible for the first time. Behind Junction Hall breakdown blocks the passage. Only a nasty crawl or a climb up into an intersected loop gives access to the lower section of the tube. The loop features stalagmites. Again they must have formed while the deeper main tube was still active so that rising heat could cause partial melting at the roof in the drained loop. The cave continues for another 250 meters (L-series). But it is now much smaller, hardly walking size and the ceiling becomes low toward the end leaving just a few centimeters for air to pass. The floor is composed of clinkery pahoehoe, grading into small aa blocks. Charcoal is found as far as behind Junction Hall, but the L-series was never entered by Polynesian explorers.

The accessible tube ends 450 meters above the lowest tip of the East Keana Bihopa Flow. Its central position in the flow lobe shows that it must be in fact the main feeding tube for the flow.

The East Keana Bihopa Flow transgresses on older lava (Kipuka Nene Series). The surface is composed of both aa and pahoehoe flows. The pahoehoe is visibly more deeply weathered than on the East Keana Bihopa Flow. Enough vegetation exists on the surface of this lava so that it was able to hold wind-driven ash of the Keanakakoi member. Today the plain is grown with exotic (i.e. post-Cook imports) grasses and a few ohia tress, most of which were burnt in a fire some years ago. This portion of the Kipuka has the appearance of a savanna. The ash cover is eroded along stream channels. During the depression in the 1930s, public works programs were used to fortify the ash against further erosion. Stones line the gullies keeping the ash from being washed into the stream. Many small dams were erected from local stones, some of which have been washed away already, evidence of occasional torrential rain storms during the last fifty years in this otherwise rather dry section of Hawaii.

In one of these streams a hole, 2.1 × 1.8 meters wide, opens up into the Upper Earthquake Cave (Figure 5). It is a 38-meter-long section of a canyon type tube, closed to our dismay upslope by break-

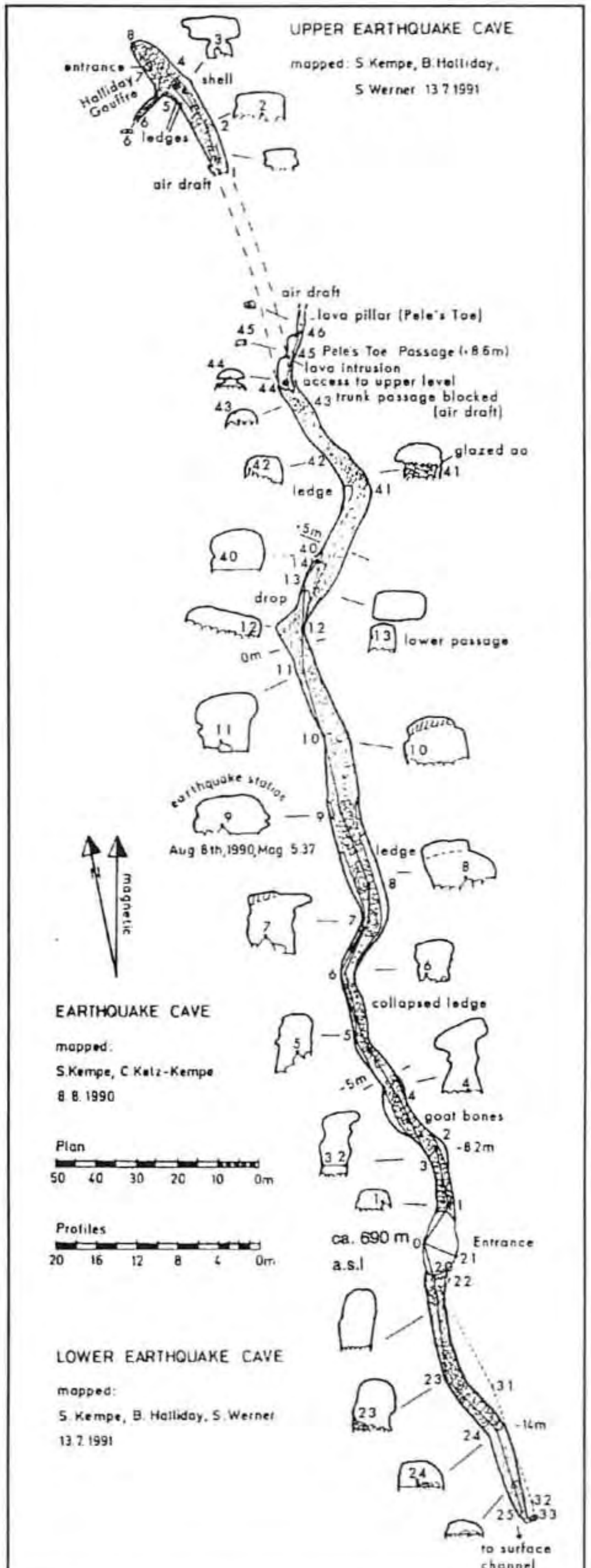


Figure 5 – Map of Earthquake Cave Tube System, Hilini Pali, Ka'u District, Hawaii.

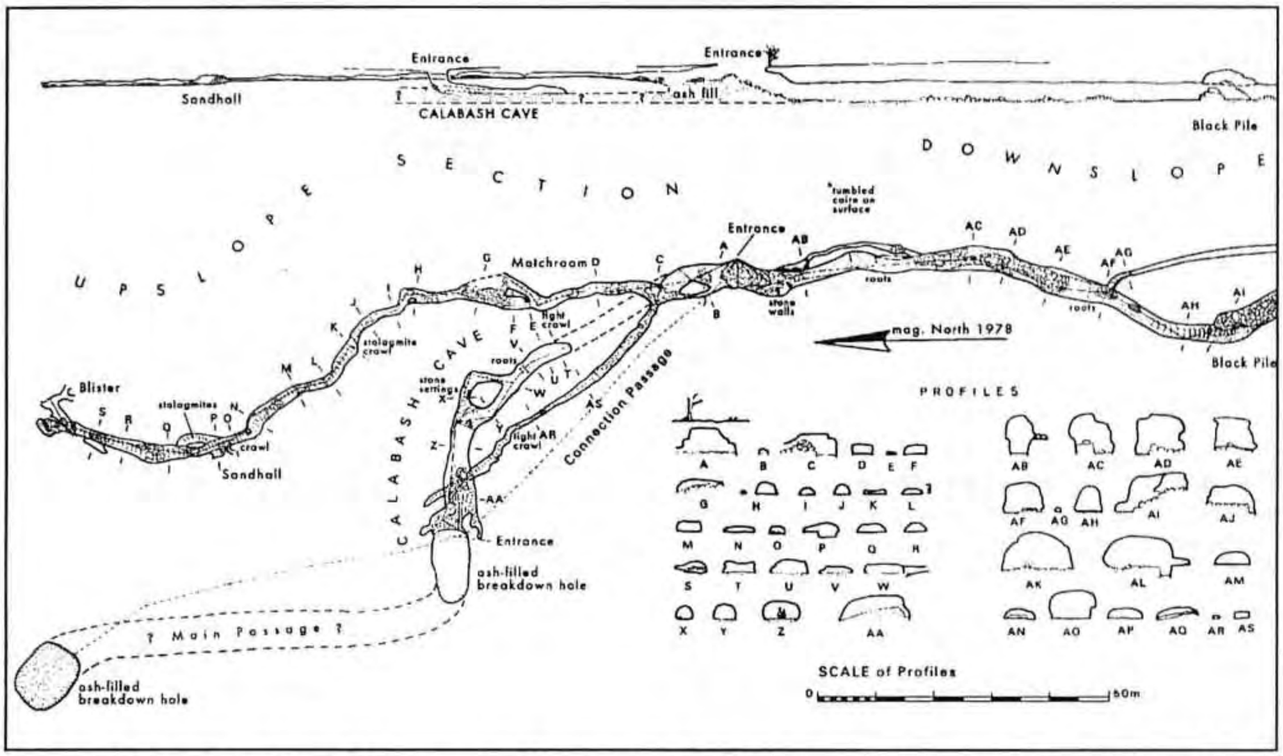


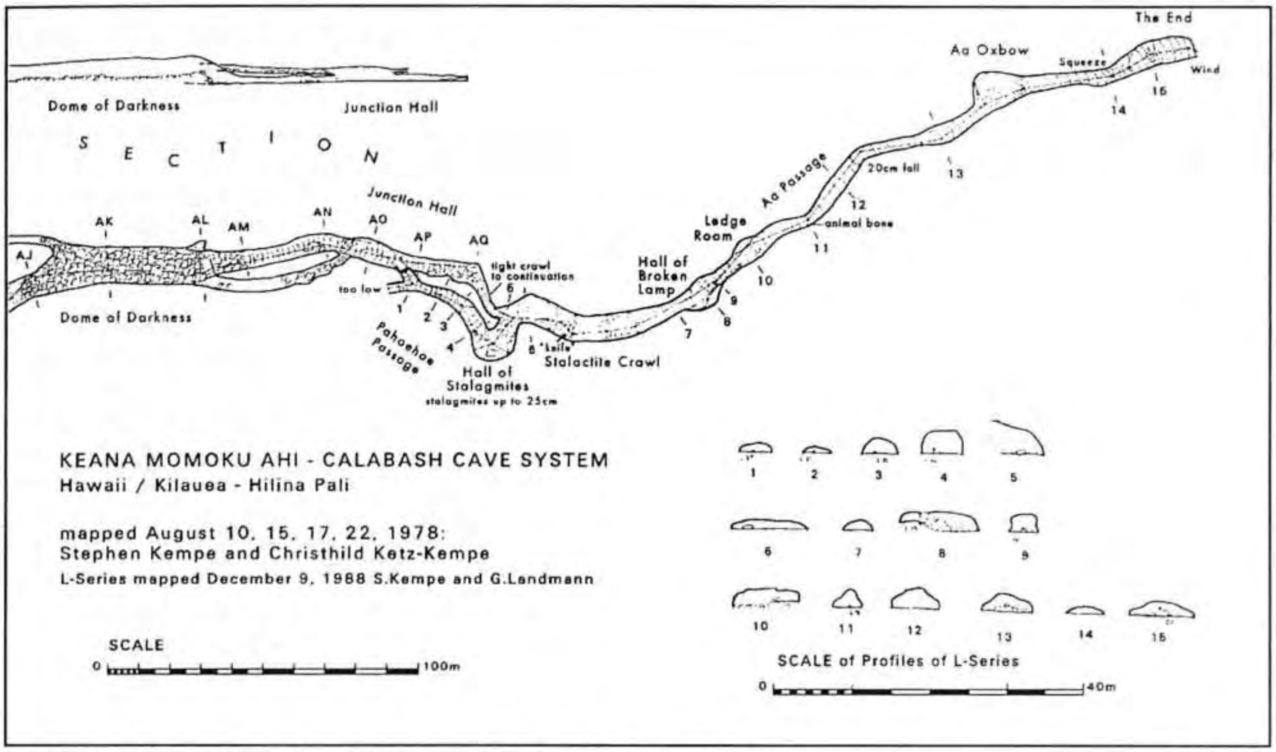
Figure 6—Map of the Keana Momoku Ahi (Charcoal)—Calabash Cave System, East Keana Bihopa Flow, Hilina Pali, Ka'u District, Island of Hawaii. Compared with the map published by Kempe & Ketz-Kempe

down. Downslope the tube is also closed by breakdown, but another, larger breakdown hole, *circa* 200 meters southwest of the Hilina Pali shelter, gives access to the same tube system. Upslope the Earthquake Cave extends for 228 meters, ending a few dozen meters below Upper Earthquake Cave. The passages is mostly higher (up to six meters) than wide with a canyonlike appearance and a meandering course. The cave is characterized by intensive breakdown from ceiling and walls, the original floor is only rarely seen. Evidence of washed-in plant material and charcoal shows that the cave floods more or less completely during rain storms, serving as a pseudokarst drain. Downslope, the Lower Earthquake Cave can be followed for 64 meters before the canyon is clogged by a deep fluvial ash plug. Beyond, the tube is discontinued and the lava entered into an open trench before it plunged over the pali several hundred meters down. An extended description of the cave is found in our paper, this volume.

Speleological Conclusions

The two cave system are quite different. The Charcoal System features parallel tubes—up to three in the section between Calabash Cave and Keana Momoku Ahi—while the Earthquake System consists of only one tube. The Charcoal System is clearly associated with a large flow lobe and appears to diminish in size towards the end of the lobe. The flow lobe has a height of three to five meters above the surrounding terrain and shows convex isohypses on the topographical map. In short, the Charcoal System is at a position where one would expect a tube.

In contrast, the Earthquake tube is not associated with any recognizable flow lobe and appears to have served as a fast lava transport route toward the pali without much local lava buildup. In fact, even today a stream gully follows roughly its course, underscoring nicely the missing buildup which should have deflected any stream course to the side of the tube position. At the pali, no lava strata are visible with a thickness comparable to the depth of the Earthquake Cave. One can only conclude that the Earthquake tube must have cut downward into the older Puna Basalts in order to obtain the clearly canyonlike character. There is further evidence of this hypothesis in the cave. Where the vertically layered wall lining fell away, one can clearly see thick horizontally stratified lava



(1979) this map includes the lowermost L-series. Note that the cross-sections of the L-series are plotted in a different scale than the other cross-sections.

beds, a structure unlike what one would expect in a tube which was formed by levee buildup and roofing. In fact, in Lower Earthquake Cave an oxidized clayey soil layer is exposed between horizontal lava beds. Clearly such a layer cannot be an integral part of a pahoehoe flow. The existence of this soil layer also shows that the tube was not a streambed canyon which was just incidentally occupied by the lava and roofed over. In a watercourse, the soft material of the former soil would have been removed by lateral erosion. In a downcutting lava flow, material not hot enough to be remelted cannot be easily eroded, in fact it could be more difficult to erode a wet soil thermally than solid lava. Figure 7B shows how the observed soil may fit into the local stratigraphy and how far the tube probably cut down into older strata. Clearly more dating has to be done before both the age of the Earthquake Cave flow and the local stratigraphy can be resolved. The outcrops in the caves may, however, provide a place to look for suitable ^{14}C samples.

With this discussion in mind, let us consider the trunk passage of the Charcoal System once more. At the Keana Momoku Ahi entrance the roof has a thickness of four to six meters and the passage a

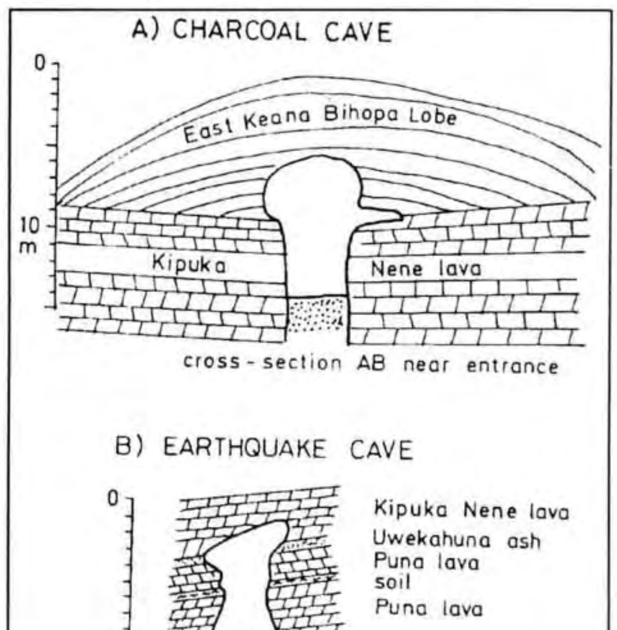


Figure 7—Conceptual models of the stratigraphic situation of the canyonlike sections of the two cave systems illustrating the downcutting of the lava flow into older rocks.

depth of six to seven meters. This is clearly more than the apparent topographic thickness of the flow lobe. One must therefore conclude that this canyonlike passage was also cut down into older strata. Along the walls horizontal shelves protrude, suggesting exposures of older lava layers. Figure 7A shows how the cross-section of the Keana Momoku Ahi could be interpreted geologically. The question remains, if the downcutting occured only locally (where for example the preexisting surface gradient increased, compare the increase in gradient at about the position of the Calabash Cave in Figure 2), or if the tube developed a voluminous "trunk type" passage throughout. If this were the case, then the near-surface and narrow upslope branches of the Charcoal System (i.e., Ash Crawl Cave and Ledge Cave) cannot be identical with the Charcoal trunk. Rather another tube must be assumed not accessible or deeply buried by ash extending upslope of ash plugs 2 and 3.

The two cave systems have another interesting feature: their ash plugs. Principally two kinds exist (Figure 8), plugs caused by aeolian deposition and plugs caused by fluvial deposition.

The aeolian plug is probably quickly deposited. Wind blowing over a breakdown pit deposits its dust load easily into this "sediment trap" because turbulence would not be high enough to carry any

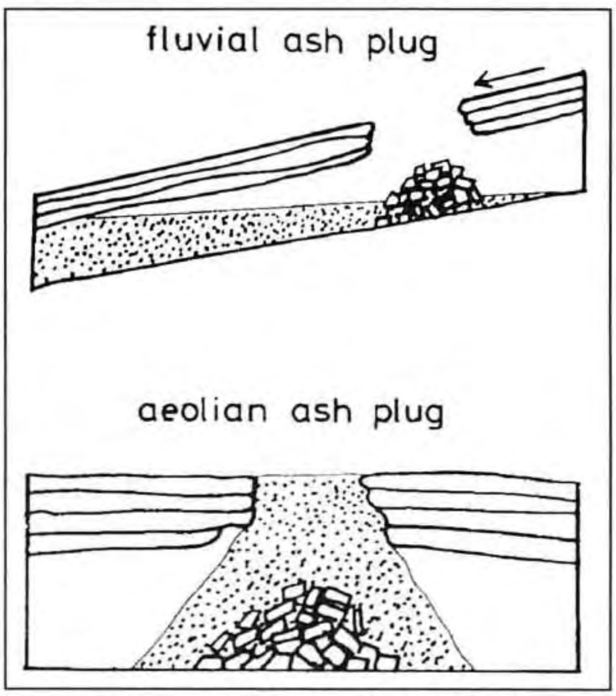


Figure 8 – Scheme of the two different kinds of ash plugs encountered in the Charcoal System.

particle out of the pit again. The dust is driven over the lip of the pit, progressively building a steep cone until the other side of the pit is reached and further deposition stops. Such steep ash slopes can be seen in the Dining Hall of Ash Crawl Cave, in Sand Hall of the Keana Momoku Ahi and in the entrance sink of the Calabash Cave. Aeolian plugs can only occur if enough loose ash is available such as after the 1790 eruption producing the Keanakakoi ash. The ash plugs therefore serve as time markers. Only those breakdown holes which were open before 1790, could be closed by the Keanakakoi ash. Considering the amount of ash available after the eruption, one must conclude that all pits older than 1790 were probably filled while those breakdown holes open today must be younger than 200 years (i.e. the Keana Momoku Ahi entrance, the Ash Crawl Cave and Ledge Cave entrance and both the Earthquake Cave entrances). An exception is the entrance to Calabash Cave where fluvial erosion of the aeolian ash plug has reopened the entrance to this cave.

Fluvial ash plugs appear in Ash Crawl Cave, Ledge Cave, Calabash Cave, Keana Momoku Ahi and Lower Earthquake Cave. They need water as a transport medium. Fluvially transported ash tends to form horizontal deposits which in places may reach the ceiling of the cave sealing it. Since running water is scarce in the Hilina Pali area – available only once every several years during rainstorms – fluvial ash plugs need a longer time to develop. The fluvial plugs we see today therefore must be younger than 200 years. For archaeologists this possibility to date deposits opens up an interesting perspective: could the now closed trunk section of Charcoal Cave above plug 2 and 3 contain untouched prehistoric remains?

Acknowledgements

We thank Jim Martin (Hawaii Volcanoes National Park) for making this study possible. He granted the research permits and provided us with the newest aerial photographs. We also thank Bill Halliday, Spike Werner, and Günter Landmann for their enthusiastic help in mapping the various caves. We even more appreciated the good company and the friendship which Sis and Bill Halliday, Carol and Spike Werner, and Martha and Jack Lockwood gave during our various stays on Hawaii. Martha and Jack Lockwood furthermore hosted us several times and introduced us to the Volcano Village community. Without Jack's en-

couragement and volcanological advice the present paper would not have been written.

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Lava Features of Olaa Cave, Hawaii

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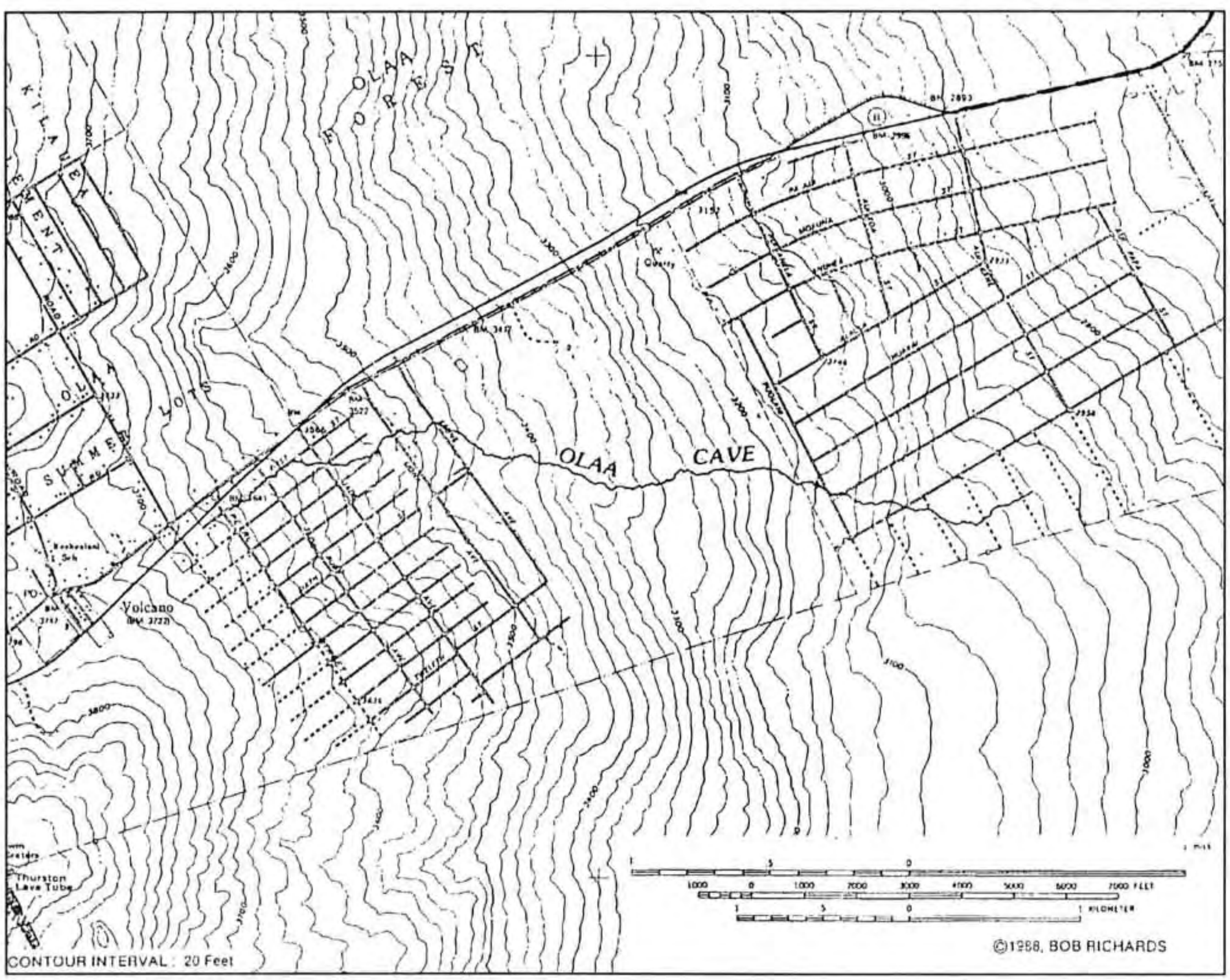
Abstract

Olaa Cave lies in a prehistoric flow that eminated from Kiluea Iki. Up to four levels of development have been noted, and 6.07 kilometers have been surveyed in the lower level. Total vertical extent is 221 meters. Prominent features of the cave include numerous lava falls up to 15 meters in height, lava lakes, a three-meter-high lava stalagmite, and invasion by newer lava flows.



Impact of Richter 6.1 Temblor Upon Malama Cave, Puna District, Hawaii, Hawaii: An Insider's View

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Abstract

In June 1989, the author was 50 feet into Malama Cave when the earthquake struck. The cave is located in the eastern rift of Kilauea Volcano, a zone of multiple crustal fractures and lava resurgences. Malama Cave is a concatenation of hollow spatter cones with several skylights opening through their mouths. This paper describes the events which took place during the 15-second seismic occurrence.

On June 25, 1989, at 17:00, Malama Cave was entered by Marlin Spike Werner and three companions, Sadanand Singh; his wife, Angie; and 10-year-old son, Samir.

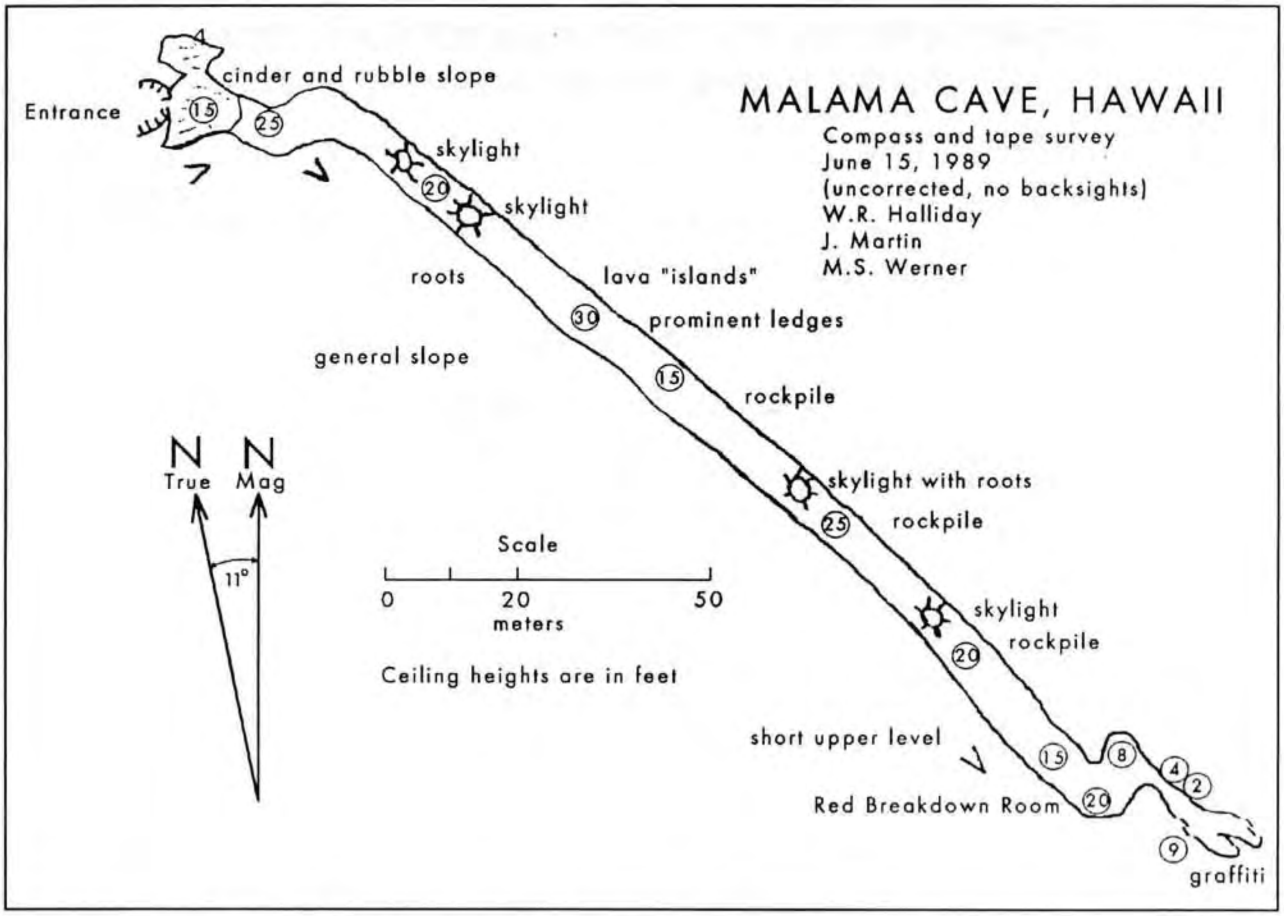
Malama Cave is located in the northeast rift zone, not far from the recently closed Pilot Geothermal Plant in the Puna District of the Island of Hawaii. The entrance to the cave is at the margin of Malama Avenue. The surrounding terrain is one of complex pseudokarst, clinkers, and tangled overgrowth of climbing fern, ohia, and ha'u. The subject cave appears to be a concatenation of hollow spatter cones, each bell-like in cross section. The deepest human penetration is probably limited to 150 feet.

The investigators picked their way carefully down the steep talus to a floor of pahoehoe, approximately 40 feet below the entrance threshold and 12 meters further in. One of the spattercones afforded a skylight at its apex, another 15 meters further down passage. Werner had placed a propane lamp at the floor and was offering Mrs. Singh assistance when the circumstances of the exploration were altered by several swift-moving events. About 15 feet in from the entrance, Sadanand Singh was bringing up the rear. Mrs. Singh was about ⅔ down-slope, and Samir was standing by the video-camera and the propane lamp at the bottom. Mrs. Caroline Werner and Kalpana Singh occupied the front seat of the Werner car, the Singh's rented car parked just ahead. The sun was shining, and several birds were resting on the wires of the telephone line that passed seven meters overhead.

Werner was reaching out to offer Mrs. Singh a hand when the floor – no – the whole setting, people, floor, walls, contained air – moved upward, forward, downward, backward, upward, forward, downward, backward, upward. . . The motion appeared to be in alignment with the axis of the cave. The air seemed to huff and puff. An irregular boulder weighing 300 pounds or more seemed to rise slowly from the talus, tilt downslope, and flop. Mrs. Singh was saying something about "Holy Jesus, Mother Mary," when Werner took her hand and said, "It's alright," – an admitted lie.

From the entrance, Sadanand called, "Samir, run," and the boy's velocity in passing was approximately 1.5 meters per second. Werner looked upward at walls and ceiling. Previous rockfalls attested to the shedding of secondary accretions – hints of rockfalls to come. A sinuous curtain of dust rained from a narrow crack which ran from the entrance to the skylight. The boulder languidly rose, teetered forward, and flopped again. Werner stood with one foot up-slope so that his stance was aligned with the axis of the cave. With each displacement of the floor his center of gravity was shifted up, left, down, right, up, left. . . Was Malama slipping into the sea?

The occupants of the Werner car watched in horror as the Singh's rented automobile began to pitch from side to side, the telephone poles whipping back and forth, their wires whistling overhead. The birds emitted something unquotable. Mrs. Werner tried to open her car door only to have



it thrown back at her. Kalpana shouted, "Daddy!" Meanwhile the slothful boulder in the cave heaved one more time, teetered, and flopped on its face to rest at Werner's feet.

The magnitude of the temblor was R = 6.1. The epicenter was 19°22'N × 155°05'W, and the hypocenter was at 9.4 kilometers (data supplied by Hawaii Volcanoes Observatory staff). The distance from the epicenter to the cave is approximately 3.17 kilometers. Although the angle of incidence at which the temblor encountered the cave was about 90°, lack of data as to senses and ranges of oscillatory displacement and planes of acceleration places limits on our evaluation of the events experienced.

In Conclusion

The participants discussed the above events. Samir suggested that the duration of the quake was three minutes. The seismologist at the Hawaii Volcanoes Observatory said the duration was subjective, and anybody's guess. Angie suggested, "maybe four minutes." By counting the seconds, one-one-thousand-two. . . the group concluded that the experience had a duration of approximately 14 seemingly interminable seconds. Risking the possibility of an aftershock, Werner returned to the cave to retrieve his video-camera and propane lamp – without incident.

Underground Observations During the Pu'u O'o Earthquake, 4:06 P.M., August 8, 1990

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Abstract

On August 8, 1990, at 4.06 P.M., we experienced an earthquake of amplitude magnitude 4.7 in a lava tube of the Hilina Pali area, Kilauea, Ka'u District, Hawaii. The epicenter was 25 kilometers away from the cave. At the moment of the quake, Christhild was sitting on rocks, clearly feeling them moving underneath her, while Stephan stood upright having the perception as if a subway train were approaching up the tube. Possibly Christhild felt faint vibrations of the precursor shocks as well. No rock was heard falling from the roof, even though the cave, later called Earthquake Cave, is littered by breakdown blocks throughout.

Description of Earthquake Cave

While mapping a lava tube cave, later called Earthquake Cave, the authors experienced an earthquake on August 8, 1990 (Figure 1). Earthquake Cave is part of a tube system with a total mapped length of 338 meters (Figure 2) located at the end of the Hilina Pali road in Hawaii Volcanoes National Park, Ka'u District. The tube is accessible through two breakdown holes. The main entrance is a 16-meter-long and 9-meter-wide hole interrupting the cave. It is located near the brink of the pali, just *circa* 200 meters southwest of the Hilina Pali shelter. It was shown to us by Dr. John (Jack) Lockwood, geologist at the Hawaii Volcano Observatory and the cave was first entered by Jack and

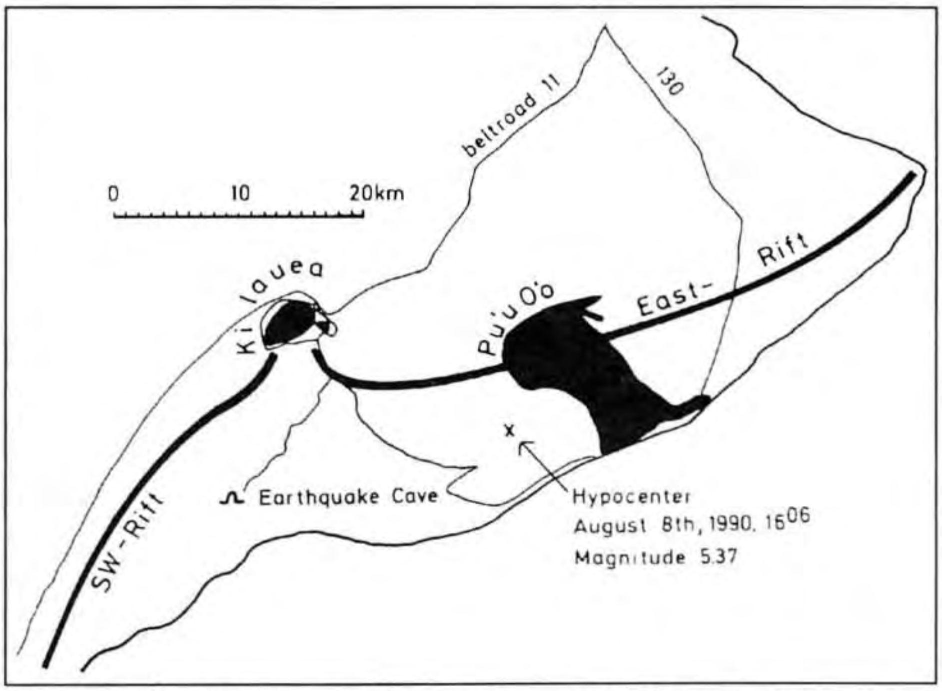


Figure 1 – Site of Earthquake Cave in relation to the Pu'u O'o Earthquake of August 8, 1990.

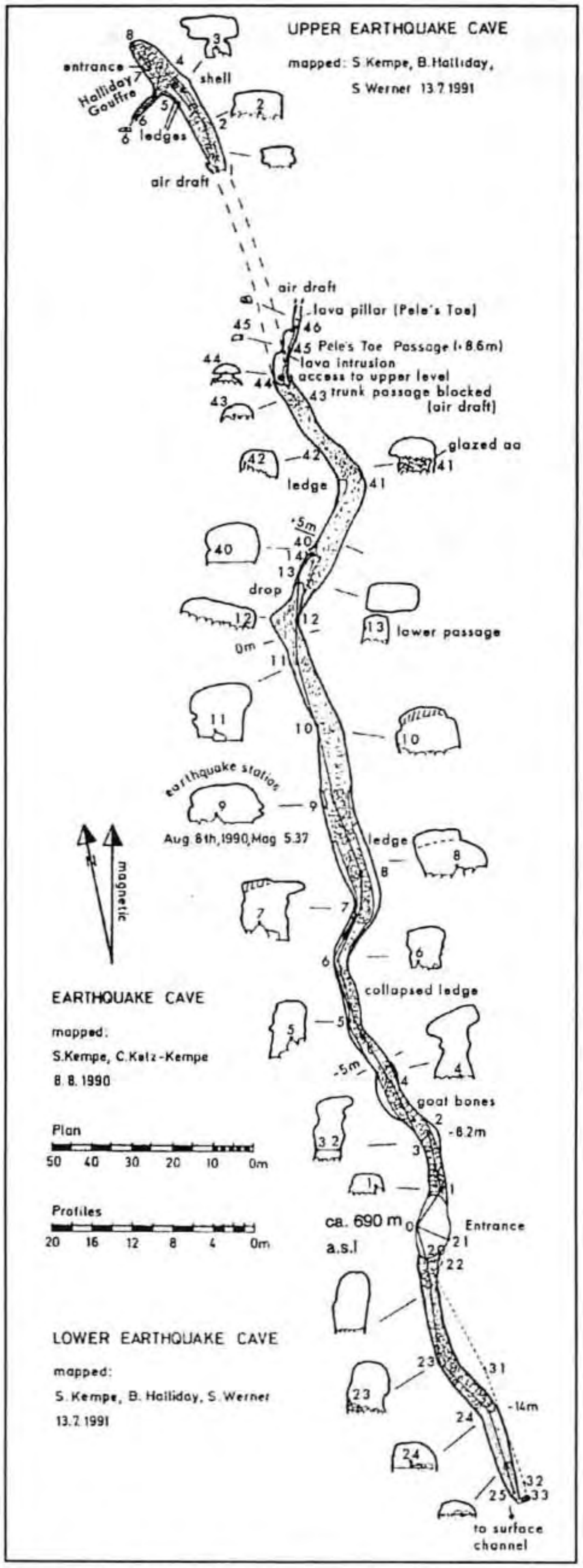
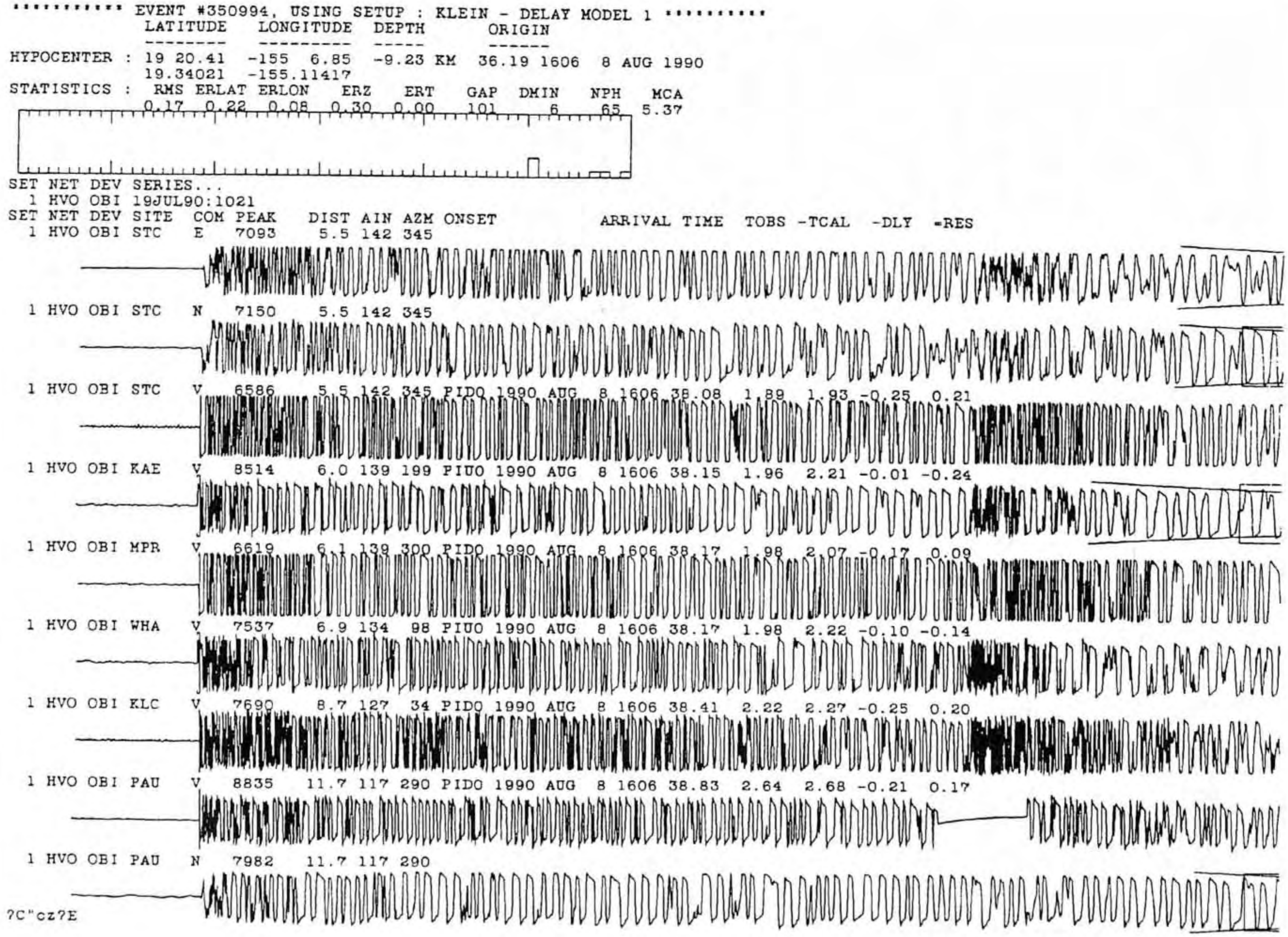


Figure 2 – Map of Earthquake Cave Tube System, Hilini Pali, Ka'u District, Hawaii.

Martha Lockwood and the authors on July 20, 1990. The other entrance is situated upslope in the bed of an occasional stream and is 2.1 × 1.8 meters wide, opening up into the tube below. It was indicated to us by James (Jim) Martin, chief ranger of the National Park. This entrance was entered July 13, 1991 by W. Halliday, M.S. Werner, and S. Kempe but has obviously been visited before (piled-up stones below the entrance).

This upper entrance leads into Upper Earthquake Cave, an isolated piece of the tube, just 38 meters long. It is blocked by breakdown at its upper and lower ends. At the ceiling a low surface tube with an air draft is accessible on the west side of the tube. The presence of pieces of wood, mats of dried grass, and bits of charcoal show that the tube floods occasionally up to the ceiling. The main entrance is roughly 280 meters away, distance and bearing between the two holes were estimated from aerial photographs kindly made available by J. Martin. From the main entrance both the Earthquake Cave proper and the Lower Earthquake Cave are accessible. The Earthquake Cave starts down a steep breakdown cone and leads into a slightly winding, six-meter-high canyon-like passage. The floor is covered with ceiling or wall breakdown throughout almost all of the tube. Often older lava beds and oxidized soil are exposed behind the collapsed wall linings. The total length is 228 meters. The tube rises roughly 10 meters above the entrance. At station 12, the tube splits into two levels, the lower of which ends after a few meters. The upper level is closed by a boulder choke at station 44. There a hole in the ceiling which offers access to a narrow surface tube which is constricted by columnar intrusions of lava (Pele's Toe on map). Air draft indicates connection to cavities further

Figure 3 – Seismometer traces of the Pu'u O'o Earthquake of August 8th, 1990 (courtesy, US Geological Survey, Hawaii Volcano Observatory). Note the sharp onset of earthquake (left) at 16.06 hours and 38.08 seconds. Stations are arranged according to increasing traveling time (top to bottom). Station codes stand for STC Steam Cracks, KAE Kaena Point, MPR Makaopuhi, WHA Wahaula, KLC Kalalua Cone, PAU Pauahi, all within the E-rift zone. Real amplitude of signal is too large to be shown and is suppressed in the plots. Station HVO OBI STC is given with eastern (E), northern (N) and vertical (V) components of movements while for most other stations only the vertical component of movement is plotted.


*********** EVENT #350994, USING SETUP : KLEIN - DELAY MODEL 1 **********
LATITUDE LONGITUDE DEPTH ORIGIN
HYPOCENTER : 19 20.41 -155 6.85 -9.23 KM 36.19 1606 8 AUG 1990
19.34021 -155.11417
STATISTICS : RMS ERLAT ERLON ERZ ERT GAP DMIN NPH MCA
0.17 0.22 0.08 0.30 0.00 101 6 65 5.37
SET NET DEV SERIES...
1 HVO OBI 19JUL90:1021
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1 HVO OBI STC E 7093 5.5 142 345
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1 HVO OBI STC V 6586 5.5 142 345 PIDO 1990 AUG 8 1606 38.08 1.89 1.93 -0.25 0.21
1 HVO OBI KAE V 8514 6.0 139 199 PIUO 1990 AUG 8 1606 38.15 1.96 2.21 -0.01 -0.24
1 HVO OBI MPR V 6619 6.1 139 300 PIDO 1990 AUG 8 1606 38.17 1.98 2.07 -0.17 0.09
1 HVO OBI WHA V 7537 6.9 134 98 PIUO 1990 AUG 8 1606 38.17 1.98 2.22 -0.10 -0.14
1 HVO OBI KLC V 7690 8.7 127 34 PIDO 1990 AUG 8 1606 38.41 2.22 2.27 -0.25 0.20
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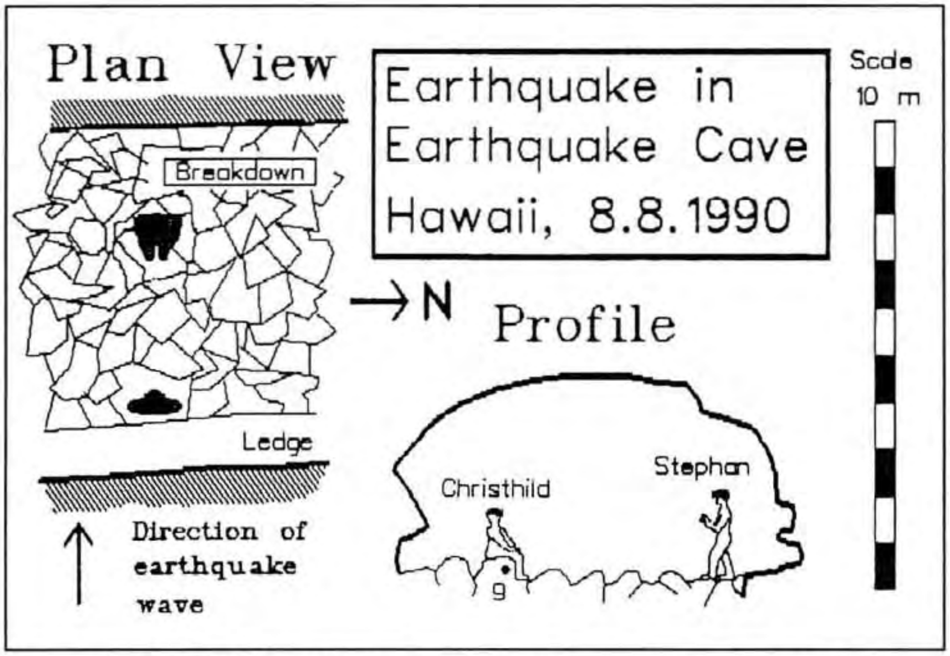

Figure 4—Sketch of the situation in the cave during the earthquake event.

uphill. Plenty of charcoal, partly in pockets high up on the walls, is found in the cave. This charcoal is similar to the plant remains in Upper Earthquake Cave, witness to an occasional flooding of the tube. In fact, it may derive from a fire which destroyed the trees in the Kipuka Bihopa area in the early 1980s. The Lower Earthquake Cave starts also as a six-meter-deep canyon and ends in a fluvial ash plug after 64 meters. A small hole connects to the surface. This hole probably serves as a drain of the cave at flood conditions. Below, the tube terminates and connects to an open channel which steeply dips over the brink of the pali. Geologically this is a unique example of a lava tube connecting to a channel. Both tube and channel appear to be cut down into older lava beds and must have transported lava over an extended eruption period.

The Earthquake

The earthquake was experienced while mapping the central part of the tube system. We entered the cave at 2:55 and left it at 5:23 P.M. The tremor occurred at 4:06 P.M. and its epicenter was just south of the Pu'u O'o vent on the East-Rift of Kilauea, Hawaii, (19°20.20'N / 155°6.77'W), i.e. *circa* 25 kilometers east of the cave (Figure 1). The shock wave must have hit the tube, which runs roughly north-south, at a right angle (Figure 2). Initially the Hawaii Volcano Observatory registered the magnitude of the earthquake as 5.37 (Figure 3), a figure which later was, according to Dr. Paul Okubo, seismologist from the Hawaii Volcano Observatory, corrected to 4.9. *The Hawaii Tribune Herald* (reporter J. Witty, August 9, 1990) related that the Pacific Tsunami Warning Center scaled the quake as M = 4.3 and that the National Earthquake Information Center, Colorado, registered it as 4.7 magnitude. The final corrected amplitude magnitude (MA) was 4.7 (pers. comm. J. Nakata, Hawaii Volcano Observatory). The hypocenter was at a depth of 9.14 kilometers. At around this depth the volcanic edifice rests on the sediments of the Pacific plate. Many earthquakes occur between 5 and 14 kilometers of depth including the 4.48 A.M. November 29, 1975 (M = 7.2) Kalapana earthquake (19°20.1'N / 155°1.4'W, depth 5 kilometers) (Tilling *et al.*, 1976). They are caused by a slip of the northeast-side of Kilauea towards the ocean on northeast-striking low-angle thrust faults (Klein *et al.*, 1987) (slip during the Kalapana earthquake was eight meters seaward). Because of its position and depth, the Pu'u O'o earthquake was seismic in origin, not directly related to volcanic activity but most probably caused by the ongoing loading of the Pu'u O'o area with fresh lava.

When the quake hit, we were at mapping station 9, 120 meters from the entrance. Christhild was sitting on the station point to rest, while Stephan stood facing her, a few meters away on the opposite side of the tube taking notes (Figure 4). While waiting for Stephan to finish, Christhild listened to the quiet tube and had the strange feeling of hearing distant voices. She commented on this and Stephan reassured her that nobody could possibly be in the cave except them. She kept on inquiring and suggested she might have felt vibrations from a car on a nearby road. Such a possibility was also rejected, since the Hilina Pali Road ends before reaching the cave area. We were still talking about Christhild's faint perceptions when the earthquake hit. Christhild felt the rocks moving uncomfortably against each other un-

derneath her. Stephan, still standing, felt mostly the air rushing through the tube having the audible impression as if a subway train would approach. Possibly the air in the tube was compressed momentarily, producing a shock wave similar to the one felt when a train moves in a tunnel. The event passed in a few seconds leaving us perplexed. The anxiety which had been triggered by Christhild's first remarks, rose sharply and we listened intensively, frozen to our places, for rockfall. Thanks to Pele, we did not hear a single stone falling. After a while we discussed what to do, and decided that the chances of a second and even larger quake would be very low and continued mapping of the cave until almost to its end.

We cannot be absolutely sure if the vibrations which Christhild took for voices or car noise were indeed some earthquake precursors or if she was just distracted by wind rushing through the tube. Because of the coincidence with the quake we think it is possible that she in fact felt precursors to the main shock. These tremors were, however, rather small, as we could see next day on the seismograms of the Hawaii Volcano Observatory. It was also quite interesting that Stephan, standing, did not feel the movement of the floor as intensively as Christhild. The same difference in the perception of an earthquake was noticed a few days before. On August 1, we witnessed a M = 4.7 quake while visiting Dr. William and Sis Halliday in their apartment, 9th floor, Hilo Lagoon. While Bill and Stephan were sitting on the sofa feeling the earthquake intensively, Christhild and Sis were standing and did not perceive the shock at all. Just the table lamp rocking showed them that a quake had occurred.

When we reached the parking lot after the earthquake in the cave at the Hilina Pali shelter, we heard a faint alarm and were speculating if there was a fire nearby. A few minutes later (5:45 P.M.) though, Jim Martin, together with his son, pulled into the parking lot and was very relieved to see us. He told that he had been sitting in the car when the quake hit, and that he had not felt anything. The park headquarters had informed him by radio about an M = 5.3 event. Headquarters also told him that tourists reported smoke in the Hilina Pali area. A park helicopter flew along the pali but could not see any fire. Jim Martin therefore thought that something might have collapsed at the pali and worried about us, knowing that we had signed up to map a tube in the area. He immediately left for the Hilina Pali lookout which he reached an hour and a half after the quake.

Conclusions

The most interesting observation of this event was that the cave roof apparently is stable enough to withstand tremors of up to magnitude 5 easily. This is even more astonishing because the floor of Earthquake Cave is littered with breakdown blocks throughout its entire length, indicating that the roof is relatively unstable already. One is therefore tempted to conclude that most of the breakdown we see in Hawaiian caves must be correlated to a few very strong quakes. Geologically speaking, quakes of 7.0 magnitude still occur frequently on Hawaii. The two last events were the South Point earthquake of 1868 (*circa* M = 7.5) and the Kalapana earthquake of 1975 (M = 7.2) (Macdonald and Abbott, 1970; Klein *et al.*, 1987, respectively). This suggests that quakes of M = 7 may be expected at frequencies of two per century. Speleogenetically only these earthquakes seem to be effective. It is, however, also possible, that even larger and rarer events are needed to dislodge large breakdown in the lava tubes of Hawaii.

One *caveat* has to be made though. It is conceivable that all or parts of the breakdown are due to other causes. In case of the Earthquake Cave the flooding of the cave during torrential storms could be such a cause. The lava is full of gas bubbles, which in part may be water-filled during the ponding of water in the cave by the talus cone at the main entrance. When the water drains these rocks will be heavier than usual and might therefore collapse into the cave. In other areas, the loading of the humus and rock composing the cave roof with rainwater, the increasing load of a growing forest, the pressure of roots or the loss of such pressure could also be forces which may account for breakdown.

We were not the first cavers to witness an earthquake in a lava tube. Wood (1980) mentions that they felt a quake in Kazamura Cave in 1979 and Dr. Marlin Spike Werner was the involuntary witness of a scary M = 6.1 event in Malama Cave recently. The reader is referred to his account in this volume.

Acknowledgements

We wholeheartedly thank Jim Martin from Hawaii Volcanoes National Park. It was lucky that his thoughtfulness and care was not needed in this instance but potentially we could have been in need

of help desperately. We also thank Carol Brian and Jennifer Nakata for helping us to obtain the Hawaii Volcano Observatory seismometer data for the August 8, 1990 earthquake.

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Caves of Southern Kauai

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Caves in southern Kauai are worthy of protection for the following reasons: (1) remaining sources of human habitation records, (2) unique biological resources, (3) geological resources, (4) burials, and (5) aesthetics. Human interference has already resulted in the loss of many surface archaeological sites in the area. Growth in human population will lead to pressures to convert arable land into more profitable enterprises. As the human population shifts and grows, a depletion in the quality of natural features on the landscape may occur. Mining of volcanic cinder has led to the flattening of volcanic cones that previously had shown a time sequence in island geology. Mining of unconsolidated and lithified sand dunes disturbed may Hawaiian burials and a record of geology at work today.

There are few caves on Kauai Island. Sea caves are present and reflect the record of the ocean's change in sea level. Lave tubes are present and are subject to urban encroachment. Limestone caves are present at the unconformity between beach rock and underlying alluvium. The unsoiled caves worthy of protection are in the southeast region of the island.

Waimea Canyon Volcanic Series

Kauai Island is a single shield volcano that rises 17,000 feet above the sea floor and a little more than 5,000 feet above sea level. The activity of the shield building Waimea Canyon Volcanic Series has a potassium-argon estimate of beginning 5.7 and ending 3.8 million years ago (McDougall, 1964). These lavas have normal remnant magnetism (Macdonald and Abbott, 1979) The aa and pahoehoe lava flows of the Waimea Canyon Volcanic Series are tholeiitic basalt, alkalic olivine basalt, and hawaiite. Early lavas generally have larger phenocrysts of olivine than those found in the post-erosional flows.

On the southeast part of the island, near the cave area, is the Haupu range of mountains. This basalt ponded caldera is on the flank of the Kauai shield volcano. Its eruptive episode probably coincided with that of the collapse and development of the summit caldera. The lavas surrounding the Haupu caldera slope away from the center of the island. Hoary Head, the highest point of the Haupu caldera, marks the top of the caldera filling lavas that remain in relief with the erosion of the less dense surrounding lavas.

Post-erosional Koloa Volcanic Series

Large amounts of sediments, deposited as erosional unconformities, mark the passage of time between volcanic series on Kauai. Nearly two million years of quiescence passed before the Koloa Volcanic Series marked the beginning of renewed post-erosional activity about 1.5 million years ago. These lavas, which covered about the eastern half of the eroded island, include nepheline basalt, alkalic olivine basalt, basanite, and melilite nephelinite. These lavas generally had a darker matrix than the rocks of the Waimea Canyon Volcanic Series. Fe^{+2} is blue black, Fe^{+3} is red (rust). The difference in color may be due only to the amount of oxidation (i.e. age). Some later post-erosional Koloa Volcanic Series lavas have reversed remnant magnetism. This series marked the end of post-erosional volcanic activity on Kauai over 100,000 years ago.

The episodes of volcanic activity within the Koloa Volcanic Series are believed to be sporadic due to the large numbers of erosional unconformities found between successive volcanic layering. Forty vents are identified from the Koloa Volcanic Series. The orientation of the vents is north-northeast to south-southwest across the island. Most of the eruptive fissures are small cinder-and-spatter cones and Strombolian-type cinder cones.

Lava Tubes in Southeastern Kauai

Because of the high value of land, many remaining lava tubes in southern Kauai are facing urban effects. Some lava tube entrances have been

plugged (Kikuchi, 1963) in the following ways: (1) filling with sugar cane residue, rocks, and debris during field operations, (2) intentional filling by cowboys to protect the herd, and (3) use for sewage disposal by local residents.

A steady flow of applications for re-zoning from agricultural to resort usage has led to other implications. Increased housing construction coinciding with resort development probably will result in deterioration of cave entrances. Presently, many cave entrances are located with difficulty in dense brush and are protected by their remoteness.

Caves were used for human burials. Skeletal remains are found near the end of an open traverse of a lava tube on the margin between pasture land and a planned residential community. Due to the high atmospheric water vapor content, much of the human bone has deteriorated. Five molars were present. Extensive disturbance by artifact hunters is evident. Holes dug in the soil in the entrance area of the cave appear to have destroyed a part of the archaeological record here and at other cave sites in the region (Kikuchi, 1963).

Two other lava tubes, on former pasture land, are natural hazards at the Kiahuna Golf Course. Evidence of recent tampering, probably during golf course development, is especially noticeable around the cave entrance areas. A sign at one entrance says, "This cave, in which the endangered no-eyed big-eyed hunting spider (*Adelocosa anops*) resides, is set aside for its protection." Populations of *Spelaeorchistia koloana* and an occasional *Adelocosa anops* are noted more than once by workers such as Howarth and Stone and more recently by Holsinger and Ferguson.

Southeastern Karst Topography

In the late Pleistocene, earthy deposits accumulated along the southeastern shoreline of Kauai during a higher stand of the sea. These small pieces of weathered rock deposited by gravity formed an alluvium sedimentary base. The sedimentary deposit is a mixture of stream-laid sand, gravel, and silt. These fragments of organic and inorganic weathered products got transported to the place of deposition during the long periods of inactivity of the Koloa Volcanic Series. Hydrochloric acid confirmed the presence of carbonates in these weathered products.

After that, sand deposits blew inland by entrainment during a lower stand of the sea. This resulted in the formation of eolian dunes. Evaporating rain water, passing through the permeable dune sand, deposited molecules of the crystalline compound $CaCo_3$ (Calcium Carbonate). Wind blown ocean spray probably resulted in deposits of NaCl (Sodium Chloride or common salt), $MgCl \cdot 6H_2O$ (Magnesium Chloride, white crystals that can absorb atmospheric water vapor until they are completely dissolved), $MgSO_4$ (Magnesium Sulphate, colorless crystals), CaS (Calcium Sulphate, a white crystalline salt, insoluble in water), and KCl (Potassium Chloride, colorless crystals that are soluble in water) (Godman, 1981). This dune sand eventually formed a well cemented, cross-bedded, eolianite. These lithified sand deposits lie atop the older alluvium.

The older alluvium, acting as a poorly permeable solute, may be transported. Unknown is how large a role rainwater, percolating through the overburden, has played in the alluvium transportation process. In the space between the older alluvium below and the lithified sand deposits above, small caves have formed. At the Grove Farm Quarry in Maha'ulepu, holes on the surface show evidence of caves broken into during mining activities.

Historical records of the Maha'ulepu area record the presence of a community of farming, fishing, and grazing activities. Due to the extensive alteration of the landscape by the sugar plantation, much of the surface archaeology is gone. Some remaining surface features are: (1) ditches and flumes of the awai irrigation system, (2) walls and C-shelters, (3) house platforms paved with ili ili, (4) petroglyph rock boulder and beach rock terraces, and (5) heiaus.

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Lava Tubes at Mauna Ulu, Kilauea Volcano, 1972-1974*

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Extensive systems of lava tubes formed several times during the eruption of Mauna Ulu from 1969 to 1974, and the general origin and behavior of the tubes through 1971 were described in previous papers by various authors. Tubes that developed from 1972 to 1974 confirmed the earlier observations and provided further insights into the development of lava tubes and their role and significance in the growth of basaltic shield volcanoes.

Lava tubes at Mauna Ulu developed by at least four different processes: (1) accretion of flat, rooted crusts across streams within confined channels; (2) accretion of overflows and spatter to levees, which built arched roofs across streams; (3) jamming together and fusing of plates of floating crust; and (4) progressive extension of pahoehoe lobes by molten distributaries beneath a solidified crust. By these various processes, tubes can develop in different parts of lava flows under a variety of flow regimes. Tubes can therefore become ubiquitous within pahoehoe flows and distribute a large fraction of the lava delivered to the surface during a sustained eruption.

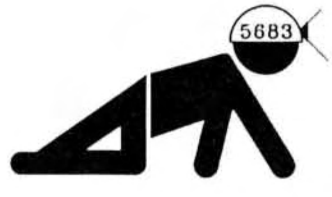
Tubes transport lava efficiently. Once formed, the roofs of tubes insulate the streams within, allowing the lava to retain its fluidity for a longer time than if exposed directly to ambient air temperature. This enables the flows to travel for greater distances and spread over wider areas. Even though supply rates were moderate at Mauna Ulu, generally about one to five cubic meters per second, the principal tubes conducted lava as far as the coast (13 kilometers distant) where it fed extensive pahoehoe fields on the coastal flats and added new land to the island. The largest and most efficient tubes developed during periods of sustained extrusion when new lava was being supplied at nearly constant rates.

Because of their ubiquity and efficiency, lava tubes exert significant control upon the shapes of shield volcanoes. Traditionally the low aspect ratio (height/diameter) of shield volcanoes has been attributed chiefly to the fluidity of basaltic lava. However, fluidity alone is not an adequate control because it depends so strongly on the temperature of the lava, and when lava is exposed to the air its temperature, and thereby its fluidity, declines rapidly. Lava tubes provide a means of insulating the lava, thereby preserving its fluidity, while they also serve as conduits that allow lava to travel for great distances across the surface. The process enables basaltic volcanoes to attain diameters that are very large relative to their heights.

At Mauna Ulu, during the episodes when surface overflows were brief and few tubes formed, a tendency was noticed for the angles of slope (and thereby the aspect ratio) of the lava shields growing around the vents to increase appreciably. In contrast, during sustained episodes when many tubes developed and much of the new lava traveled through them for longer distances, the slope angles of the shields tended to increase only slightly. The highly variable character of the eruptive activity prevented the relations among the volumes of surface flow versus tube flow and the resulting rate of change of the slope angle from being rigorously documented. However, future eruptions at basaltic shield volcanoes may provide opportunities to test these relations.

*a poster exhibit

Vulcanospeleology of the Mainland USA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Historical Misunderstandings About Lava Tube Systems and Lava Tube Caves of Lava Beds National Monument, California.

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Abstract

Until quite recently the relationship between caves, lava tubes, lava tube systems, and tube-fed lava flows of Lava Beds National Monument, California, has been poorly understood. How this could be in an age of vulcanospeleological enlightenment is endemic and perpetuated by the monument's geographic, demographic, and political isolation. The only monument-wide geologic study – which addressed the fundamental relationship of lava tubes to lava flows – and a few other brief but valuable geologic appraisals, were never published and therefor escaped reconciliation with contemporary understanding of lava tubes. As a consequence, local misconceptions flourished by default until recently, when the Federal Cave Resource Protection Act required that caves be delimited.

Lava Beds National Monument

Lava Beds National Monument lies on the northern slope of the huge Medicine Lake Volcano, a shield volcano of enormous bulk. The monument is roughly rectangular in shape, enclosing 72 square miles, at an elevation of about 5,200 feet at the south end and 4,100 feet at the old shoreline of Tule Lake which forms the northern boundary. Virtually the entire monument is covered with volcanic rock, of which about two-thirds is Basalt of Mammoth Crater, a late-Pleistocene basaltic lava. From several different vents, but principally Mammoth Crater, it was distributed by lava tube systems, leaving numerous flows with terrace-like borders ranging up to 30 feet high, separated by valley-like depressions in between. Most of the caves are in this basalt.

Nearly all of the individual caves are lava tube caves that are segments of several extensive lava tube systems. The caves range in length from a few yards to the longest, Catacombs Cave, with about 6,900 feet of surveyed passage. Some are complex horizontally, having many interconnected branches. Others are vertically complex, having several levels. Depths range from surface tubes to 150 feet below the surface in the lower levels of some of the master tubes.

The lava tube systems are extensively collapsed, but many of the segments – the individual caves – have suffered little collapse and exhibit an abundance of flow features, such as lava flowstone and the many forms that result from it. Benches, linings, stalactites, ribbed walls, shelves, lava falls, and all kinds of flow lines are abundant. As a rule, speleothems (secondary mineralization) are seldom well developed in lava tubes, and Lava Beds is no exception. Ice, technically a speleothem, is plentiful in caves having a suitable shape.

Monument is Isolated

Lava Beds National Monument probably encloses the heaviest concentration of lava tubes and lava tube caves in the continental U.S.* However, despite the presence of so much tube-fed lava so close to home, the Monument has escaped the intense scrutiny that vulcanospeleologists have devoted to other areas. There are some obvious reasons for this, and some obscure reasons.

First, the monument is isolated geographically and demographically. It is 60 miles from the nearest city, Klamath Falls, which is not large enough to support a caving organization. It is about 50 miles from the nearest interstate highway and, until recently, visiting there entailed driving on

*There may be heavier concentrations at Craters of the Moon National Monument and elsewhere in Idaho – time will tell.

some gravel roads. It is 300 and 350 miles from large population centers, Portland and San Francisco respectively. There are no accommodations in the park except a small campground; few accommodations in the usual sense nearer than Klamath Falls, 60 miles to the north; and no services whatsoever within 25 miles of park headquarters. The weather is reliably unpredictable and, at an elevation of 4,500 feet, often very cold in the winter and spring.

For its own reasons, and perhaps because of local pressure, the Park Service has not seen fit to expand facilities to accommodate more overnight visitors. In short, there are more attractive places where lava tubes may be studied; for example, all around other flanks of the Medicine Lake Volcano, Mount St. Helens National Volcanic Monument, and near Trout Lake, Washington.

Left Out of Vulcanospeleology

Lava Beds missed out on the rapid expansion of vulcanospeleology that began in the mid 1960s. They have a fine library for use by researchers and authors, but until recently it contained little about lava tubes, *per se*. In 1936, and occasionally thereafter, respectable studies of the lava tubes and systems in the monument were completed. These works, which are in the monument library, would have contributed greatly to early vulcanospeleology, but were distributed only internally, and never published (Fisher, 1934; Glaeser, 1936; Hatheway, 1969; Lewis and Anderson, 1936; and Peck, 1976). As a consequence, the theories and terms they contained were never reconciled with the observations of others. One of these [Lewis and Anderson contained by far the largest block of terms and descriptions for lava tube features up to that time. For most part, they were based solely on local observations and conclusions. Predictably, they contained fundamental misunderstandings and embodied much local convention. For example, the term "chimney" was applied to hornitos as well as spatter cones, cinder cones became "buttes," and these names hang on to this day. Until recently, because there was little else to refer to, local convention dominated by default.]

Failure to recognize the fundamental relationship between lava tubes and the emplacement of lava many miles from its source hampered understanding of lava tubes at Lava Beds for many years. Lava tubes were something that occurred in lava flows when the top, and later the sides, hardened. The vital role of lava tubes in spreading lava so thinly, over great areas, was virtually ignored. Even as recently as 1990, in a long-awaited U.S. Geological Survey publication (Walters, 1990) there is little enlightenment beyond: "Lava tubes typically form in the interior of thick lava flows." Lava tubes were seen as places where the lava drained away, but never as the place where it came from, a far more important distinction. A few researchers, up to snuff vulcanospeleologically, have examined and written about specific lava tubes and systems in the monument during the past two decades. The only comprehensive, monument-wide study of the lava tube systems – which enumerates only selected, developed caves – was completed by Lewis and Anderson in 1936.

How Many Caves?

No one can say, with reasonable certainty, how many individual caves there are in the Monument. Many surveys have been initiated, but none have been completed. Over 400 cave names appear in the literature, probably 200 of those have been located and explored to some extent, but only about 75 have been described well enough to be positively identified.

In 1934, Fisher wrote that 293 caves had been discovered, about 130 had been explored, and about 50 had been named and developed to some extent. The number 293 became legendary, appearing in writings through 1985. Some accounts rounded the number off to 300 caves, and indeed, a 1934 map bore 303 individual cave symbols. In 1936, Glaeser (1936) documented about 130 additional caves, but clearly some of these overlap the legendary 293.

Segmentation

The numbers above are not especially meaningful, however, because until 1990 no systematic protocol for distinguishing individual caves was needed or acknowledged. Whether one will be employed remains to be seen. As a result, many distortions of reality thrive. For example, in 1928 the entire cave loop section (about five miles worth of frequently segmented lava tubes) of the Headquarters System was included in Labyrinth Cave. By the mid-1980s, Labyrinth Cave had deflated to a more plausible, respectably competitive, but oddly precise length of 15,666 feet. (Presumably this length varied a little with seasonal temperature.) Applying the rule of segmentation recommended by the

International Union of Speleology (UIS) – that collapses wider than they are deep, segment a lava tube – Labyrinth Cave actually has about 3,800 feet of passage. However, its true nature is still not completely resolved. Along its course are several relatively small openings in the roof, that are skylights by any known definition. Two of these openings have stairways and are designated entrances – not to Labyrinth Cave – but to Thunderbolt Cave and Lava Brook Cave.

Stewart Peck (1976), while a summer employee at the monument, completed a survey of caves in the Cave Loop area. He was quite aware that the Labyrinth Branch was extensively segmented, and listed a total length of 12,845 feet, of which he noted that 1,310 feet was collapse trench. He also (correctly) noted that the longest tube ". . .not intersected or broken by a collapse. . ." was probably Catacombs Cave, at 6,562 feet. Catacombs has since been inflated to 7,475.00 feet (decimal added) and re-surveyed (by one of the most respected cave surveyors in the northwest) to 6,900 feet. Even though Peck's article was published, and is in the monument library (Peck, 1976), a prominent 1990 publication about some Lava Beds caves asserts that Golden Dome, Labyrinth, Hopkins Chocolate . . . and Blue Grotto caves [are] "several interconnected but separately named caves."(Waters *et al.*, 1990) In fact, the above caves are all separated from each other by one or more segmenting collapses. For example, the nearest points between Golden Dome and Blue Grotto are separated by four collapses – two of which are two or more times longer than they are deep – and two other short caves. The caves named above are segments of the Labyrinth Branch (of the Headquarters System) but are not interconnected in any real sense.

In 1990 – following passage of the Federal Cave Resources Protection Act, implementation of a cave management plan, and initiation of a cave inventory conducted by the Cave Research Foundation – it has become necessary to be more specific about which caves are which. The management at Lava Beds has never deliberately ignored or rejected increasing knowledge of lava tubes. The monument has specific needs in interpretation, and there never has been a need to accommodate other than the typical visitor, who could hardly care less about things like segmentation.

Underlying the determination of individual lava tube caves, of course, is the matter of segmentation. Indifference to it has contributed more to misunderstanding of Lava Beds caves than any other factor. The only consensus regarding it that exists (the UIS principle), holds that if a collapse sink's largest dimension measured horizontally exceeds its depth, the tube is segmented, resulting in multiple caves. This resolution is so simple, however, that it is vulnerable to artifices employed to join caves together for competitive purposes. I like it for its simplicity and because it provides something tangible to measure. Interestingly, initiatives aimed at broadening this consensus are seldom acknowledged, perhaps because to do so would acknowledge its existence. I look forward to the time when the need for a principle of segmentation is acknowledged and discourse may begin about specifics.

And Then . . . Bridges

Almost as frustrating as the lack of consensus about segmentation is the pervasive designation of segments of lava tubes as "natural bridges." Bridges at Lava Beds range widely in width. The longest is the 350-foot-long segment of the Headquarters Lava Tube System designated Heppe Bridge. (It was named by J. D. Howard, an early explorer who disdained caves without an area of total darkness.) The smallest is probably the "partial bridge" (whatever that is) described in Waters (1990). At Lava Beds, bridges are managed as caves, but the recently adopted cave managment plan further complicates the distinction with the following obfuscatory provision: "A bridge is any naturally occurring geologic feature that spans a space and whose span is wider than long."

Very little understanding of the relationship of tube-fed lava flows, lava tube systems, lava tubes, and lava tube caves is reflected in literature about Lava Beds. Even some of the most recent works infer that lava tubes are there because of the lava flow, when exactly the opposite is true. "System" has been applied to individual caves, to groups of caves, but only occasionally to entire systems. Even today, many who collect data have no clear idea of what a system is. Nearly 100 "systems" have been named. Many of these names are similar, to be sure, but there are only about nine alignments inside the monument that are arguably lava tube systems. Some "systems" have been judged and named on the basis of observations of a single segment, without apparent reference to the source of lava or its destination. At the same time, individual segments of systems are seldom recognized as parts of the whole.

Naming, re-naming, and re-identifying caves, without reference to or regard for the literature, has created difficulty. For example: (1) the two-level cave now known as Merrill Cave was known at various times as Bear Foot Ice, Bear Paw Ice, Bearpaw Ice, Ice Cave, Little Bear Paw, Lower Merrill, and Merrill Ice Cave. Bearpaw Cave, nearby, was known at differing times as Bear Foot, Bear Paw, Big Bear Paw, and Upper Merrill. (2) A short, two-level segment of the Headquarters System master tube, known appropriately as Compound Bridge since 1917, was recently re-named Natural Bridge, despite the existence of several dozen "Natural Bridges" in the monument. (3) Recently, a short, deep segment of the same master tube, shown on Forest Service, Park Service, and popular maps and in several pieces of literature, as Duffy's Well as far back as 1918, was arbitrarily renamed Old Still Well (Sowers *et al.*, 1990).

Natural Bridge Cave, a feature of the Cave Loop tour, is a two-level segment of the master tube of the Headquarters System with over 300 feet of passage. It was originally named Compound Bridge by J. D. Howard in 1917. Despite the presence of the name painted in large yellow letters on the edge of a large piece of floor crust just inside the upper entrance, and repeated confirmation in the literature, including "The origin of geographical, geological, and historical feature names in Lava Beds National Monument" (1965), not to mention a super-abundance of "natural bridges" in the monument already, a few years ago it was renamed Natural Bridge.

At least five cave numbering systems have been employed as a means of identifying Lava Beds caves, the first in 1936. A second series of numbers appeared in 1959, two more in 1989, and the latest in 1990. Fortunately, none of the numbering systems have anything in common. Otherwise there might be a lot more misunderstanding about Lava Beds caves than there already is.

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Geology and Mineralogy of Lava Tube Caves in Medicine Lake Volcano, California

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Medicine Lake Volcano is a large shield volcano that lies in the northeast corner of California, just south of the California-Oregon border. This Pleistocene to Holocene volcano is located in the southeastern portion of the Cascade Geomorphic Province. The volcano has developed as a large shield over 33 kilometers in diameter which attains an elevation of 2,417 meters. The north slope of the mountain is covered with bunch grasses and sage at the lower elevations adjacent to highly alkaline Tule Lake. Further up slope a mixed sage and pinyon-juniper woodland is present while a ponderosa pine forest covers the upper third of the volcano. The southern slopes of the mountain are cloaked in mixed ponderosa and hardwood forest. Except for Medicine Lake, a caldera lake, and short-lived ephemeral streams, the volcano lacks permanent surface water. The eruptive rocks range in composition from basalt to rhyolite. More mafic flows and breccia comprise the bulk of the volcano with a thin covering of more silicic pumice, ash, and obsidian flows. The basaltic lavas have compositionally changed throughout their eruptive history such that the earliest lava is more silicic (approximately 53% SiO_2) and the latest more mafic (approximately 47% SiO_2). This results in lava fields which change composition along their length.

In a zone on both the northern and southern flanks at approximately 1,370 meters in elevation are many cinder and composite cones from which long, tube-bearing lava flows emanate. A wealth of volcanic features of special interest to speleologists and cavers are present in these areas. Many of the tube systems' roofs failed shortly after their draining. The resulting landforms can be divided into three types of collapse features: long, sharp-edged

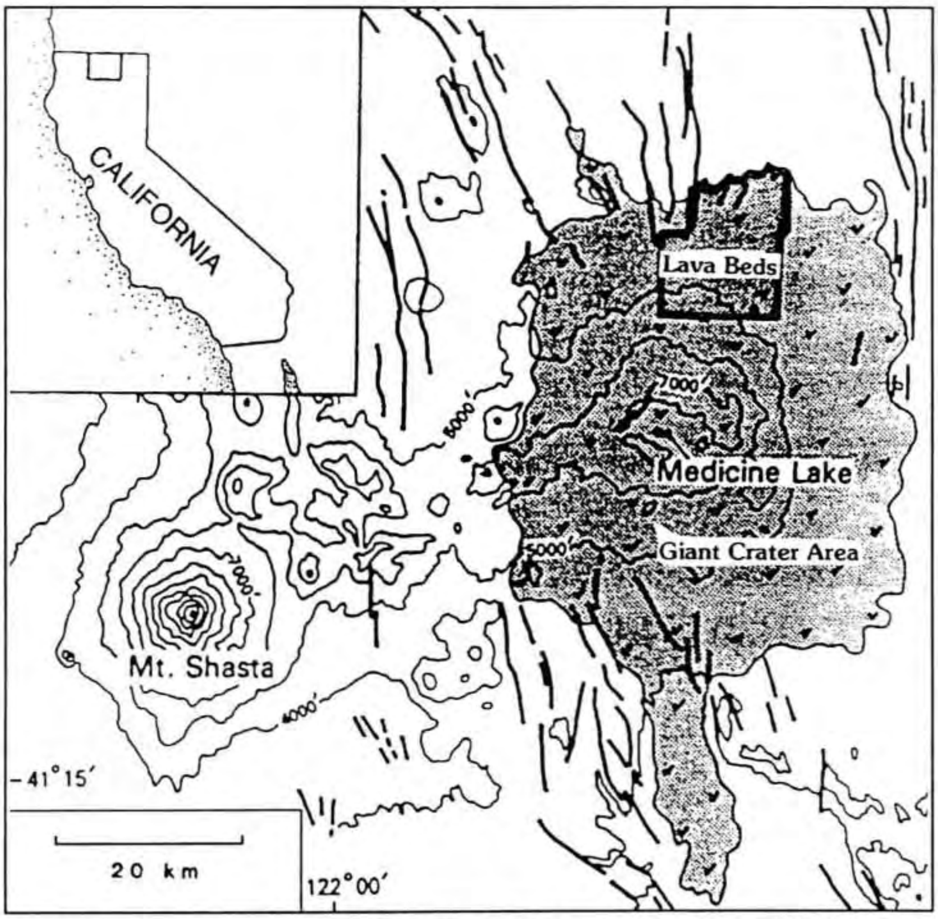

Figure 1—The location of Medicine Lake Volcano. (Figure modified from J. Donnelly-Nolan, 1987)

Figure 2— The profile of Medicine Lake volcano as seen from the margin of Tule Lake located at the north base of the volcano. Notice the many smaller cinder cones on the main shield of the volcano. These cinder cones mark the 1,370-meter-high zone of cave-bearing basaltic lava flows. Mt Shasta is visible in the upper right background.

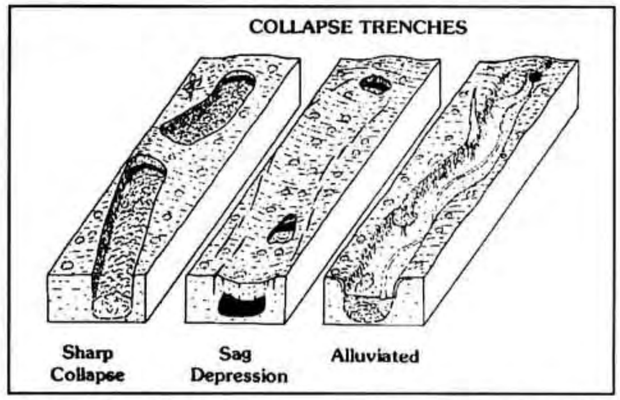

Figure 3—Of the three types of collapse trenches present on Medicine Lake volcano, sharp-edged trenches are most common.

collapse trenches; shallow sagged, partially collapsed, partly squeezed down tube-cum-trenches; and alluviated trenches. The sharp-edged trenches have clean walls and partially preserve cave passage profiles under overhanging trench edges and in reentrants. The shallow sagged trenches have not undergone chaotic collapse but have plastically sagged, either closing or leaving very low passages. Alluviated trenches are uncommon. These features have had their floors thinly veneered with sediments and subsequently vegetated. These trenches appear to be either sharp-edged or sagged in origin.

Spatter cones or rootless vents (hornitos) are present along the axes of portions of the tube systems. These hornitos range up to 20 meters in diameter and 10 meters high and, in some cases, allow access to otherwise sealed cave segments.

During the eruptions of the past 11,000 years, the pre-existing soil and basalts were covered with volcanic debris. Channels cut into this debris were quickly lined and extended upwards as overflowing lavas built up the edges of the channels. Some erosion downward into the lava deepened the channels and tubes. Succeeding overflows built up the channel until it finally roofed over. As the main flows ceased, minor lobes congealed, leaving flat floors and thin linings. Collapse in the tubes, soil formation at the ground surface, and minor speleothem deposition were the final modifications to the surviving tubes.

Approximately 18% of these tubes are preserved as accessible caves. The slope along the length of manv of these caves commonly averages three degrees although sudden drops over the controlling underlying topography are present. Over 300 caves are known from these flows. The caves range from short grottos under ten meters long to braided systems nearly seven kilometers long. Passage

Figure 4—Scott Fee standing at the entrance to Skull Cave provides scale to the size of a typical sharp-edged collapse trench in Lava Beds National Monument. This trench leads into both Skull Cave, a deep ice cave with very large (18-meter diameter) passages and sub-fossil animal and Native American bones as well as into Inclined Cavern, a smaller (10-meter diameter) passages ice cave.

Figure 5 – Big Bertha's Chimney, named after pioneer settler Bertha Heppe, leads into a short segment of lava tube at the vent through which the Valentine Cave andesitic basalt flow erupted.

The sources of these minerals are varied. The silicates appear to have been leached from the unstable pumice and glassy ashes. The calcite, gypsum, barite, and unnamed salts have drawn their carbonate and sulfate from the wind-blown dust derived from the largely carbonate lake margins. The oxide and hydroxide minerals (exclusive of ice) have been derived by weathering of the relatively deeper soils of the upper, well-watered and vegetated slopes of the volcano. Ice is present as permanent deposits in at least 20 caves and appears as seasonal decorations in a great number of caves. There is a rough zonation, controlled by elevation, of the secondary mineralization in the lava tubes. This zonation appears to follow the availability of ground water, soil composition, and vegetation patterns. On the flanks of the volcano the less mobile oxide, hydroxide, and miscellaneous "minerals" form in the caves higher on the volcano where soils are well developed and

sizes range from 0.25-meter high crawlways a meter wide to "dirigible passages" up to 25 meters in diameter. Vertical pits up to 20 meters deep are common where passages either stoped their way to the surface or collapse between overlying levels occurred. While breakdown is pervasive, small to large areas of original pahoehoe floors with differing surface textures are found in nearly every cave. Wall and roof decorations of lava glaze are very common even in the smallest of surface tubes. However, in many of the moderate- to large-sized caves, consecutive collapse of the linings have removed most of the tube's original glaze. Hardened cascades and lava falls are common in the caves as are frozen lava lakes and pools. Rafted blocks of lava and lava balls encased in the pahoehoe floor are scattered along the length of many tubes.

Fourteen minerals, mineraloids, and rocks identified by x-ray diffraction are found as speleothems in the tubes.

Figure 6 – Charmaine Legg relaxes in a 0.6-meter-high crawl in Mammoth Cave. Note the near-aa textured cauliflower lava floor and sharks tooth lava stalactite ceiling, both of which make travel into these parts of the cave unpleasant.

Figure 7—A scanning electron microscope photograph of a moonmilk found in Catwalk Cave. The granular background is fine-grained calcite, calcium carbonate; the square tabular crystals in the foreground are gypsum, hydrous calcium sulfate; and the bladed crystals at the top are barite, barium sulphate. Scale bar at lower left is 20 microns—0.000,000,020 meter—long.

Figure 8—Ice stalactites in Crystal Ice Cave in Lava Beds National Monument are comprised of 0.3-meter-long stacks of 2-centimeter-diameter hexagonal ice plates. Many other unusual ice speleothems are present in this ice cave. In some locations very finely powdered gypsum is found on the surface of ice stalagmites and floors. The powder has been literally squeezed out of the mineral-charged waters as the water froze.

ground water abundant. The more mobile silicate, carbonate, and sulfate minerals are found further down slope in areas of thinner soils and less ground water. Ice and basalt speleothems are found throughout the elevational range of the caves studied. The minerals found inclued:

ice	H_2O	common, especially seasonally
goethite	$FeO \cdot (OH)$	rare
pyrolucite	MnO_2	rare
romane-chite	$BaMn^{+2}Mn^{+4}{}_8 O_{16}(OH)_4$	rare
gypsum	$CaSO_4 \cdot 2H_2O$	uncommon
barite	$BaSO_4$	rare
calcite	$CaCO_3$	very common
unnamed	$Na_2SO_3 \cdot 7H_2O$	rare
unnamed	$Na \cdot SO_4 \cdot CO_3 \cdot nH_2O$	rare
cristobalite	SiO_2	very common
silhydrite	$3SiO_2 \cdot H_2O$	rare
amorphous silica	SiO	moderately common
basalt and andesitic basalt		ubiquitous

Mineral Groups Found as Speleothems					
Stalactites	•		•	•	
Spathites			•		
Flowstone	•		•	•	•
Crusts	•	•		•	•
Coralloids	•		•		
Moonmilk		•			
	CO_3	SO_4	SiO_2	O_2	NO_3

This manuscript benefited greatly from discussions and reviews from Julie Donnelly-Nolan, Aaron Waters, and Edward Helley of U.S. Geological Survey; Gary Hathaway and Charisse Sydoriak of the National Park Service; and Mike Sims of the Cave Research Foundation, for which we are grateful.

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Figure 9—Typical eight-meter-diameter passage in Gelsies Grotto, an over-700-meter-long tube. Note extensive collapse masking original floor and large amounts of calcite and cristobalite speleothems on the walls. In another portion of this cave one can see where a later lava stream coursing through the cave heated, deformed, and finally eroded down nearly 1.5 meters into the solid basalt floor of the cave.

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Lava Caving Areas in New Mexico

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The complex geological history of New Mexico includes a number of episodes of active volcanic eruption and lava flow, some particularly recent. This has left throughout the state a number of significant lava fields called malpais (Spanish for badlands). Some of these malpais areas are noted for an abundance of lava tubes while other areas have geological, mineralogical, biological, and paleontological features that make them worthy of study.

Although there are many lava flow areas throughout New Mexico, three malpais areas are of special interest. El Malpais near Grants, the Valley of Fires near Carrizozo, and the Aden Crater area near Las Cruces (Figure 1) have significant vulcanospeleological resources while being accessible to the general public and popular with the local caving community. It is our intention to provide just enough information about these areas to spur interest towards further study of the vulcanospeleological resources in this region of the United States.

Figure 1 – Selected lava caving areas in New Mexico.

El Malpais

Recently designated a national monument, the El Malpais flow (170 square miles) contains the most extensive lava tube systems in the state. El Malpais National Monument is located in Cibola County, southwest of Grants, New Mexico (Figure 2). The monument ranges in elevation from 6,500 feet (1,980 meters) to the 8,372-foot (2,552-meter) summit of Cerro Bandera, on the Continental Divide. The predominant vegetation on the malpais includes sage, juniper, pinon, and ponderosa pines, with stands of aspen along the flow margins. Because of the high elevation, year-round ice is found in over 100 of the lava caves and crevices, perhaps more here than in any other lava flow area in the country.

Nearly a dozen major lava flows within the monument have been ordered chronologically by

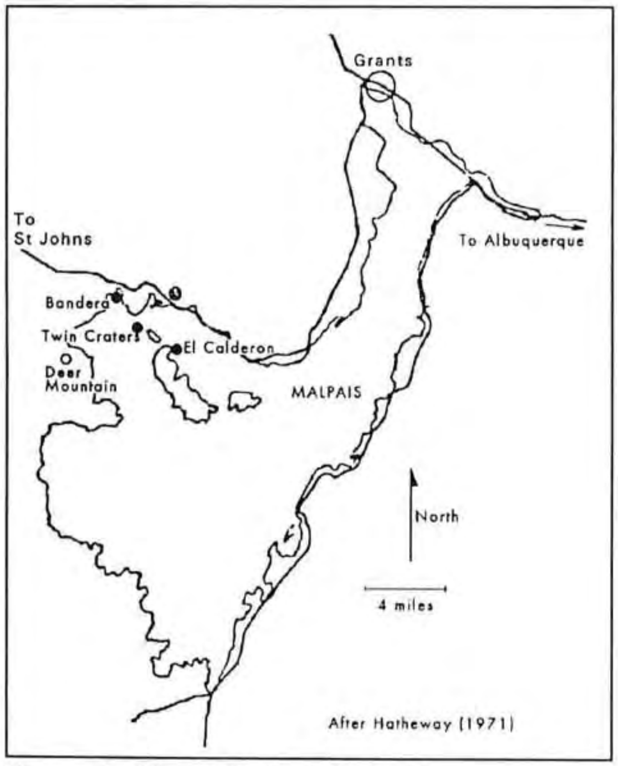

Figure 2 – The El Malpais Lava Flow.

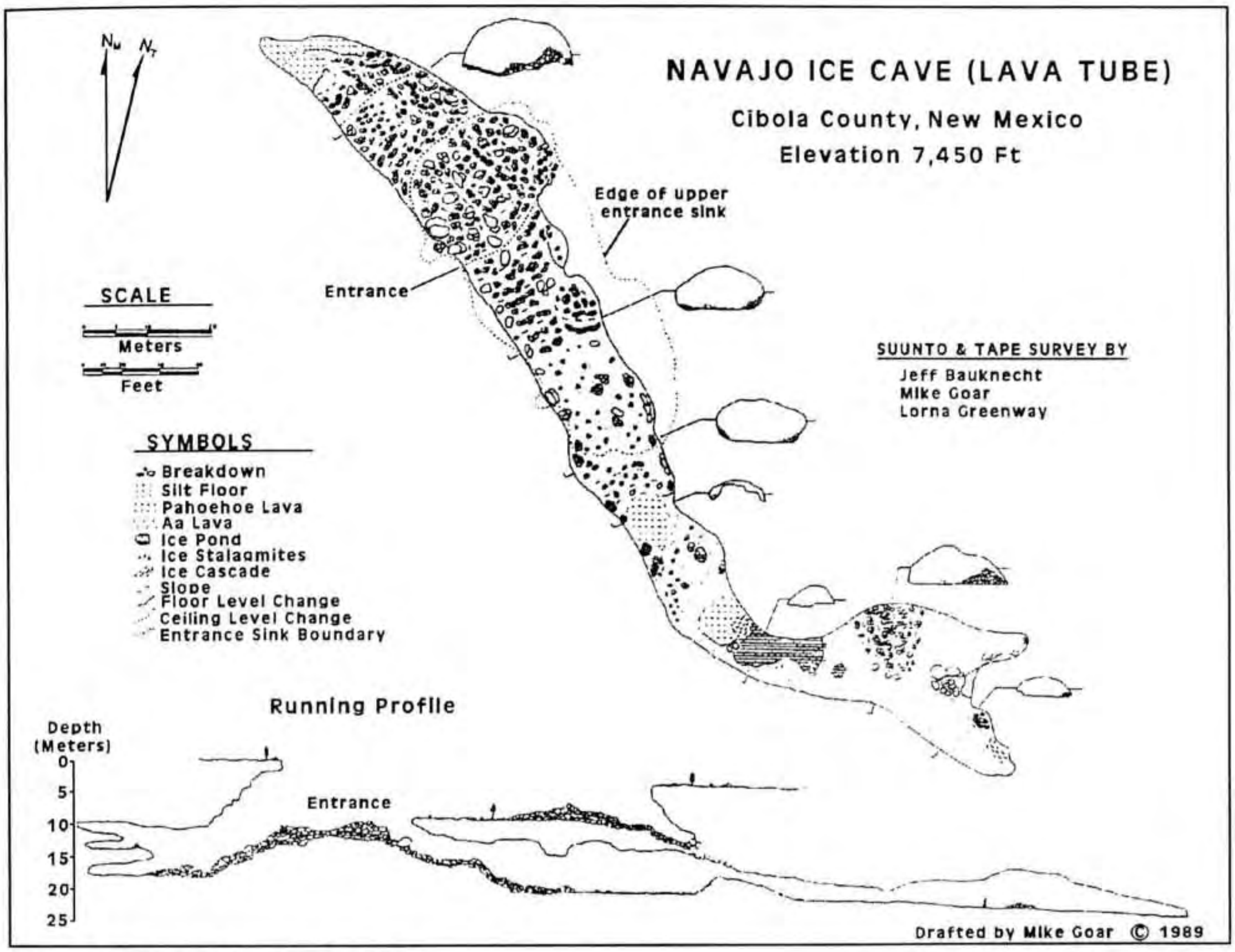

Figure 3 – Map of Navajo Ice Cave.

Hatheway (1971) according to stratigraphic position and surface characteristics. The oldest flow is Tertiary and originates from the Cerro Encierro cone. Laughlin and West (1976) approximate an age of 188,000 years to an early flow at the base of Bandera Crater, but it is now thought that the main flows from Bandera Crater may be as recent as 10,000 years before present (Laughlin *et al.*, 1982). The McCartys flow may be as recent as 400 to 1,000 years before present (Maxwell, 1986).

Of the many lava features in the monument, especially striking are collapse structures, spatter cones, and tree molds. Classic examples of pahoehoe, aa, and blocky flows frequently occur adjacent to each other. El Malpais lava tubes feature colorfully banded walls and ceilings, lava, and other secondary speleothems including spectacular ice formations. Ceiling skylights are common; parallel tubes are sometimes interconnected by windows forming "braids"; tubes may be "stacked," intersecting at different levels. Floor subsidence in some tubes has left elevated shelves, "curbs," or "sidewalks," along the passage walls.

Only a few of the flows within the El Malpais National Monument occurred under conditions favorable for lava tube development. The most prominent of these, the Bandera Crater Flow, produced a tube system which can be traced for over 16 miles (Hatheway, 1970). A survey by Kent Carlton in 1988 revealed nearly 20% of the system uncollapsed. The lava caves of the Bandera tube system can be quite large (50 feet to 70 feet in cross section) and contain abundant year round ice. Navajo, Brewers, and Classic caves were recently surveyed in the Bandera system.

Ice formations in Navajo Ice Cave (Figure 3) include frozen ponds, ice needles (up to three centimeters long), and large (four to seven centimeters in diameter) hexagonal crystals. Lava straws can be observed in the cave as well as thick charcoal

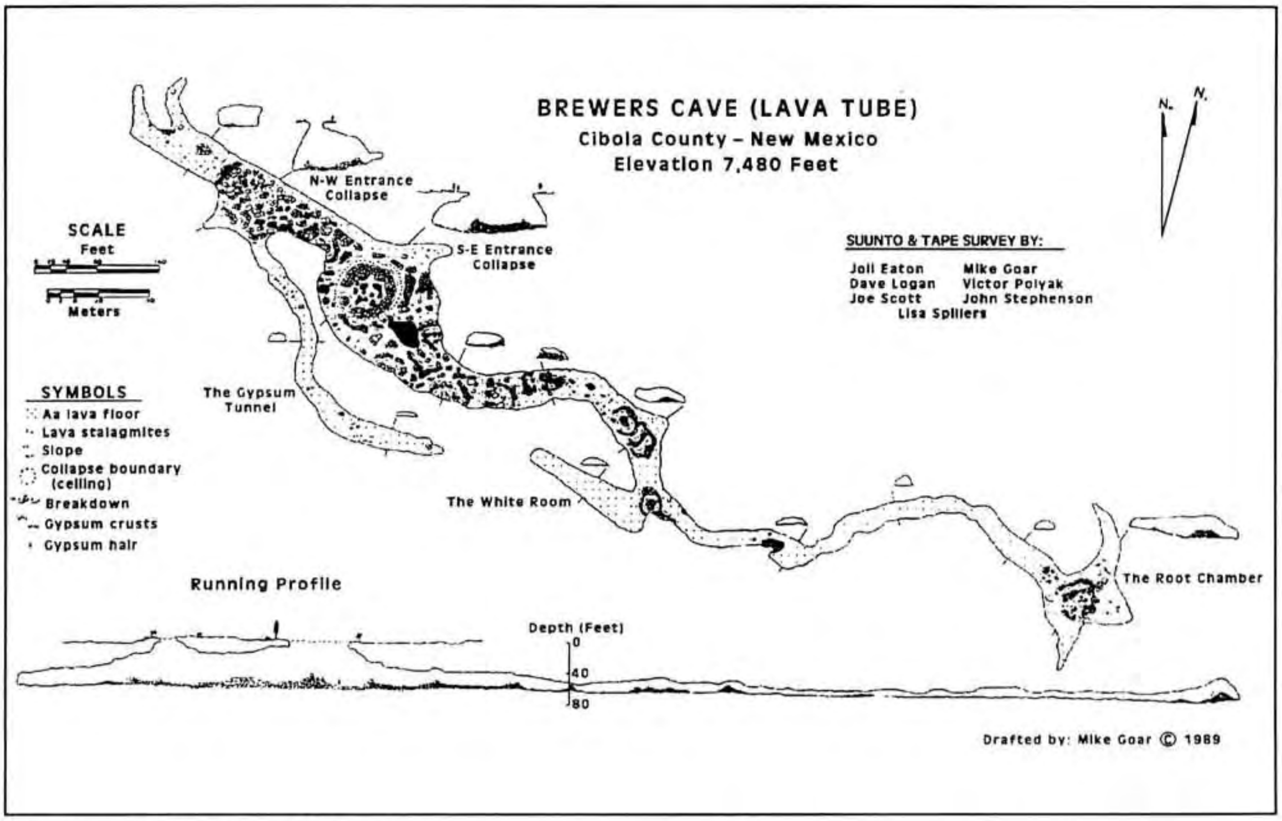

Figure 4—Map of Brewers Cave.

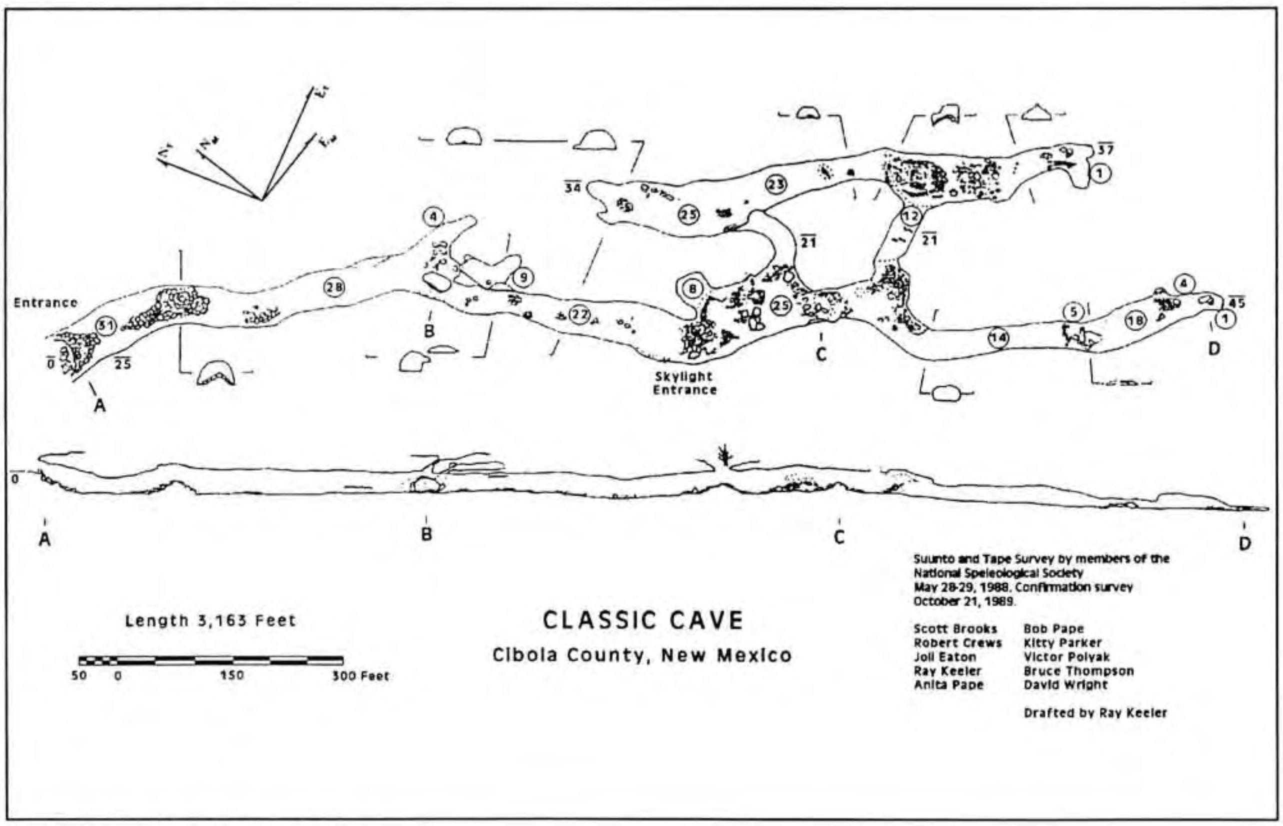

Figure 5—Map of Classic Cave.

floor deposits. Thin lava blisters, some forming honeycombs, occur on the walls in the back of the cave. Associated with these blisters are lava coralloids, some fully developed into lava popcorn. In some areas, the same material composing the coralloids occurs in the form of thin (0.5-centimeter) crusts.

Brewers Cave (Figure 4) is representative of the impressive size that is attained by many of the tubes in the Bandera system. Two collapse entrances, one 10 feet in diameter and the other over 50 feet in diameter, dramatically light the northern end of the tube which has a 50- by 70-foot cross section. Unusual secondary mineral deposits are found in Brewers Cave. A coarsely crystalline snow-like mineral on the floor of a side passage is easily soluble in water, bitter to taste, and yet effervesces with hydrochloric acid. A transparent white efflorescence with hairs up to one centimeter long covers a 0.5-meter by 0.5-meter area of wall and floor in one location. From site observations, it is thought that it may be mirabilite or epsomite. Bats were observed in the cave during our visit and we noted several bat skeletons and decomposing bodies on the floor.

Elsewhere in Brewers Cave, moist, white pasty moonmilk deposits occur on, between, and under pieces of floor aa in association with deposits of bat guano. Further moist moonmilk deposits, up to 1.5 centimeter thick, occur on a 4.5-meter by 1-meter area of wall associated with carbonate popcorn and frost work. The texture of this moonmilk is cotton-like to cottage cheese-like with a pearly to satin-like luster. Like the floor deposits, it is white except where it has been stained locally to colorful hues of blue, red, and orange. Hundreds of water droplets glisten from speleothems and rock surfaces at this locality.

Another large lava tube, Classic Cave (Figure 5), has a walk-in entrance as well as a skylight midway to the back. Near these two entrances the cave has moss, lichen, fern, and plant communities. Parallel passages in this tube are connected in two places by smaller tunnels.

An outstanding example of interconnecting passageways can be also found in Braided Cave which is part of the Hoya de Cibola flow further to the south. This appropriately named lava tube is one of the longest in the national monument and is currently being surveyed. Braided Cave is noted for its beautiful mineral stained walls, banded with "ribs" of color. It also contains a profusion of lava formations, including lava helictites. Secondary speleothems of unidentified mineralogy occur from the tips of, or as crusts over, some of the lava formations.

To the east of the Bandera flow is the El Calderon flow. One of the lava tubes in this flow, Junction Cave (Figure 6), dips more steeply (7°) than is

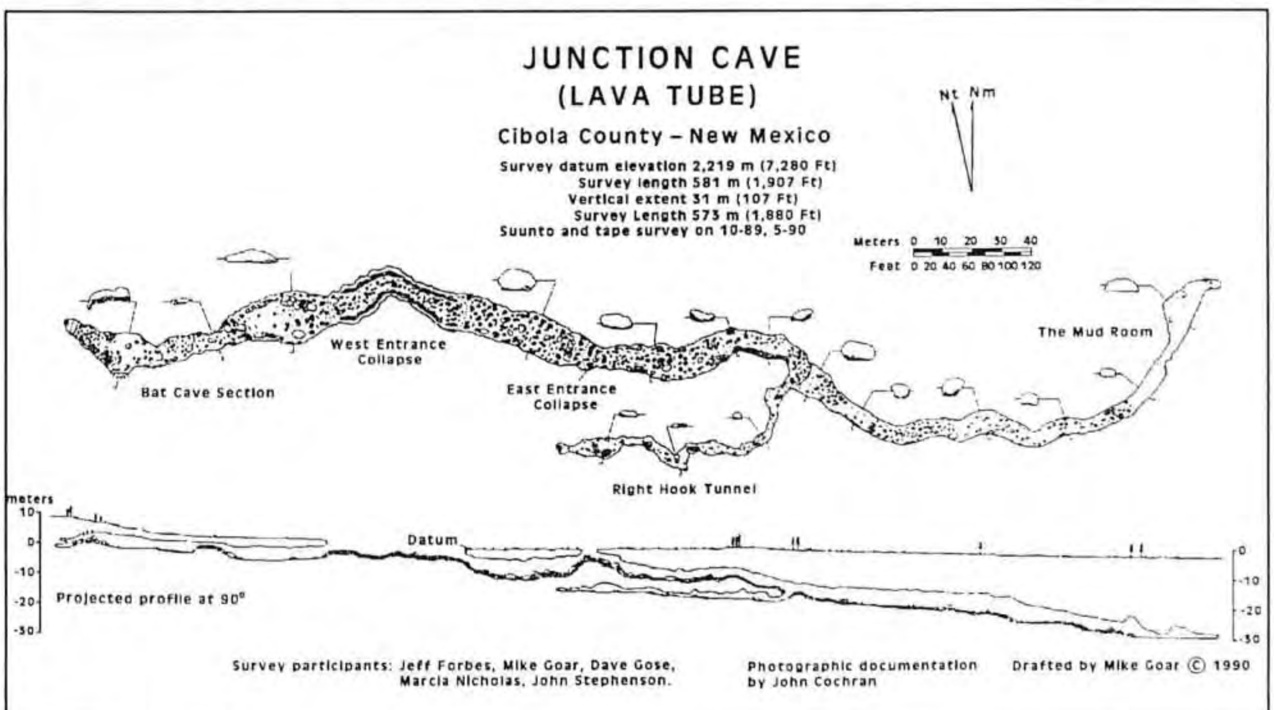

Figure 6 – Map of Junction Cave.

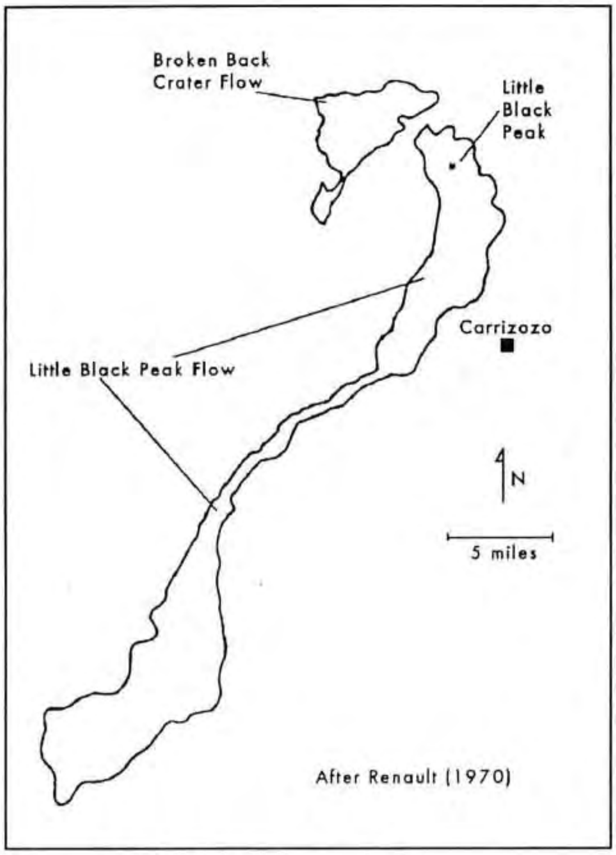

Figure 7—The Carrizozo Lava Flow.

typical of most of the lava tubes in the monument and is the only lava tube in the area known to have occasionally been flooded by water. A remnant water line can be seen along the walls midway back in the tube. Here, the breakdown floor dips 100 feet below the entrance level to a termination in a mud floored room. The shallower eastern end of Junction Cave is the roost for a summer colony of bats. There is also a colony of thousands of Mexican Freetail bats in Bat Cave, another lava tube of the El Calderon flow, which lies to the east of Junction Cave.

Carrizozo Malpais

The Carrizozo lava flow covers an area of 127 square miles of western Lincoln County, just west of Carrizozo, New Mexico (Figure 7). The flow lies on the northern end of the Tularosa Basin in a transition zone between the upper Chihuahuan Desert and dry northern grasslands at an elevation of 5,250 feet. Part of the flow is included in the Valley of Fires State Park.

The Carrizozo lava flow originated from two major sources, Broken Back Crater and Little Black Peak. The older flow, from Broken Back Crater, is overlain by the much more recent flow from Little Black Peak. The Little Black Peak flow, which extends to the south for a distance of 44 miles, occurred 1,500 to 2,000 years ago (Weber, 1979). It was the result of the most recent of a number of explosive episodes which interrupted periods of fluid lava eruption. The Little Black Peak cinder cone is 85 feet high with

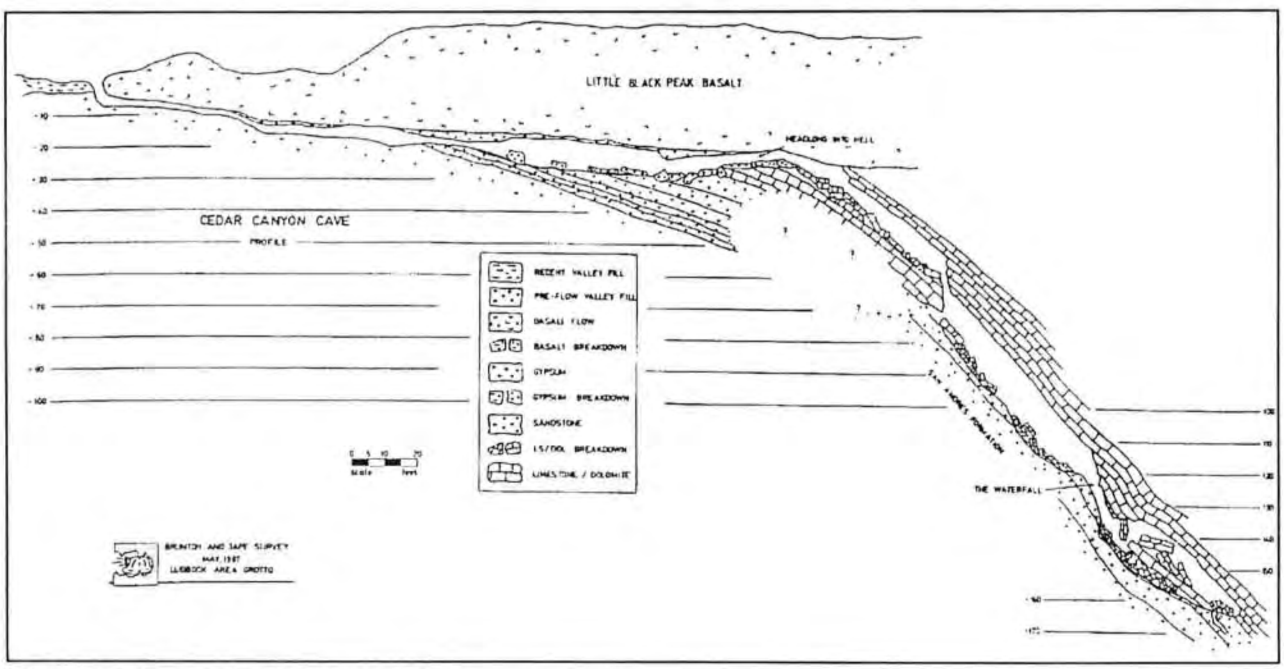

Figure 8—Map of Cedar Canyon Cave.

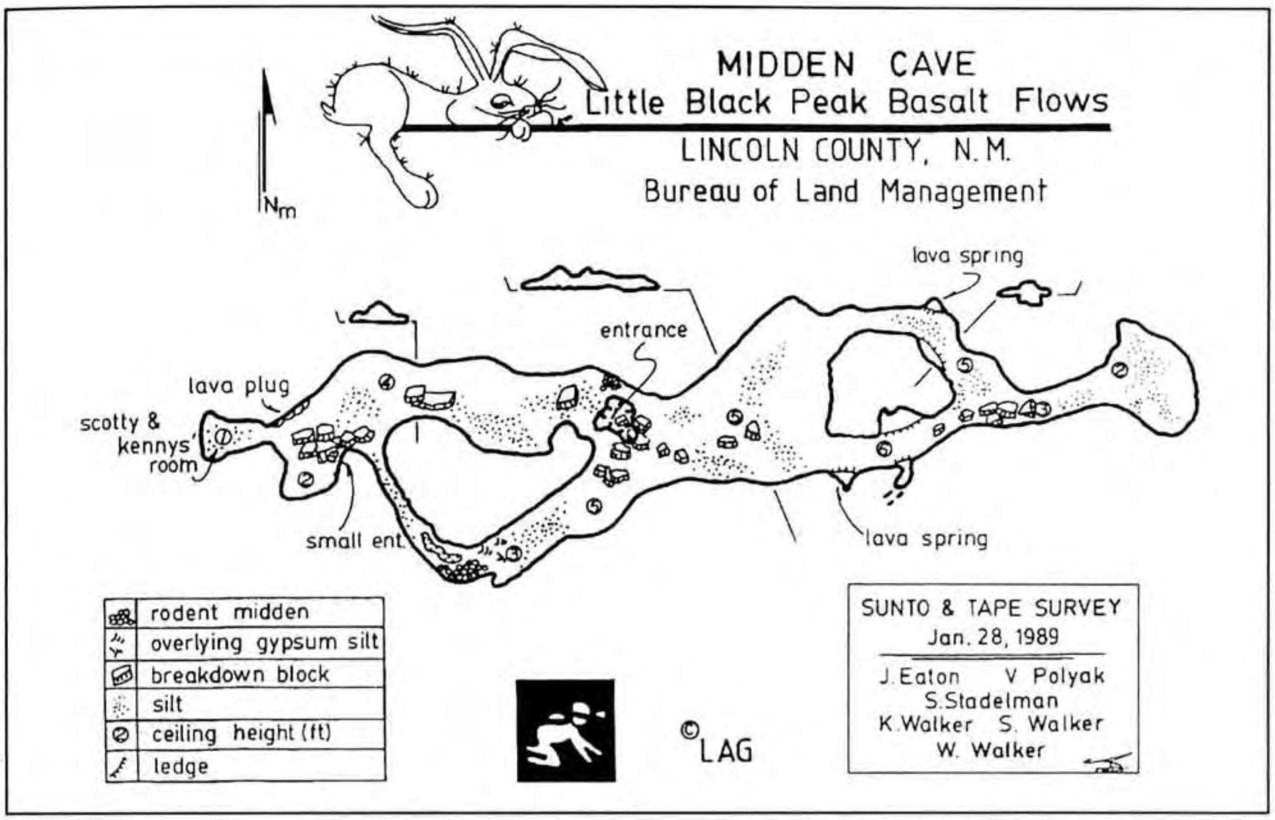

Figure 9—Map of Midden Cave.

an interior crater 32 feet in depth. Weber estimated that there is approximately one cubic mile of olivine basalt contained in the total volume of the flow.

The Carrizozo lava flow covers the Permian Yeso and San Andres Formations, which have been contorted by solution collapse and folding, and vary in thickness up to 160 feet (Weber, 1979). At the margins of the flow there are several known caves: Cedar Canyon (Figure 8), Crocketts, and Milrace Caves, which follow the contact between the Permian formations and the basalt. The caves dip steeply, attaining depths greater than in other caves known elsewhere in the Yeso and San Andres formations. Milrace Cave is one of the deepest (110 meters) gypsum caves in the world.

The Carrizozo lava flow has excellent examples of pressure ridges and a number of deep collapse structures. The ropy lava corrugations, some of which are braided, are prominent over much of the flow surface. Although the flow has not been fully explored for lava tubes, several in the vicinity of Little Black Peak have been found and surveyed, including Midden Cave (Figure 9) and Metate Cave (Figure 10). These caves occur in the Little Black Peak flow unit. The Carrizozo lava tubes discovered thus far are fewer and smaller than those in the El Malpais flow.

Aden Crater

The Aden lava field is located in southwestern Dona Ana County, about 23 miles southwest of Las Cruces, New Mexico (Figure 11). The flow covers about 25 square miles of high Chihuahuan Desert at an elevation of 4,300 feet (1,310 meters). A portion of the flow is part of a Wilderness Study Area being managed by the Bureau of Land Management, while the remainder is leased public land.

The source of the flow is Aden Crater, a 50-foot high basaltic shield volcano, situated in the northwestern part of the flow. The volcano is estimated to be 100,000 years old (Burnsom, 1991) and once held a lake of lava, which later withdrew down the primary vent to leave a number of collapse pits in the center, some as deep as 100 feet (Hoffer, 1975). Tension cracks and pressure ridges are common within the crater and a number of small lava tubes a few feet in diameter can be found beneath the pressure ridges (McMillan, 1991).

Features of the Aden lava flow include explosive craters with rims three to ten meters high, and small lava tubes 0.3 to 0.6 meters in diameter which are as long as 100 meters (Hoffer, 1975). Horseshoe shaped lava ridges called "herraduras,"

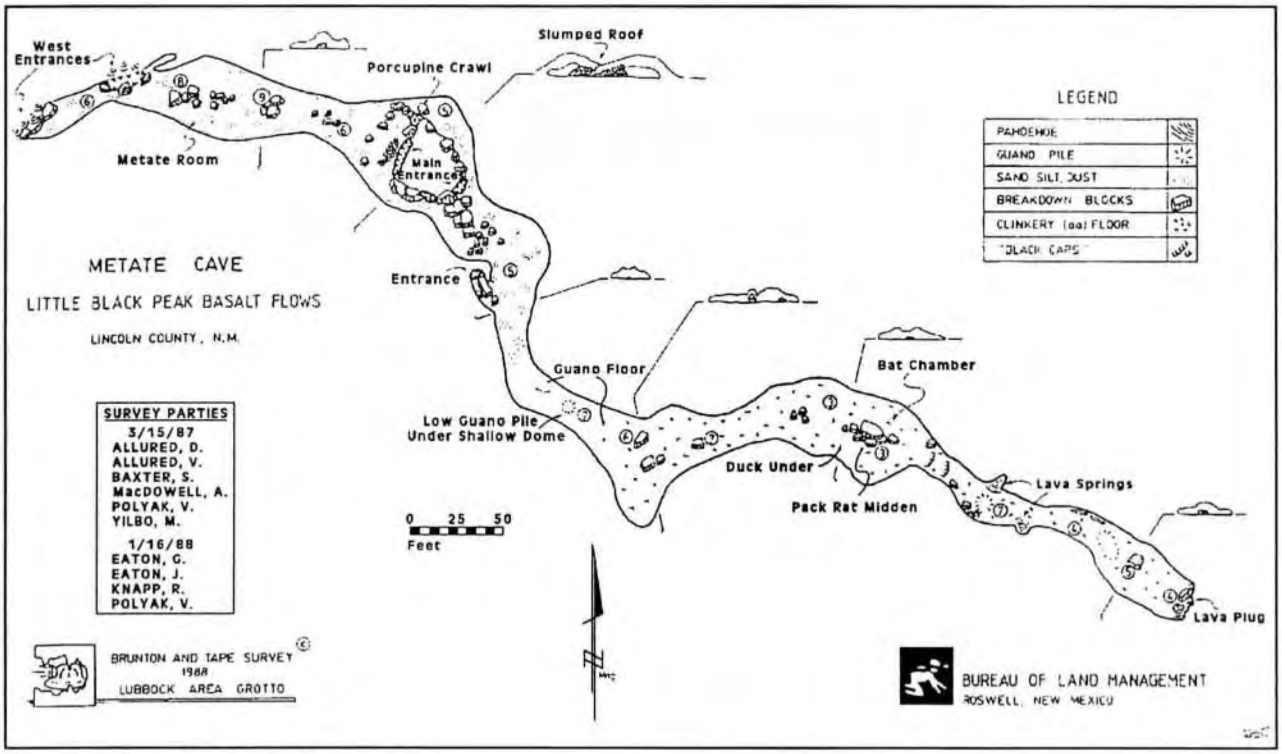

Figure 10—Map of Metate Cave.

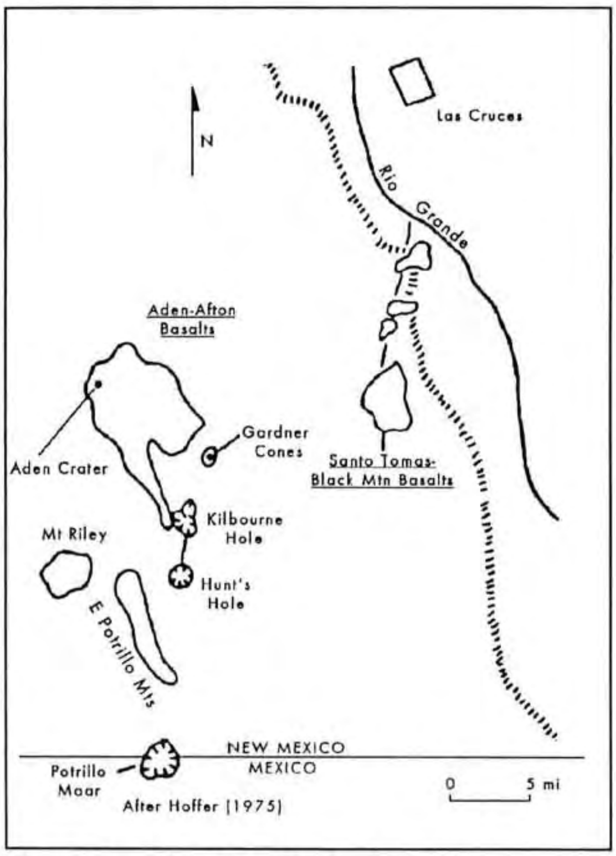

Figure 11—The Aden Crater Lava Flow.

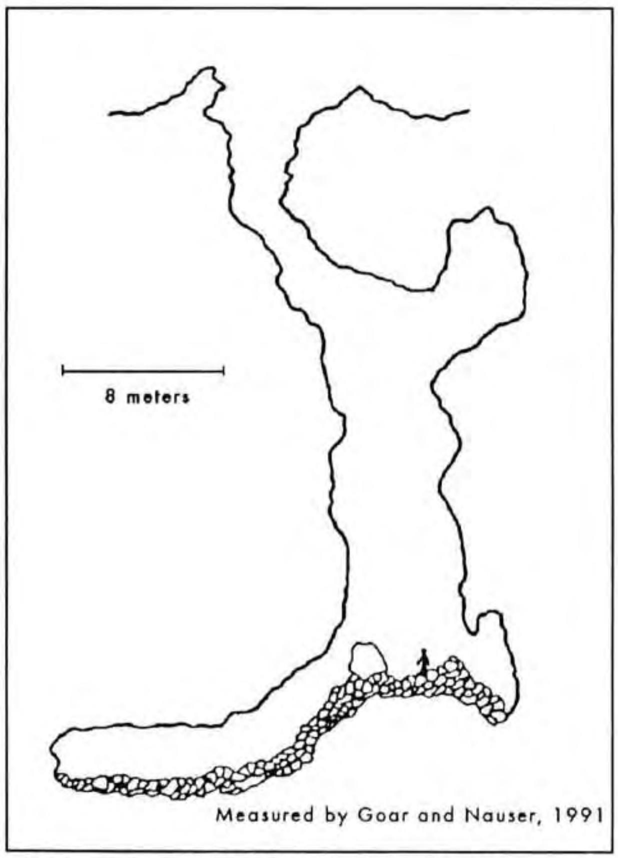

Figure 12—Profile View of the Aden Crater Fumarole.

which occur where cracks in the upper crust of the flow are perpendicular to the flow direction, have been identified by Hoffer at Aden Crater. The Aden flows are highly vesicular olivine basalts in layers 0.5 to 5 meters thick (Hoffer, 1975).

One interesting feature of Aden Crater is a 37-meter deep fumarole (Figure 12) located on the east rim. Used today by local cavers for practicing single rope technique, it was the site of the discovery of a late Pleistocene ground sloth (*Nothrotherium shastense*) in 1928 (Simons and Alexander, 1964). The exceptionally well preserved sloth was unearthed from beneath bat guano deposits at the bottom of the fumarole. Much of the soft tissues and hair taken from the specimen was desiccated but still intact. The ground sloth was dated at 11,000 years before present.

Summary

Even though there are many malpais areas in New Mexico, the El Malpais, Valley of Fires, and Aden Crater areas possess a wealth of vulcanospeleological resources for researchers, cavers, and the general public. In addition to being sources of scientific interest, these areas are rich in scenic beauty and are easily accessible to visitors, making them a marvelous living laboratory in which to study many of the natural processes which have shaped the southwestern United States.

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General Geology and Development of Lava Tubes In New Mexico's El Malpais National Monument

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The El Malpais area of New Mexico is one of the newest National Park Service units. It is located in the northwest part of the state near the town of Grants at an elevation of approximately 2200 meters. The El Malpais, (Spanish meaning "bad country") is a high, lightly forested grassland surrounded with typical southwest mesa topography. A mix of open juniper-ponderosa pine woodland covers the bare to thinly soil covered lava areas whereas a bunch grass-sage-rabbitbush vegetation mantles the deeper soil covered areas. A three-agency cooperative agreement has resulted in U.S. Forest Service wilderness and Bureau of Land Management special management areas surrounding the Park Service monument core.

Deformed preCambrian metasedimentary rocks and flat-lying Mesozoic sedimentary rocks underlie the monument. A series of Pliocene- to Holocene-age lava fields overlie the older rocks. The basaltic lavas have compositionally changed throughout their eruptive history such that the older basanites and alkali-olivine basalts range between 45 to 48% SiO_2 while the younger olivine basanites, basalts, and mugearites range from approximately 46 to 51% SiO_2. This has resulted in lava flows which change composition along their length. Scattered throughout some of the lava units are both deep crustal olivine and pyroxene and partly melted Mesozoic quartz-rich sedimentary rock xenoliths. The oldest and youngest flows containing the known caves have been dated at 1.3 to 0.75 million years old by potassium-argon methods and 1,000 to 400 years old by archaeological methods.

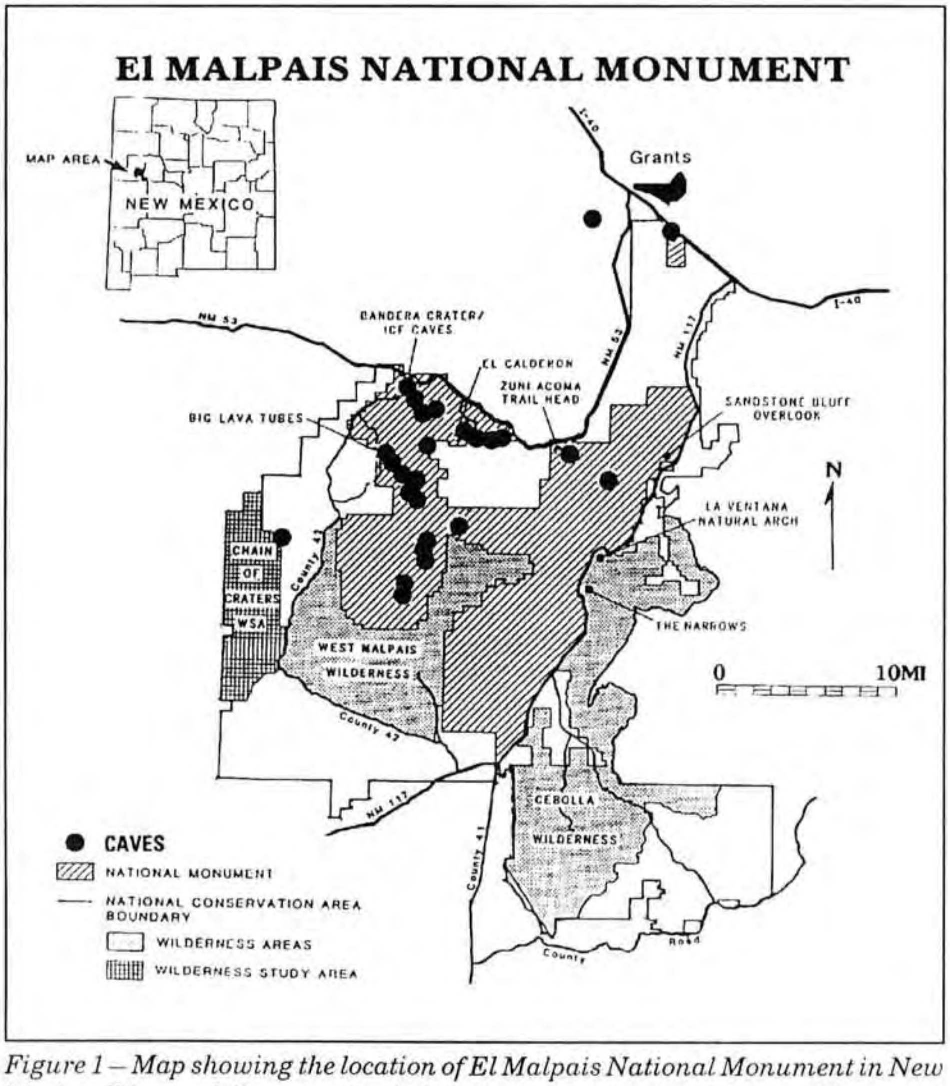

Figure 1 – Map showing the location of El Malpais National Monument in New Mexico. Diagonal lines are Park Service areas, shaded areas are Bureau of Land Management wilderness, and the cross hatched area is Forest Service wilderness. Large circles mark some of the major cave areas.

Figure 2 – The area of the El Malpais is a 2,000-meter-high ponderosa pine forest with large open areas of sage brush. The tumulus shown here is over 40 meters long and 7 meters high and probably overlies a lava tube that has no natural entrance at present.

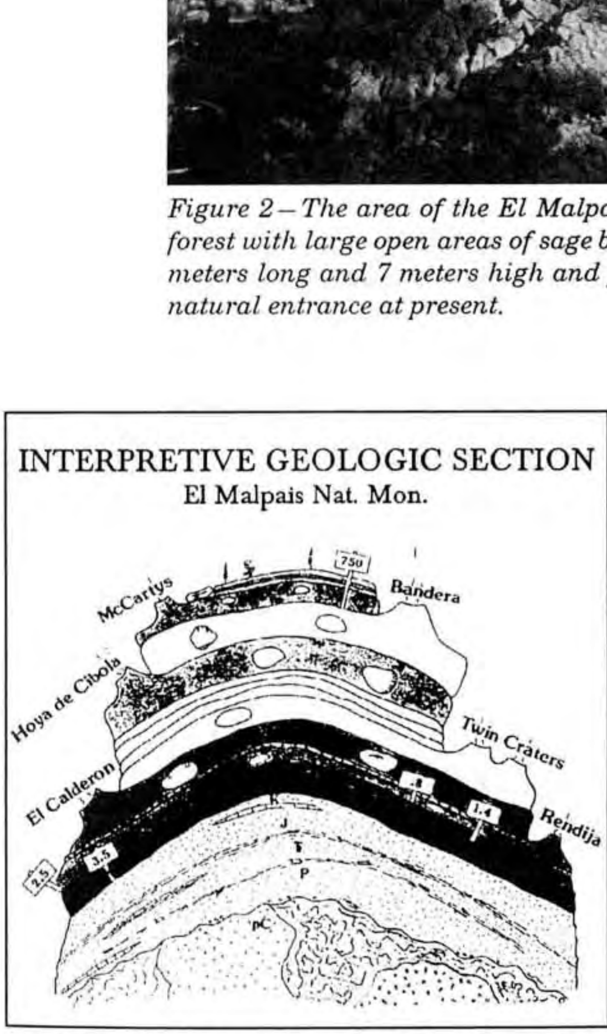

Figure 3 – This interpretive geologic column of the rock units exposed in the area of the El Malpais. Bedrock units dating from the preCambrian on up through the last 600 years of the Holocene are present. Numbers in boxes are the approximate ages of the lava flow units in Ma. The Rendija, El Calderón, Twin Craters, Hoya de Cibola, Bandera, and McCartys flows contain major lava tube systems in the Monument.

In the major cave area, five approximately kilometer-diameter volcanoes with Spanish names such as El Calderón (The Caldron) and La Tetra (The Teapot) have disgorged lava flows containing tubes in varying states of preservation. Many of the tube systems' roofs failed shortly after their draining. The resulting landforms can be divided into three types of collapse features: long, sharp-edged collapse trenches; shallow sagged, partially collapsed, partly squeezed down tube-cum-trenches; and alluviated trenches. The sharp-edged trenches have clean walls and partially preserve cave passage profiles under overhanging trench edges and in reentrants. The shallow sagged trenches have

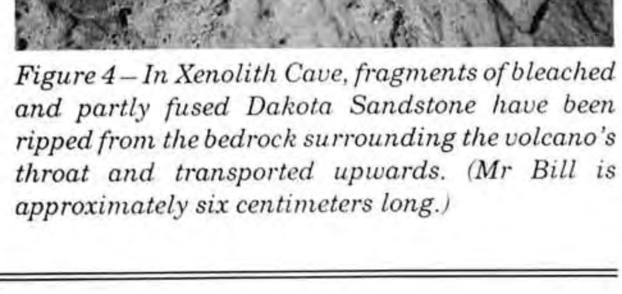

Figure 4 – In Xenolith Cave, fragments of bleached and partly fused Dakota Sandstone have been ripped from the bedrock surrounding the volcano's throat and transported upwards. (Mr Bill is approximately six centimeters long.)

Figure 5—Pat Rice of the U.S. Geological Survey in a typical nine-meter-diameter passage in Junction Cave, one of the more popular caves in the Monument. Plugging of the lower end of the cave by breakdown and in-washed silt has led to ponding of flood waters and subsequent high water "bath tub rings" along the cave walls. Note the large amount of ceiling breakdown present on the floor and the extensive calcite crusts lining the upper passage walls and ceilings above the bath tub ring.

not undergone chaotic collapse but have plastically sagged, either closing or leaving very low passages. Alluviated trenches are scarce but have been thinly veneered with sediments and subsequently vegetated. These trenches can be either sharp-edged or sagged in origin. One of the main cave forming flows, the Bandera Crater flow, is 45 kilometers long and contains 28 kilometers of identifiable tube, most of which is collapsed or sagged trench. This and the other major flows contain dozens of caves ranging from 50-meter-long natural bridges to 3,400-meter-long caves and over-one-kilometer-long systems. Tube sizes generally are large with many caves having 8-meter-wide and 12-meter-high passages but several of the caves contain passages up to 15 meters in diameter. As is common with other lava tube terrains, most of the caves have areas of extensive roof and wall lining collapse. As a result, a substantial portion of the caves have few primary wall and floor surfaces

Figure 6—Gypsum usually forms crusts in lave tubes of the El Malpais, but at Oe Puna Beach in Four Windows Cave it has built up 0.3-meter-high banks that have been subsequently eroded by dripping water to form rillenkarren.

Figure 7—At the back of Braided Cave, Mr Bill inspects a four-centimeter-high seam of mirabilite (hydrous sodium sulphate) angel hair which forms each spring. As summer dries the cave, the mineral disintegrates and falls to the floor as powder, only to be redeposited as angel hair the following spring.

intact. Where the tube interiors are intact, the pahoehoe walls and floors show a variety of features and textures. Rafted blocks are present in several of the caves. Many of the caves are braided or dendritic in pattern; however, unitary tubes are present.

Ten minerals and rocks have been identified by x-ray diffraction as speleothems in the Monument's caves. These include:

ice	H_2O	common, especially seasonally
gypsum	$CaSO_4 \cdot 2H_2O$	very common
epsomite	$MgSO_4 \cdot 7H_2O$	uncommon
mirabilite	$Na_2SO_4 \cdot 10H_2O$	rare
thenardite	Na_2SO_4	rare
calcite	$CaCO_3$	very common
trona	$Na_3H(CO_3)_2 \cdot 2H_2O$	rare
burkeite	$Na_6(SO_4)_2(CO_3)$	rare
cristobalite	SiO_2	uncommon
basalt		ubiquitous

The sources of the minerals is varied. The gypsum, epsomite, mirabilite, thenardite, calcite, trona, and burkeite appear to have drawn their carbonate and sulfate from wind-blown dust derived from weathering of the Mesozoic sedimentary rocks. The cristobalite appears to have been leached from the unstable pumice and glassy ash. Ice is present as permanent deposits in at least four caves and appears as seasonal decorations in a great number of other caves.

Speleothems in El Malpais National Monument					
Bubbles			•		
Coralloids	•		•		
Crusts	•	•			
Crystals		•		•	
Flowstone	•		•		•
Helictites			•		
Moonmilk	•				
Stalactites			•		•
Stalagmites	•	•	•		•
	CO_3	SO_4	SiO_2	CO_3/ SO_4	O_2

Chart of speleothems and their mineral compositions in the lava tubes of El Malpais National Monument.

Native Americans utilized the caves quite extensively, leaving cultural remains in many caves. Spaniards, Mexicans, and gringos apparently did

Figure 8—Cottonballs of mirabilite and thenardite (anhydrous sodium sulphate) on the floor of Braided Cave. (Microbus is five centimeters long.)

not make great use of the lava tubes except U.S. Army troops quarrying ice from Bandera Ice Cave, thus left little record of their passing in the caves.

This manuscript benefited greatly from discussions with and reviews from Ken Mabery, Cindy Ott-Jones, and John Morlock of the National Park Service; Edward Helley and Julie Donnelly of the U.S. Geological Survey; and T.M. Duke McMullen of the Sandia Grotto, National Speleological Society.

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Lava Tubes of Pisgah, Southern California

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Abstract

Pisgah is a basaltic cinder cone and lava flow located about 175 miles northeast of Los Angeles, in the central Mojave Desert. More than 200 lava tube caves are present of which about 30 are more than 100 feet in length, and the longest (SPJ Cave) is about 1,300 feet. Many of the caves consist entirely of crawlways. The lava flows are geologically young (probably late Pleistocene) and are well preserved due to the dry climate (less than five inches of precipitation per year), which allows only sparse vegetation. Nearly all of the lava tubes are either semi-trenches (leveed channels) or surface tubes.

The longest of the caves include Glove, QQ/Cat, B, C10, C12, C13N, RC3, Finis, O12, O30, Russell Stewart, A, Owl 1, Owl 2, Owl 3, and Woodsey Owl; all of which also have relatively large passage size. Some of the primary lava features of the caves include remelt, drip pendant stalactites, linings, rafted breakdown, breakdown jams, dip-layered stalactites, tube roof crustal plates, hornitos, a lava tube formed in aa, multilevel passages not superposed, layered lava, blowout pockets, spatter, pillars, columns, and well preserved details of roof crusts.

My own studies at Pisgah have included exploration, surface surveying, cave surveying, photography, cave weather magnetism in lava, lava cave morphology, micro-stratigraphy, and cave visitation as well as study of the formation of lava tube caves.

Introduction

Pisgah lava field is located in the Mojave Desert of Southern California. The lava flow is probably of late Pleistocene age, and the surface is well preserved due to the low rainfall – less than five inches per year. A basaltic cinder cone and lava flow are present, and pahoehoe flows cover much of the area. Surface features include a driblet spire about three feet tall.

There are many caves, such as "A" Cave. Although the passage size is comfortably large, the whole cave is only about 100 feet in length. Pisgah is a fine place for family outings. The main entrance to SPJ Cave is a picturesque spot. SPJ is the longest cave at Pisgah at about 1,500 feet. Most of the cave passages at Pisgah are small, and crawlways in SPJ Cave are common. Many of the caves are very short such as Not Either Cave, which is about 40 feet in length. New discoveries are often made, such as Woodsey Owl Cave, dug open a few years ago. Woodsey Owl is a single-passage cave about 450 feet in length. One of the minor exploration challenges was a high lead in Woodsey Owl Cave. It was eventually free-climbed, but didn't go more than a few feet. C13 North Cave has a portion of large walking passage, including a nice lining curb. Nearby, an upper level overflow extends to the side.

Surface Tubes and Tube Roofs

The lava tubes that are most abundant are surface tubes. Most of the cave entrances are collapsed portions of the roof. Many of the surface tubes have the original details of the roof well preserved, some even have the delicate upstream edge of the roof preserved. With much of the roof collapsed, it is possible to see relationships like a smaller tube fed as an overflow from a larger tube.

There are numerous examples of surface tube junction pools, some of which have collapsed, exposing the several small tubes that were fed from the pool. Some small surface tubes have been buried by later lava. The entrance to QM, a cave about 35 feet long, was almost completely buried by an

aa flow. If the area was covered with forest it might not even be possible to recognize that the aa and pahoehoe are different flows.

Roof crust details that are well exposed at Pisgah include many examples of incomplete separation of the crust from molten lava below. The roof crust of KB, a natural bridge about 40 feet long, has a massive lower phase, with rubble on top. It appears to be similar to the underriding of lobes described by Baldwin in the 1880 to 1881 Hawaiian lava flow that formed Kaumana Cave. One of the well preserved features is a cast of ropy pahoehoe. In Station 8 Cave, a natural bridge about 100 feet long, the cast surface at the top is the underside of overlying lava. The layer in the middle is the initial roof stratum with remelt on its underside. The bottom layer is a ceiling lining with remelt on the underside.

Caves

A map of Pisgah shows that the caves are located east of the cinder cone, within about 1½ miles. Three tube flows – C, Q, and Owl – contain most of the caves that are more than about 100 feet in length – the rest are less.

Glove Cave has three entrances that are near the middle of the cave. The cave is about 1,100 feet long, much of which is walking passage, so it is very popular to visit. Glove Cave has good examples of remelt stalactites, as do many of the lava tube caves at Pisgah. There is also a stand of dip-layered stalactites that seem to have grown larger by collecting successive thin frothy layers of lava. Blowout pockets are common at Pisgah. The surface of a shelf in Glove Cave has remelted and sagged. It has also collected some lava drips from remelt stalactites above. Just to the left of the same remelted shelf, lava welled up through a lining partition and subsided again. Much of the downhill part of Glove Cave is walking passage with a dust floor. In rare times of heavy rain, water flows on the floor leaving a dry stream bed. The middle portion of Glove Cave had the roof fall in while the tube was still hot. The lava found its way through the lower half of the breakdown, and now the passable route through the cave involves doubling back and clambering over breakdown.

QQ/Cat Cave is a segment of the main tube of the Q flow. It has a free drop of 20 to 43 feet at the entrances. Cat Cave was first entered about 12 years ago, and a connection to QQ Cave was later made by digging out hard lava from the floor of a crawlway. Cat Cave has cotton-like deposits of thenardite (sodium sulfate) on the floor that have not yet been trampled by careless visitors. Some of the thenardite makes masses of long needle-like crystals. At the upper end of Cat Cave there is a breakdown jam that was welded in place by molten lava. A small cascade flowed between some of the breakdown blocks. In a closer view of the breakdown jam, blue-grey parts are the lava infilling, and brown rock with shiny spots is the breakdown. Cat Cave also includes some tight crawls. The Southern California Grotto maintains a register in QQ/Cat Cave to monitor traffic.

Glove Cave also has a register, where we collect two to three hundred names per year. Visitation is now two to three times what it was ten years ago. The Pisgah lava field is visited often because it is easily accessible to people from all over Southern California. Land ownership of the caves is about evenly divided between the Bureau of Land Management and railroad land. South of the cave area is the 29 Palms Marine Corps base.

Lava Pseudokarsts of Mount St Helens: The First Decade After the 1980 Eruptions

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Abstract

The pseudokarst of the Cave Basalt Lava Flow of Mount St Helens underwent only minimal direct impact from the 1980 eruptions of that volcano. However the caves and other pseudokarstic forms underwent a wide variety of impacts depending on their location and exposure to runoff of varying load and velocity. An entire new pseudokarst developed in ash cloud deposits and avalanche debris on the north side of the mountain. It continues to undergo rapid evolution.

Introduction

On May 18, 1980, deposition of avalanche debris and ash cloud material created a rapidly evolving, sharply localized volcanic pseudokarst in the valley north of Mount St Helens, Washington. A small quantity of directed blast material also is exposed on the surface of this study area.

Also beginning on May 18, 1980, complex eruptional and perieruptional events caused major surface and subsurface changes in the northern (upslope) part of the volcanic pseudokarst of the Cave Basalt Lava Flow, as defined by Greeley and Hyde (1972), on the south side of the mountain.

The writers initiated systematic observations on the Cave Basalt Lava Flow on June 22, 1980, and in the Spirit Lake Pseudokarst on October 9, 1982, including ground, subsurface, and aerial studies. As the rapidity of change decreased in both areas, the frequency of studies decreased to once per year toward the end of the first decade. Beginning July 1980, some of these observations were reported in numerous publications of the National Speleological Society and its Cascade and Oregon Grottos, the Western Speleological Survey, and the proceedings of Mount St Helens symposia of Eastern Washington University. We now summarize and analyze the findings of the first decade following the 1980 eruptions.

Part I: Cave Basalt Lava Flow Pseudokarst

Most of the major changes observed on and in the Cave Basalt Lava Flow pseudokarst were the result of perieruptional mudflows and other flood deposits, not tephra fall or earthquakes. Tephra fall from the 1980 eruptions measured several centimeters at the upper end of this lava flow (about five kilometers south of the 1980 crater rim) (Figure 1), two to three centimeters at the main entrance of Ape Cave (about 8.5 kilometers from the crater), and much less farther south. Additional tephra accumulations from October 1980 eruptions were not measured because of administrative restrictions on access but are believed to have been comparatively small. Tephra fall was vertical, with little eddying or drifting (Halliday, 1981, p 4). Only in the case of vertical or steeply sloping cave entrances did more than trivial quantities of tephra enter any cave. Some invertebrate fauna was affected by surface accumulations of tephra (Crawford, 1980) but the caves otherwise were not significantly impacted by the eruptions *per se*.

Figure 1 — U.S. Forest Service road and path at the main entrance of Ape Cave in June 1980 showing tan, powdery-appearing tephra on the ground and vegetation.

cade of study. Underground, it was seen best in Ape Cave in the late summer and autumn of 1980 (Figure 2). Small amounts entered Ape Cave from the main entrance (and probably also through the upper two entrances which could not be studied under administrative restrictions). It also entered through two small ceiling cracks downslope from the main entrance. All these were the result of local runoff caused by light rain. Similar material later entered the part of the cave crossed by the Hopeless Cave Mudflow through several drip points, resulting in very small mud ponds in floor depressions. All these entry routes for tan mud entering Ape Cave sealed spontaneously within a few weeks.

On the other hand, pluvial reworking of tephra and admixture with pre-1980 materials caused a succession of changes in the area above and below the ground surface. Some were minor, short-lived phenomena. Others were extensive and continued to evolve throughout the first decade of study.

In the summer of 1980 light rains resulted in early separation of a tan powdery tephra component which readily formed small local mud tongues, ponds, and flows above and below the ground surface (Halliday, 1981, p 4). Even when extensively mixed with pre-1980 materials on flood plains (see below), in favorable locations this tan component formed small but distinctive mud ponds and tongues on the surface throughout this de-

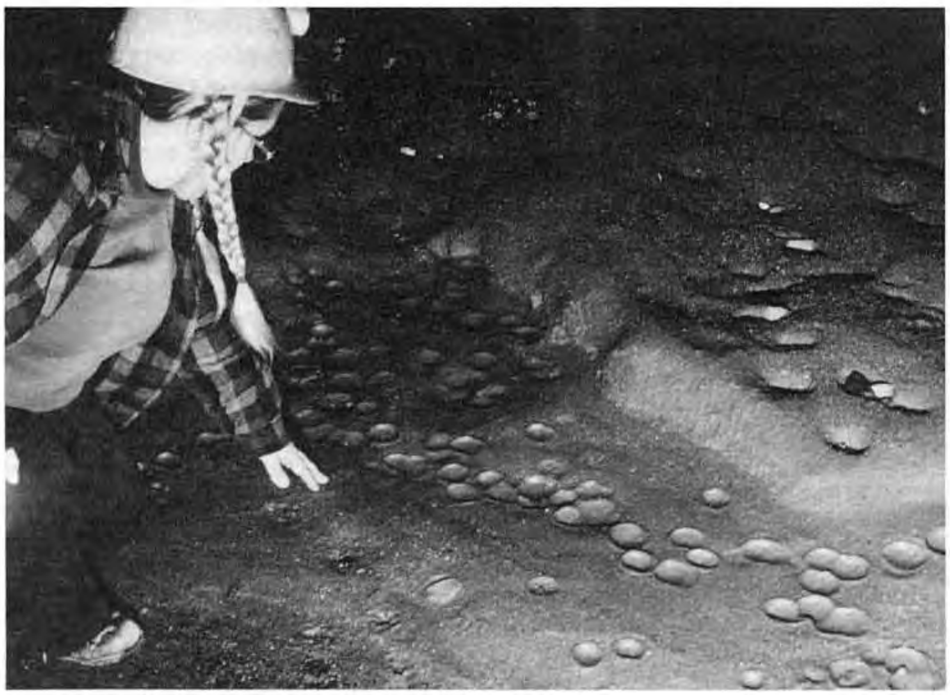

Figure 2 — Drip cavities in the unconsolidated gray tephra tongue in Ape Cave. Note the different appearance of drip cavities in partially consolidated pre-1980 flood deposits in the background.

Figure 3—Aerial view of the Gremlin Cave Mudflow in 1986. The upper entrance of Gremlin Cave is in the clearcut in the lower left part of the photo. The lower entrance is at the edge of the mudflow below the center of the photo. Road 81 cuts diagonally across the upper left of the photo and the main Road 81 Mudlfow cuts across the road in upper right center.

On June 22, 1980, the entrance sink of Hopeless Cave was half-full of tan mud and tongues of similar material (together with small pebbles of pumice) were photographed entering non-spelean swallets about 200 meters northeast of Hopeless Cave. In addition, they carried small quantities of sand. Also on that date a wide, thin mudflow consisting primarily of tan mud was observed covering about 100 meters of Forest Service Road 81 (formerly Road 818) on the east edge of the lava flow, about six kilometers from the new crater. In this locality numerous small boulders and some pre-1980 material derived from local headward erosion was incorporated in it. Similar material was observed in two convergent, newly-eroded gullies about one kilometer farther upslope. Downslope from Road 81, one small tongue of this mudflow was found entering Little Peoples Cave. About 250 meters upslope from the main entrance of Ape Cave, in the drainage axis of the upper part of this lava flow, a mudflow ponded by another Forest Service road appeared to be composed almost entirely of the tan tephra component. Administrative restrictions (Halliday, 1981) precluded investigation of the dry stream course between the Road 81 Mudflow and this mudpond.

On August 23, 1980, a larger mudflow with a different appearance was found in and around the lower entrance of Gremlin Cave. This was part of a mudflow complex crossing Road 81 about one half of a kilometer east of the western edge of the lava flow and about one kilometer northwest of the Road 81 Mudflow, about seven kilometers from the crater (Figure 3). It appeared to arise independently of the Road 81 Mudflow, and was named the Gremlin Cave Mudflow. In contrast with the tan mudflows cited above, the Gremlin Cave Mudflow was gray in color and generally was sandy to gravelly in consistency. In Gremlin Cave it formed a thin slurry with some gravelly elements (Halliday, 1981, p 6, and 1986, Fig 4). Some of it probably was pre-1980 material.

On August 23, 1980, the tan-colored mudflat on and alongside Road 81 in the eastern part of the lava flow was found partially covered by a pond of welded tuff. Its maximum thickness was a few centimeters. Part of it had a reddish tint suggesting incorporation of a pre-1980 material not observed elsewhere at any time. Welded tuff also was found lining the principal gully along the east boundary of the lava flow one kilometer upflow from the pond (Figure 4). Here it lacked any red tint.

All the above phenomena were destroyed or heavily modified by several days' heavy rain at the beginning of November 1980. The gully which had been lined by welded tuff was enlarged by a factor of more than ten, and all trace of the welded tuff lining was destroyed. A series of new, nearly parallel gullies incised Road 81 in most of its course across the lava flow. A sloping flood plain incised by dendritic gullies was deposited atop and on both sides of the road. Locally, trees were debarked more than two meters above the surface of this new plain. Near the road, boulders as much as one meter in diameter were left wedged between trees more than a meter above the new ground surface.

Figure 4—A shallow stream gully along the east side of the upper part of the Cave Basalt Lava Flow in August 1980 showing the welded tuff lining.

Since early November 1980 the geomorphic history of this pseudokarst has been the reworking of the 1980 materials plus addition of much additional pre-1980 material washed into the area by subsequent rains. In and upslope from the pseudokarst, runoff is very rapid because of the slick, bare surface resulting from tephra fall and pluvial deposits. Vegetation is returning locally, but much of the surface still is easily degraded by comparatively low velocity runoff. Deposition continues to predominate as far downslope (south) as the narrows of the lava bed at the lower end of Ape Cave. However, some erosion by low-load stream flow has been noted both above and below ground, with continuing frequent reworking of deposits. Tongues of coarse- or fine-grained floodplain material have been observed enlarging and lengthening at different times and at different rates. Several such tongues now cross Road 81 east of the Gremlin Cave Mudflow. With comparatively light rainfall, small tongues and ponds of tan and gray fine-grained material still leach out of the stream deposits but characteristically are quickly overrun by coarse-grained material.

Following installation of a protective barrier near the lower entrance of Gremlin Cave, its lower entrance crawlway reopened spontaneously. A succession of very small terraces reaching the ceiling of another crawlway about 100 meters downslope suggests that it also became plugged and reopened spontaneously. In the lower entrance area, degradation has been predominant since 1983 or 1984. On one visit when several centimeters of snow remained on the surface, an active snowmelt stream was observed eroding sandy stream deposits in the cave. Unconsolidated gray mud appeared briefly in Ape Cave, much like the initial slurry in Gremlin Cave.

As the main Road 81 Mudflow increased in bulk, one of its tongues entered the vertical lower entrance of Sand Cave then buried it and backfilled nearly all

As a result of this heavy rainfall, the general color of the countryside changed dramatically (Halliday, 1981, p 6). Prior to the heavy rain, the general color was a uniform tan, including the vegetation, to which tephra clung tenaciously. The texture of the ground surface was powdery. After the rain, the natural color of the vegetation returned except for moss and low ground cover which were still covered. The ground surface varied from light to dark gray, depending on how much fine-grained gray tephra had been leached. In areas lacking major flood deposits, the texture of the ground surface changed from powdery to gravelly.

As far south as the narrows of the lava flow near the lower end of Ape Cave, the landscape became dominated by new flood plains or tongues of flash-flood deposits. Hopeless Cave and the adjacent flat were buried in a wide flood plain two to three meters thick. Locally, this was termed the Hopeless Cave Mudflow. Had its crest been a few centimeters higher, part of it would have overrun a Forest Service road near Hopeless Cave and entered Ape Cave (Halliday, 1981, p 6).

To a lesser degree, the Gremlin Cave Mudflow also took on the characteristics of a sloping flood plain. The cave slurry mentioned above was replaced by sandy to gravelly inwash. This new inwash temporarily blocked the lower entrance crawlway. Similar material entered Little Peoples Cave from a new tongue of the Road 81 Mudflow.

Figure 5—Mud flow tongue which invaded the upper entrance of Sand Cave showing the canyon incised by later low-load high-velocity water. Behind the caver is backfilling from the lower entrance. Originally this was walking passage, now filled.

the upslope section of the cave. A smaller tongue of the same mudflow entered the upper entrance of the cave several months later. It deposited a sandy tongue about one meter high and several meters long. Subsequently this sandy tongue has undergone several small episodes of minor erosion by low-load local runoff (Figure 5).

About 200 meters upslope from Sand Cave, the small vertical entrance of a previously unknown cave was found washed open on October 25, 1981. Named Mud Pond Cave for its most prominent feature, this cave was observed in 1982 and 1983 but on June 3, 1984, it was found reburied and presumably filled.

The Hopeless Cave Mudflow has enlarged and undergone especially notable repeated reworking. It also has propagated downslope, with additional ponding on the narrow neck of the lava flow near the lower end of Ape Cave. Some mud swallets not associated with any known cave developed in that area beginning around 1987.

On March 7, 1981, a different phenomenon was observed in an aggradation-free area between Gremlin Cave and Flow Cave: three resurgences of tan-colored mud. They were found only on that date and their source could not be identified.

At the end of the first decade of study, nearly all of the impacts of the eruptions were upslope from the narrows of the lava bed near the lower end of Ape Cave. South of this point a narrow gully extends downslope from the mud pond previously mentioned. Initially it courses along the west edge of the lava flow then crosses its western arm and parallels the west side of Green Mountain (a kipuka in the lower part of the lava flow). It drains all surficial runoff of the northern part of the lava flow. Except for a few small overflow areas of this gully, and minor local residuals of tephra fall, the southern part of the Cave Basalt Lava Flow shows no significant alteration by the 1980 eruptions and perieruptional events.

Part II: The Spirit Lake Pseudokarst

Beginning October 9, 1982, we began observations on what we call the Spirit Lake Pseudokarst. This is a distinctive, sharply localized area located at and near the former outlet of Spirit Lake, about five kilometers north of the new crater. It comprises most of the Spirit Lake blockage as defined by Glicken *et al.* (1989). The pseudokarst is about one kilometer long (north-south) and 1.5 kilometers wide (east-west). It is immediately east of the depression called Pumice Pond which was the site of spectacular immediate post-eruptional ablation. All except its northwestern tip is 200 to 300 meters south of the buried stream course of the north fork of the Toutle River (Lipman and Mullineaux, Fig 129). None of the features or processes below appear related to the buried stream course.

Figure 6—Aerial veiw of Spirit Lake Pseudokarst looking south taken in 1983. Brownwater Sink (left) and Greenwater Sink (right) are near the center. Two conical "craters" are to the right of Greenwater Sink. Three small sinks are present above and left of Brownwater Sink. At the right edge of the photo are two shallow closed depressions partially cut off by the edge of the photo. The lower (northern) one is heavily modified by construction work on the Spirit Lake Drainage Tunnel seen extending across the lower part of the photo. Ice Sink is near the right edge, below the center.

Other closed depressions exist in the extensive post-eruptional surfaces of this drainage basin, but are scattered and much smaller than those described below. It is the assemblage of large and small closed depressions and other pseudokarstic phenomena in this sharply circumscribed area that merits its identification as a specific geomorphic unit.

Recent publication of detailed geological and hydrological studies of this area (Glicken *et al.*, 1989) has greatly clarified understanding of its origin, nature, and features. But the field studies in that 1989 report terminated in October 1984. The topography of this area has continued to evolve rapidly and extensively. Some of the maps, descriptions, and interpretations in the 1989 report are in need of updating.

When we first observed it in 1982, the surface of this pseudokarst consisted of a gently rolling pockmarked slope of finegrained May 18, 1980, ash cloud deposits from which rose hills consisting of shattered fragments and blocks of the old north flank of Mount St Helens. Some showed surprisingly little contortion of pre-eruption stratigraphy. Some minor directed blast deposits are present near the north edge of the pseudokarst area and some minor reworked undifferentiated pyroclastics near its south edge, but neither has any part in the findings and processes described here. All its pseudokarstic features are in one or more of the units of the debris-avalanche deposits of May 18, 1980, or the ash cloud deposits which immediately followed, or both. Geological terminology in this report is that of Glicken *et al.* (1989).

In this topography we found closed depressions of several types and sizes, sinking ephemeral streams, centripetal drainage, karren, vertical shafts, natural bridges, and (later) one horizontal cave about 15 meters long. Glicken *et al.* (1989) noted that its ridges were as high as 230 feet and the closed depressions as deep as 150 feet. The largest type of closed depression here characteristically has different components of the May 18, 1980, deposits in different segments of its walls. These have the appearance of irregularly rounded sinks with wide, flat bottoms.

The slope and rapidity of erosion of each part of the walls of these large sinks is determined by the type of 1980 material present at that location. Blocky areas of the dark colored "andesite-and-basalt unit" of the avalanche produced comparatively steep, fairly erosion-resistant slopes. Less steep and less resistant slopes are seen where the wall is a less blocky portion of this unit or the grayer "older-dacite unit." The tan ash cloud deposit forms either gentle or near-vertical slopes. While it is highly vulnerable to pluvial erosion, it characteristically forms short-lived vertical or steep fracture faces. The largest closed depression (along the

northeast edge of the pseudokarst) has only a low ridge of ash cloud material forming most of its northern rim. It may be breached within a few years by headward erosion of a branch of the ephemeral stream course which forms the north margin of the pseudokarst.

Five major sinks of this type have been identified in the study area. Their floors are aggrading rapidly, and are composed primarily of reworked ash cloud deposits (Figure 6). About two meters aggraded in the easternmost one ("Brownwater Sink") between October 1982 and summer 1983.

Figure 7—Same view as Figure 6 taken in 1985. Water is present in Brownwater and Greenwater Sinks and in one of the three sinks to the southeast but they are still separate. Also a shallow pond is present in the large, shallow southwestern sink. Ice Sink is larger and shallower.

In October 1982, the floor of the second large sink from the east ("Greenwater Sink") was similar in nature. In the summer of 1983 it was quite different, with a crust several centimeters thick overlying quicksand. In some areas it undulated alarmingly underfoot.

Prior to 1984 small parts of these two sinks and another near the southwest corner of the pseudokarst contained shallow seasonal ponds. Since 1984 the ponds have been permanent and, in the case of Brownwater Sink and Greenwater Sink, the ponds have occupied the entire sink floor (Figure 7). It is not known whether their surfaces all represent the same water table. The smallest example of this type of sink, about 200 meters west-southwest of Greenwater Sink, has never been observed with a pond. The large shallow sink at the northwest corner of the pseudokarst was badly disturbed by construction activities but has begun to show shallow internal sinks at its eastern end which vary in location and size from year to year. Here it is separated from Greenwater Sink only by a low divide of ash cloud deposits which appears likely to be a very short-lived feature.

Prior to ponding, the floors of Brownwater Sink and Greenwater Sink showed numerous short-lived pseudokarstic phenomena including isolated vertical pipes up to 3 meters deep and 1.5 meters in diameter (Figure 8). At times, multiple strand lines of pumice pebbles and large internal sinks were present. In October 1982 an ablation pocket more than two meters in diameter was observed in the southeast wall of Brownwater Sink (Figure 9). Fewer and smaller examples of vertical pipes and strands were noted in the large shallow sink at the southwest corner of the study area. In Greenwater Sink, inner sinks seen in 1983 appeared to be the result of impact of a single blocky rock slide onto the plastic crust (Figure 10) (Halliday, 1986).

In these flatbottomed sinks, the locations of vertical pipes and internal sinks differed from year to year. The feeder gullies of the sinks were stable in position but not in size, widening markedly from year to year (predominantly in ash cloud deposits). Feeder gully depths consistently decreased due to rapid degradation of ash cloud surfaces plus aggradation of floors of the gullies and sinks. Their walls tended to remain steep to vertical due to block slumping. Rapid headward erosion of the gullies was characteristic. U.S. Corps of Engineers personnel attempted to halt headward erosion of a large gully at the northeast margin of Brownwater Sink by bulldozing large rocks into it. This pro-

Figure 8 – Looking down a vertical pipe in the floor of Brownwater Sink in 1983. Seen more than a meter below the surface is an electrical cable that was on the surface one year earlier.

duced no significant change in the rate of headward erosion.

In 1982 three shallow sinks were noted in ash cloud deposits in the southeast section of the pseudokarst (Halliday, 1986, Fig 5). In 1990, no trace of any closed depression remained in this area. The sinks were replaced by dendritic branches of a feeder gully of Brownwater Sink. The first stage in this small area of centripetal drainages was headward erosion by small gullies in the wall of the lowest of these three sinks. This breached the lower walls of the upper two sinks so that they briefly drained to the lower example. Then headward erosion by the feeder gully of Brownwater Sink integrated this entire sub-area into the drainage of Brownwater Sink.

Quite different in appearance from the type of closed depression just discussed are four steep-walled conical "craters." Each is entirely walled with blocky avalanche debris (part of the margin of some is composed of ash cloud deposits). All of these "craters" are smaller than the smallest of the "sinks." They are radially symmetrical and are 15 to 100 meters wide at the surface. The largest (a few dozen meters west of Greenwater Sink) has a small flat of sand at the bottom. They have the appearance of "phreatic-explosion pits" (Lipman *et al.*, 1981, p 509 and Plate I) but no aprons or other accumulations of ejecta could be found atop ash cloud deposits on their rims (also, aprons appear to be absent in the supposed examples depicted in Figure 288 of that reference). We concur with Glicken *et al.* (1989) that the mechanism of formation of both the "sinks" and "craters" is "problematical." The conical "craters" may be steam vents on a grand scale. The large flat-bottomed sinks appear to have been formed by a combination of constructional processes (emplacement of ridges of debris-avalanche deposits), differential compaction of loosely packed debris-avalanche deposits, and ablation of transported glacier fragments. Ephemeral post-eruption large-scale ablation like that at nearby Pumice Pond cannot be ruled out.

Figure 9 – Internal sink in Brownwater Sink in 1982. This was not present in 1983.

Figure 10 – Collapse features on the floor of Greenwater Sink in 1983 showing an impact sink from blocky avalanche and a pond in the largest internal sink (upper left).

Ablation sinks in this study area characteristically were extremely ephemeral features. Only one ("Ice Sink") verified example was present for more than one year. Ice Sink is an inner sink in the western slope of the large closed depression on the northwest margin of the study area. It was not present in October 1982 and opened in early summer 1983. An ice wall was photographed in July 1983 (Glicken *et al.*, 1989, Fig 8) but was covered by slumped hillside material 20 to 30 centimeters thick in August 1983 (Halliday, 1986, Fig 9). Since then it has increased in width but its depth has decreased. The depth of fill overlying any residual ice is not known. Much smaller collapse-type ablation sinks were observed especially in the low hill southwest of Ice Sink in 1982 and 1983. Without exception these were in ash cloud deposits but their walls and floors were mostly underlying debris-avalanche deposits.

A specific type of vertical shaft was entirely limited to thick ash cloud deposits commonly occurring in dendritic or linear groups. Originally we included them with the type of vertical pipe found in the floors of the large flat-bottomed sinks. Now we consider them to be a type of pipe typical of "badlands pseudokarst" and have observed similar examples in South Dakota, Arizona, and Nevada. In the Spirit Lake Pseudokarst they are found on ash cloud flats and slopes of gentle to moderate gradient (Figure 11). Almost invariably a gully or sink wall is nearby and roughly parallel to their alignment (Halliday, 1986, Fig 11). These shafts occur along the

Figure 11 – Badlands pseudokarst in ash cloud deposits north of Brownwater Sink showing aligned shafts and gullies.

course of deep, narrow gullies that have become roofed by block slumping followed by pluvial erosion. Their maximum width is about two meters and maximum depth is about five meters.

Ephemeral local runoff enlarges the bottoms of these gullies, soon causing block slumping, collapse of slumped blocks, widening, and development of parallel cracks which repeat the process. Headward erosion occurs as high-velocity water enters the upper end of each crack. Following the concepts of Parker (1963) and Parker and Jenna (1967) we consider this to be stress crack piping.

We found one cave 15 meters long extending from the bottom of one such shaft to a gully. It persisted for two years despite widening of the shaft and gully. A little "flowstone" of ash cloud particles was present.

Because of the friable nature of their walls, only a few of these pits could be descended safely except where recent erosion had opened a sloping ingress. All were observed to have vertical or overhanging walls of homogeneous ash cloud material. In every case traces of a central ceiling crack were found in the ceiling of grottos or natural bridges at one or both ends of the shaft.

With rainfall, these shafts enlarge and coalesce, re-establishing gullies. Especially stable examples are located in flats north of Brownwater Sink and on the northwest wall of the shallow closed depression near the southwest corner of the study area. The surface of both areas is undergoing rapid degradation, however. Probably both will disappear within the next few years. Similar shafts are developing in ash cloud deposits on the south side of Coldwater Ridge north of the study area.

Perhaps due to minor case-hardening, some horizontal pipe orifices in the sides of large gullies have been observed to be more stable than the gullies themselves or the vertical pipes up-slope from them. At the southeast corner of the study area, a short natural bridge was open (or temporarily closed by slumping and streamwash) from 1982 through 1990. Meanwhile the gully behind it widened from a mere crack to more than two meters and the cliff face receded several meters.

The landscape of the Spirit Lake Pseudokarst continues to evolve and follow-up studies are planned for 1995 and 2000.

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Recent Discovery of Secondary Mineral Deposits in an Idaho Lava Tube

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Abstract

Secondary mineral deposits of gypsum, mirabilite, thenardite, and cristobalite have long been known and, in fact, are quite common in the lava tubes of southwestern Idaho. Until recently, calcium carbonate deposits were only found in a few tubes in very small amounts and were thought to be quite rare. The recent "rediscovery" of Helens Hidden Hide-Away lava tube has significantly changed this thinking. The deposits in this lava tube are not only quite extensive but extremely varied in structure. As this is a very recent discovery, only basic preliminary work will be presented in this paper. It is hoped this will stimulate interest for further and more intensive study of the lava tubes of southwestern Idaho.

Introduction

A large number of lava tubes in southwestern Idaho contain some extremely impressive secondary mineral deposits. Gypsum and mirabilite can be found coating entire lava formations and in some cases entire rooms. Thenardite and cristobalite can also be found throughout Idaho's lava tubes, although in smaller individual concentrations. To a lesser degree, iron- and copper-based deposits have been found. On rare occasions, and in very small quantities, calcium carbonate deposits have been found.

The recent exploration of Helens Hidden Hide-Away has uncovered an extensive deposit of calcium carbonate, never before thought possible in an Idaho lava tube. Not only is there an impressive amount of deposition, but the individual structural variations could rival some limestone caves.

Since the study of Helens Hidden Hide-Away began, several other lava tubes have been discovered that may also contain large calcium carbonate deposits. As the work on Helens Hidden Hide-Away has not been completed and the work on the other tubes has not yet begun, this paper will deal with Helens Hidden Hide-Away as a truly unique find.

Only very preliminary work has been completed on Helens Hidden Hide-Away as there is not a large, knowledgeable, interested scientific base to draw upon. It is hoped that this paper will stir interest in the truly unique lava tubes of southwestern Idaho.

Background

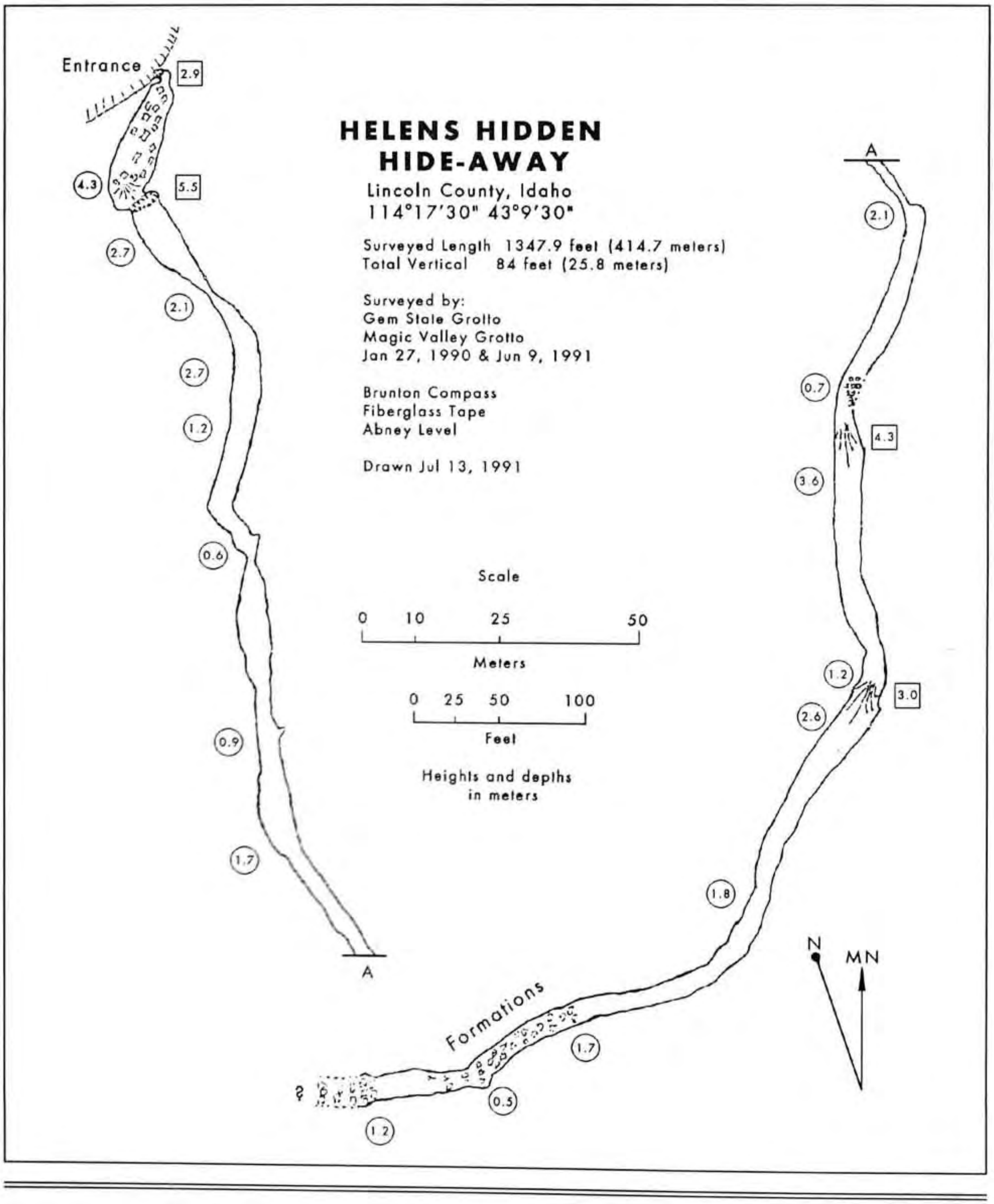
The background of Helens Hidden Hide-Away has been hard to uncover and is based mostly on verbal information gathered from locals. The first known account of the cave's exploration came in the early 1930s when Helen Lee's, (for whom the cave is named), future husband took her to this cave on their first date. While they were in the cave they found some bones and alerted the university in Pocatello, Idaho. They sent the bones to the museum there where they were identified as prehistoric bear. A team was sent down for preliminary studies. (Confirmation has not been made and further information is pending.)

The next account came less than a year ago when Jim Woods from the Herrit Museum in Twin Falls, Idaho, made a few trips into the cave, presumably to also look for archaeological or paleontological artifacts. (Again confirmation has not been made and further information is pending.)

These are the only known visitations to the cave. It can be assumed, though, that there have probably been many unrecorded visits by locals. This assumption is verified by the signs left behind of tin can kerosene lanterns and a barbed wire and wood ladder.

Geology and Hydrology

Helens Hidden Hide-Away is located in the Central Snake River Plain next to, but not in, the Shoshone Ice Cave Flow. This flow is one of the youngest and least altered flows in the area. It starts at Black Butte Crater and flows generally southeasterly, covering almost 210 square kilometers. It was originally thought that Helens Hidden Hide-Away was in this flow but subsequent research has shown it to be from a much older flow originating in a shield volcano just to the east. The age difference is quite obvious when comparing the bare lava of the Black Butte Crater



Flow to the soil covered area around Helens Hidden Hide-Away.

Less than sixty kilometers to the northeast is the Lost River Range. These mountains are predominantly dolomite and limestone and probably account for a percentage of the soil make-up in the area.

Less than 400 meters to the north of the cave runs the Richfield Canal. It is a raised earthen structure and prone to a fair amount of leakage. This canal takes its water from the Big Wood River and is the major source of irrigation water for the entire area. The Big Wood River originates in the Lost River Range and has apparently changed its course many times in the area around the cave. One of the presumed old courses, which is now an intermittent run-off, actually runs over the cave.

Cave Morphology

Helens Hidden Hide-Away is a lava tube that trends in a southwesterly direction for approximately 450 meters. Total vertical depth is 25.8 meters. The vertical depth is attained from a 2.9-meter vertical drop at the entrance, a 5.5-meter vertical drop 25 meters in, and a 4.3- and a 3.0-meter sloping drop about half way in. Passage widths average two to three meters and passage heights from 4.5 to less than 0.5 meters with the majority under 1.5 meters.

The first half of the cave is typical for the majority of Idaho lava tubes: dry and dusty with the floor covered in small "klinker" breakdown. A few short areas have sandy floors. About half to three-quarters of the way in the tube starts exhibiting cavernous weathering features not seen in other Idaho lava tubes. These sculpted features look a lot like heavy water erosion in limestone and sandstone.

At about 375 meters the cave the formations start appearing. At first they look old and dried and are scattered around the walls and ceiling. It is in the last 25 to 30 meters of the cave that the formations completely take over and cover the entire ceiling, walls, and most of the floor. Here the formations are actively growing with water constantly dripping everywhere. The majority of the formations are a coralloidal structure, but draperies, rimstone, flowstone, conulites, and drip cups can all be found.

The cave appears to end in breakdown in the formation room, but has not been fully explored due to the tight quarters and fragile nature of the formations.

Mineral Analysis

Methods

Field testing was done using dilute hydrochloric acid. Laboratory testing was done using energy dispersive x-ray spectroscopy, scanning electron microscopy, cross section analysis, and atomic absorption spectrophotometry.

Analysis

All analysis was done on formations found on the floor, assumed to be from natural breakage.

Field tests showed fizzing when dilute hydrochloric acid was applied to the formations. This led to the assumption that they were calcium carbonate.

Energy dispersive x-ray spectroscopy, (EDX), was done on three structurally different samples: a drapery, a coralloid, and a round knob. The drapery showed a makeup of 58.53% calcium, 38.35% silica, 1.78% magnesium, and 1.33% chlorine. The coralloid showed a make-up of 65.56% calcium and 34.44% silica. The round knob showed a make-up of 66.59% calcium, 28.95% silica, and 4.46% magnesium. These percentages are not the actual amount of each element present as EDX reports percentages based on total elements detected and EDX can only detect the elements sodium through uranium.

Cross section analysis was done to determine if the structures were helictites. The analysis showed concentric growth rings with no central capillary canal verifying they are coralloidal formations formed from seeping or splashing water.

Scanning electron microscopy was done to analyze crystal structure. This was not successful as the preparation required desiccating the sample which destroyed the surface structure.

A sample of water was taken from the Richfield Canal directly above the cave. Direct aspiration atomic absorption spectrophotometry was done for five elements. The results were calcium 36.0 ppm, magnesium 7.5 ppm, iron 0.01 ppm, sodium 5.7 ppm, and copper <0.01 ppm.

Conclusions

Preliminary analysis shows these formations to be at least partly calcium carbonate. It is not known if the silica content is bound with the calcium or is simply interdispersed. The data seems to indicate that elemental make-up may play some part in the different structural formations.

The source for calcium and magnesium is most likely from the dust deposited from the Lost River Range. As this dust is covering a vast majority of Idaho's southwest desert, and other lava tubes do not have these formations, the water source from the Big Wood River and the Richfield Canal must play a major role in dissolving and redepositing the minerals.

As research and testing progresses on Helens Hidden Hide-Away and exploration and testing begins on other Idaho lava tubes we hope that more accurate and conclusive theories can be made about Idaho's "limestone lava tubes."

Acknowledgements

First and foremost I would like to thank Gordon and Gloria Sorenson. They are the owners of the cave and have provided free access to the cave throughout the study project. Without their cooperation and support this paper would not have been possible.

I would like to thank Helen Lee for whom the cave is named. She is the one who first showed me where the cave was and provided me with the background information.

I would like to thank the members of the Gem State Grotto and Magic Valley Grotto who provided assistance in exploring, mapping, and data gathering.

I would like to thank Barry Pharaoh at the Idaho State Health Laboratory for his atomic absorption analysis of the Richfield Canal water.

And lastly, I am extremely grateful to Jim Rigg at Boise State University for his analysis work with the energy dispersive x-ray spectroscopy and scanning electron microscopy.

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Lava Tube Systems of Lava Beds National Monument

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Abstract

Nine major lava tube systems have their origin in, or pass through, Lava Beds National Monument. Six of the ten are in the Pleistocene Basalt of Mammoth Crater, two are in younger basalts, and one is in an apparently contemporaneous basalt. Some parts of four of the systems, those with popular caves, have been studied at some length. The nature of the other five is not well known because they are remote, not served by roads or trails, in areas that are vegetated by mountain mahogany, and extremely difficult to traverse. Only three monument-wide studies of the monument's lava tube systems exist, and they are cursory at best.

Overall Assessments

Only three overall assessments of lava tube systems inside Lava Beds national Monument exist. They are Lewis and Anderson (1936), Hatheway (1969), and Donnelly-Nolan (1987). Nolan's geologic map clearly shows most of the systems, identifying them as either lava tubes or lava tube caves. All three, while not detailed, roughly agree on the number of systems, about nine. Lewis and Anderson show about 12 or 13 possible systems, but it is important to note that their study was completed before high-resolution aerial photographs were available.

Six of the ten systems are in the Pleistocene Basalt of Mammoth Crater, one in the Holocene Basaltic Andesite of Valentine Cave, one in the Pleistocene Basalt of Caldwell Ice Caves, and one in the Pleistocene Basalt of the Castles. The largely tube-fed Mammoth Crater Basalt, which covers roughly two-thirds of the monument, and roughly an equal area outside it, was erupted from a series of vents along a now-buried southern extension of the Gillem Fault. It should be no surprise, therefore, that most of caves inside the monument are segments of lava tube systems formed within it.

The Mammoth Crater "distribution center," an area bounded by Bearpaw Butte on the north, Hippo Butte on the east, Mammoth Crater on the south, and the Callahan Lava Flow on the west, is complex. Waters (1990) contends that this area was a large lava lake, and that the lava tube systems assigned to Modoc Crater, Bearpaw Butte, and Bat Butte had their source in this lake. Although this theory is at odds with that of Donnelly-Nolan and others, the existence of such a lake should not be dismissed. The Bat Butte and Bearpaw Butte systems could be branches of the Modoc Crater system, which could have originated in the lava lake (above). However, it is more likely they originated at their respective vents along the Gillem fault south of Fleener Chimneys.

In addition to the nine systems described here, there are several minor alignments of two or three caves each. Their volume and location indicate that they are probably branches of the major systems, but since the basalt of Mammoth Crater erupted from several different vents, the possibility that they could be systems in their own right cannot be discounted.

Detailed below are the nine major systems. The average slope length is based on the traverse length. A comparison of the map length and traverse length provides a very rough approximation of each system's sinuosity.

1. Modoc Crater System

Pleistocene Basalt of Mammoth Crater.
Map length: 41,400 feet, 7.8 miles.
Traverse length: 56,500 feet, 10.7 miles.
Average slope: 0.92 degrees.

Traceable from the east side of Bearpaw Butte to Fern Cave near the south shore of old Tule Lake,

the Modoc Crater System is the longest in the monument. It is extensively segmented and many of its segments were developed for tourists during the 1920s and 1930s. Only five of the individual caves are presently maintained for tourist use. About 15 others are abandoned as developed sites, and about two-thirds of those are within a wilderness area set aside in the 1970s.

The system is characterized by a mature, multilevel master tube ranging to 120 feet below the surface, most of which is now collapsed. Though there are no known branches of significance, it is likely that some exist in the five-mile-diameter delta at the distal end of the system. The master tube lies alongside the older Schonchin Butte lava flow for about six miles. Most of the open segments display considerable erosion down into unconsolidated pre-flow strata. Erosion is especially obvious in the lower level of Skull Cave. Several segments are glacieres, most notable of which are Merrill, Skull, and Frozen River caves.

Just southwest of Schonchin Butte there is a rare example of an eruption that rose through the path of an older lava tube. About one mile northeast of Bearpaw Butte, the system's master tube impinged against Schonchin Butte, then veered sharply eastward. Just up-tube from this bend, perched atop the lava tube like a monstrous hornito, stands one of the "Castles." The Castles are two prominent spatter vents on the southwest flank of Schonchin Butte – two of numerous other vents, mostly to the north, that erupted a high-alumina basalt through the Mammoth Crater Basalt (Nolan). There is a cave, consisting of a complex open vertical conduit, that is entered through this spatter vent (West Castle Cave), that has been mistaken for a lava tube. It is not part of the Modoc Crater System, and what effect the younger eruption had on remaining cavernous parts of the master tube, if any, is not known.

The Modoc Crater System and various sections of it are also known as: Bear Foot Rift, Bearpaw Butte System, Bearpaw-Merrill-Skull line of breakdowns, Bearpaw-Skull lava tube system, Bearpaw-Skull-Fossil system, Bearpaw-Skull line of breakdowns, Bearpaw-Skull line of lava tubes, Bearpaw-Skull System, Bearpaw Tubes, Cave Loop-Post Office Distributary Tube, Heppe-Modoc Lava Tube, Heppe-Modoc Lava Tube System, Heppe-Modoc System, Mammoth Bearpaw collapse trench, Mammoth Bearpaw lava-tube drainage system, Merrill Ice-Skull Cave lava tube, Merrill-Skull System, Merrill-Skull Trench, Merrill-Skull Trench System, Merrill Trench, Modoc Crater Tube, Modoc Lava Tube, Modoc System, and Skull Cave Rift.

2. Headquarters System

Pleistocene, Basalt of Mammoth Crater.
Map length: 26,600 feet, 5.04 miles.
Traverse length: 34,300 feet, 6.5 miles (master tube only).
Average slope: 1.78 degrees (master tube only, first quarter of a mile is steep).

(The above data are based on the assumption that Craig Cave is a segment of the system.)

Traceable from the north side of Mammoth Crater to (possibly) Craig Cave, the system is characterized by a mature master tube and prominent dendritic development in a mile-long section of overflows known as the Cave Loop area. Uncollapsed segments of the multilevel master tube range to 150 feet below the surface and, like the Modoc Crater System, part of the extraordinary depth resulted from erosion into unconsolidated pre-flow surfaces.

There are three major branches in Cave Loop area, and possibly a major branch about half a mile from the source at Mammoth Crater. Angleworm-Lost Pinnacle Cave and The Bowers (Cave), located about midway between the Indian Well campground and Skull Cave, appear to be segments of yet another branch of this system.

The Headquarters System and various sections of it are also known as: Big Rift, Blue Grotto System, Catacombs Lava Tube System, Catacombs Rift, Catacombs System, Cave Loop-Labyrinth System, Cave Loop Lava Rift, Cave Loop Line of Lava Tubes, Cave Loop-Post Office Trench, Cave Loop-Post Office Distributary Tube, Cave Loop Road Lava Tube System, Cave Loop-Sentinel System, Cave Loop System, Cave Loop to Post Office Series of Caves, Craig System, Headquarters Flow, Headquarters Flow System, Headquarters Lava Flow, Heppe-Cave Loop Road-Post Office-Craig System, Heppe-Catacombs Flow, Heppe-Modoc System, Heppe Rift – "three bridges in the Heppe Rift," Heppe System, Indian Well-Doc Yock System, Labyrinth Cave System, Labyrinth Caves System, Labyrinth Cave System Trench, Labyrinth Lava-Tube System, Labyrinth System, Lava tube system of the Cave Loop area, Mammoth Crater-Headquarters System, Mammoth Crater-Heppe

Trench, Mammoth Crater Lava Tube, Mammoth Crater-Post Office Cave line of breakdowns, Mammoth Crater System, Mammoth Crater Tube, Mammoth Crater Tube I, Mammoth Cave Lava Flow, Mammoth-Heppe System, Mammoth-Heppe-Natural Bridge Lava-Tube Cave System, Mammoth-Sentinel-Labyrinth System, Paradise Alleys-Catacombs Lava-Tube System, Paradise Alleys-Ovis System, Post Office Trench, and Post Office System.

3. Tickner-Valentine System

Holocene Basaltic Andesite of Valentine Cave.
Map length: 17,200 feet, 3.26 miles.
Traverse length: 18,480 feet, 3.5 miles.
Average slope: 2.23 degrees.

The system and various sections of it are also known as Tickner-Berthas System, Tickner Cave Tube, Valentine Cave Lava Flow, Valentine Cave Tube, Valentine Channel, Valentine Distributary, Valentine Flow, Valentine System, Valentine Trench, and West Valentine Distributary Trench.

The system formed in the Basaltic Andesite of Valentine Cave, branched to flow around both sides of Caldwell Butte, but does not include Caldwell Caves. Traceable from Tickner and Berthas Cupboard Caves, about a quarter of a mile south (outside) of the monument and about one mile east of Mammoth Crater, around the northwest side of Caldwell Butte to Valentine Cave where the flow spreads north and east. Tickner and Berthas Cupboard Caves, or parts of them, appear to be part of the vent structure – or rift tubes. There are several lava tube segments beyond Valentine, but none can be positively ascribed to this system.

4. Bearpaw Butte System

Pleistocene, Basalt of Mammoth Crater.
Map length: 7,400 feet, 1.4 miles.
Traverse length: 11,800 feet, 2.1 miles (includes both branches).
Average slope: 1.7 degrees.

Traceable from the north flank of Bearpaw Butte north-northeast, for about 1.36 miles, where it is buried by the younger Basalt of the Castles, the system branches about one mile from Bearpaw Butte. Balcony and Boulevard caves are segments of the left, or northwest branch. The relatively small cross section of the latter caves suggests that this system did not continue far beyond the point where it is covered by Basalt of the Castles.

The system is also known as: Balcony-Boulevard System, Bearpaw Butte Tube, Bearpaw System, Castle Basalt System, East Bat Butte Trench, [System] North of Bearpaw Butte.

5. Caldwell System

Pleistocene Basalt of Caldwell Ice Caves.
Map length: 5,500 feet, 1.04 miles.
Traverse length: 6,300 feet, 1.2 miles.
Average slope: 2.9 degrees.

The Basalt of Caldwell Ice Caves cannot be distinguished from the Basalt of Mammoth Crater by hand specimen or remnant paleomagnetism, but differs chemically. The lava tube system is traceable from about a quarter of a mile outside the monument, south of Caldwell Butte, northeast about 1.2 miles to the main monument road, where it is buried by the Basalt of Valentine Cave. Although relatively voluminous at the point of burial, its host flow does not reappear from beneath the Basalt of Valentine Cave within the monument, suggesting that it could not extend much more than a mile.

Also known as Caldwell Ice Caves System, Caldwells Rift, Caldwell Trench, and Ice Caves Tube

6. Bat Butte System

Pleistocene Basalt of Mammoth Crater.
Map length: 15,300 feet, 2.9 miles.
Traverse length: 18,700 feet, 3.5 miles.
Average slope: 1.78 degrees.

This system is traceable from the vent area around and on the north side of Bat Butte to about one mile past Black Crater where its western side is overlain by Holocene basalt of the Devils Homestead flow. A half-mile-long section of the system south of Fleener Chimneys is marked only by some extraordinary tumuli. The distal part of the system has the appearance of being much older than others in the Mammoth Crater Basalt.

This system is also known as Bat Butte System, Fleener System, Fleener Trench, and "Rift North of Bear Foot," and is sometimes confused with the Fleener Trench, a major channel that developed in the younger Devils Homestead lava flow, adjacent to Fleener Chimneys.

7. Mammoth Crater II

Pleistocene Basalt of Mammoth Crater.
Map length: 1.5 miles.

Traverse length: 9,500 feet, 1.8 miles.
Average slope: 1.2 degrees.

First identified and named by Hatheway (1969), this system begins near the pit craters on the north flank of Mammoth Crater and trends northwest between Bearpaw Butte and Eagle Nest Butte. There are no named caves in this system.

8. Upper Ice System

Pleistocene Basalt of Mammoth Crater.
Map length: 4,500 feet, 0.8 miles.
Traverse length: 5,300 feet, 1.0 miles.
Average slope: 1.3 degrees.

Traceable for one mile, from the west flank of Mammoth Crater to south side of Eagle Nest Butte (Cinder Cone) where it is buried by the Callahan Flow, this alignment is mostly collapse trench and the only named cave is Upper Ice Cave.

9. Hardin Butte System

Pleistocene Basalt of the Castles.
Map length: approximately 0.5 miles.
Traverse length: approximately 0.5 miles.
Average slope: Unknown.

The Hardin Butte system apparently formed in Basalt of the Castles, South of Hardin Butte, in an area where the Castles Basalt intermittently covers the andesite of Schonchin Butte. Very little is known about this system. It was first identified by Hatheway in 1969. Donnely (1987) found only surface tubes in this flow. The possibility of a northern extension of this system is raised in the notes of J. D. Howard, an early cave explorer: "There are nine natural bridges northeast of 'Sand Butte,'" now known as Hardin Butte.

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Vulcanospeleology of the World


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Lava Caves in the Hallmundarhraun Lava Flow, Western Iceland

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Abstract

Hallmundarhraun is located in the Borgarfjörður region in western Iceland. The flow is of Holocene age. Tephrochronological studies and ^{14}C datings suggest that the absolute age of the flow could be about 1,050 years, thus it flowed in historical times, in the early tenth century. The flow covers an area of approximately 200 square kilometers. The volume of the flow has been estimated to be two to three cubic kilometers.

This particular flow is unique and outstanding among Icelandic flows due to the enormity of speleological phenomena. Four out of five Icelandic lava caves exceeding one kilometer in length are in the Hallmundarhraun lava flow. The total number of caves and caverns is 12. In some of the caves archaeological remains are to be found, mostly cattle and sheep bone fragments, cairns, fences, and piles of rock. Little is known about these remains.

Brief Outline of the Geology of Iceland

Iceland is predominantly of volcanic origin. The exposed volcanic pile is mostly basalt (80 to 85%) of tholeiitic composition. Altogether Tertiary rocks cover about 50,000 square kilometers or about one half of the total area of Iceland. Radiometric dating suggests that the oldest exposed rocks are 12 to 16 million years old.

Few indications of speleological formations have been noted in the Tertiary lava pile. Walker (1959) mentions a roughly circular section of infilled lava tube 6.5 to 8.0 meters in diameter.

The Plio-Pleistocene and upper Pleistocene areas cover about 40,000 square kilometers occupying broad and distinctive zones between the Tertiary area and the neovolcanic zones. The boundary between Tertiary and Plio-Pleistocene is somewhat arbitrarily fixed at the base of the Mammoth magnetic polarity event (3.1 million years ago) when the first widespread tillites appear in the strata. The Upper Pleistocene formation comprises rocks formed during the Brunhes magnetic epoch which began 0.7 million years ago, excluding the Postglacial which is referred to as rocks formed 13,000 to 10,000 years ago – until 874 AD when the first settlers came to Iceland – younger formations are thus "historical."

Postglacial volcanism continued along the same pattern as during former interglacial periods and the composition of volcanics is similar to those formed in the Tertiary, Plio-Pleistocene, and Upper Pleistocene. Total lava production in postglacial time is estimated to be 400 to 500 cubic kilometers and the lavas cover about 12,000 square kilometers or about 10% of the surface of Iceland.

Volcanic Activity in Historical Time

Volcanic activity in Iceland in historical time has produced large quantities of lavas and is a direct continuation of the prehistoric postglacial activity and is confined to almost the same areas, i.e. within the neovolcanic zones. Nearly every type of volcano found on the face of our globe is represented in Iceland, and the diversity of volcanic phenomena is much greater than to be expected on an oceanic island.

The number of known volcanic events is about 250 for the last 1,100 years, but the total number of individual flows has never been estimated, as the volume of each ranges from less than 0.1 cubic kilometers to 12 cubic kilometers in the Skaftáreldar (Laki) eruption in 1783. That particular flow is the greatest single lava flow erupted on the earth in the last 1,000 years.

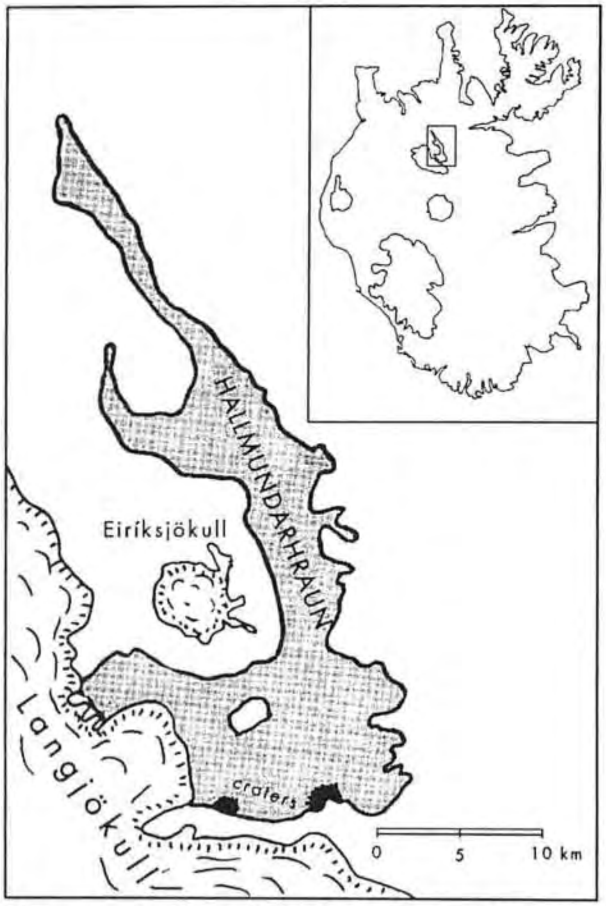

Figure 1—Hallmundarhraun, western Iceland.

Hallmundarhraun

Hallmundarhraun is the largest lava flow in the Borgarfjörður area in western Iceland, originating from craters just off the flanks of the Langjökull glacier. The area of the flow is about 200 square kilometers and the volume has been estimated to be about two to three cubic kilometers. Two craters are visible just off the edge of the Langjökull glacier but others and a possible eruptive fissure could be covered by the advancing ice of the glacier. A ^{14}C dating of peat from beneath the Hallmundarhraun lava flow was published by Saemundsson (1966), giving the age 1,190 ±100 years before present.

Recent reinvestigations of the age of the lava flow were published by Jóhannesson (1989) using tephrochronological methods. The lava flow overlies the "Settlement layer" formed around 900 AD. It is belived that the eruption forming Hallmundarhraun occurred during the first decades of the tenth century.

The distance from the distal margin of flow to the craters is about 50 kilometers. Near the craters the flow is about 600 meters above sea level, the surface being extremely rough, nearly void of any vegetation, and sandy. Large outwash plains exist near the Eiríksjökull glacier. Further downslope the surface type changes form from an aa lava to more pahoehoe-like lava. Numerous large collapsed tumuli, shrinkage cracks, pressure ridges, and other cooling and contracting phenomena are present.

The Lava Caves of Hallmundarhraun

Altogether 12 lava caves are known in the Hallmundarhraun lava flow, thus earning the lava flow a special recognition among Icelandic flows. Of five lava caves exceeding one kilometer in total length currently known in Iceland, four are in Hallmundarhraun. Three of the largest caves of Hallmundarhraun have been surveyed, and the remaining ones have only been explored to some extent. Following is a short description of lava caves known in Hallmundarhraun.

1. Surtshellir – Stefánshellir Cave System

The total length of this system is about 3,500 meters. It comprises two lava tubes separated by a collapse pit. Although the lava tubes have been given two seperate names, it is belived that they constitute one major system. The cave drops 18 meters in its whole length. Maximum width of the passage is 27 meters, the main passage has an average height of eight meters and the maximum height is ten meters. Ceiling thickness varies from nine meters to zero meters with ten areas of complete ceiling collapse providing the entrances to the system (McKain, 1989).

Surtshellir is the down-flow segment, with 1,970 meters of passage. The cave's ceiling is extensively collapsed, but original floor can be seen in large parts of the cave and flow structures are well preserved on the cave's walls. In one side of the passage archaeological remains consisting of stone benches, fire places, and bone fragments occur. These have suggested the theory that inhabitants lived in the cave because of suitable temperature shortly after the eruption, contrary to a famous Icelandic legend where outlaws had supposingly built and occupied the cave as early as the tenth

century. Surtshellir has been known to locals for a long time, the first mentions of the cave are in the old Icelandic Sagas.

Stefánahellir, the up-flow segment of the system, was rediscovered in the early 1950s and near the entrance was a small cairn. The cave comprises a maze of passages and the cave's ceiling is not collapsed to any extent, as it is in Surtshellir. The total length of passages is about 1,520 meters. The up-flow beginning of the system is a lava seal, the ceiling dropping rapidly to meet the last lava level. The roof rises rapidly and forms a passage 7 meters high and 13 meters wide. The main passage continues relatively linear for about 300 meters, then it assumes its maze-like pattern. The surface of the floor and walls changes from being glazed to more scoriaceous. Less than 35 meters separate the south terminus of Stefánshellir and the north terminus of Surtshellir.

2. Kalmanshellir

The cave closest to the crater area is Kalmanshellir. It has not been surveyed but by viewing aerial photographs it can be estimated that the cave is several kilometers long. The cave is extensively collapsed and the internal surface is highly scoriaceous. The cave has numerous entrances through ceiling collapses, is partially filled with aeolian sand, and is terminated by ice. In some parts of the cave a thin sheet of lava has divided the cave into two levels.

3. Víðgelmir

Víðgelmir is 33 kilometers southwest of the craters. The cave is the most voluminous lava cave in Iceland. The volume has been estimated to be 148,000 cubic meters. The total length of the cave is 1,585 meters, average height 9.2 meters, maximum height 15.8 meters, average width 10.2 meters and maximum width 16.5 meters. Víðgelmir was surveyed by the Shepton Mallet Caving Club from Britain, in 1972. Since then the cave has not been visited due to a frozen siphon 35 meters from the entrance. The condition of the siphon, whether it is frozen or not, depends upon the mean annual temperature in the cave. The level of the frozen water in the siphon rose to the present level in the 1960s, having been dry and passable from 1930 through 1960. In October 1991, local farmers finished the previously attempted opening of the cave by the Icelandic Speleological Society. Inside temperature of 2.7° Celsius had melted the ice tongue toward the closed entrance of the cave. The Icelandic Spelelogical Society installed a gate on the cave to protect the delicate lava formations inside.

Figure 2 – The entrance to Viðgelmir. (photo S.S. Jónsson)

4. Hallmundarhellir

Hallmundarhellir is a few kilometers south of Kalmanshellir. The total length is not less than 300 meters, but the cave has not been surveyed. The entrance to the cave is almost filled with aeolian sand. In one side passage there is evidence of human inhabitation: piles of rocks, a fire place, and bone fragments.

5. Hvassi

This is a small cave close to Hallmundarhellir. The total length is about 200 meters. The cave has not been surveyed.

6. Rjúpnahellir

A cave passage leads from a huge roof collapse only few hundred meters from the edge of the lava flow near the mountain Syðra-Sauðafell. This cave

is extensively collapsed and the total length is not known, but undoubtedly exceeds 200 meters.

7. Sandi

A less than 100-meter-long cave in the Hallmundarhellir vicinity, Sandi possibly belongs to the same lava tube system as Hallmundarhellir. A connection possibly exists.

8. Bergþórshellir

This is a tumulus close to Víðgelmir. The diameter is about 25 meters and there are two short side passages.

9. Skeggjahola

Skeggjahola is a small tumulus cave near Víðgelmir. It has been known since a human skeleton was found in the cave in the 1930s.

10, 11, 12 Franshellir, Eyvindarhola, Beinahola

These are small tumulus caves near Reykjavatn Lake. The caves are all small, with a diameter of less than 20 meters. In all the caves, archaeological remains have been found and the caves have therefore been noted.

Acknowledgements

We want to thank Dr. Haukur Jóhannesson at the Icelandic Museum of Natural History for revising the manuscript.

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Preliminary Speleological Investigations in Surtsey

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Abstract

The volcanic island of Surtsey, off the south coast of Iceland, was formed during a submarine eruption which was first noted on November 14, 1963. The eruption lasted for almost four years, ceasing on June 5, 1967.

Earthquakes were noted several hours prior to the eruption and probably triggered the formation of a fissure on the sea floor about 400 meters long, with a bearing of approximately 035°.

Phreato-magmatic activity of Vulcanian type, later termed as Surtseyian, producing large quantities of pyroclastic material, was dominant for the first weeks and months. After five months of explosive activity, a rim of volcanic ash and fragmented rocks had built up around the volcanic vent. Lava of alkali-basaltic composition started to flow from the western crater on April 4, 1964. Observations indicated that large portions of the lava extruded from the craters flowed sub-aerially in tubes and canals. Shortly after the eruption two caves were found on the island.

The first specific speleological expedition took place in 1990. In two days, seven caves were discovered, three of which have now been surveyed. The caves are both vertical and horizontal. Most of the caves are to be found in and around the crater on the western side of the island. The area of the island is 1.9 square kilometers.

The longest and most voluminous cave, SU-03, has one opening in a large pit (roof collapse) on the western side of the island, stretches for 181 meters to the east-northeast, and opens into the crater. Some of the caves are still quite warm and exhibit extensive mineral encrustations.

Introduction – History of Lava Extrusion

Surtsey is a volcanic island located about 33 kilometers south of the coast of Iceland and 20 kilometers from the only inhabitated island of the Vestmann Islands archipelago, Heimaey. First signs of the eruption that later formed the island were noted by fishermen on the fishing vessel Ísleifur II on the 14th of November 1963. Columns of steam and pyroclastic material were rising 50 to 60 meters above the surface of the sea. The depth of the sea-water was 130 meters prior to the eruption. The explosive activity increased rapidly and on the 15th of November an island had formed, some 10 meters in height and about 500 meters long. It was named Surtsey.

Phreato-magmatic explosion activity of the Surtseyian type continued restlessly, with a steam column rising from the vents sometimes reaching nine kilometers in height. In January 1964 activity ceased in the eastern crater and on April 4, 1964, it ceased in the western crater. The feeder pipe had evidently been isolated from the sea-water and lava was extruded. The rims of the ash-crater/tuff-rings, were then about 170 meters above sea level and the total area of the island 1.2 square kilometers. Lava continued to flow from the western crater until April 29, 1964. Columns of volcanic ash and debris continued to be ejected, adding to the crater rims and the surface of the island. In later stages, quiet effusive lava eruption continued until June 5, 1967 with only minute production of pyroclastic material. When all volcanic activity ceased, the area of the island was 2.8 square kilometers. Further details on the history of the lava flow in Surtsey are summarized in Table 1.

EXTRUSION EVENTS OF LAVA IN SURTSEY		
1964	January	Phreato-magmatic activity ceases in the eastern crater.
	April 4	Phreato-magmatic activity ceases in the western crater and lava is extruded.
	April 29	Extrusion of lava ceases from the western crater.
	July 9	Lava is extruded again from the western crater.
1965	May 17	Last ejections of lava from the western crater.
1966	August 19	Lava starts to flow from the eastern crater.
	December 12	A small ejection of lava from a small crater on the inside rim of the eastern ash-crater.
1967	January 1-4	A small quantity of lava is ejected through a hornito/spatter cone on the outside rim of the eastern ash-crater.
	January 1-8	A small ejection of lava from a small crater on the inside rim of eastern ash-crater.
	January 2	Lava is ejected from a small crater on the outside rim of the eastern ash-crater.
	January 2-7	Lava is ejected through a fracture on the inside of the eastern ash-crater.
	June 5	The last ejections of lava from the eastern crater.

Table 1 (Based on Jakobson, S.P. & J.G. Moore; 1982 and Einarsson, Th.; 1968).

The Speleology of Surtsey

Prior to the expedition mentioned later no attempts had been made to search for and explore the cavities within the lava flow in Surtsey, despite its small area. Two caves had been noted by an Icelandic entomologist who explored them to some extent (Ólafsson, 1982). Other scientists who visited the island, shortly after and during the eruption do not make any valuable comments on the formation and development of lava caves in their reports. The only known phenomenon believed to be of an speleological origin, apart from those mentioned by Ólafsson (1982), was a large pit with steeply cut edges on the western side of the island. Viewed by the authors on an aerial photograph, it resembled a roof collapse. Other areas of speleological interest were not known.

Surtsey Expedition

On May 1, 1990, an application for a research permit was sent to the Surtsey Research Society which, on behalf of the Icelandic Nature Concervation Council, handles such matters. When permission was granted, the date for the expedition was set as July 9, 1990. Members of the marine rescue team "Björgunarfélag Vestmannaeyja" on Heimaey took the expedition members to Surtsey. Getting ashore in Surtsey can be difficult due to the great surf and the lack of a sheltered area to land a boat.

A hut was built in Surtsey during the later stages of the eruption and rebuilt in a different location in 1982. A base camp was set there. The first task of the expedition was to descend the large pit/collapse mentioned earlier, and explore it to its full extent.

Speleological Investigations – Results

The caves and cavities in Surtsey are numbered according to the numbering system of the Icelandic Speleological Society. Altogether seven new caves were found and explored, whereof three were surveyed. The caves found by Ólafsson (1982) were given the numbers SU-01 and SU-02, but surf erosion had destroyed the cave given the number SU-02, so that number was assigned to another cave.

The number **SU-02** was given to a cave located on the south slope of the eastern crater. The cave is seven meters long dipping 70° downwards. The cave is closed at the end by what seems to be a lava seal, the surface is highly scoriaceous and the bot-

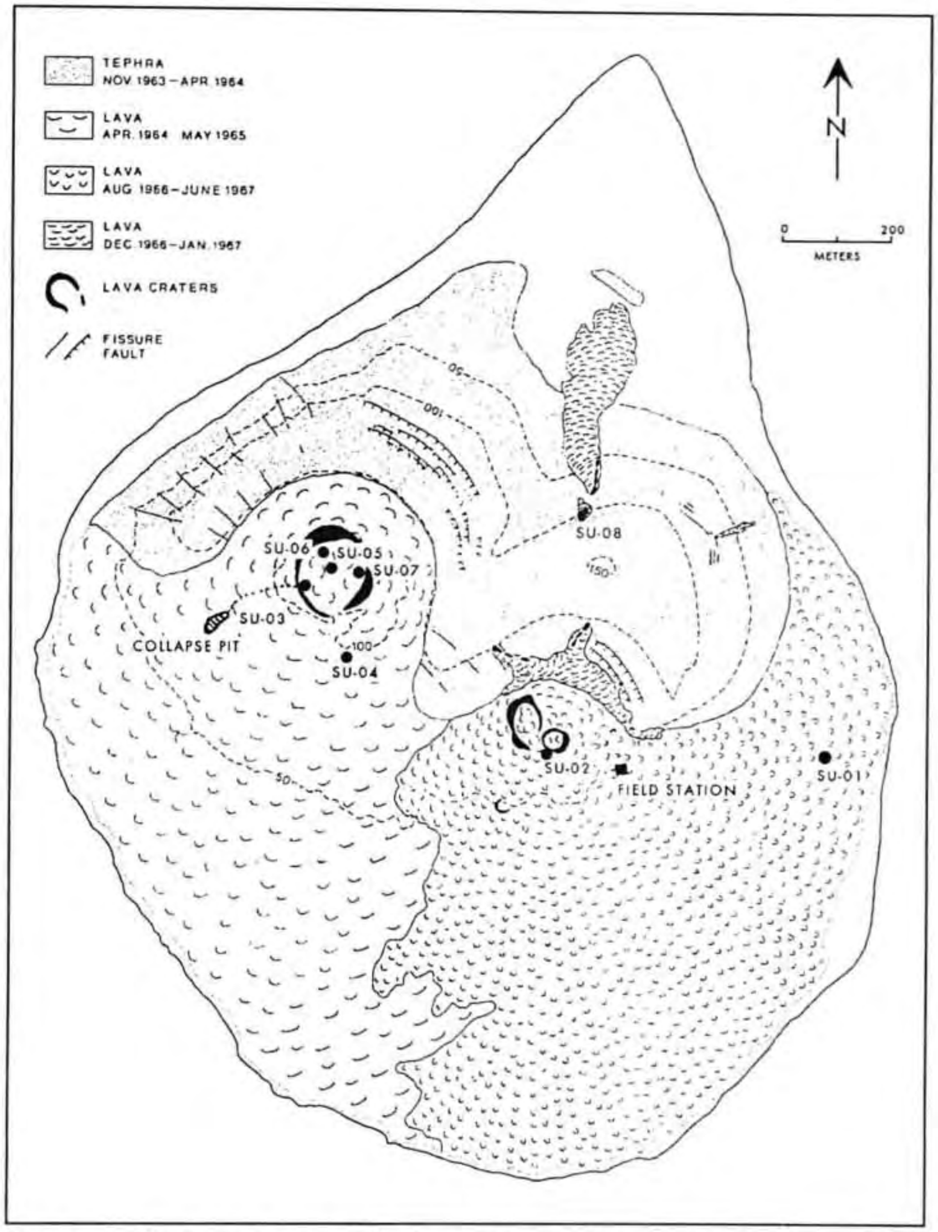

Figure 1 – Geological map of Surtsey, showing known cave entrances (after Jakobsson, S.P. & J.G. Moore; 1982).

tom is covered with debris collapsed from the ceiling and aeolian sand. Steam arises from among small rubble covering the floor. Inside temperature is 35° Celsius. The average area of the tube is about one square meter.

SU-03 (Figures 2 and 3) is a cave on the eastern side of the island. It leads from the large roof collapse formerly mentioned and opens into another pit inside the crater. The bearing of the cave is 080° and the total length is 181 meters.

The average depth of the roof collapse is close to 15 meters. Its shape is elliptical, its maximum length is about 25 meters and its maximum width is 14 meters. The walls expose four, one- to two-meter-thick layers of lava with imbedded reddish scoria. The eastern entrance to the cave is from the northeast end of the collapse. The shape of the entrance is roughly square, collapse from the ceiling has not been extensive but is notable. From the entrance the cave dips 25° downward for a length of 25 meters. The slope is covered with aeolian sand. From the upper edge of the entrance to the surface of the lava is 16 meters. The first noted evidence of the original glazed wall surface of the lava tube is 25 meters below the surface of the lava. Glazed original wall surface is also visible 20 meters inside the cave from the eastern entrance. On the other hand, the cave's ceiling is heavily collapsed and the original floor is not seen anywhere.

This lava tube was undoubtedly extremely voluminous prior to the ceiling collapse, and it is evident that huge volumes of lava have been fed through the tube to the threshold of the flow. Earlier papers describe huge columns of steam and vapors rising from the sea in front of the lava edge (Einarsson, Th.; 1965). No surface trenches were noted and no flowing, molten lava was visible at the surface of the flow. A theory of sub-aerial lava eruption through a fissure was proposed, but its capability of explaining the origin of the heat source, causing the sea to boil, becomes vague when such lava-feeders as SU-03 are found.

Halfway inside the cave extremely large pieces of rock nearly close the passage and are a major

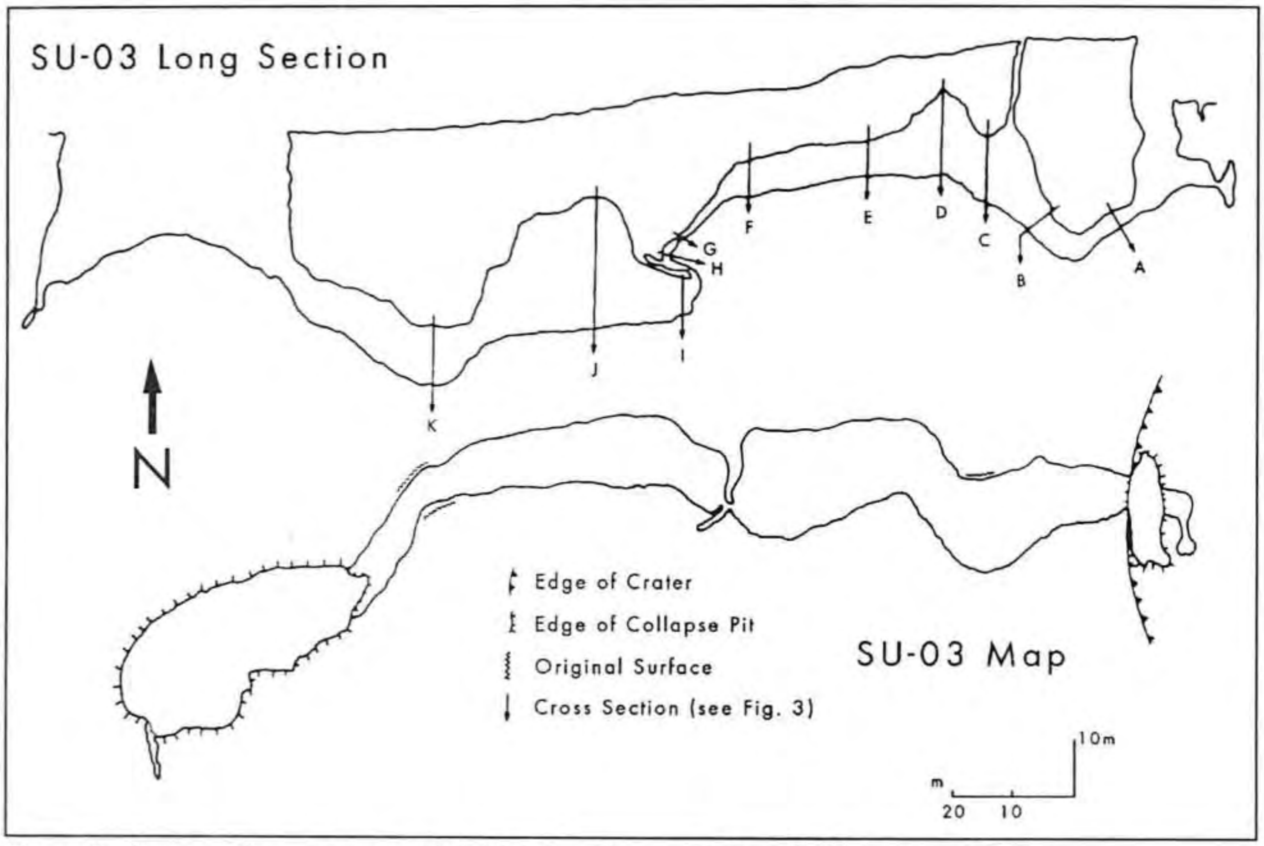

Figure 2 – Long section and map of SU-03 (after Jónsson, S.S. & B. Hróarsson; 1990)

obstacle. A narrow opening was found after a close scrutiny, forming a nearly vertical passage of three meters.

The eastern half of the cave is both wider and lower than the western half. In a large cupola, ten meters from the eastern entrance, a small skylight was noted but could not be located on the surface. Just inside the western crater the cave is terminated. A large lava-pool has evidently been formed inside the crater and in its final stage the cave has served as a resurgence for the lagoon. Shrinkage cracks and pressure ridges are present inside the crater. As seen in Figure 2 the difference in height between the two edges of the eastern entrance is almost ten meters.

Secondary mineral encrustations can be found throughout the cave. Gypsum is the most abundant mineral, but water-soluble sulfates, such as thenardite, can also be found, though they are slowly dissolving. The identification of those minerals has not been confirmed. Water-soluble minerals, associated with sea water derived halide, were found in great quantities shortly after the Surtsey eruption ceased (Jakobsson, S.P., pers comm). It can thus be fairly concluded that most of the minerals, such as

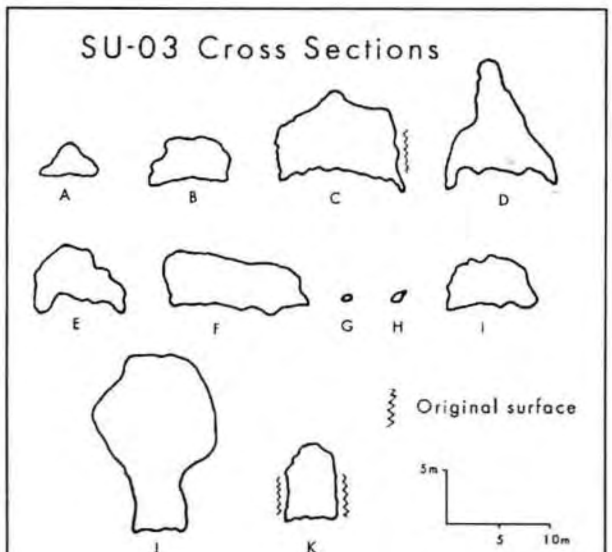

Figure 3 – Cross sections of SU-03 (after Jónsson, S.S. & B. Hróarsson; 1990).

gypsum, thenardite, and sulfur are precipitated from magmatic gases. Therefore the occurrence of secondary minerals on the cave floor, debris, and fractured rocks from ceiling and roof collapses,

Figure 4 – The entrance to SU-02. (photo S.S. Jónsson)

indicate that the ceiling has collapsed shortly after or in the final stages of the eruption. Thermal conditions and unavailability of dissolved material does not allow for the formation of these minerals after the temperature dropped.

Total length	181 meters
Maximum height of ceiling	16 meters
Maximun width	13 meters
Average height	6 meters
Average width	7 meters
Maximum area	125 $meters^2$
Volume	7,600 $meters^3$

Table 2 – Dimensions of SU-03.

SU-04 is a superficial lava tube southeast of the western crater. A hornito is situated atop the cave providing an entrance. The bearing of the cave is 180°. From the hornito the cave extends 5 meters to the north but 128 meters to the south. Total length is 137 meters. The roof has two skylights, 9 and 17 meters south of the entrance. The cave is horizontal and nearly straight, with minor bends (1° to 5°). In the middle of the cave a ridge of fine grained sand has formed, having been washed down a narrow crack along the whole extent of the cave's ceiling. In some areas the cave is nearly filled. A belly crawl has to be made all the way to reach the end, a tumulus with a flat scoriaceous floor.

Mineral encrustations are extremely abundant, almost covering the whole inside of the cave. An inside temperature of 35° Celsius makes exploration very uncomfortable and prevents repeated visits. One 19-centimeter lava stalagmite was found and several two- to seven-centimeter lava stalactites.

SU-05, in the middle of the western crater, is a large pit, 20 meters deep and 8 meters wide. The structure of the inside walls of the pit indicates that it is not a collapse, since flow marks and spatters of lava are present. A trench with flow marks, leading into the pit from the southern edge, suggests that lava has flowed down into the pit in the later stages of the eruption, possibly after the formation of the lava pond mentioned earlier. The pit widens at the bottom and the existence of further passages is possible. This cave was not descended and awaits further exploration.

SU-06 is a cave inside the western crater. It is situated in the northern slope of the crater. The entrance is narrow, less than one meter wide, and dips 65° downward to the north. An apron of aeolian sand creeps down the slope. Near the bottom of the cave is a vertical drop of five meters which ends in a lava seal.

SU-07, inside the western crater, is another unexplored pit. The entrance is only 1.6 meters wide but no signs of the bottom could be found. The cave was not explored.

SU-08, on the outside slope of the eastern tephra ring, is a spatter cone/hornito that ejected a small lava flow. The cone is hollow and seems to be deep. The cave was not explored.

Conclusions

It is the authors' opinion that the visit to Surtsey was very successful. Seven new caves were discovered, three of them were surveyed but others have not yet been explored. The area is undoubtedly of great interest to vulcanospeleologists and much work is to be done there in the near future.

The abundance of vertical or near vertical caves is surprising. The term crater-cave has been used to describe these phenomena and to categorize them among other features of vulcanospelological

origin. The anomalous temperature in some of the caves is also noteworthy. So is the occurrence of mineral encrustations.

Acknowledgements

We thank the Surtsey Research Society for granting permission for the expedition.

Dr. Sveinn P. Jakobsson at the Icelandic Museum of Natural History receives special thanks for providing helpful information on evaporation and alteration minerals in Surtsey and for encouraging the authors.

Dr. Haukur Jóhannesson is thanked for revising the manuscript.

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The Undara Lava Tube System, North Queensland, Australia: Updated Data and Notes on Mode of Formation and Possible Lunar Analogue

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Abstract

The Undara Lava Tube System, North Queensland, Australia, is remarkable not only for its geology, but also for unique flora and vertebrate and invertebrate fauna. This paper considers some aspects of its geology.

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

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

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

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

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

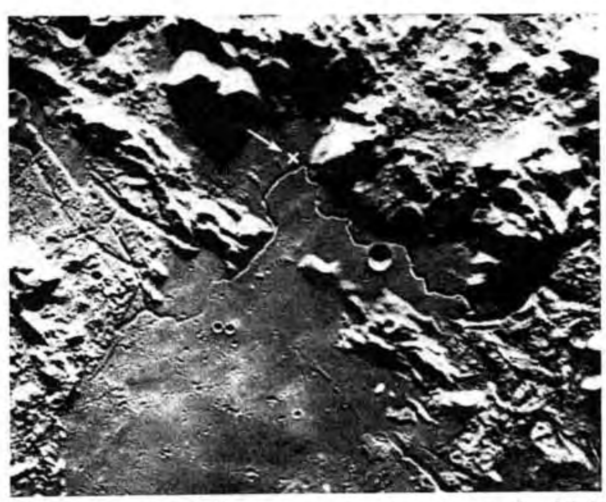

Figure 1 – MOON – a meandering channel which may represent a collapsed lava tube in a lunar mare area near Apollo 15 landing site, indicated by arrow to cross. (Photo: Astronaut A.M. Woden, NASA Apollo 15 Mission)

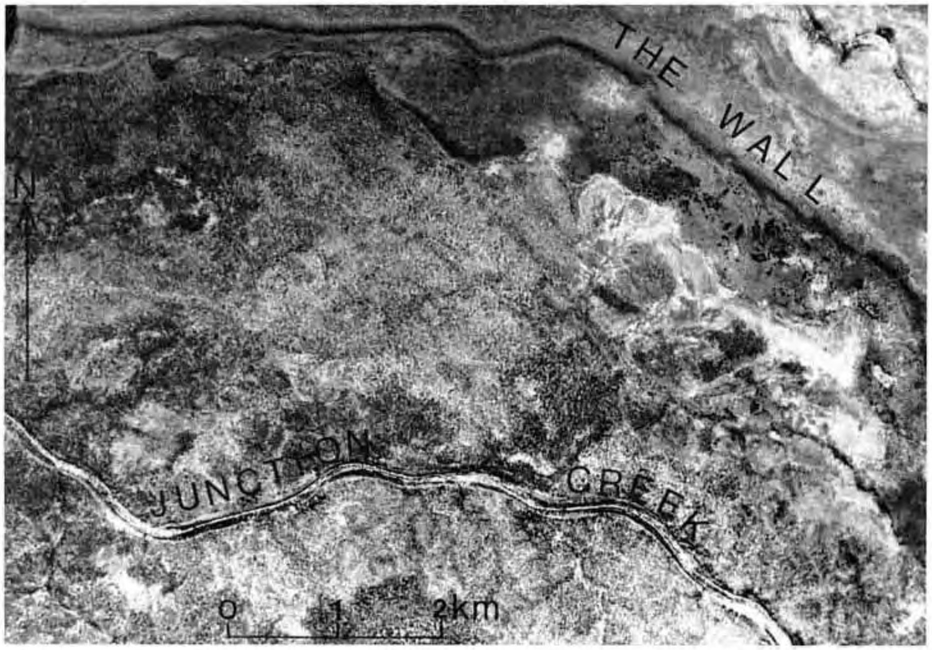

Figure 2a—EARTH—Vertical aerial photograph of the western end of the Wall Section of the Undara Lava Tube System (north at top). This low basalt ridge is 35 kilometers long and may be analogous to the sinuous ridges on the moon. (Photo: Department of National Mapping, Australia)

Introduction

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

As an analogue to the smaller basaltic ridges of the Moon (Figure 2b), the length and shape of The Wall (Figure 2a) of the Undara Lava Tube System is considered Earth's best volcanic feature (Greeley, written communication, 1972 and 1991).

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

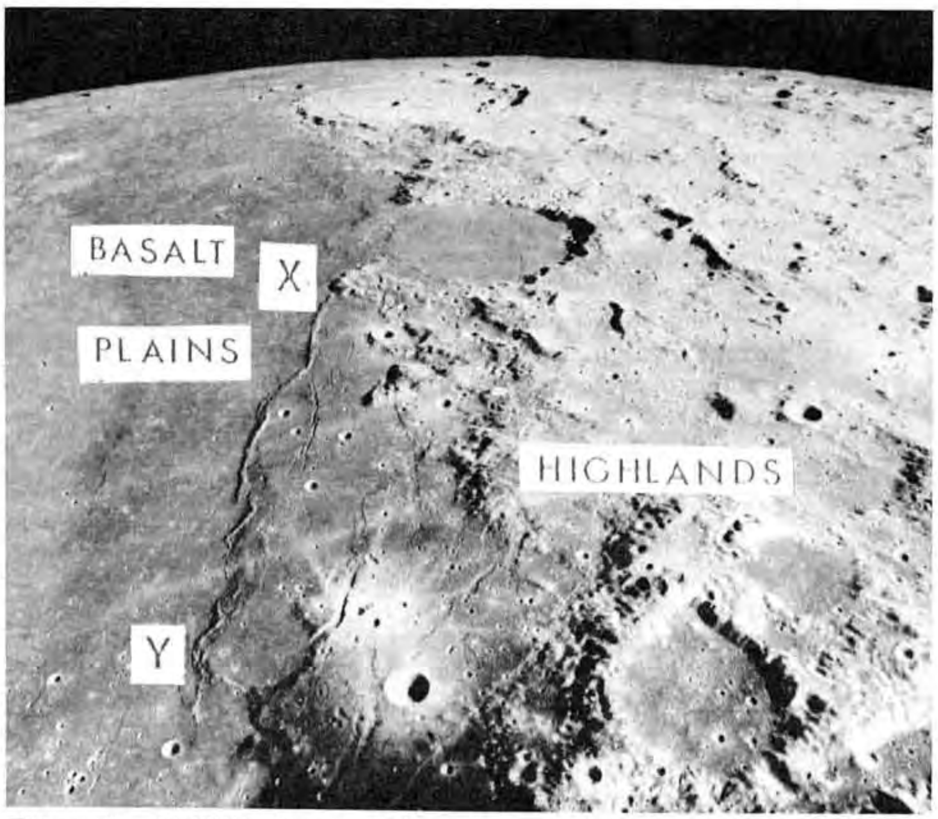

Figure 2b—MOON—View north across the eastern boundary of Mare Serenitatis (basaltic) and Highlands. X-Y indicates basaltic ridge. Circular depressions are impact craters. (Photo: NASA Apollo 17 Mission)

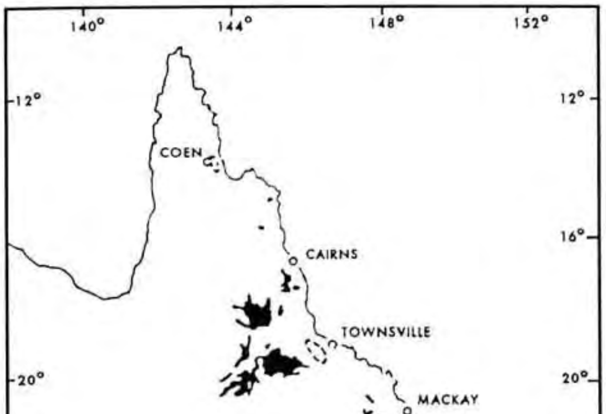

Figure 3 – Cainozoic basalt outcrops of eastern and southeastern Australia occur within 400 kilometers of the coast and extend for over 4,000 kilometers. (Stephenson et al., *1980)*

presented – six pages, including figures and references. From this initial study stemmed increasing interest and the current paper aims to place before you an account of our discoveries to date.

Location and Geological Setting of the Undara Lava Tube System

Cainozoic volcanism in eastern Australia extended more than 4,000 kilometers (Figure 3, Stephenson, Griffin, and Sutherland, 1980). In north Queensland, within 200 kilometers of the east coast, there are five major provinces (Figure 5).

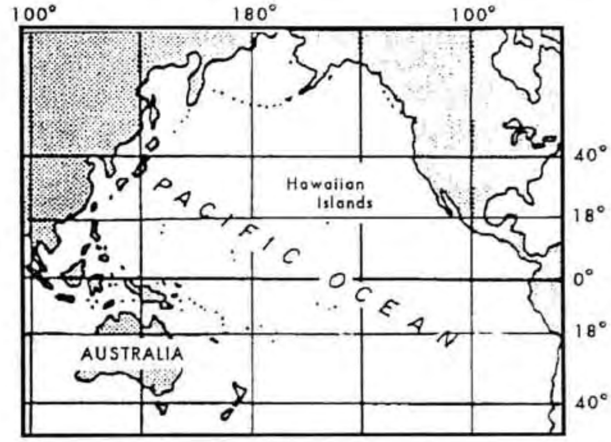

Figure 4 – Map of the Pacific Ocean to show relative locations of the Hawaiian Islands and northeastern Australia.

The Undara Lava Tubes are found within lava flows from the Undara Volcano (Figure 6) which is located approximately 200 kilometers southwest of Cairns in North Queensland, Australia. This volcano is situated near the center of the McBride

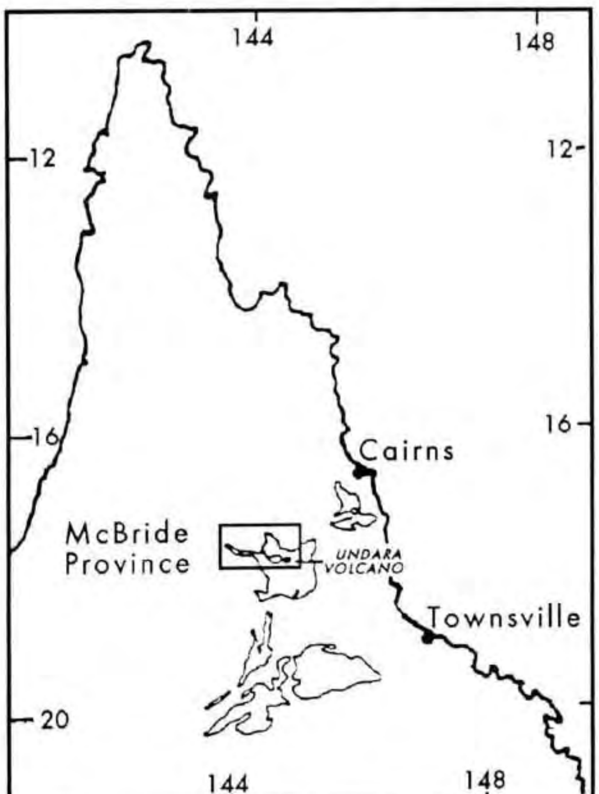

Figure 5 – The main areas (provinces) of Cainozoic basalt outcropping in northeastern Australia. The boxed area is shown in Figure 7.

Figure 6—Aerial oblique view of Undara Crater, 340 meters across, looking west. The tube system commences in the line of the depressions that runs away from the crater towards the right. (Photo: Tom Atkinson)

Province (Figure 5) which covers approximately 5,000 square kilometers (White, 1962), and topographically forms a broad dome. There are over 160 vents in the province (Griffin, 1976), the majority of which are in the central region.

The Undara Volcano (Figure 7) rises to 1,020 meters above sea level (ASL) and is the highest point in the McBride Province. Its impressive crater (Figure 7) is 340 meters across and 48 meters deep with inner slopes of up to 40°. The rim rises only 20 meters above the surrounding lava field. Outward slopes from the rim vary from 30° to 5° on the northwest side where the major outflows occurred.

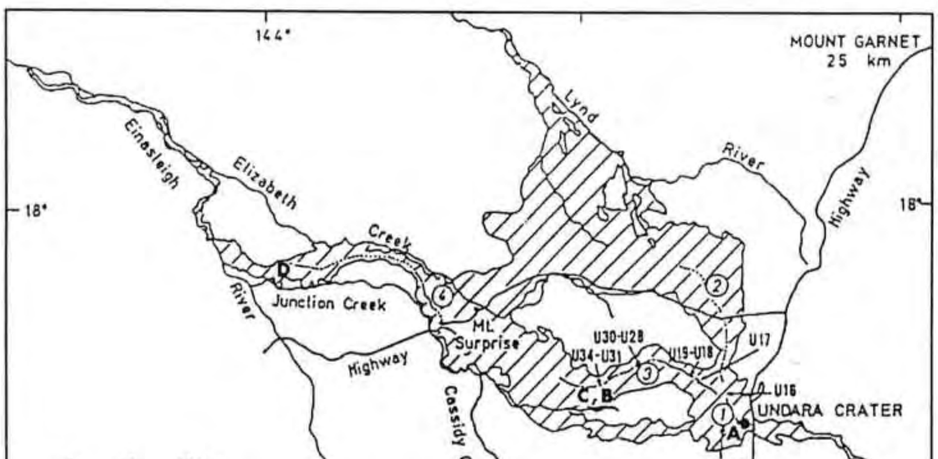

Figure 7—The Undara lava field. Circled numbers denote sections of the lava tube system referred to in the text, namely: 1. Crater Section; 2, North Section; 3, Yaramulla Section; 4, Wall Section. Other numbers are locations of cave entrances as shown in Figure 12. Letters "A" to "D" denote locations of basalt specimens chemically analysed (Appendix 1).

The crater walls are mainly covered by angular blocks (up to several meters across) of highly vesic-

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

In the McBride Province, only one volcano, Kinrara, is younger than the Undara Volcano (White, 1962). The Undara lava flows cover 1,550 square kilometers in the McBride Province and are basaltic in composition. Appendix 1 gives chemical analyses of four basalt specimens from the Undara flow.

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

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

Lava flowed in all directions from the Undara Crater, but the main flow was to the northwest (Figure 7). The flow to the north was approximately 90 kilometers long and entered the Lynd River. The voluminous northwest flow, however, followed precursors of Junction Creek, Elizabeth Creek, and the Einasleigh River (Figure 7) for more than 160 kilometers to become the longest single

Figure 8—Aerial oblique view of wide collapse depressions aligned with and/or adjacent to the Yaramulla Section of the Undara Lava Tube System, North Queensland. Kalkani Volcano, a cinder cone, not connected with Undara, is on the left. (Photo: H.J.L. Lamont)

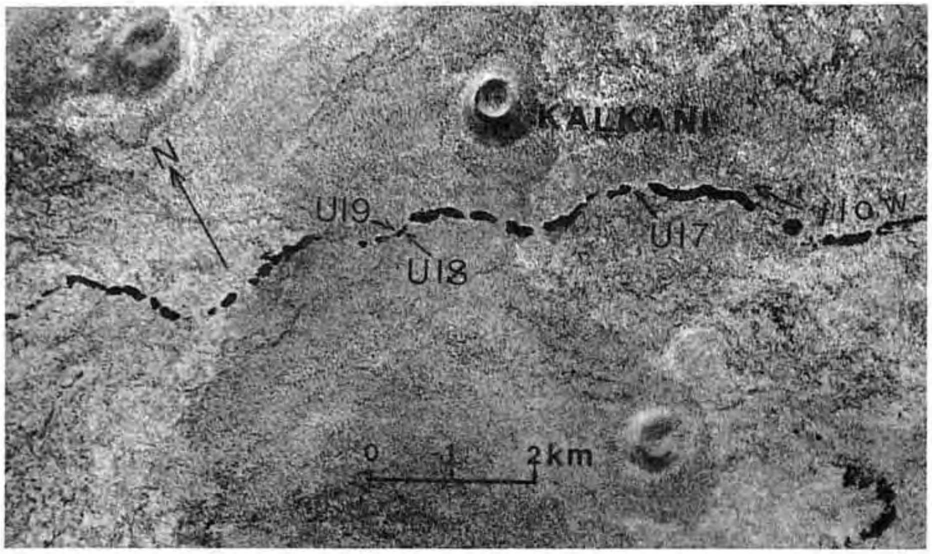

Figure 9—Vertical aerial view of wide collapse depressions aligned with and/or adjacent to the Yaramulla Section of the Undara Lava Tube System, North Queensland. (Photo: Department of National Mapping, Australia)

volcano lava flow in the world (Walker, personal communication, 1989). Walker considers that to reach a length in excess of 160 kilometers, Undara's eruption may have continued for several years.

The Undara lavas were erupted at temperatures ranging from 1,175° Celsius to 1,220° Celsius (Roeder and Emslie, 1970, cited in Atkinson, Griffin, and Stephenson, 1975). They do not appear to have unusual viscosities (Shaw, 1972; Bottinga and Weill, 1972; cited in Atkinson *et al.*, 1975) which accords with the conclusions of Walker (1973), that very long lava flows reflect continued high effusion rate. Stephenson and Griffin (1976) reached a similar conclusion in a study of eight long basaltic flows in Queensland.

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

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

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

The lava tube system from the Undara crater has been divided into the following five sections (Figure 7) in order to describe the locations of the caves and arches:

Crater Section—extending north from Undara Crater for four kilometers; average slope 1°.

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

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

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

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

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

Investigations of the Undara Lava Tube System

The Undara Lava Tubes had attracted the attention of three geologists prior to the investigations described in this paper. When discussing the distribution of volcanic centers in the McBride Province, Twidale (1956) noted two lineaments; he

incorrectly interpreted the aligned collapses (Figures 8 and 9) as "... a clear arcuate fissure ... with a center of eruption at its southeast end". Best (1960) and White (1962) subsequently recognized the lava tube system. Without opportunity for detailed investigation, they interpreted the pattern of collapse features (Figures 8 and 9) as a collapsed lava tube, with north and west branches.

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

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

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

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

(3) To investigate the geomorphology of The Wall.

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

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

In 1989, 100 volunteers (in groups of 20) from London-based Operation Raleigh camped on site for three months to investigate areas not explored by the author. Under the guidance of Q.N.P. and W.L.S. Officer Goodwin, they surveyed collapse depressions in the Undara Crater National Park and in 10 kilometers upflow from Bayliss Cave, an area never previously studied. They discovered and surveyed 23 new caves. Their systematic search in the North Section resulted in the first discovery of caves in this section, *viz.* Dingbat, Hot Hole, and Wishing Well Caves, about 21 kilometers north of the Crater. Their assistance in collection of specimens and data of flora and fauna led to valuable additions to the records of the Undara lava field.

Figure 10 – Road Cave, north wall. Lava level lines extend from floor to roof of this cave. They are among the most distinctive yet discovered in the system and are more easily studied than at other locations as they are in daylight at the eastern entrance. (Photo: H.J.L. Lamont)

Methods

The Undara Lava Tube System can be clearly located on aerial photographs (Figures 8 and 9). It stands out because many of its collapse depressions support rain forest type vegetation which contrasts sharply with the open forest of the surrounding country. Some of the caves, for example Barkers Cave (Cover Photo and Figure 13) and Road Cave (Figure 10), have been known for more than 100 years. The majority of caves, however, were located by systematic exploration of col-

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

ASP * Number	Cave	Length	Maximum Width	Maximum Height	Survey by
U1	Hanson	40	12	3	**
U2 U3e	Dunmall Arch	-	6	2	**
U4	Taylor	108	16.3	10.8	**
U5	St. Pauls	30	-	-	**
U6	Sarah	10.7	0.9	1.4#	**
U7	Peter	13.8	9.9	3.8	**
U8	Ollier	49.4	10.4	3	**
U9 U10e	Harbour Bridge	35	14.3	5	**
U11 U12e	Greeley	103	12.4	3.8	**
U13	Frances	14#	6	3	**
U14	Opera House	30	10	7.5	**
U15	Peterson	102	17.1	3.7	**
U16	Stevens	70.4	8.8	3	**
U17	Pinwill	150	21	8.9	**
U18	Traves	67	14	10.6	**
U19	Atkinson	101.2	28	7.8	**
U21	Stephenson	156#	> 25#	> 10#	PD
U22	Arch	10.5#	28#	9#	PD
U23	Ewamin	162#	21#	> 8#	PD
U24	Picnic I (down)	420	22	15	PD
U25	Picnic II (NE)	45	12	> 14#	PD
U26	Dave I (up)	50	10#	8#	PD
U27	Dave II (down)	27	-	-	PD
U28 U29e	Road	220	21.2	9.4	**
U30	Bayliss additional (1988)	> 950 > 400	18.9	11.5	** PM, DR
U31	Darcy	99	16.3	6.3	**
U32 U33e	Matthew	40	7#	3#	**
U34	Barker	560+	19.8	13.5	CS
U35	Raleigh I	23	15.8	7.3	OR
U36	Raleigh II	29.8	17	8.5	OR
U37	Lost World	74.2	13.5	5.7	OR
U38	Tween	24	11.5	6.5	OR
U39	Eptesicus	42	22#	6.1#	OR
U41	Inner Dome	68	22	7.5	OR
U42	Wind Tunnel	293	32	8#	OR

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

ASP * Number	Cave	Length	Maximum Width	Maximum Height	Survey by
U43	Short Little Arch	15.8	5#	2#	OR
U44	Mikoshi	46.6	14#	11#	OR
U45	Misplaced Arch	22	22#	11#	OR
U46	Nasty	127	15	8#	MG
U47	Fortune	52.9	4.4#	2.5#	OR
U48	Temple of Doom	49.5	6#	4.5#	OR
U49	Fun	33.2	9.8	1.25	OR
U50	Ding Bat	60.4	17.1	7#	OR
U51	Hot Hole	171.9	13.5	3.5	OR
U52	Wishing Well	104	13	3.3	MG
U53	Moth	9.2	4	1.8	OR
U54	Sunset	> 30	5.2#	2.2#	OR
U55	Wallabys Hideaway	38.5	9	4#	OR
U56	Expedition I	30#	12	5#	DI
U57	Expedition II	28	20	4#	DI
U58	arch (unnamed)	8.5	10	2.2#	OR
U59	Tom Tom	34	9.5	2.5	OR
U60	arch (unnamed)	16	13	2.5#	OR
U61	Komori	> 85	9	3#	OR
U62	Speaking Tube	25.2	7.7	3.2	OR
U63	Flat Ceiling	80	15#	3#	DI
U64	Branch	10	10#	2#	DI
U65	San	25	10#	2#	DI
U66	Graham	22	3#	3#	PS
U67	Upper Secret	150#	-	-	PS
U68	Lower Secret	70#	-	-	PS
	Total	6,324.7			

* Australian Karst Index (Matthews, 1985)
** V. and A. Atkinson and assistants
Abbreviations: PD = P. Dwyer, PM = P. Mainsbridge, DR = D. Ray,
CS = C. Shannon, OR = Operation Raleigh, DI = D. Irvin, FS = F. Stone.
# Estimate only

lapse depressions by the author and assistants between 1972 and 1974, members of the Chillagoe Caving Club 1985 to 1988, and Operation Raleigh volunteers in 1989.

Initially the cave entrances were marked with a 10-centimeter square painted on a conspicuous block at the base of each entrance collapse. These squares were used as the datum for cave surveys.

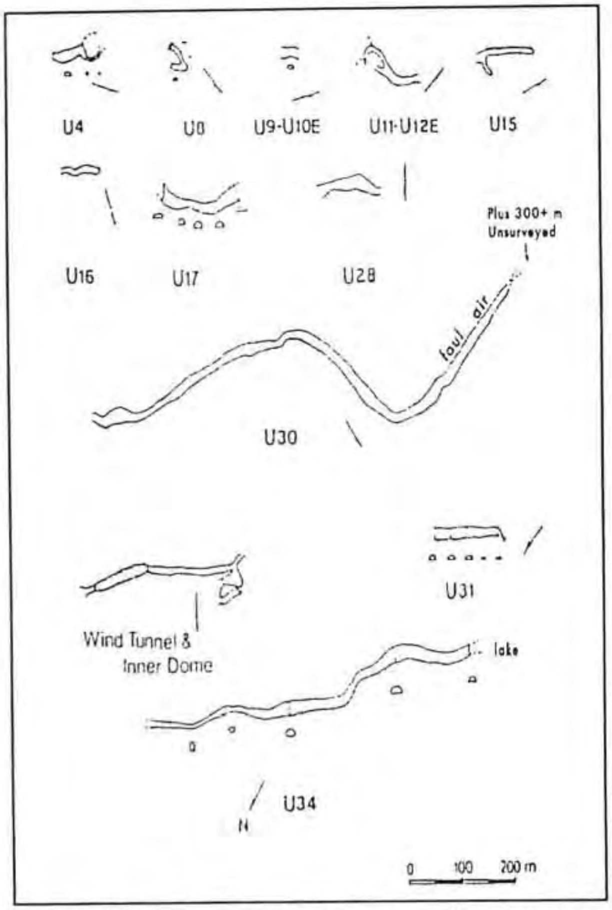

Figure 11 – Maps of selected caves with some cross sections. Localities – see Figure 7; cave names – see Figure 12; Cave U11-12E is Greeley Cave (Atkinson et al., *1975); The Wind Tunnel and Inner Dome (1988) are shown. The 1987 extension of Bayliss Cave is not shown as it has not yet been surveyed.*

A surface datum was painted to correspond as closely as possible with the cave datum in order to ascertain roof thickness. Steel posts were left as surface markers to correspond with cave survey stations.

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

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

The results of the surveys were presented (Atkinson *et al.*, 1975) as plans with some transverse profiles (Figure 11) and as a longitudinal profile through the source crater and representative caves (Figure 12), the first such profile ever to include the crater of origin.

Caves and Arches

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

Features of the Caves and Arches

Although the Undara Lava Tubes formed in a very short period 190,000 years ago, they have retained many original features. These features show minimal alteration due to their protection from weathering.

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

Figure 11 shows the plans of representative caves. Most of the cave passages are elongate in the direction of the lava flow. Figure 12 shows longitudinal profiles through representative caves in the Crater Section and Yaramulla Section of the System. These profiles illustrate the variation in shape, size, and roof thickness of the caves.

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

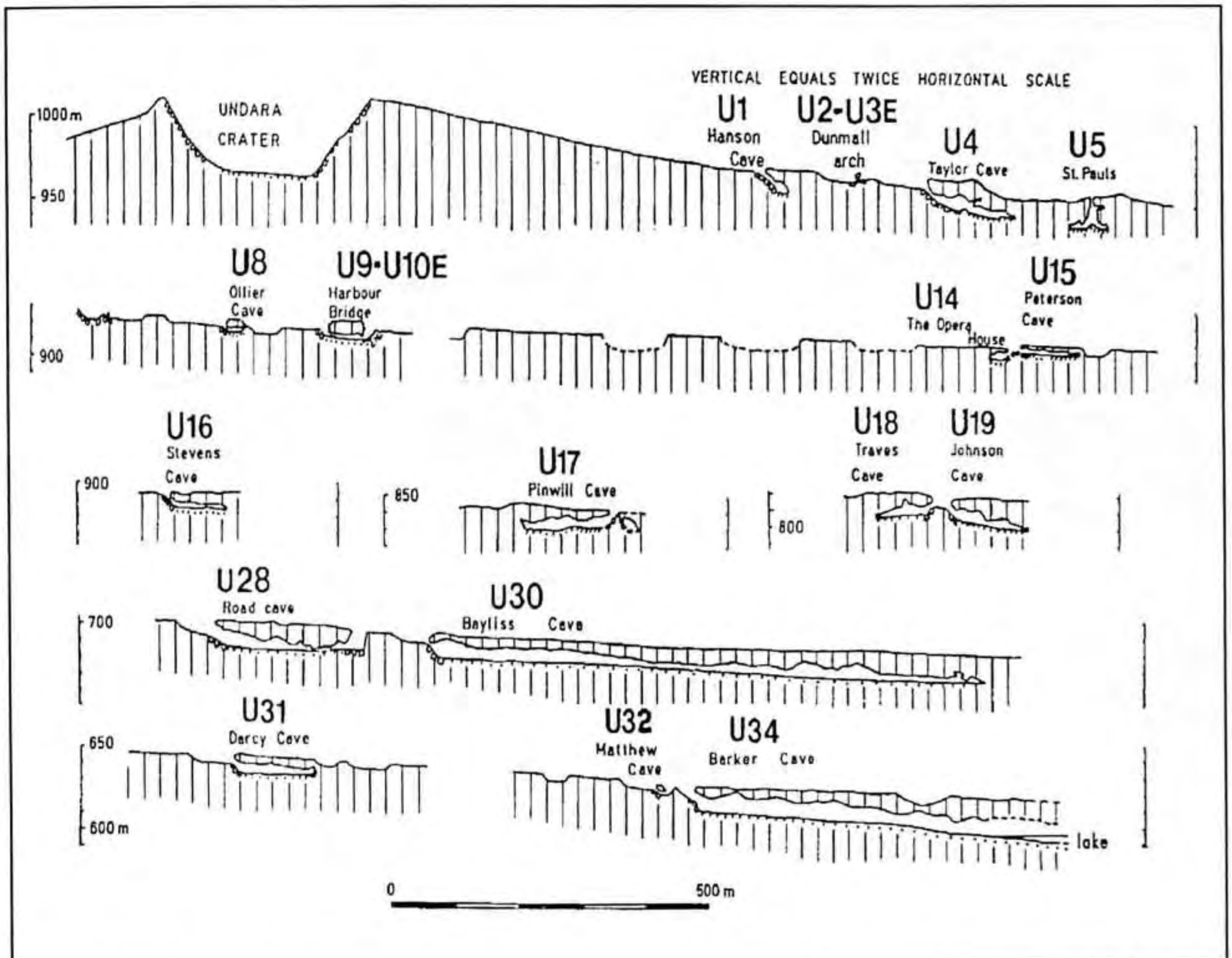

Figure 12—Longitudinal profiles of various caves down flow from Undara Crater. The A.S.F. Cave Register numbers are shown. Floor symbols: sediment (.....), ropy lava (/////) (Atkinson et al., *1975).*

Lava Tube Floors

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

At the entrance to Barkers Cave (Figure 13), the floor is arched, with a single rope structure running down-flow. Beyond this, the floor has distinct marginal gutters (Cover Photo) up to one meter deep. Fine lava level lines on the outer walls of the gutters correspond, but are absent on the inner walls, which show some evidence of formation as levees. The raised central portion of the cave is therefore interpreted as a final channel flow in this cave.

Good examples of ropy lava are visible in Pinwill Cave and the South Chapel of St. Pauls. In a central position near the entrance to Barkers Cave, crust fragments, approximately eight centimeters thick, have been rafted at varying oblique angles (Figure 15) in a manner similar to ice slabs on a frozen river. In Peterson Cave there is a small floor surface where lava drops from roof re-melt appear to have pitted the floor, as rain drops pit a muddy surface.

Prolonged flow at constant level is evidenced by the "pavements" in Taylor Cave (Figure 14). Where rate of flow is less against a convex bank, lava consolidates in a manner similar to the deposition of alluvium on convex banks of rivers.

Walls and Roofs

There is a lava lining on the walls and roof of most caves. Typically the lining is a single layer of

Figure 13—Bakers Cave viewed from the entrance collapse. Some of the original arched floor is exposed and has a distinctive longitudinal "rope" structure. It is noted with interest that a distinctive pattern of vesicles on the large block in the center foreground can be matched to one in the cave "roof" directly above it. (Photo: H.J.L. Lamont)

up to 20 centimeters, but in places may approach one meter in thickness. At various locations the tube lining has fallen off the wall to expose the host lava behind it. The lining is sometimes multi-layered. The best example of this is in Pinwill Cave where 15 layers, 2 to 4 centimeters thick are revealed at one location (Figure 15). At the entrance to the same cave, a thin slab of lining called The Table has become dislodged and now rests in a near horizontal position (Figure 17).

On most walls and roofs are some areas of very low vesicularity and showing drip and dribble structures resembling cake icing (Figure 18). At the entrance to Barkers and Picnic Caves these drips are deflected. In historic tubes such surfaces have been seen forming by remelting and, because of their luster are appropriately termed "glaze," but in the Undara tubes the remelt surfaces have weathered to a dull or earthy luster.

In places there are lavicicles (lava stalactites), commonly two centimeters to three centimeters and occasionally up to eight centimeters long, suspended from the roof, inclined walls, and in wall cavities (Figure 19). Lava stalagmites are rare, as are lava columns. No "straw" stalactites have been found – no doubt because of their extreme fragility.

In most caves, lava level lines and ledges on the walls represent fluctuating lava levels. The highest levels are usually evident close to the roof, as seen in Taylor, Road (Figure 10), Arch, Ewamin, Picnic I, Picnic II, and Barkers Caves (Cover Photo). The lava level lines usually slope down-tube at low angles, probably reflecting the original tube slope.

Termination of the Lava Tubes

The caves generally terminate down-flow with collapses, or with a gentle downward curve of the ceiling to a silt floor. Barkers Cave ends in a lake, the cave ceiling steadily declining to water level. Several caves have down-flow entrances and have little or no silt on their floors. Pinwill Cave (Figure 21), The Opera House (Figure 22), Picnic, and Wishing Well Caves terminate with walls.

Figure 14 – Taylor Cave. The prominent "pavements" (1 and 2) are evidence of an extended period of constant rate of flow. Solidification has been greatest at the apex of convexity, as in a fluvial river. There is a cylindrical opening (3) in the roof above the figure. The location of this opening suggests that some lava ponded in the Death Adder depression (in alignment to the north) may have drained back into the tube through this conduit.. (Photo: H.J.L. Lamont)

Human Use of the Undara Lava Tubes

There is little evidence that the Undara lava tubes were used in prehistoric times. Local Aborigines claim that their people would have avoided such places. No drawings or evidence of fires have been found in the caves, though some artifacts were found at one cave entrance.

Collapse Depressions and Their Relationships to Caves

This account would be incomplete without reference to the collapse depressions associated with the Undara Lava Tube System. For convenience these depressions are divided into two types, namely: narrow depressions, 30 to 50 meters wide, and wide depressions, 50 to 100 meters wide. Geologists and local residents had long questioned how the wide depressions had formed. The author correlated their appearance with an historic lava pond in Hawaii (Figure 23, from Macdonald and Abbott, 1972, p. 42). With the wonderful cooperation of D.W. Peterson (USGS), from across the Pacific came the confirmation.

Narrow Depressions

Narrow depressions commonly give entry to the lava tube caves suggesting that they were formed by the collapse of segments of the tube. Vegetation within these depressions differs little from that of adjacent open forest. However, rain forest trees and vines are found at most cave entrances, often concealing

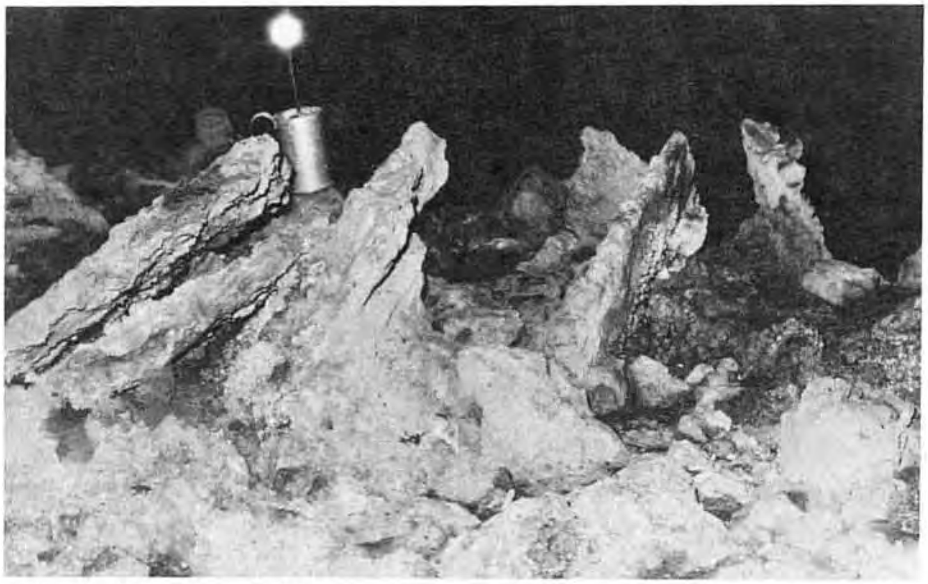

Figure 15—"Rafted" blocks of the crust of the final flow have jammed at various angles. Location: Barkers Cave. (Photo: Vernon Atkinson)

them and, as a result, cave entrances are difficult to locate on aerial photographs.

Wide Depressions

Wide depressions form a strong linear pattern, made conspicuous by rain forest vegetation (Figure 8). They seldom give access to caves and display features which distinguish them from the narrow depressions. Wide depressions vary in shape from circular or oval to elongate in the direction of the lava flow. An exception to this is seen west of Barkers Knob where depressions are less regular in shape and location, although there is some indication of three branching alignments. The erratic shapes are interpreted as possible indication that the flow traversed marshy ground in this area.

Figure 16—Multi-layered lining. Up to fifteen layers are exposed at this location in Pinwill Cave. (Photo: Vernon Atkinson)

Most wide depressions have elevated rims, suggesting that they represent former lava ponds as are seen associated with historic flows in Hawaii (Figure 23). Rims and slopes of the depressions are made up of blocks of various shapes and sizes. Local areas of blocks possessing flat upper surfaces with low vesicularity are thought to be segments of lava pond crust because of the similarities to collapsed lava pond crusts in Hawaii and Oregon, USA (Peterson and Greeley, personal communication 1974; Greeley, 1971a). Near the base of some depressions the lower surfaces of some blocks are moulded and occasionally contain embedded fragments. In rare cases, blocks have retained an original ropy lava surface.

Peterson and others of the U.S. Geological Survey in Hawaii (written communication, 1975) have observed that lava becomes ponded in specific areas, particularly where the slope is small. Once formed, the ponds tend to perpetuate themselves during the life of the flow, even when the flow front has advanced further. These ponds crust over and the molten lava beneath the crust is interconnected with lava tubes that had been developing in the flow both upstream and downstream from the pond. The crusted surfaces of these ponds have

Figure 17—"The Table"—a thin sheet of lining near the entrance to Pinwill Cave shows a degree of plastic deformation. (Photo: Vernon Atkinson)

been observed to subside as the flow dwindles and the ponded lava drains back into the tube. The wide depressions of the Undara lava flow have been interpreted as former lava ponds.

There is a depression 60 meters north of the entrance of Taylor Cave. This long depression lies directly in line with the entrance section of the cave. The cave was found not to terminate in a collapse beneath the depression, as was expected, but close to the edge of the depression. The cave branches and the two passages roughly follow the outer margins of the depression. Each branch closes to an inaccessible tunnel and near its termination the east branch divides again. The lava level lines in the east branch are nearly horizontal and proceed along both sides of the cave and across the wide pillar at the end (Figure 24).

The relationship of the Taylor Cave passages to the depression suggests the collapse interfered with the still functioning tube. When the lava pond drained and its crust collapsed the tube bifurcated

Figure 18—Lava dribbles in Barkers Cave. (Photo: H.J.L. Lamont)

Figure 19—Lavacicles up to six centimeters long in Bayliss Cave. (Photo: Vernon Atkinson)

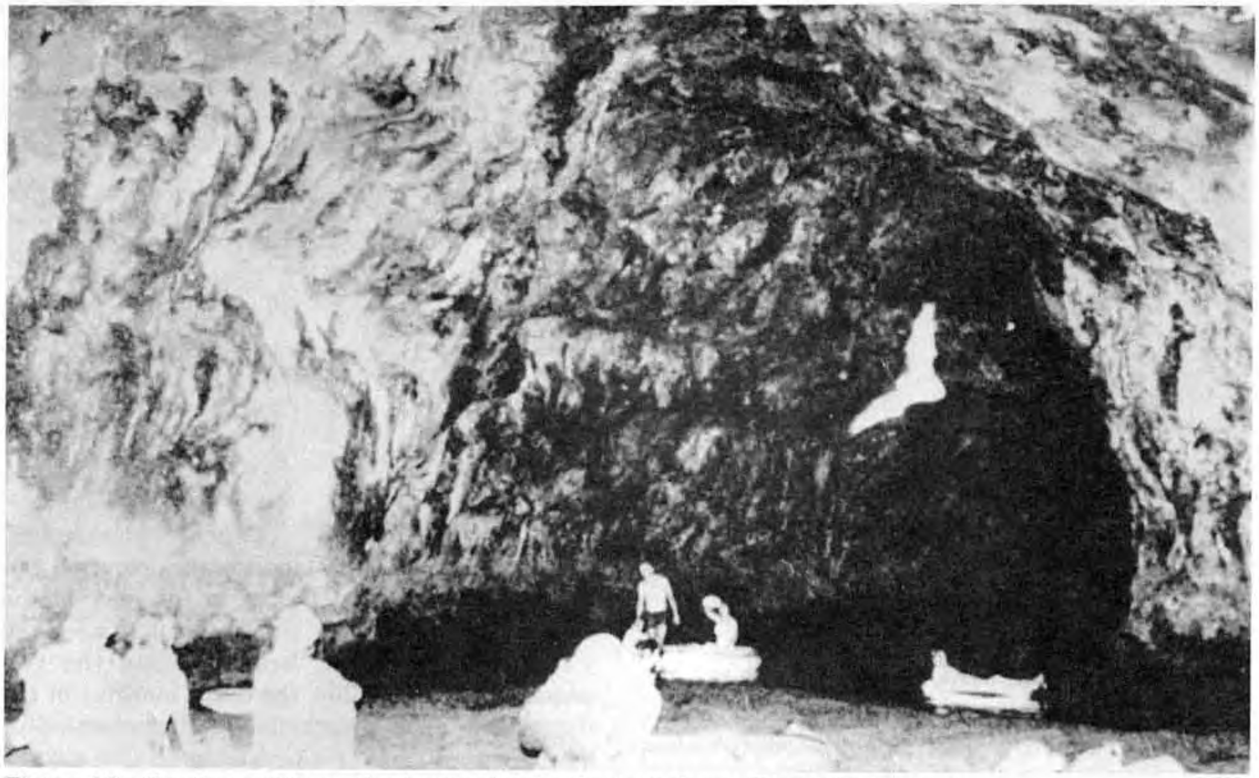

Figure 20 – Boating party on the terminal lake, Barkers Cave. (Photo: R. Dutton)

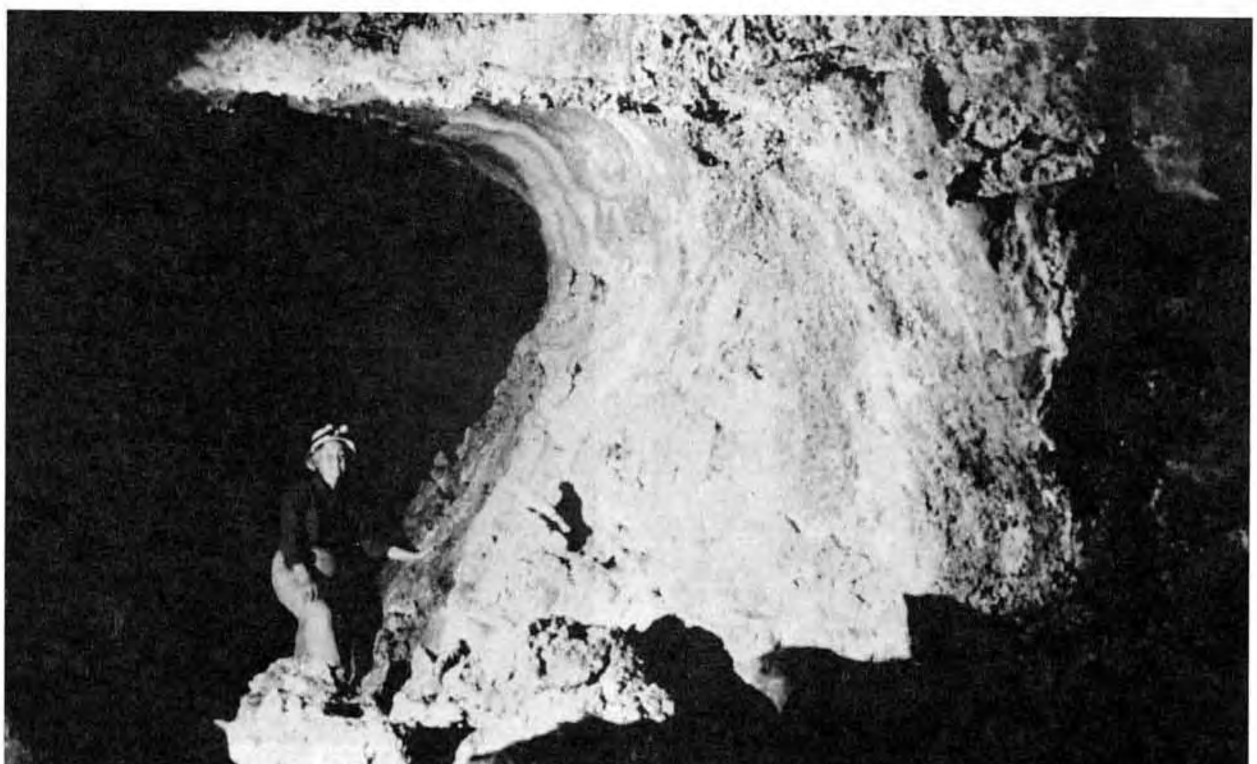

Figure 21 – "The Wave" – termination of Pinwill Cave which has a downflow entrance. (Photo: Mick Williams)

Figure 22 – Termination of The Opera House (note wings). Entrance is down flow. (Photo: H.J.L. Lamont)

around the collapse, but was then constricted and eventually dammed. Subsequently the dammed lava inside the tube drained through minor outlets. A cylindrical vent in the roof of Taylor Cave (Figure 14) is interpreted as a location where some of the lava that ponded above the main tube drained back into it. A minor lava fall, approximately one meter high, emerges from under the floor of the west

Figure 23 – Island of Hawaii, 1895, Halemaumau Crater within Kilauea Cladera. The lava lake is held in a lava ring (a ring-shaped levee) built up by spattering and repeated overflows such as those visible in the picture. (Photo from Ray Jerome Baker collection, Bishop Museum, Honolulu)

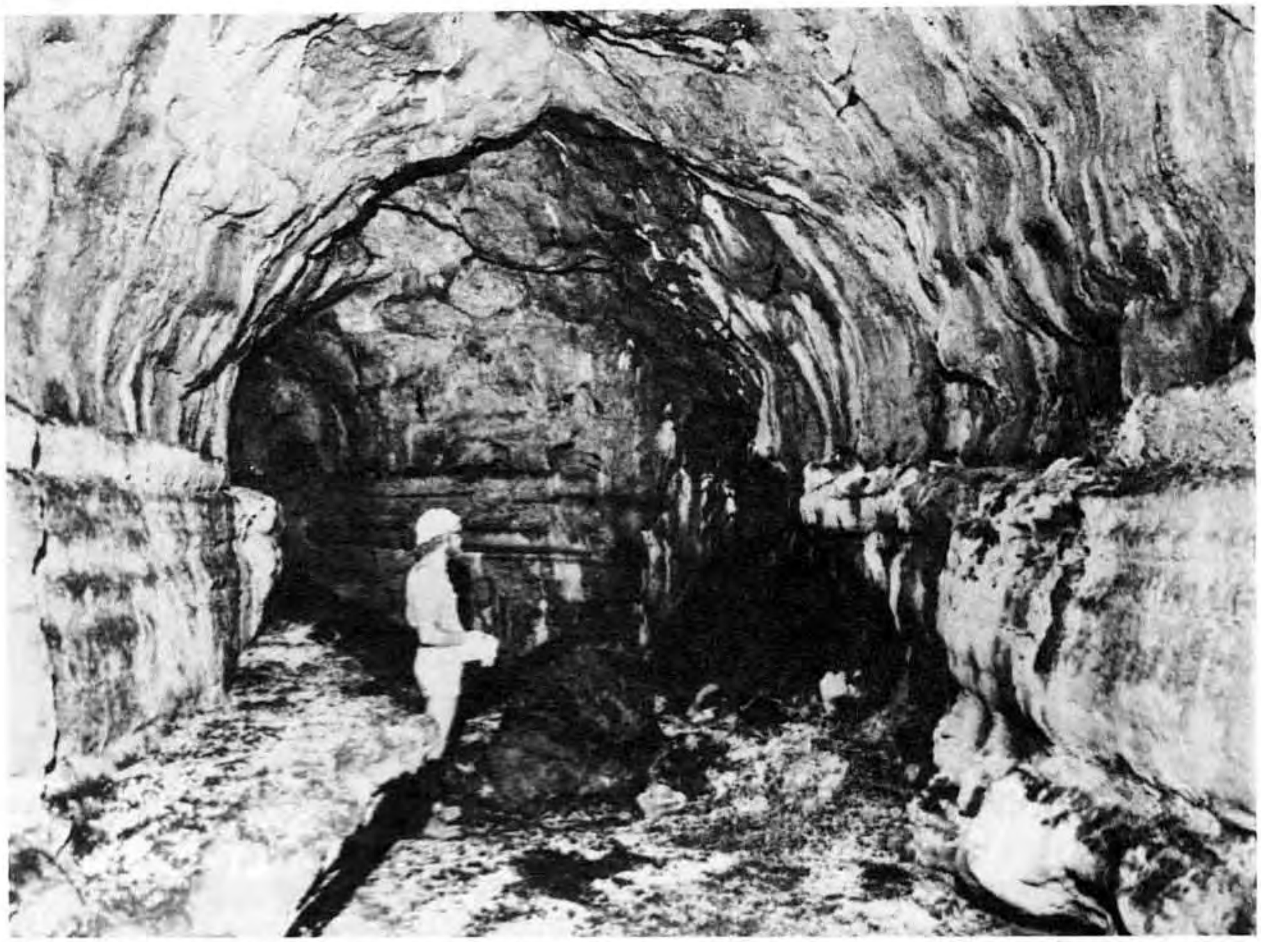

Figure 24—Termination of Taylor Cave (east branch) as two closing tunnels beyond the figure. Note horizontal lava level lines and ledges on walls and central column. (Photo: H.J.L. Lamont)

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

Figure 25 shows how Barkers Cave changes its course, deviating around a major depression 220 meters west of the cave entrance. There is a small cavity in the cave roof under the eastern end of the depression and circular holes up to 1.5 meters across on the inner slope of the depression. This seems to indicate that the lava which had ponded in the depression drained back into a flowing tube, forcing it to alter its course.

The Wall

The Wall (Figures 2a, 26, and 27) consists of a very long, narrow ridge that rises up to 20 meters above the general level of the flow and can be traced for 35 kilometers. The upper surface of the ridge is relatively flat and varies in width from 70 meters to 300 meters. Its down-flow slope averages only

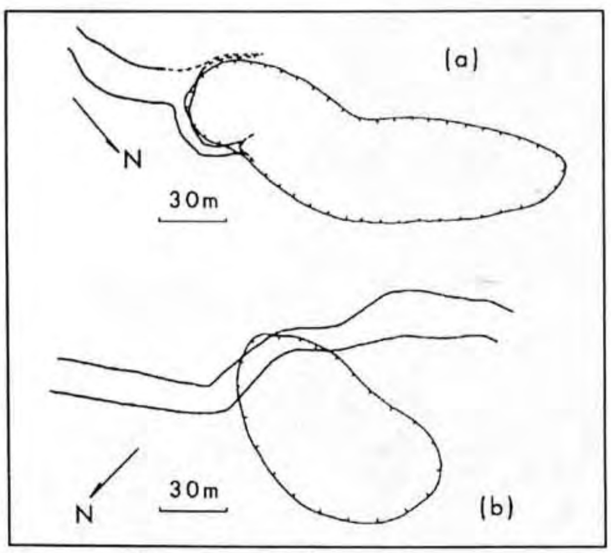

Figure 25—Relationship between surface depressions and caves: (a) Taylor Cave; (b) Barkers Cave (Atkinson, et al., *1975)*

Figure 26—Oblique aerial view of "The Wall" from the south. Note megacolumns flanking central collapsed area at the termination. (Photo: Jon Edmonds)

1.72 meters per kilometer with occasional undulations. The side slopes of the ridge are up to 29°. There are several depressions within five kilometers of the termination of The Wall. One of these depressions may represent a collapsed lava pond which drained into the tube below. Edmonds Lake, a narrower axial oval depression has been interpreted as a collapsed segment of the tube.

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

Mode of Formation of the Undara Lava Tube System

Lava rivers and associated tube systems are the main distributors of the liquid rock during a pahoehoe lava eruption. The lava tube system and caves associated with it are formed in a short time; in the case of the Undara Lava Tubes, probably in several years (Walker, written communication, 1991). Evidence of how the lava tube system and the caves in it formed has been preserved for 190,000 years. This, together with observations of caves forming in active and recent lava flows in Hawaii (Jaggar, 1947, cited in Wood, 1976; Wentworth and Macdonald, 1953; Greeley, 1971b, 1972a and 1987; Macdonald and Abbott, 1972; Cruikshank and Wood, 1972; Peterson and Swanson, 1974; Peterson and Holcomb, 1989), and Iceland (Kjartansson, 1949, cited in Wood, 1976), has resulted in the following discussion of the mode of formation of the Undara Lava Tube System (Figure 28).

A river of pahoehoe lava, confined in a valley, quickly crusts over and develops a roof. The flow also begins to solidify against the valley walls and floor (Figure 28a). The roofing occurs in several different ways including growth of semi-solid surface crusts by cooling, crusts floating down the channel jamming and accumulating at obstructions, and the growth of levees from the channel sides through repeated overflows, splashing, and splattering. Examination of the roofs in the Undara lava tubes indicates that most of the roofing took place by the growth of semi-solid surface crusts.

As solidification of the roof, walls, and base continue, the flow becomes concentrated within a cylinder (Figure 28b). If the eruption ceases at this

Figure 27—Termination of "The Wall" viewed from the north. Arrows point to the megacolumns on the horizon. (Photo: Tom Atkinson)

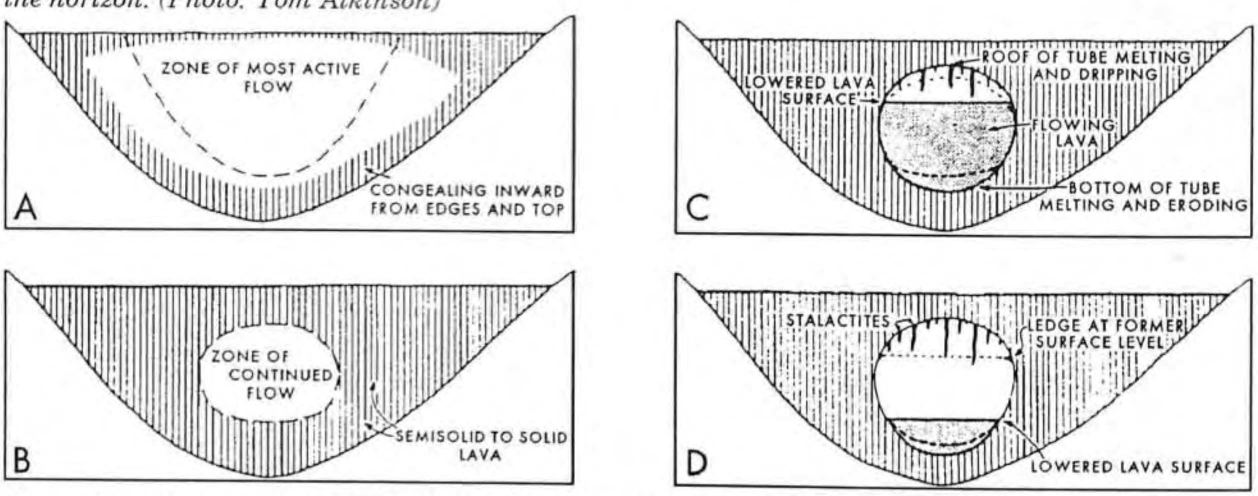

Figure 28—Stages observed in the development of the lava tubes in Hawaii (after Macdonald and Abbott, 1972). Examination of evidence in the Undara Lava Tubes indicates that this explanation is directly applicable.

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

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

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

d. *Further diminution of supply lowers the level of the surface of the liquid which finally congeals to form the floor of the tube.*

Figure 29—Roof structure inside Peterson Cave (east branch). The prominent arched flow unit just above the observer's head has a ropy interface. Higher ropy interfaces also occur. (Photo: H.J.L. Lamont)

Once the Undara Lava Tube System was formed in the major eruption, there was subsequent thickening of tube roofs by later flow units (Figures 16, 17, and 29). Some of these flow units passed over ropy surfaces and now bear rope imprints on their lower surfaces. The low incidence of ropy surfaces and imprints at Undara support the observation by Macdonald and Abbott (1972) that ropy structure is often evident only over a small proportion of any flow. Figure 30 shows the thickness of various lava tube cave roofs: (a) Taylor, (b) Harbour Bridge, (c) Peterson, (d) Pinwill, (e) Road, (f) Barker.

time, and the tube drains completely, its cross section is circular.

When the supply of lava diminishes during an eruption, it no longer fills the whole tube. Volcanic gases escaping from the flow into this cavity may ignite producing temperatures considerably higher than that of the molten lava. This may cause some remelting of the roof with drips of lava forming lavicicles (Figure 28c) which are commonly vertical. Deflection is rare and is thought to be caused by a current of very hot air. In the Undara Lava Tube caves deflection has been noted near the entrance to Picnic I and Barkers Caves.

Effusion rates fluctuate during an eruption but whenever a constant rate is maintained, near-horizontal ledges of lava solidify on the tube walls—lava level lines. Further diminution of the flow lowers the level in the tube and finally the flow congeals to form the floor (Figure 28d).

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

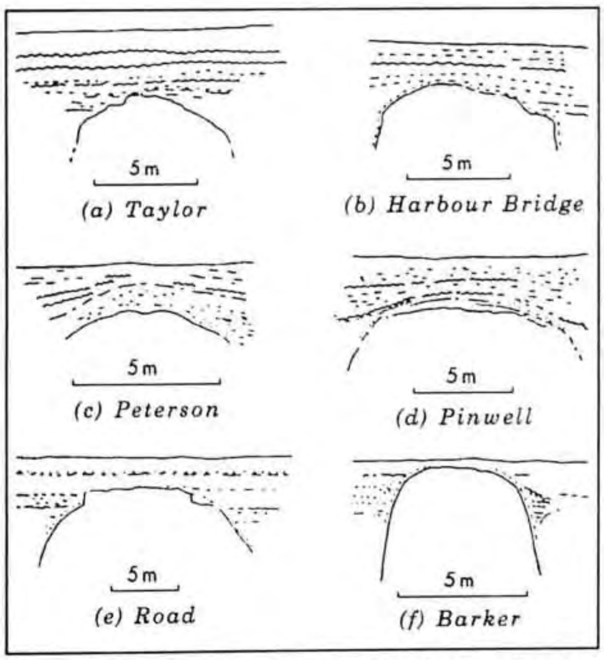

Figure 30—Cave entrance structures showing thickening of roofs by successive surface flow units. Flow units are represented by wavy lines for recognised flow unit surfaces. Other near-horizontal lines are major vesicle zones. (Diagram: P.J. Stephenson)

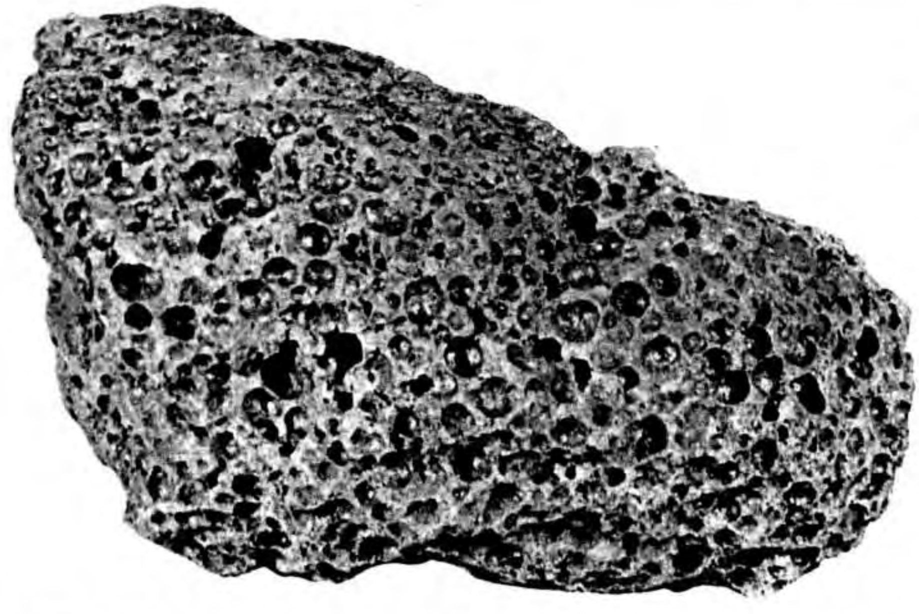

Figure 31—Lunar vesicular basalt. More than half this specimen is "pore" space. The pores or vesicles, are formed by frothing and bubbling during volcanism and indicate high gas activity at one time on the Moon. The appearance in the hand specimen and under the microscope show no marked difference from terrestrial basalts but there are slight chemical differences. (MacKenzie et al., *1982) (Photo: NASA, USA)*

Subsequent flows, as well as thickening of the tube roofs, may form additional lava tubes. If these connect with existing caves, a complex cave system will develop. In the Undara Lava Field there is such development in the Crater Section and in the proximity of the Wind Tunnel.

Beyond the Yaramulla Section, the continuation of the lava tube system is The Wall. That it is 20 meters above the associated lava field with a minimal gradient, suggests that it represents an elevated channel flow whose "toe" solidified initially where The Wall now terminates. This caused a temporary blockage which allowed the channel to roof over to form a major lava tube. The large polygonal jointing (Figures 26 and 27) is taken to evidence considerable roof thickness. A surge of lava through the tube broke down the toe of the flow and continued a further 70 kilometers. Slumping of the tube roof at the termination left a colonnade of roughly columnar blocks (Figure 27). It would be of great interest to confirm the structure of this unusual feature by geophysical investigation or drilling near the center of the ridge.

Conclusion

Favorable topography and a very high rate of effusion, coupled with an efficient lava tube system, allowed one flow from the Undara Volcano to extend 160 kilometers to become the longest single-volcano flow in the world. This flow contains the longest lava cave in Australia. Within the caves and arches of the lava tube system, protection from weathering has allowed the preservation of many features similar to those in active and recent lava flows. From such features it can be concluded that the lava tube system and the caves in it formed in a manner similar to those that have been observed forming during historic eruptions of pahoehoe lava.

Acknowledgements

The author is indebted to many people for their help and assistance in the field and elsewhere – too many to name here.

Special thanks are due to:

Associate Professor Stephenson and Dr Griffin for permission to use material from our joint paper.

My husband, Vernon, and our family; Peter Stanton, Q.N.P. and W.L.S.; Associate Professor Stephenson; Professor Greeley (Arizona State University); Drs. Halliday (Tennessee), Peterson (U.S.G.S.), and Stevens (U.Q.); and Julia James (S.U.) for their continued interest and enthusiasm.

Mr H. J. Lamont, J.C.U.N.Q., for the fine cave photographs.

Mick Godwin, Q.N.P. and W.L.S., Cairns, who has done so much toward completing the Undara records and who arranged my safe entry to (and return from) the caves discovered in 1988.

Audrey Durham and Greg Atkinson for editing, formatting, and much more.

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APPENDIX 1

UNDARA LAVA TUBE SYSTEM MAJOR ELEMENT CHEMICAL ANALYSES
Specimen locations are shown on Figure 7

*These analyses on samples dried at 110°C
n.d. = not determined

	A	B	C	D
SiO_2	48.85	49.30	49.50	48.20
TiO_2	1.82	1.70	1.67	1.75
Al_2O_3	15.23	15.40	15.90	15.80
FeO_3	2.52	11.00	10.53	4.46
FeO	7.46	trace	0.06	6.38
MnO	0.16	0.15	0.15	0.17
MgO	8.55	8.10	7.10	7.85
CaO	9.16	8.02	8.39	8.02
Na_2O	3.90	4.20	3.87	3.57
K_2O	1.75	1.77	1.53	1.71
H_2O+	0.35	n.d.	n.d.	n.d.
H_2O-	0.17	*	*	*
P_2O_5	0.64	0.50	0.34	0.72
CO_2	0.13	n.d.	n.d.	n.d.
Total	100.69	100.14	99.04	98.63
Locality (Fig 7)	A	B&C	B&C	D

Analyses
"A": Host rock, Barkers Cave entrance,
"B": Cave lining, Barkers Cave entrance.

Analyses:
"A" T.J. Griffin, using XRF; Na, flame photometric; Fe^2, by titration.
"B"-"D" P.J. Stephenson and T.J. Griffin, using Atomic Absorption (HF-Boric Acid digestion); P, spectrophotometric; Fe^2, by titration.

APPENDIX 2

Author's first map and transverse sections,
Undara Lava Tube System.

Data: Tom and Anne Atkinson, 1972.

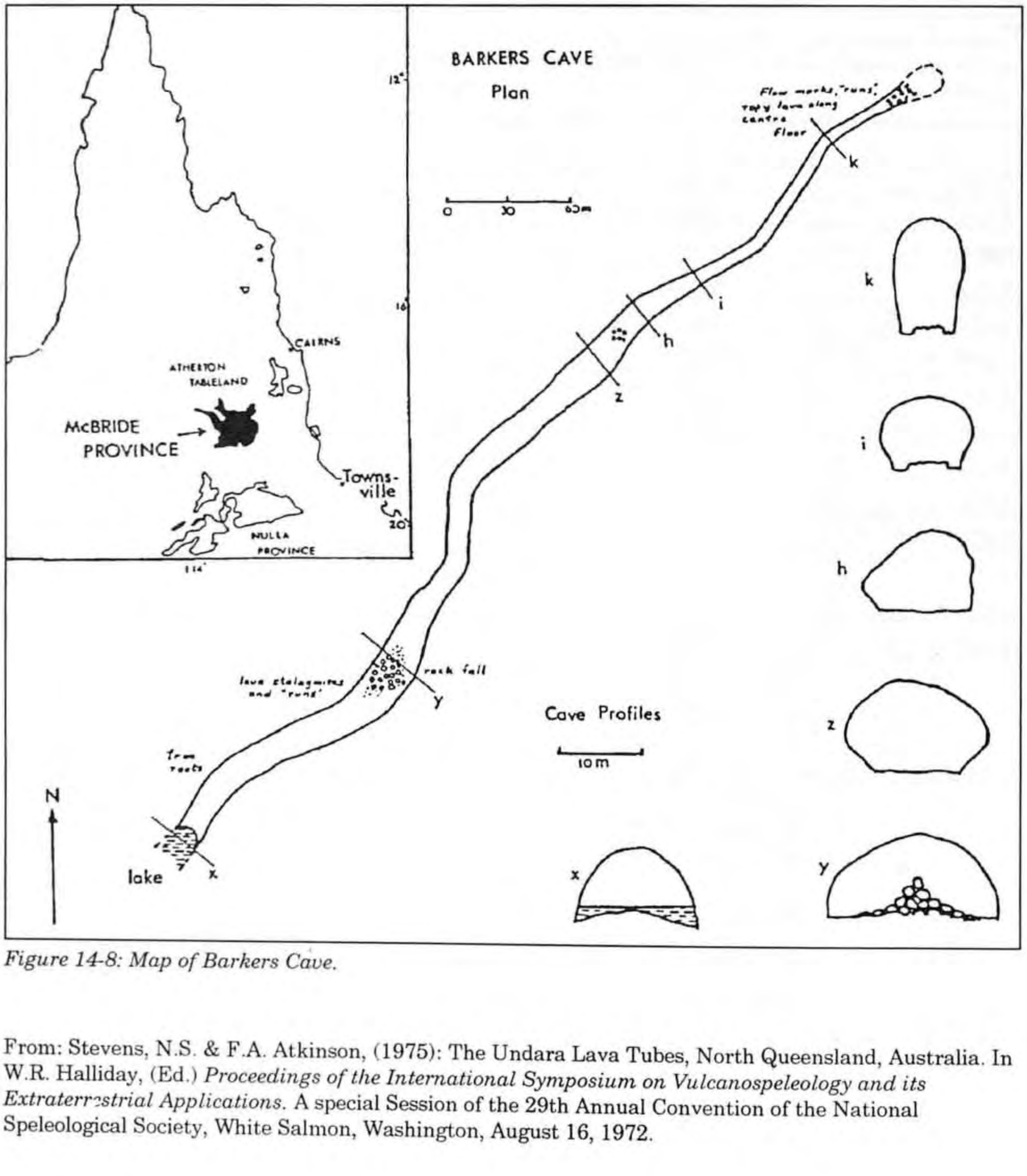

Figure 14-8: Map of Barkers Cave.

From: Stevens, N.S. & F.A. Atkinson, (1975): The Undara Lava Tubes, North Queensland, Australia. In W.R. Halliday, (Ed.) *Proceedings of the International Symposium on Vulcanospeleology and its Extraterrestrial Applications.* A special Session of the 29th Annual Convention of the National Speleological Society, White Salmon, Washington, August 16, 1972.

Caves and Pits from the Azores With Some Comments on Their Geological Origin, Distribution, and Fauna

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Abstract

In 1989 Ogawa published an account of the distribution of volcanic caves and pits from the Azores. Further work in the last few years justifies an updating of the information. Ogawa listed 33 caves and 7 pits; now these numbers are 88 and 24. In this paper the caves and pits are listed according to their occurrence in the islands of the archipelago: Corvo (1;0), Flores (0;0), Faial (3;1), Pico (28;8), Graciosa (16;1), São Jorge (7;5), Terceira (20;6), São Miguel (10;3) and Santa Maria (3;0). Some data on the location, length, elevation, and fauna of each cave and pit are also given. During recent speleological expeditions by Os Montanheiros to the islands of Faial, Pico, Graciosa, São Jorge, Terceira, São Miguel, and Santa Maria over 10,000 meters of lava tubes and 400 meters of pits were surveyed and a total of 17 new maps are presented in this work. The longest lava tube, Torres Cave (Pico), is 3,350 meters long, 15 meters high, and 22 meters wide. The biggest pit, Algar do Montoso (São Jorge), is 137.5 meters deep. Presently 75% of the known caves have less than 300 meters. Some caves really belong to a single longitudinal lava tube broken into different sections. We also present some comments on the more relevant characteristics of each of the main caves and the distribution of lava tubes, pits, and related lava flows in each island. A short narrative of Azorean geology and some information for the preservation of the caves as well as some comments on the relict hypogean fauna are also provided.

Introduction

The Azorean archipelago is located in the North Atlantic, at the triple junction of the Eurasian, African, and North American plates. The distance between the Azores and the mainland is about 1,390 kilometers west of Cabo da Roca (the western most point of the European continent). It is formed by nine volcanic islands, aligned on a west-northwest to east-southeast trend, that are distributed in three groups: the western group with Corvo and Flores; the central group with Faial, Pico, Graciosa, São Jorge, and Terceira; the eastern group with São Miguel and Santa Maria (Figure 1).

The biggest island is São Miguel with 757 square kilometers and the smallest is Corvo with 17 square kilometers. Santa Maria is the most southern island (37°N, 25°W), and Flores is the most western one (31°W). The most northern one is Corvo (39.7°N) (see Table 1 and Figure 1).

The distance between Corvo and Santa Maria, the most widely separated islands, is about 615 kilometers. Corvo lies at approximately the same distance from the Iberian Peninsula and Newfoundland.

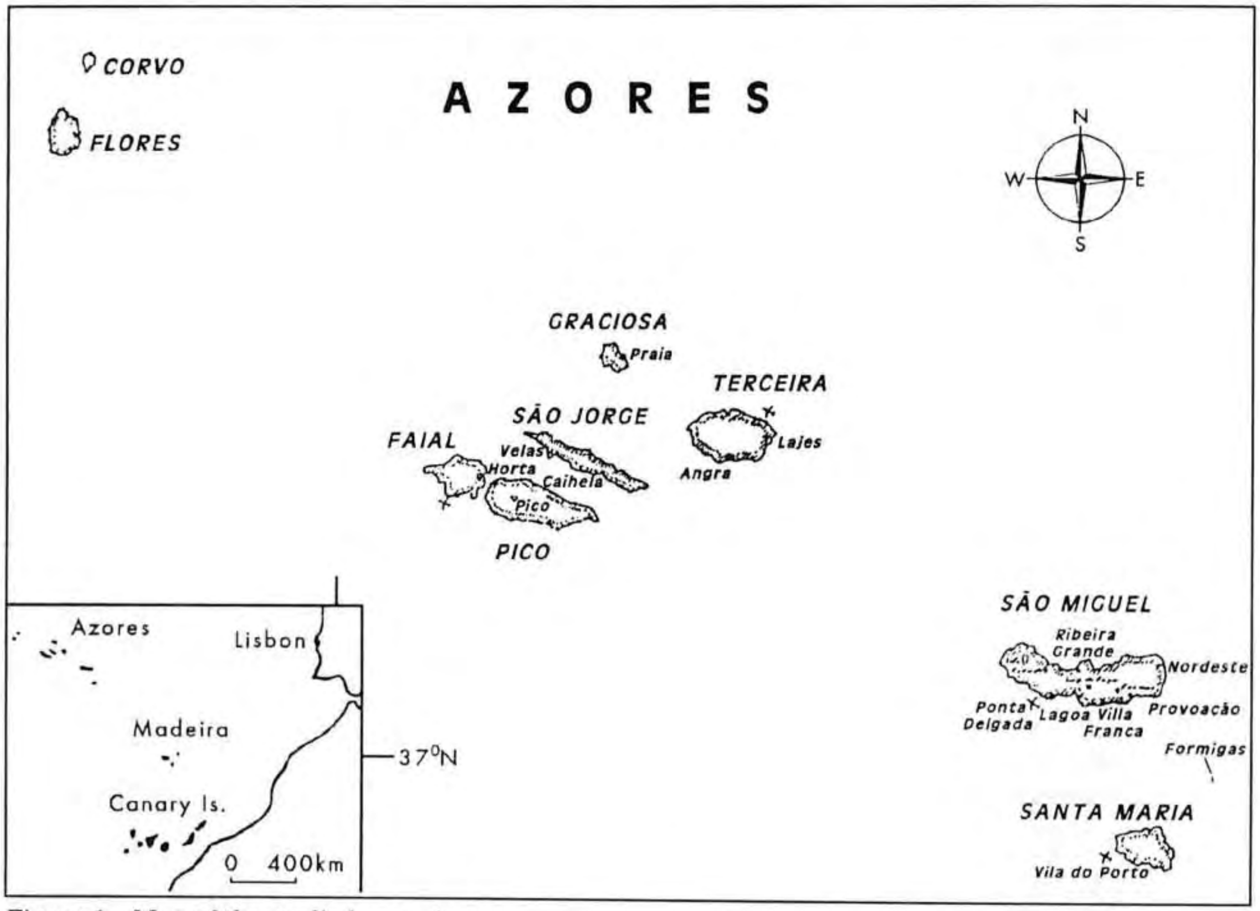

Figure 1—Map of the studied area, Azores.

All the information concerning the longitude, latitude, area, maximum altitude, and geological age of each island are given in Table I.

Age and Origin of the Islands

All of the islands have a volcanic origin and there are many examples of historical volcanic eruptions

Island	Long.(W)	Lat.(N)	Area (km^2)	Altitude (m)	Age (million years)		
					A	B	C
Corvo	30.8	39.7	17	718	?	?	?
Flores	30.9	39.4	142	915	0.010	0.62(2.9)	1.8
Faial	28.5	38.6	172	1,043	2.6	0.73	0.73
Pico	28.2	38.5	433	2,351	1.1	0.037	0.037
Graciosa	27.8	39.1	62	402	0.62	0.62	2.5
São Jorge	27.9	38.7	246	1,053	2	0.55	0.55
Terceira	27.2	38.7	402	1,023	2	0.30	2
São Miguel	25.5	37.7	757	1,103	4	4.01	4.01
Santa Maria	25.1	36.9	97	587	8	8.12	8.12

Table I—Comparison of the physical characteristics of the nine Azorian islands.
A = Forjaz (pers. comm.); B = Abdel-Monem et al. *(1975), Feraud* et al. *(1980); C = Queiroz (1990)*

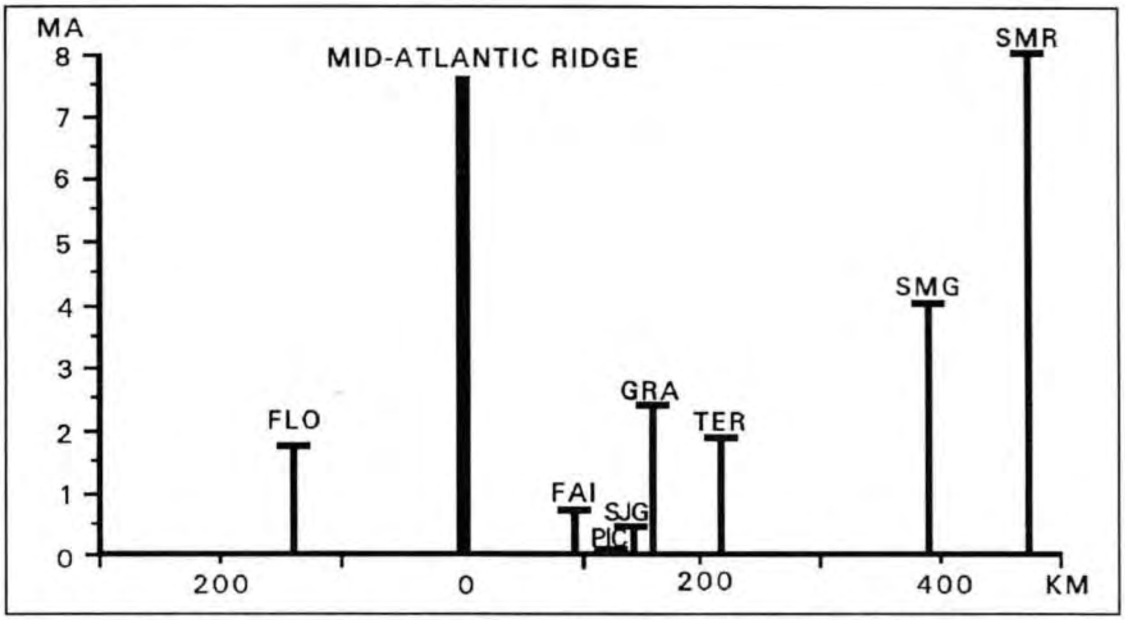

Figure 2 – Relation between the age of each of the Azorean islands and the Middle Dorsal Atlantic. The geological ages are those proposed by Queiroz (1990) (Modified from Borges, 1991).

(see Weston, 1964). The geological age of the nine islands is very dissimilar. Since their formation took a long period of time, these islands present a recent volcanic morphology (e.g., Pico) or a more eroded, ancient formations (e.g., Flores and Santa Maria). There are several studies concerning the geological dating of the Azorean islands, but unfortunately there is no agreement on the age of some islands.

Three alternatives are proposed: one following Forjaz (pers. comm.) (column A), another with the results obtained by Abdel-Monem *et al.* (1975) and Feraud *et al.* (1980) (column B) with the K/Ar method, and finally one following Queiroz (1990) (column C). This last author follows, in part, Abdel-Monem *et al.* (*op. cit.*) and Feraud *et al.* (*op. cit.*) but also other recent studies (e.g., Forjaz, 1986b; White *et al.*, 1976; Azevedo *et al.*, 1986, all in Queiroz, *op. cit.*).

In Figure 2 we present the data of Queiroz (1990) in a graphical way. The age of the different islands of the archipelago is not positively correlated with their distance to the Middle Dorsal Atlantic (Feraud *et al.*, 1980). The same could be inferred from the ages proposed by Forjaz (pers. comm.) or Abdel-Monem *et al.*, (1975)/Feraud *et al.*, (1980).

As we can see from Table 1, different ages have been proposed for some islands, but nevertheless the eastern group is the older one, with 8.12 million years (Santa Maria) (Abdel-Monem *et al.*, 1975), coming from the middle of the Miocene. Serughetti and Roche (1968) (in Ryall *et al.*, 1983) propose about 2.9 million years of age for Flores (Column B, Table 1), but Azevedo *et al.* (1986) (in Queiroz, *op. cit.*) estimates the age of this island at 1.8 million years. The central group is the youngest one.

We would also like to point out that the geological datings of the Azorean islands are far from being considered totally correct, mainly because the geological samples dated were probably not taken from the older stratigraphic layers (Nunes, pers. comm.).

The western part of each Azorean island is, geologically, the most recent one. This is connected with the seismo-volcanic mechanisms of this archipelago (Forjaz, pers. comm.), which is important because the occurrence and distribution of the Azorean lava tubes are somewhat related to recent lava flows (see below).

Speleological Studies in the Azores

The earliest reference concerning the occurrence of caves in the Azores is difficult to establish. Probably the work of Fouque (1873) – who briefly discussed lava tubes and pit caves on Terceira, Pico, and Graciosa – is one of the first. However, before his work, Webster (1821) mentioned caves

in and near Ponta Delgada (São Miguel). Later, Pickering (1908) gave a follow-up on Fouque's exploration of the large pit Furna da Caldeira da Graciosa (Furna do Enxofre) on Graciosa Island.

The earliest speleological study recorded from the archipelago was made by Forjaz (1963) with a fine description and sketch of Furna de Henrique Maciel (Pico). Unfortunately the map of the cave is not presented. Recently (May 1990) two French speleologists (P. Brunet and C. Thomas) accompanied by one of us (A. Silva) made a map of this interesting cave (unpublished).

In 1966, a work of the Portuguese group Mocidade Portuguesa – Centro de Instrução Especial de Espeleologia – describes the cave of Pau Velho (Gruta dos Balcões) (Terceira) with an incomplete map. This map was reproduced later by Halliday (1980). In 1967 Os Montanheiros made a fine map of this cave, later completed by Montserrat and Romero (1983) (see below).

Mottet (1970, 1972, 1974) presented some data on the geomorphology of some caves from Terceira (e.g., Gruta das Agulhas, Gruta do Natal, Gruta dos Balcões), but no maps are available.

Arruda (1972) studied and described some caves and pits from Pico: Furna Abrigo, Furna de Henrique Maciel II, Furna de Manuel José Lima, and Algar do Alto do Morais. Although the maps of the Algar do Alto do Morais and Furna de Manuel José Lima are probably incomplete, this author presents a fine map of Furna Abrigo.

The American speleologist, W. R. Halliday, (see Halliday, 1980 and also Anonymous , 1978) visited the Azores in April 1980 and worked out the first checklist of the Azorean caves and pits (Halliday, 1981). He listed the following caves and pits: Corvo (0;0), Flores (0;0), Faial(0;0), Pico (2;2), Graciosa (1;1), São Jorge (1;2), Terceira (11;2), São Miguel (3;0) and Santa Maria (0;0) (see also Table II). In these works we can find some sketches of the caves and pits but no impressive maps were presented. Some of these sketches (e. g., Algar do Carvão , G. dos Montanheiros) were put at the disposal of W. Halliday by Os Montanheiros.

Authors	Caves	Pits	Total
Halliday (1981)	18	7	25
Ogawa (1989)	35	7	42
The Authors	88	24	112

Table II – Evolution of the knowledge of the number of caves and pits from the Azores.

The first complete maps of the Azorean caves were presented by Montserrat and Romero (1983). Three lava tubes (Balcões, Pau Velho, Natal) are described and mapped and one lava tube (Agulhas) and one pit (Algar do Carvão) from Terceira are described by these authors. More recently Chinchon *et al.* (in press) presents further studies on Gruta dos Balcões, now the best studied lava tube in the whole archipelago.

Recently, Hayes and Braga (unpublished) presented at the 5th International Symposium on Vulcanospeleology (Japan, 1988) the first checklist of caves and pits from São Miguel.

Two biospeleological expeditions were carried out in the Azores directed by N.P. Ashmole (Edinburgh University) and P. Oromí (La Laguna University). These expeditions were supported by the National Geographic Society, USA, in July through August 1987 and 1989 (the latter also with the participation of one of us P. Borges)(see Oromí *et al*, in press; Oromí and Borges, in press; Borges and Oromí, in press). Oromí *et al.*(*op. cit.*) presented the description of the biologically studied caves during the first of these expeditions (July through August 1987).

The most recent catalogue of the Azorean caves and pits was made by Ogawa (1989) (Table II), listing 35 caves and 7 pits. Since then, several speleological expeditions have been made in the Azorean islands by the Terceira (Azores) Os Montanheiros speleological group.

For a long period of time (1963 to 1987) the activity of Os Montanheiros had a recreation and tourist orientation, but also some speleological studies were made during several expeditions in the Azores:

1963 to 1976 – Several speleological visits were made to Graciosa, directed by A. Luís and R. Azevedo. The results of these visits are presented in Table III;

1967 – A speleological expedition directed by A. Luís to Pico. Two caves were visited (Gruta do Henrique Maciel and Furna Frei Matias);

1972 – A speleological expedition directed by A. Luís to São Jorge. As the main results of this visit, several sketches were made of the lava tubes Gruta da Beira and Gruta do Leão and the pit Bocas do Fogo. All of them were revisited and completely mapped (see Plates 5, 6, and 7) in recent expeditions of Os Montanheiros (see below, S. Jorge-88 and Montoso-90);

1975 – A speleological expedition directed by A. Luís to Flores and Corvo. No caves were found on these islands;

1976 – A speleological expedition directed by R. Azevedo to Pico. The lava tube, Gruta dos Montanheiros was explored for the first time and an access ladder was built;

1978 – A speleological expedition directed by A. Silva to São Miguel. Several lava tubes and pits were explored (e.g., Gruta do Esqueleto, Gruta da Rua do Carvão, Algar da Batalha).

However, some of the works cited before (e.g., Mottet, 1974; Halliday, 1980, 1981; Montserrat and Romero, 1983; Chinchon *et al.*, in press; Ogawa, 1989; Oromí *et al.*, in press; Oromí and Borges , in press; Borges and Oromí, in press) were possible only thanks to the kind assistance of Os Montanheiros during part of the field work. Only recently a scientific goal was adopted by Os Montanheiros. The present work is done by three members of this group.

During the last years Os Montanheiros organized or took part in several expeditions to the islands of Flores, Faial, Pico, Graciosa, São Jorge, São Miguel, and Santa Maria (also the local island, Terceira). They have explored and mapped over 10,000 meters of caves and 400 meters of pits. The expeditions were:

1988 – October 31 to November 11, **S. JORGE-88**, Speleological Expedition to the island of São Jorge;

1989 – May 21 to 26, **BIOSPEL-89**, Biospeleological Expedition to the island of Pico (Azores);

1989 – July 4 to 11, **FLORES-89**, Zoological Expedition of the University of Azores (Dept. of Biology);

1989 – October 10 to 14, **FAIAL-89**, Biospeleological Expedition to the island of Faial (Azores);

1990 – March 3 to 11 and 17 to 21, **BIOSPEL-9O**, Biospeleological Expedition to the island of Pico (Azores);

1990 – June 8 to 16, **ST. MARIA-90**, Zoological Expedition of the University of Azores (Dept. of Biology);

1990 – August 9 to 29, **BIOSPEL-90-S. MIGUEL**, Speleological Expedition to the island of São Miguel (Azores);

1990 – September ll to 15, **MONTOSO-90**, Speleological Expedition to the island of São Jorge;

1991 – March 28 to April 3, **TORRES-91**, Speleological Expedition to the island of Pico (Azores);

1991 – June 6 to ll, **ARCOSPEL-91**, Speleological Expedition to the island of Pico (Azores).

The aim of the present contribution is to present a commented checklist of all the known Azorean caves and pits (see Table III, below). A total of 19 new maps or sketches of lava tube caves, littoral caves, and pits are presented. Some remarks on the conservation of the caves and on their fauna are also made.

Checklist of the Azorean Caves and Pits

Table III is a revised catalogue of the Azorean caves and pits (following four pages). Unfortunately in some cases the data presented is incomplete (e.g., caves from Graciosa). It includes the main name and other common names of each cave and pit, their location, the known length or depth in meters, and the minimum-maximum height and width also in meters. We also present data related to the altitude (elevation) of the main entrance of each cave and pit and the UTM coordinates. Finally, in each case we state whether there are maps and studies of the fauna available.

The data from Graciosa Island presented in Table III should be viewed with caution because it is based on incomplete notes taken by A. Luís, J.M. Fagundes, and R. Azevedo between 1963 and 1976 (speleological visits of Os Montanheiros to Graciosa).

The following abbreviations are used on the maps:

a = mapped by Arruda (1972)

b = mapped by Montserrat and Romero (1983)

c = mapped by the French speleologists, P. Brunet and C. Thomas accompanied by one of us (A. Silva) (unpublished)

d = mapped by Os Montanheiros speleological group and by the Amigos dos Açores ecologist group during the Biospel-90-S. Miguel, Speleological Expedition to the island of São Miguel (Azores)

Mont = mapped by Os Montanheiros speleological group

Ogawa = mapped by Ogawa (1989)

Sketch = only a sketch, made by Os Montanheiros, is available.

We also use in Table III the symbols: ? = information not available and ?? = not confirmed.

Seven maps are presented (Figures 3 to 7) with the location of the lava tubes, littoral caves, pits, and the main lava flows (information based on Anonymous, 1980 a, b, and c) in seven of the nine Azorean islands. The notation is the same as that used in the Checklist (Table III). For the caves we use the symbol "*" and for the pits the symbol "0."

Island and No.	Main Name	Other Names	Location	Length/ Depth (m)	Height (m)	Width (m)	Elev. (m)	UTM	Map	Fauna
1. Corvo										
Lava Tubes										
1	Gruta do Corvo		?	?	?	?	?	?		
2. Flores										
	No Caves Known									
3. Faial										
Lava Tubes										
1	Furna das Anelares	Lombega	Lombega	35.5	0.7-4.0	1.4-2.5	80	3482/42663	Mont	yes
2	Gruta do Cabeço do Canto	Concheiros	Cabeço do Canto	21.4	0.3-5.10	0.5-7.5	346	3420/42740	Mont	yes
3	G. do Parque do Capelo		Parque do Capelo	55.3	0.35-1.50	0.4-3.40	300	3452/42727		
Pits										
4	Furna Ruim		Cabeço Verde	-55		20.6-73.1	565	3467/42722	Mont	yes
4. Pico										
Lava Tubes										
1	Furna da Areia	F. do J. Maria	Caminho do cais Mourato	?	?	?	?	?		
2	F. da Laje	F. da Ti'Adelina; F. do Ranheta	Lajido	?	?	?	10	3755/42688		
3	F. da Miragaia	F. do Chico	Miragaia do Norte	50	?	?	140	3720/42661		
4	F. das Casas		Lugar das Casas	?	?	?	20	3709/42685		
5	F. do Carregador	Algar do Barrela; F. dos Algares	Algares	20	2	?-6.0	330	3716/42641		
6	F. do Frei Matias		Estrada Nova (Longit.)	666	?-7.2	?-14.2	680	3735/42609	Mont	
7	F. do Henrique Maciel	F. do Estácio	Santo António	812>??	?-4.5	?-4.0	140	3825/42649	c	yes
8	F. do Poço Novo	D. do Germano; F. do Calote	Poço Novo (Near the seaside)	?	?	?	?	?		
9	F. do Poço Velho		Canada do Poço Velho	?	?	?	?	?		
10	F. do Tancaim	F. do Tanquinho; F. do Ranheta	Tambor (Mistério de St Luzia)	?	?	?	275	3731/42655		
11	F. dos Bodes		Cabeço-Chão	?	?	?	?	?		
12	F. dos Caldeirões		Canada dos Caldeirões, Bandeiras	?	?	?	110	3721/42668		
13	F. dos Mendonças		Canada da Travessa	?	?	?	?	?		
14	F. dos Montanheiros		Curral Queimado, Brejos	741	0.45-6.79	0.40-8.59	785	3831/42610	Mont	yes
15	F. D'Água	Bandeiras I; Bandeiras II F. dos Faustinos	Bandeiras (Mistério de St Luzia)	250+100	?-2.0	?-5.0	100	3738/42670		
16	F. Manuel José Lima		Santo António, Miragaia	52	0.5-5.0	?-6.0	140	3773/42670	a	
17	F. Nova I		Farrobo (Mistério de St Luzia)	270.1	0.75-4.0	1-2.50	230	3741/42658	Sketch	
18	F. Nova II		Farrobo (Mistério de St Luzia)	?	?	?	210	3741/42659		
19	Gruta da Barca		Estrada Marginal, Barca	?	?	?	0	3675/42670		

Island and No.	Main Name	Other Names	Location	Length/ Depth (m)	Height (m)	Width (m)	Elev. (m)	UTM	Map	Fauna
4. Pico (cont)										
Lava Tubes										
20	G. da Capucha	Agostinha; João Serafim	Canada da Capucha, Bandeiras	310.78	0.43-5.10	1.8-10.95	75	3730/42675	Mont	yes
21	G. das Torres		Cabeço Bravo, Creação Velha	3,350	0.50-15.0	1.1-22.0	300	3681/42618	Mont	yes
22	G. do Capitão-Mor		Cais do Pico	300	?	?	30	3850/42649	c	
23	G. do Galeão I		Panha do Galeão, S. Caetano	255.9/-7.0	3.0-16.0	2.0-10.0	100	3749/42545	Mont	
24	G. do Galeão II		P. do Galeão (Ringue) `	50	0.4-1.1	0.41-1.25	60	3748/42541	Sketch	
25	G. do Ruivo		Carregador	70	?	?	?	?		
26	G. do Soldão	Malha; Soldado; Moiro; Terra Tapada	Mistério da Silveira	1,150	0.40-5.96	0.43-5.39	10	3868/42526	Mont	yes
27	G. dos Arcos		Arcos (Mistério de St Luzia)	216.5	0.30-2.10	1.0-1.60	50	3778/42686	Sketch	yes
28	G. dos Esqueletos		Igreja de St Luzia	91	0.80-1.60	1.0-2.10	130	3780/42674	Sketch	yes
Pits										
29	Algar da Furna Abrigo		Pico do Pico	-39		10.0-13.0	1,200	3750/42598	a	
30	A. do Alto do Morais		Canada do Mato (Frei Matias)	65/-10		12.0-30.0	1,015	3755/42605	a	
31	A. do Cabeço Bravo		Cabeço Bravo (Creação Velha)	323/-28.5	4.5-9.0	1.8-15.0	400	3698/42611	Sketch	
32	A. do Cabeço da Negra		Campo Raso, Candelária	?/-15.0	?	?	75	3695/42562		
33	A. do Capitão	Tambor III	Tambor (Mistério de St Luzia)	?/-5.5	?	?	200	3731/42658	c	
34	A. do Lanchão	A. do Cadete; A. do Ti Alfredo	Banderias (Mistério de St Luzia)	40.5/-5.5	0.40-5.0	0.50-2.0	110	3721/42667	Sketch	
35	A. do Tambor	Cratera do Cabeço	Tambor (Mistério de St Luzia)	97.4/-31.5	1.0-3.5	1.20-7.40	244	3733/42657	Sketch	
36	A. do Vale da Nogueira		Vale da Nogueira	?	?	?	?	?		
5. Graciosa										
Lava Tubes										
1	Furna da Labarda		?	7.4	?	?-4.40	?	?		
2	F. da Maria Encantada	F. do Castelo	Cume da Caldeira	56.5	?-2.80	2.5-5.7	200	4151/43207		
3	F. do Anel		?	50.4	?	?-3.50	?	?		
4	F. do Canto		?	11.3	?	?-10.80	?	?		
5	F. do Cardo		?	15	?	?-2.20	?	?		
6	F. do Gato		?	11.0	?	?-6.60	?	?		
7	F. do Linheiro		?	8.2	?	?-10.0	?	?		
8	F. do Luís		?	12	?	?-9.0	?	?		
9	F. do Manuel de Ávila		?	14.7	?	?-8.10	?	?		
10	F. do Queimado		?	12.5	?	?	?	?		
11	F. dos Bolos		?	8	?	?-6.50	?	?		
12	F. D'Água		?	10.5	?	?	260	4148/43211		
13	F. Ferrada		?	3.4	?-6.20	?-8.10	?	?		

Island and No.	Main Name	Other Names	Location	Length/ Depth (m)	Height (m)	Width (m)	Elev. (m)	UTM	Map	Fauna
5. Graciosa (cont)										
Lava Tubes										
14	Galeria do Forninho		Luz	96	0.80-3.5	?-7.30	?	?		
15	Gruta da Canada das Furnas	Furna do Roque	Canada das Furnas	83	1.9-6.5	3.4-6.10	125	4148/43208		
16	G. do Bom Jesus		Bom Jesus	16	0.55-2.10	2.25-8.0	50	4115/43255	Mont	
Pits										
17	Furna do Enxofre		Caldeira da Graciosa	-42		100	137	4159/43199	Ogawa	
6. São Jorge										
Lava Tubes										
1	Furna das Pombas	G. do Cais da Urzelina	Urzelina	?	?	?	0	4029/42782		
2	F. do Poio	F. da Lagos de St Cristo	Fajã de St Cristo	?	?	?	25	4189/42758		
3	F. do Pombal	Mina D'Água	Pombal, Fenos, Manadas	?	?	?	510	4048/42769		
4	Gruta da Beira		Beira	183	2.50-10.0	2.50-15.0	275	3952/42839	Mont	yes
5	G. da Granja		Velas	?	?	?	?	3958/42817		
6	G. da Lomba do Gato		Gueimada, Velas	?	?	?	250	3967/42816		
7	G. do Leão		Presa do Leão, Velas	177	0.5-6	0.8-3	250	3964/42818	Mont	
Pits										
8	Algar das Bocas do Fogo	Bocas de St Amaro	Lixeira de St Amaro	55.3/-12.0		30.0-50.0	521	3982/42817	Mont	yes
9	A. do Montoso		Pico do Carvão	269/-137.5	9.0-50.0	9.0-70.0	784	4048/42791	Mont	
10	A. do Pico da Maria Pires		Pico da Maria Pires	?	?	?	663	4000/42814		
11	A. do Pico dos Suspiros I		Pico dos Suspiros	?	?	?	920	4049/42792		
12	A. do Pico dos Suspiros II		Pico dos Suspiros	?	?	?	920	4049/42792		
7. Terceira										
Lava Tubes										
1	Forna de St Maria		Cabrito, Porto Judeu	320	?	?	450	4841/42852		
2	F. do Cabrito		Cabrito, Porto Judeu	200	?	?	400	4841/42849		
3	F. D'Água		Cabrito, Porto Judeu	250	?	?	450	4843/42845		
4	Galeria da Ribeira Seca		Ribeira Seca	60	?	?	175	4918/42813		
5	Galeria Queimada	Cafua Velha	Biscoitos, Pau Velho	639.9>??	0.3-2.5	0.26-10.9	473	4768/42895	Mont	
6	Gruta Branca Opala		Biscoitos, Pau Velho	87.3	0.9-3.1	1.1-2.8	280	4781/42923		
7	G. da Achada		Biscoito das Fontinhas	169	0.25-2.40	1.5-4.0	310	4868/42870		
8	G. da Madre de Deus		Porto Martins	244	0.5-10.8	0.5-21.0	210	4940/42816	Mont	yes
9	G. das Agulhas	G. da Salga	Porto Judeu	250.5	0.5-5.4	1.2-4.5	5	4909/42775	Mont	yes
10	G. das Feiticeiras		Outeiro do Bogango	?	?	?	600	4724/42854		
11	G. das Mercês		Canada dos Marcos, Feteira	69	0.60-2.70	1.2-1.7	135	4869/42784		
12	G. de Santo António		Porto Martins	302.1	0.35-9.40	0.6-18.0	220	4936/42818		
13	G. do Caldeira		Biscoitos, Pau Velho	148	0.40-2.60	1.1-5.6	260	4774/42911		yes
14	G. do Camelo		Cabrito, Porto Judeu	255.87	0.30-3.80	1.7-11.3	465	4841/42850	Mont	

Island and No.	Main Name	Other Names	Location	Length/ Depth (m)	Height (m)	Width (m)	Elev. (m)	UTM	Map	Fauna
7. Terceira (cont)										
Lava Tubes										
15	G. do Chocolate		Biscoitos, Pau Velho	109.7	0.50-6.20	0.4-3.6	250	4781/42924	Mont	yes
16	G. do Coelho		Lagoa do Negro	186.7 ??	1.0-2.1	1.2-3.5	540	4764/42879		
17	G. do Natal	Galerias Negras; G. do Cavalo	Lagoda do Negro	389	0.50-7.0	0.8-12.0	540	4766/42878	b	
18	G. do Pau Velho	G. dos Principiantes	Biscoitos, Pau Velho	245.5	1.0-4.0	0.4-12.0	350	4778/42908	b	
19	G. do Zé Grande		Serretinha	31.61	0.40-2.10	1.9-3.8	125	4867/42781	Mont	
20	G. dos Balcões		Biscoitos, Pau Velho	2,713	0.30-6.0	0.25-7.0	390	4778/42906	b	yes
Pits										
21	Algar do Carvão		Algar do Carvão, Porto Judeu	120/-90	1.6-40	2.10-20.0	629	4810/42865	Mont	yes
22	A. do Funil		Biscoitos	-22		11.0-20.0	500	4778/42879		
23	A. do Mistério		Biscoitos	151/-12	0.50-2.10	0.5-2.4	545	4763/42877		
24	A. do Negro		Lagoa do Negro, Biscoitos	16/-5.5		16	540	4762/42876		
25	A. do Pico das Dez		Pico das Dez, St Barbara	60/-20	0.30-3.50	1.0-4.5	350	4698/42849		
26	A. do Pico Gaspar		P. Gaspar, Lagoda do Negro, Bis	8.5/-18		2.35	540	4764/42873	Sketch	
8. São Miguel										
Lava Tubes										
1	Gruta da Canada da Giesta		Pico da Pedra, Ribeira Grande	?	?	?	145	6228/41831		
2	G. da Quinta-Irene		Ribeirinha, Ribeira Grande	30	?	?-20.0	105	6329/41879		
3	G. da Rua do Carvão	Algar da Rua de Lisboa	Domingos Rebelo, P. Delgada	694.9	0.3-5.1	1.0-12.7	38	6159/41779	d	
4	G. da Rua do Paim	Algar da Rua do Paim; G. da Fábrica de Tabaco	Rua do Paim, P. Delgada	285.4	0.5-5.1	1.2-10.5	71	6158/41785	d	
5	G. das Arribanas		Arrifes, Serra Gorda	?	?	?	275	6153/41828		
6	G. das Escadinhas		Ribeirinha, Ribeira Grande	31.2	0.44-1.6	0.75-5.1	140	6331/41868	d	
7	Gruta de Água de Pau		Água de Pau	323.1	0.2-2.6	0.8-6.6	2	6295/41752	d	yes
8	G. do Esqueleto		Lagoa do Fogo, R. Grande	188.2	0.3-9.5	1-12.5	250	6311/41843	d	yes
9	G. do Pico da Cruz	Furno do Pico da Cruz	Pico da Cruz, Pico da Pedra	98.5	0.6-2.9	0.85-5.4	273	6217/41830	d	yes
10	G. do Pico do Enforcado		Capelas, Ponta Delgada	184.8	0.45-3.20	0.7-6.0	245	6160/41868	d	yes
Pits										
11	Algar da Batalha	Gruta da Batalha	Fajã de Cima, Ponta Delgada	51.9/-9.5	0.4-3.3	0.5-5.7	240	6198/41837	d	
12	A. da Merda	Gruta da Ribeirinha	Ribeirinha, Ribeira Grande	54.5/-5	0.9-2.5	?-3.7	150	6331/41870	d	
13	A. do Pico Queimado		Pico Queimado/Pico do Sapateiro	10/-37.3	12	1.6	250	6283/41830	d	yes
9. Santa Maria										
Littoral Caves										
1	Furna das Pombas	Furna Velha	Vila do Porto	337	0.5-14.5	0.4-12.5	0	6663/40900	Mont	yes
2	Furna dos Anjos		Anjos	117.85	0.65-8.6	0.44-11.2	10	6639/40969	Mont	yes
3	Gruta do Romeiro		Ilhéu do Romeiro de S Lourenço	?	?	?	40	6745/40947		

New Maps and Sketches of Some Azorean Caves and Pits

Herewith we present 13 new maps and 4 sketches of 12 lava tube caves, 2 littoral caves and 3 pits. A short characterization of each is presented. The four sketches (Gruta das Torres, Algar da Bocas do Fogo, Galeria Queimada and Gruta das Agulhas) will soon be published as maps.

Faial

1. Gruta Das Anelares (Gruta da Lombega) (Plate 1; Figure 3, lava tube 1)

Location: Lombega (Faial); Elev: 80 m; UTM: 3482/42663; Length: 35.5 m; Height: 0.70-4.00 m; Width: 1.40-2.50 m.

During the Torres 91 Expedition to the island of Pico Os Montanheiros had the opportunity to study and map a small lava tube at Lombega, Faial. Later named by us Furna das Anelares, because of the ring-like (*anel* in Portuguese) stalactites commonly dispersed all over the ceiling. This is a small lava tube with only one entrance, a skylight situated 3.40 meters above the ground.

The floor is of aa lava and the ceiling is completely covered with thin brown stalactites (blade like) and ring stalactites.

Fauna: During the visit to this cave we had the opportunity to collect some specimens of one interesting hypogean species. The species is probably the troglobitic *Cixius cavazoricus* Hoch (Homoptera, Fulgoroidea) described from Gruta do Cabeço do Canto (see below). They were collected on roots situated at the north part of the cave (see points 3 and 3' of the map, plate 1).

2. Gruta do Cabeço do Canto (Gruta dos Concheiros) (Plate 2; Figure 3, lava tube 2)

Location: Cabeço do Canto, Capelinhos (Faial); Elev: 346 m; UTM: 3425/42740. Length: 21.4 m; Height: 0.30-5.10 m; Width: 0.50-7.50 m.

During the Faial-89 Biospeleological Expedition to the island of Faial we had the opportunity to visit the Capelinhos area. On information from a local person we went to the Cabeço do Canto and found a small lava tube there. The entrance is covered with ashes of the Capelinhos eruption (1957-58) and the floor of the cave is covered with many collapsed rocks.

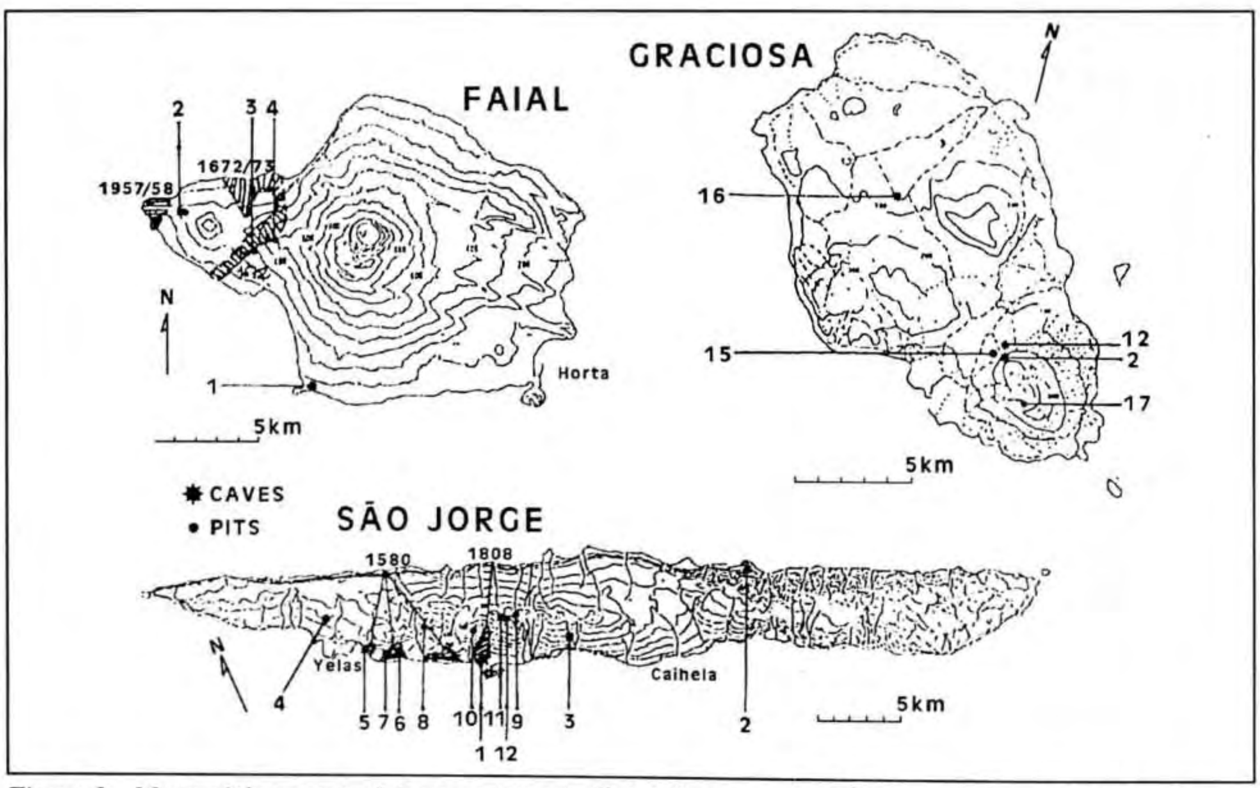

Figure 3—Maps of three central Azorean islands, Faial, Graciosa, and São Jorge, showing the location of the lava tubes and pits (see also Table 3).

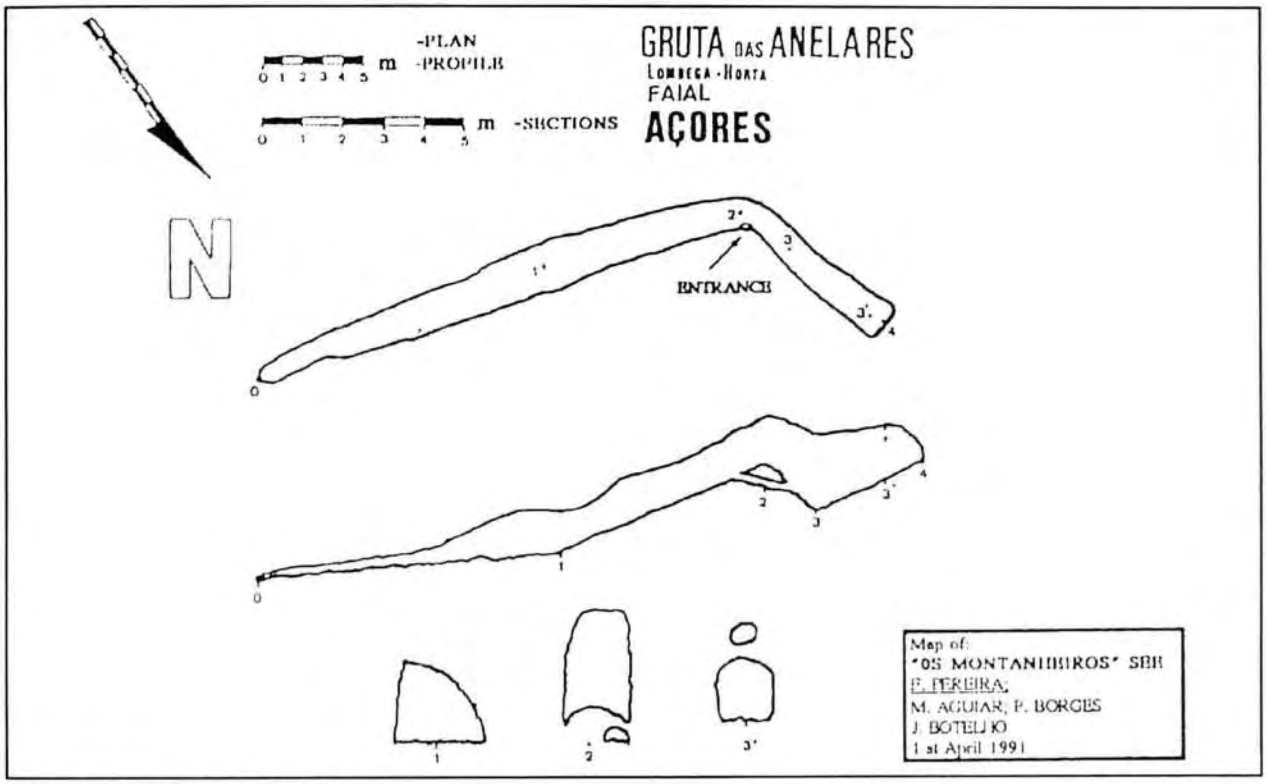

Plate 1 – Gruta das Anelares.

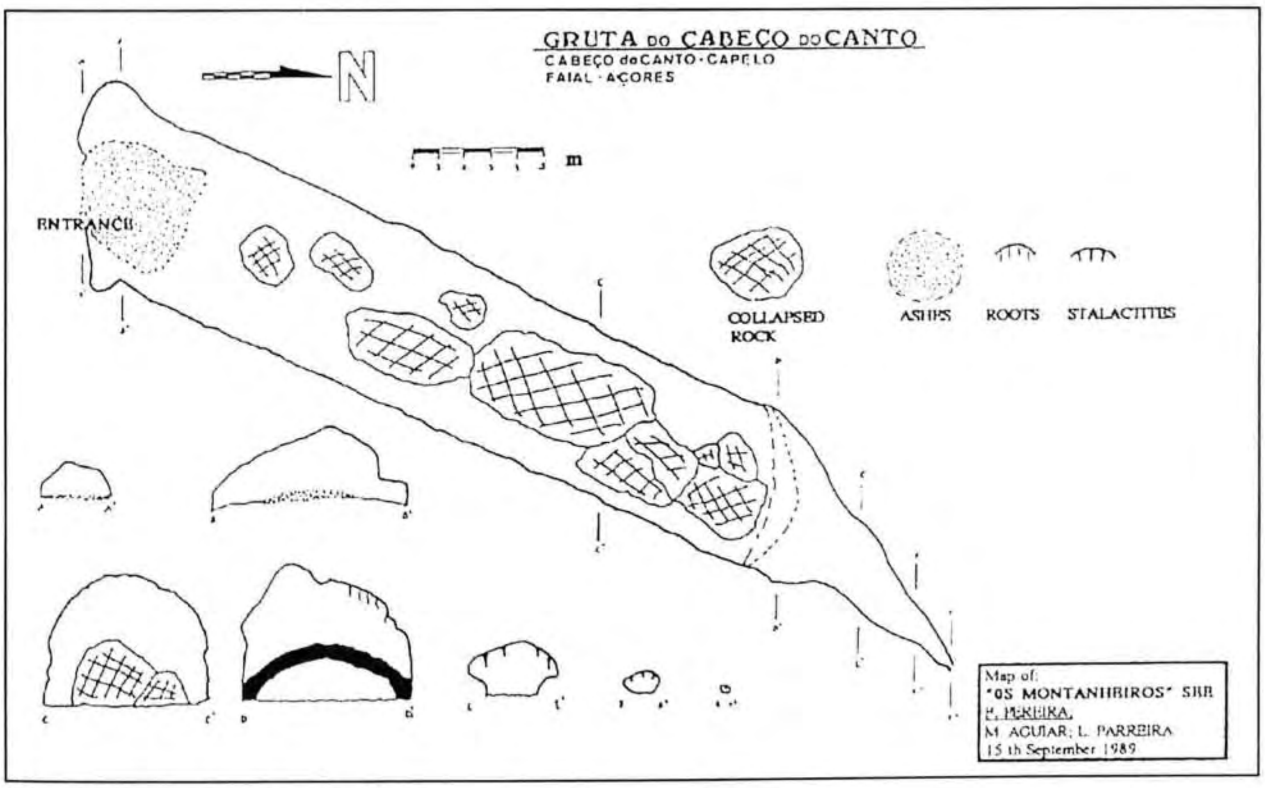

Plate 2 – Gruta do Cabeço do Canto.

There are two obvious levels of drainage shown on the double gallery at the end of the cave. In this part the upper level forms an arch (double ceiling) and the walls are reddish. Some small lava stalactites are present.

The Cabeço do Canto volcano is part of a recent complex of volcanoes aligned over a fracture line that connects the Caldeira do Faial and the Capelinhos Volcano.

Fauna: Recently Hoch (manuscript) described the troglobitic species *Cixius cavazoricus* Hoch (Homoptera, Fulgoroidea) with type specimens collected by us in this cave. The specimens were collected in roots situated in the north part of the cave (see sections D-D'and E-E' of the map). *Cixus cavazoricus* Hoch is a relict species, i.e., a cavernicolous species which has no close epigean relatives on the same, or neighboring islands (Hoch, *op. cit.*). Mainly to ensure survival of this organism, this cave should be protected.

Pico

3. Furna dos Montanheiros (Plate 3; Figure 4, lava tube 14)

Location: Curral Queimado, Brejos, Regional Road nº 3, km 17 (Pico); Elev: 785 m; UTM: 3831/42610; Length: 741 m; Height: 0.45-6.79 m; Width: 0.40-8.59 m.

The cave is a typical lava tube and was mapped during the Biospel-90 Biospeleological Expedition of Os Montanheiros.

The main entrance is a skylight situated 400 meters from the west part of the tube where another skylight (hornito) occurs. The access is a wooden staircase constructed by Os Montanheiros.

It is a unitary "throughway" system, with remarkable formations that make it one of the most interesting lava tubes in the Azores.

The floor of this volcanic tunnel is of aa or pahoehoe type. There are several levels of drainage registered on the walls by lateral benches (*bancadas*). The same occurs in the impressive lava tubes Gruta dos Balcões (Terceira) and Gruta das Torres (Pico) (see below).

The west part of the cave is the most interesting one with some notable formations on the floor, like a model lava tube at reduced scale that shows how a large lava tube can be formed. In this part of the cave the lava flow was oxidized by the entrance of air (due to the compression of gases), and as a

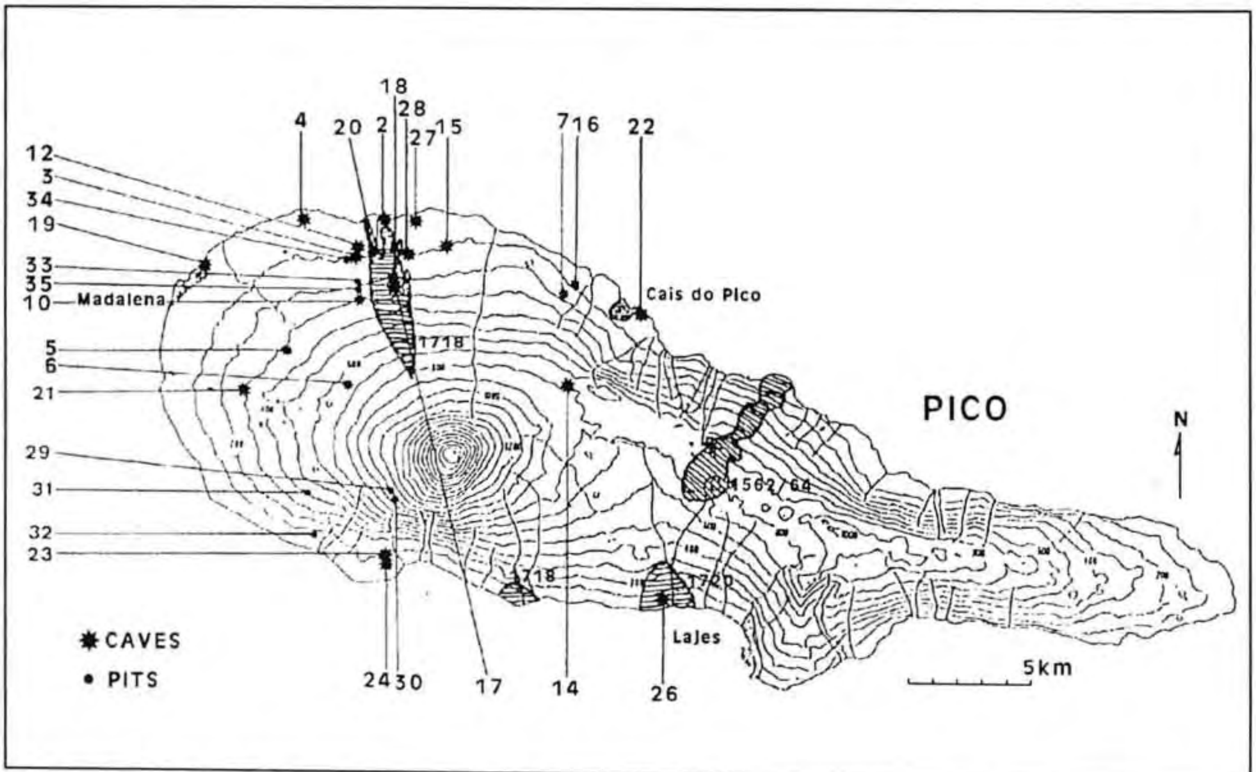

Figure 4—Map of Pico Island showing the location of the lava tubes and pits (see also Table 3).

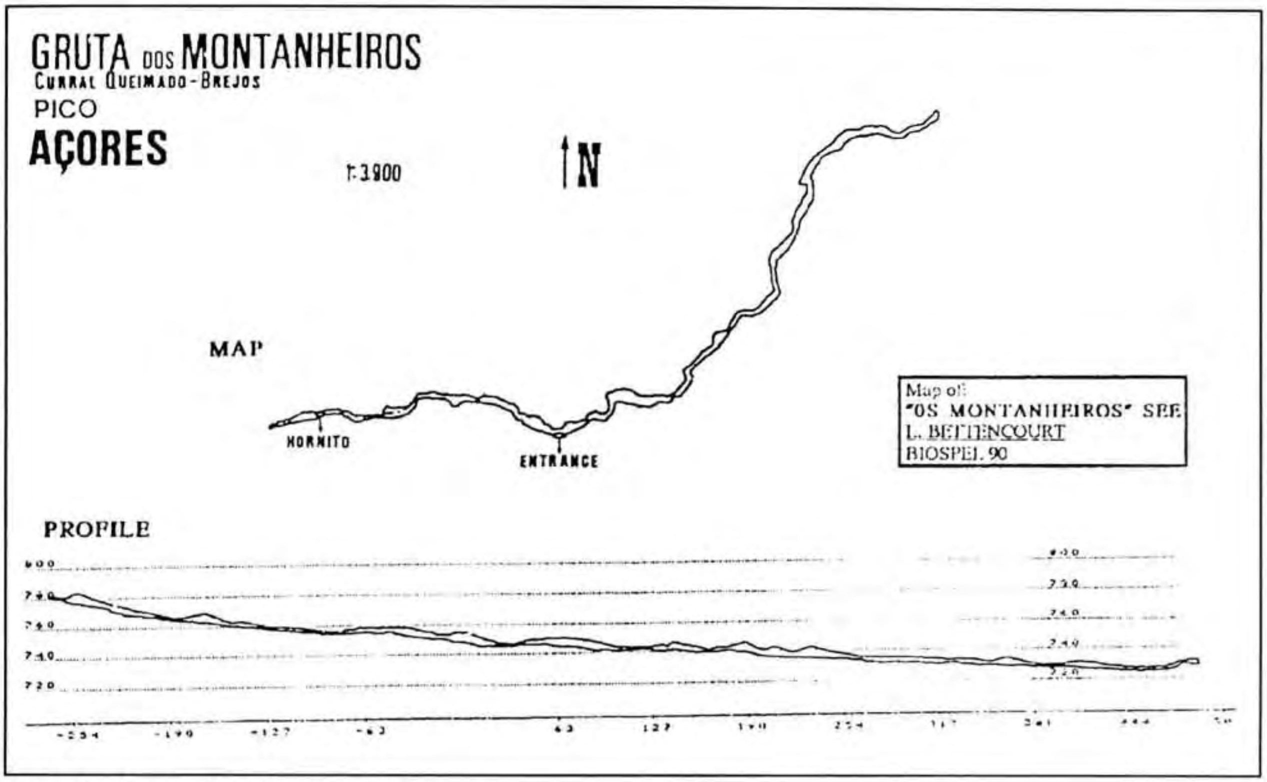

Plate 3 – Gruta dos Montanheiros.

consequence the rock is reddish. There are multiple levels. Fortunately the tube is well preserved with almost no collapsed rocks from the ceiling or walls.

In the north part of the tube there are some areas with collapsed rocks and in other parts we can find a collapsed rock covered by the lava flow. Several types of stalactites (lava-drops) cover the ceiling of all the cave.

Fauna: Biospeleologically this is one of the best studied caves in the Azores. As a consequence of the biospeleological expedition directed by N.P. Ashmole and P. Oromí (1987), a hypogean ground beetle was described, *Trechus picoensis* Machado (see Oromí *et al.*, 1990).

Later, another carabid species (present only in the skylight area of the cave) was described, Trechus montanheirorum Oromí and Borges (see Oromí and Borges, in press). The type specimens were collected during the former expedition and during the Biospel-89 and Biospel-90 Biospeleological Expeditions of Os Montanheiros. The origin and speciation of these two interesting Trechus species are discussed in Borges and Oromí (in press).

In this cave we also found two new species of Collembola, *Onychiurus* sp. and *Pseudosinella azorica* Gama, both with obvious adaptations to cave life (Oromí *et al.*, 1990).

Other species, common to other Pico caves (e.g., Soldão, Capucha, Arcos), could also be found in Gruta dos Montanheiros, like the undescribed *Cixus* sp. (see Hoch, in press) and the spider *Theridion pico* Merrett and Ashmole.

Speleologically and biologically Gruta dos Montanheiros is one of the most important caves of the Azores and should be protected.

4. Gruta das Torres (Plate 4; Figure 4, lava tube 21)

Location: Cabeço Bravo, Creação Velha (Pico); Elev: 200 m; UTM: 3681/42618; Length: 3,350 m; Height: 0.50-15.00 m; Width: 1.10-22.00 m.

This is now the most impressive volcanic lava tube in the Azores, with 3,350 meters mapped and more than 600 to 800 meters only visited for a total length of about 4,000 meters. In the list of the world's longest lava tubes revised (second revision) by Crawford (1979) the Gruta das Torres would occupy the seventh place. Gruta dos Balcões (Terceira) is now the second longest one in the Azores.

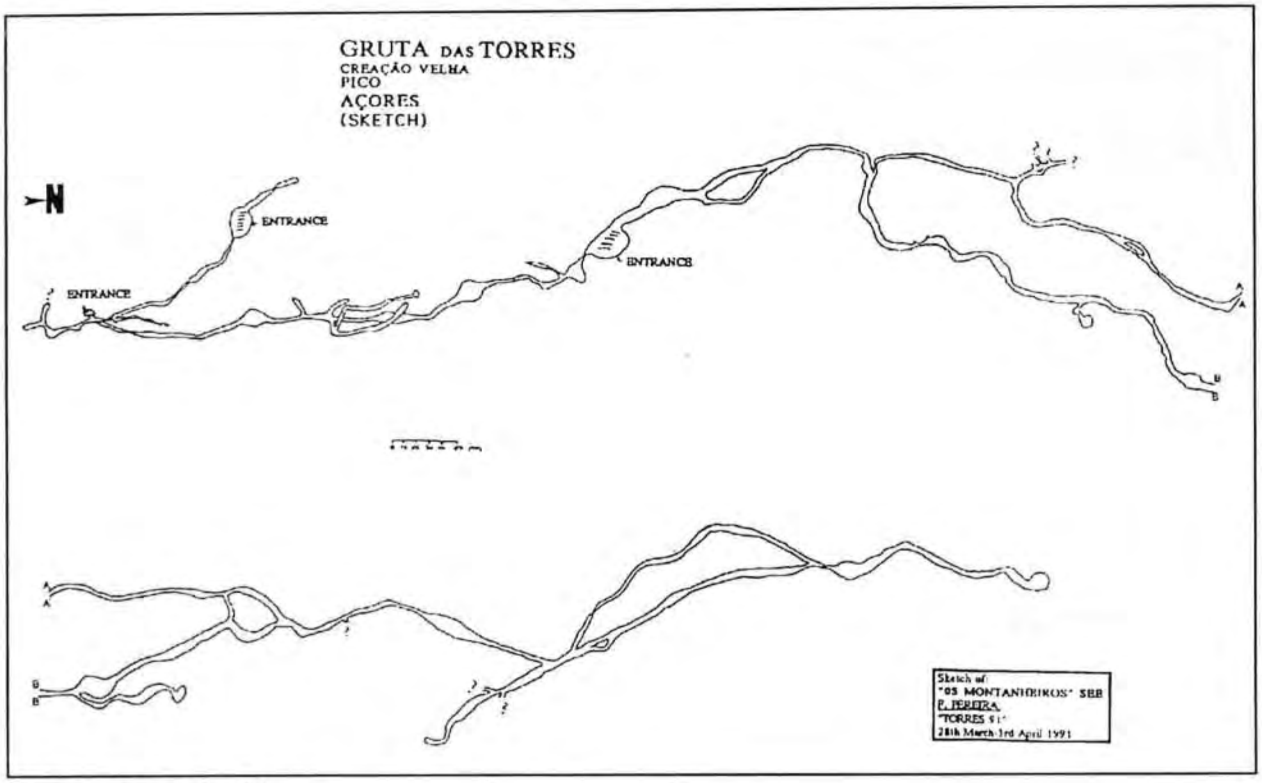

Plate 4—Gruta das Torres.

Between March 28 and April 3, 1991, a team of seven members of Os Montanheiros undertook a speleological expedition, Torres-91, to this magnificent cave, mapping and filming it.

The cave lies in lava fields of the northeast volcanic sector of Pico Mountain, southeast of Creação Velha.

It is a three-dimensional braided system with some remarkable formations. The floor is aa or pahoehoe type. There are at least 11 levels of drainage registered on the walls by lateral benches and three cornice levels. The height of 15 meters and the 11 drainage levels give an idea of the majesty of this lava tube cave.

This lava tube has two entrances, one, a skylight near one extremity, the other, 600 meters down, a large cone formed by the slumping of the roof. All over the main tube (about 2,500 meters in length) there are great blocks of lava collapsed from the roof making progress very difficult, but in some areas the floor is clean and of a beautiful pahoehoe lava or aa lava. In the main tunnel we can find some impressive lava gutters. The most interesting formations are in the secondary tunnels, some of them are unique. Sometimes there are very low crawlway passages.

Fauna: The undescribed *Cixius* sp. (see Hoch, *op. cit.*) was collected by us during the Torres-91 Speleological Expedition of Os Montanheiros to this cave. We have also put a set of pitfalls in the cave but the arthropods collected by these traps are still undetermined.

São Jorge

5. Gruta da Beira (Plates 5 and 6; Figure 3, lava tube 4)

Location: Beira (São Jorge); Elev: 275 m; UTM: 3952/42839; Length: 183 m; Height: 2.50-10.0 m; Width: 2.50-15.0 m.

This cave was mapped during the Speleological expedition of Os Montanheiros directed by A. Luís to São Jorge in 1972 and later revisited by the recent S. Jorge-88 Expedition of Os Montanheiros.

The cave is located in the Rosais Volcanic Complex, mainly with porphyric basalts. The lava tube has a north-northwest orientation, flowing to south-southwest at the sea direction.

The entrance, measuring ten by six meters, is a hollow in the collapsed roof of the cave. In the southern part of the tunnel there is a large room filled with earth. Several collapsed rocks from the

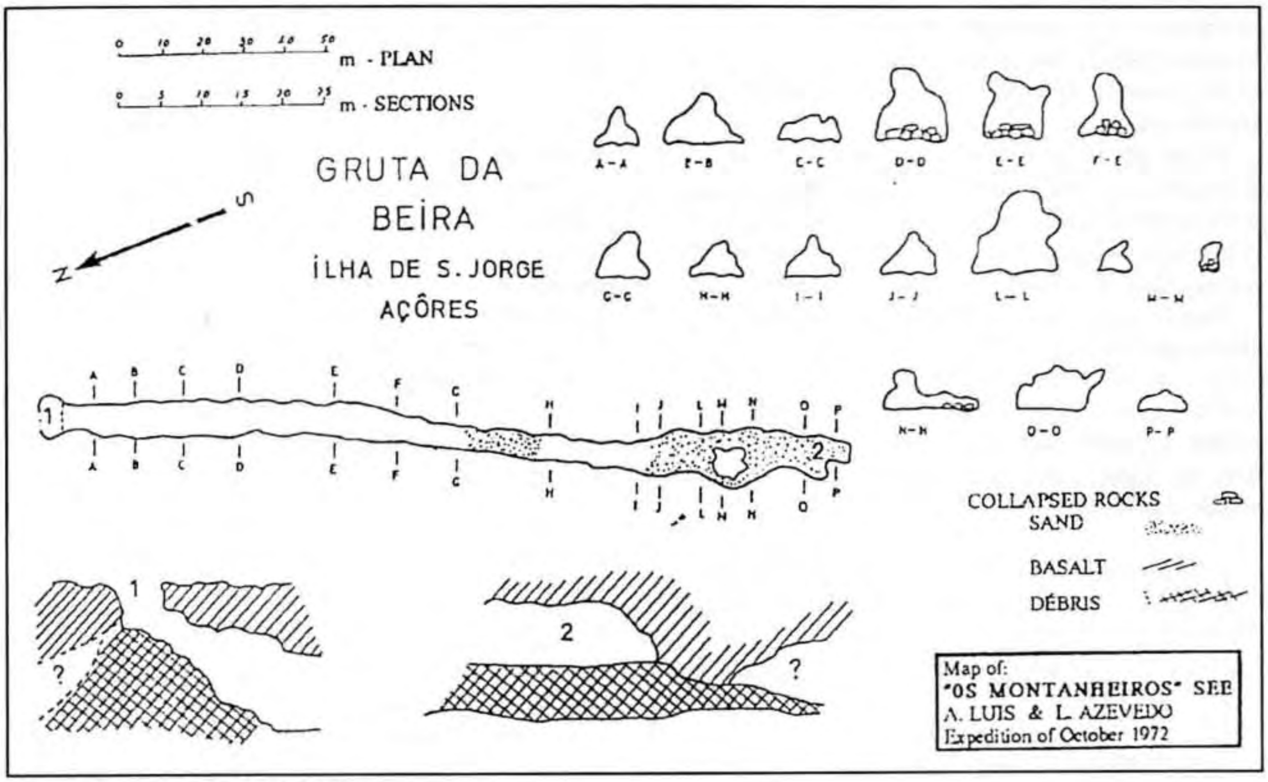

Plate 5 – Gruta da Beira (plan).

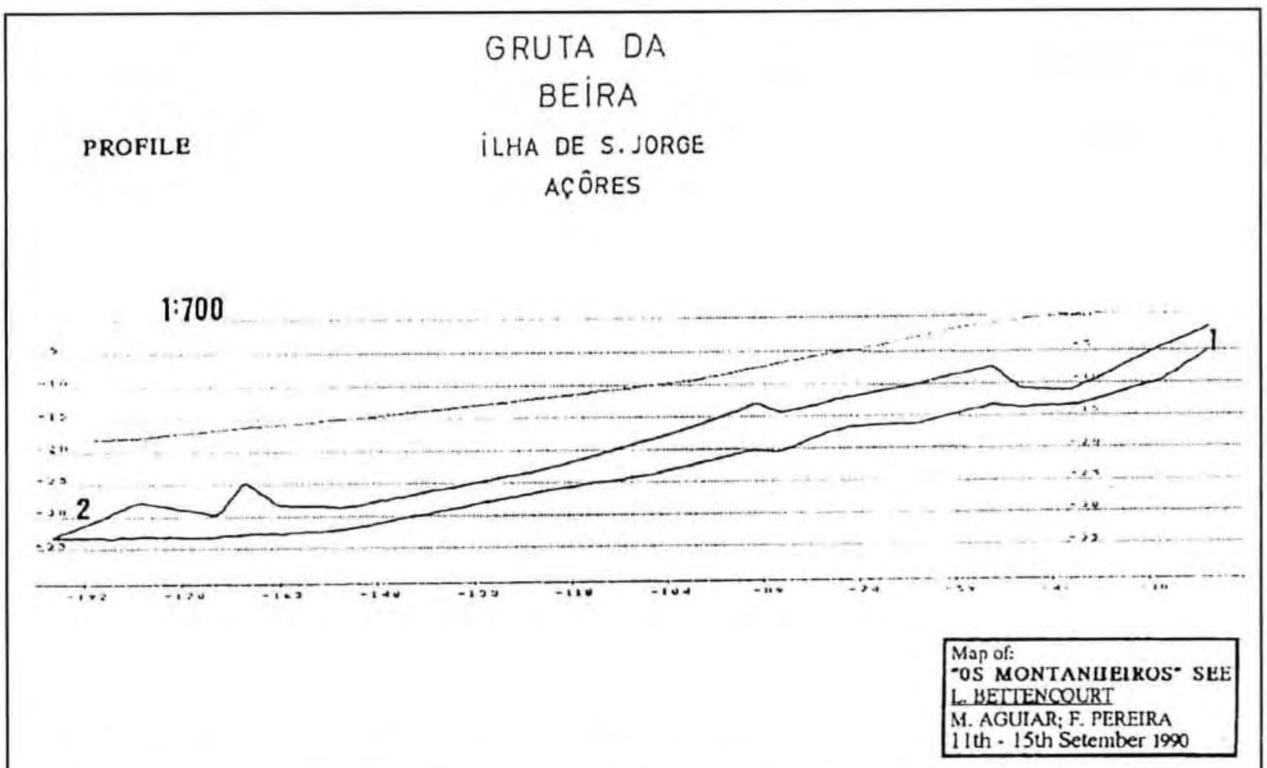

Plate 6 – Gruta da Beira (profile).

ceiling can be found all over the cave. The floor, and to some extent the lateral walls, are covered by earth, because of water infiltration from the roof and the entrance.

There are no lateral benches, but many stalactites can be found covered with a white substance similar to that found in Gruta das Agulhas (Terceira) (see below). Because of its dimensions and beauty, this lava tube should be protected.

Fauna: As a result of the biospeleological expedition directed by N.P. Ashmole and P. Oromí (1987), two troglobitic species were described from this lava tube, the pseudoscorpion Pseudoblothrus oromii Mahnert and an isopod (Trichonoscidae) Gen. sp. indet. that probably represents a new genus (see Oromí et al., 1990).

6. Gruta do Leão (Plate 7; Figure 3, lava tube 7)

Location: Presa do Leão (Queimada), Velas (São Jorge); Elev: 250 m; UTM: 3964/42818; Length: 177 m; Height: 0.50-6.00 m; Width: 0.80-3.00 m.

As with the previous cave, this lava tube was mapped during the speleological expedition to São Jorge of Os Montanheiros directed by A. Luís in 1972 and later revisited by the recent S. Jorge-88 Expedition of Os Montanheiros.

We think that this cave was formed by the lava flows of the eruption of 1808 (Bocas de St. Amaro). The entrance is a hollow, 0.6 by 0.4 meters, with a six-meter vertical drop. The gallery is narrow and high with a considerable slope. There are yellowish formations near the entrance, probably with the same composition as those present in the Algar das Bocas do Fogo (see below). Some collapsed rocks from the ceiling and walls are present.

Fauna: Unknown.

7. Algar das Bocas do Fogo (Bocas de St. Amaro) (Plate 8; Figure 3, pit 8)

Location: Lixeira de St. Amaro (São Jorge); Elev: 521 m; UTM: 3982/42817; Length: 55.3 m; Depth: 12.0 m; Width: 30.00-50.00 m.

This pit was mapped during the recent S. Jorge-88 Expedition of Os Montanheiros.

Algar das Bocas do Fogo is a volcanic crater in which the chimney has three openings that lead to a chamber of 30 by 50 meters. The best access is the larger opening with a drop of 40 meters. The 1808 eruption of St. Amaro originated at two openings with two lava flows.

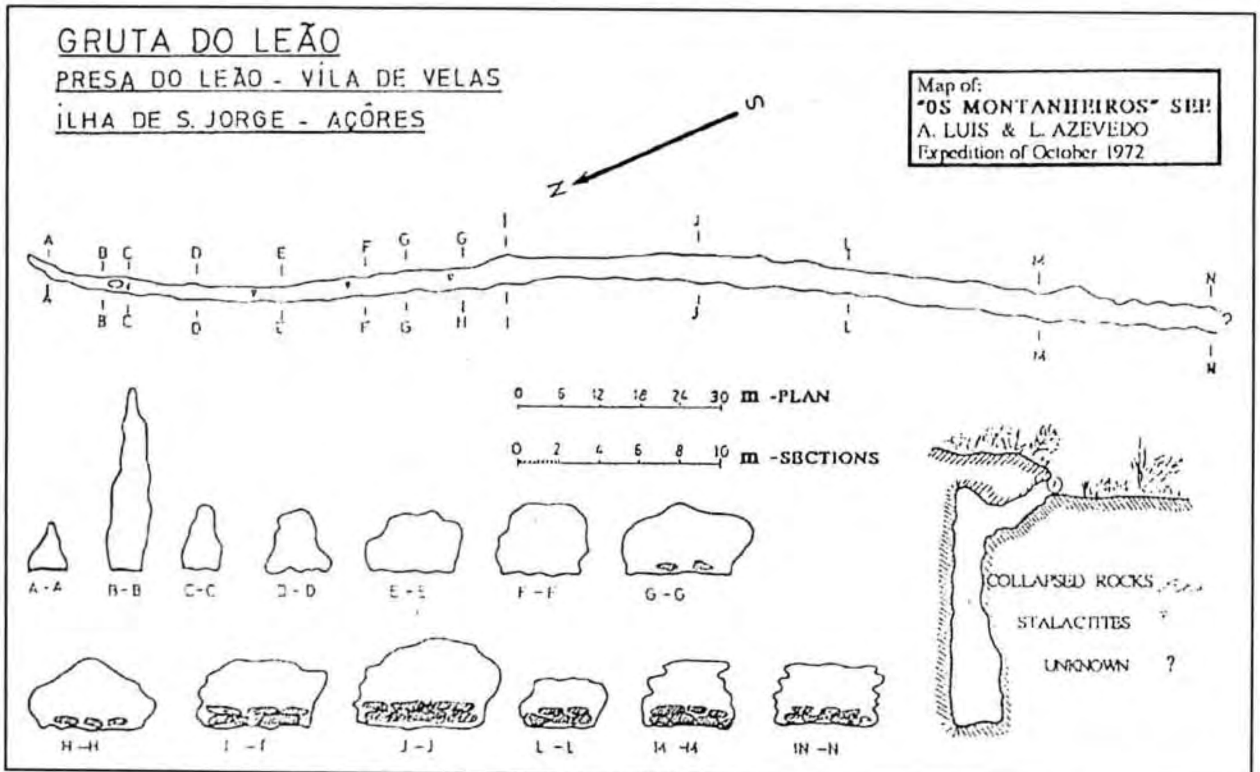

Plate 7—Gruta do Leão.

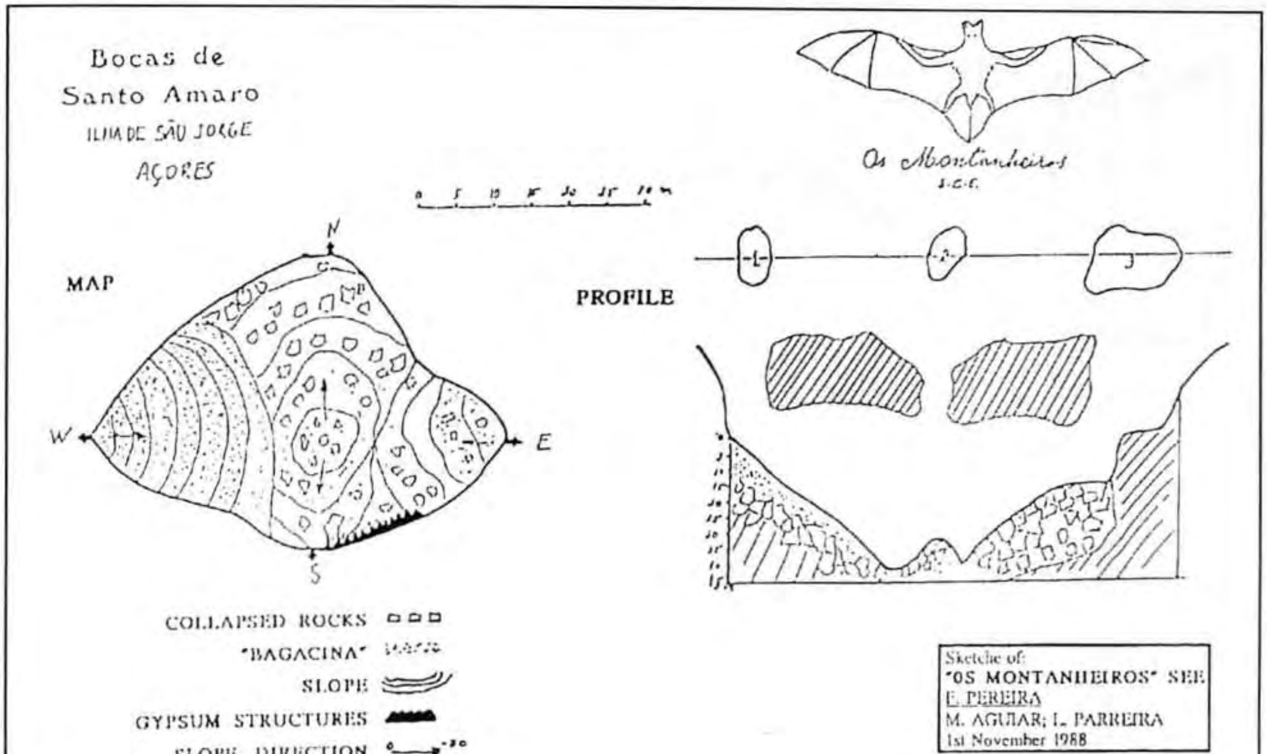

Plate 8 – Algar das Bocas do Fogo.

Due to the materials accumulated under the lateral openings, the floor has a "V" cross section. A small cone of volcanic materials is present under the central opening. The two lateral ramps are 30 and 20 meters long with a drop of 15 and 10 meters. On the walls of the south part of the crater there are some deposits of white gypsum.

Fauna: During the biospeleological expedition directed by N.P. Ashmole and P. Oromí (1989), a new species of a troglobitic ground beetle was found and described later, Trechus jorgensis Oromí and Borges. Unfortunately only a female is known.

8. Algar do Montoso (Plate 9; Figure 3, pit 9)

Location: Pico do Carvão (São Jorge); Elev: 1,019 m; UTM: 4048/42791; Length: 269 m; Depth: 137.5 m; Height: 9.00-50.00 m.; Width: 9.00-70.00 m.

This pit was mapped during the recent Montoso-90 Expedition of Os Montanheiros.

The Pico do Carvão is an extinct volcano with one crater and three openings – two of them closed and the third one open. This last volcanic chimney has three orifices (1, 2, and 3 from plate 8), the Algar do Montoso (named incorrectly by an error of toponymy, the correct name should be Algar do Carvão).

Of the three vertical pits, only the second and third (see plate 8) are used for vertical caving. Number 2 is more suitable, being formed by several terraces with a drop of 60 meters, ending in a large chamber of 150 by 70 meters (height 40 to 50 meters).

After reaching the bottom of pit number 2 the floor has a steep slope; a small lake covered by plant debris carried in by the rain water lies at one extremity. The ceiling and walls lost part of their cover because of the collapse of large basalt stones.

As in the Algar do Carvão (Terceira) (one of the most beautiful volcanic chimneys of the Azores), there are dripstone and flowstone formations on the walls, which are composed of obsidian or pitch-stone, as well as locally profuse silicious (SiO_2) speleothems.

Pit Number 1 has a vertical drop of 80 meters ending in a circular chamber measuring 50 by 30 meters. The assemblage resembles very well an inverted funnel.

Pit Number 3 is a small well, 20 meters deep, all covered by a reddish stone, typical of the hornitos, that ends in a "throat" without any passage.

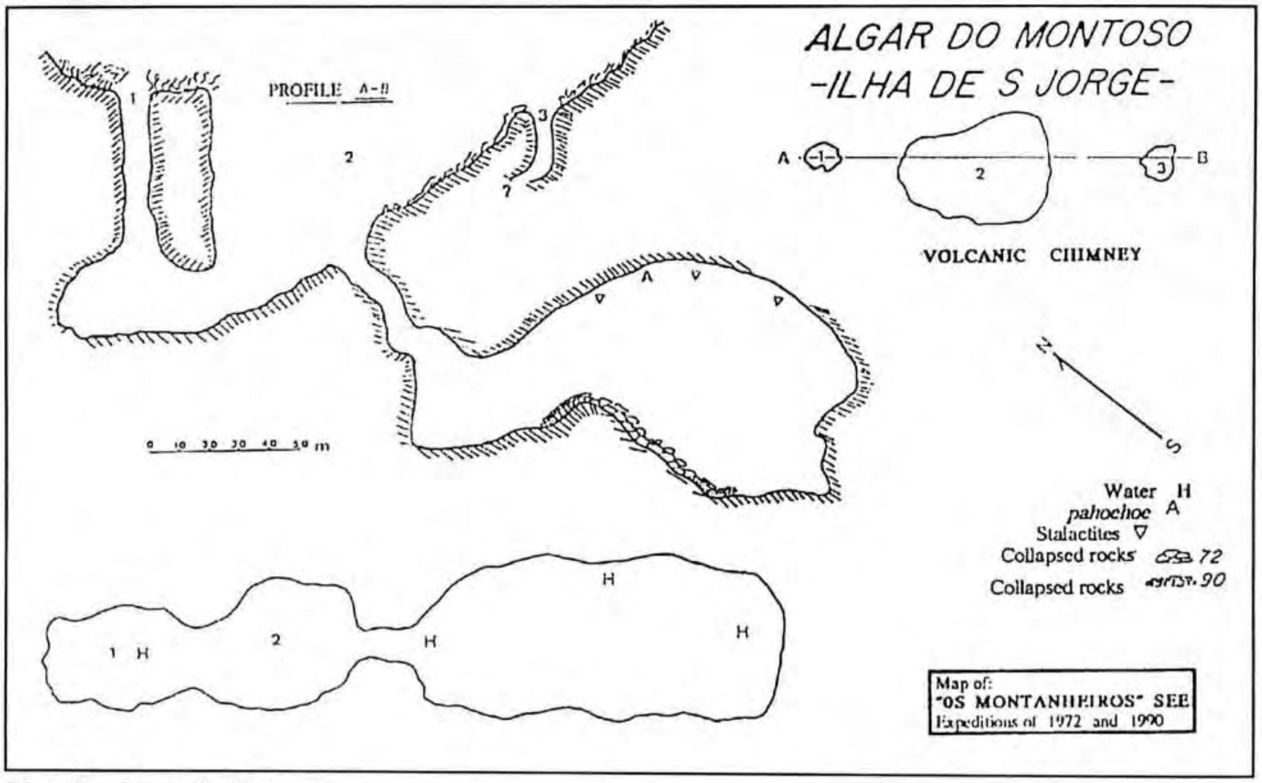

Plate 9—Algar do Montoso.

The Algar do Montoso is the Azores' deepest pit and could be developed as a show cave like Algar do Carvão (Terceira).

Fauna: Unknown.

Terceira

9. Galeria Queimada (Cafua Velha) (Plate 10; Figure 5, lava tube 5)

Location: Pau Velho, Biscoitos (Terceira); Elev: 473 m; UTM: 4768/42895; Length: 639.9 m; Height: 0.30-2.50 m; Width: 0.26-10.9 m.

The Galeria Queimada is located in the historical lava flow of Pau Velho (1761). Like the larger Gruta dos Balcões (situated in the same lava flow) it is a three-dimensionally braided system. It is a cave with some planimetric complexity and is not completely mapped (see ? in plate 10). It is the second biggest lava tube on Terceira and one of the most beautiful.

After the entrance, the broader part of the ceiling has a particular design, forming two large "teats" (*mamelones* from the Spanish). There are some unusually colorful limonite speleothems forming columns. Near the end of the main tube there is a beautiful structure of limonite forming a "waterfall." In the main tube the floor is mostly of aa lava, but in the narrow, low secondary tubes the floor is pahoehoe type. In several parts of the lava tube the floor is covered with mud and water. Polymorphic stalactites (lava-drops) occur on the ceiling, some of them being very interesting.

Fauna: Unknown.

10. Gruta das Agulhas (Gruta da Salga) (Plate 11; Figure 5, lava tube 8)

Location: Porto Judeu (Terceira); Elev: 5 m; UTM: 4909/42775; Length: 250.5 m; Height: 0.50-5.40 m; Width: 1.20-4.50 m.

This is a mildly braided lava tube cavern (Halliday, 1981) formed by lavas from the eruption of Pico do Refugo. It was studied especially by Mottet (1974) because of its outstanding sequence of flow features. The cave was named "Agulhas" (needle) because of its needle-like lava formations of vitrified silica (opal) about 0.2 to 0.5 centimeters long.

The main entrance is at sea level. The floor is aa or pahoehoe. There are at least four levels of drainage registered on the walls by lateral benches.

In the middle of the cave there is evidence of a false floor which shows where the lava has drained away leaving a small tube (30 meters long and 0.5

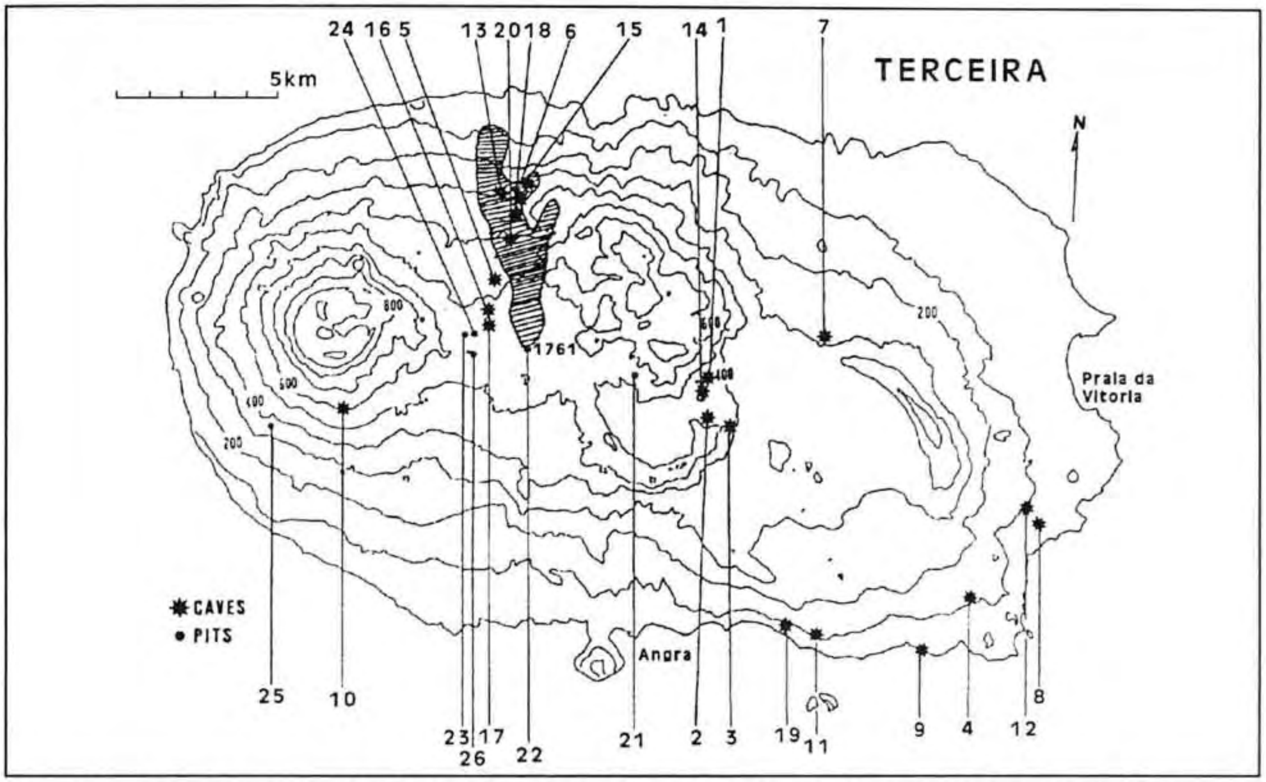

Figure 5—Map of Terceira Island showing the location of the lava tubes and pits (see also Table 3).

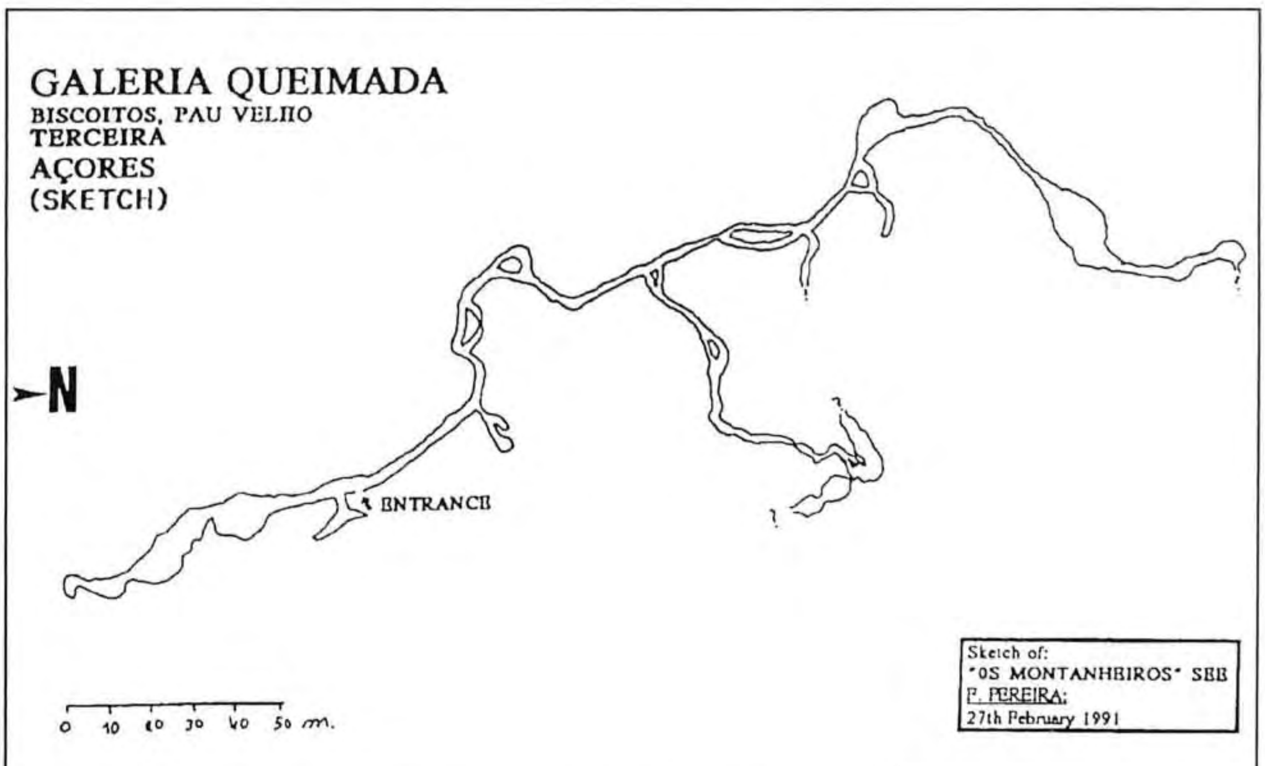

Plate 10—Galeria Queimada.

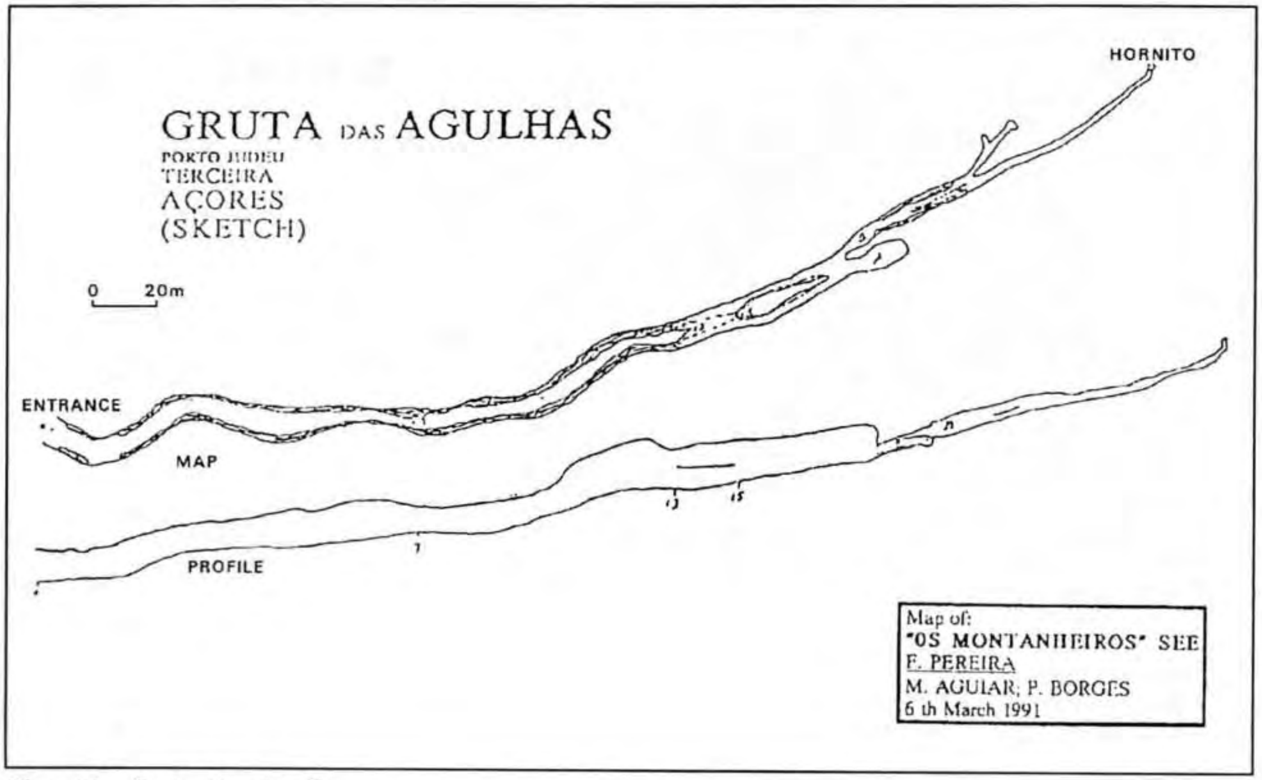

Plate 11 – Gruta das Agulhas.

to 1.2 meters high) inside the main lava tube. On the lateral walls there are oblique striated marks as a consequence of the accelerated escape of gases.

Fauna: As a consequence of the biospeleological expedition directed by N.P. Ashmole and P. Oromí (1987), several new interesting species were found and described from this cave: the hypogean Pseudoscorpion, *Pseudoblothrus vulcanus* Mahnert and the Amphipod (*Talitridae*), *Macarorchestia martini* Stock (*Macarorchestia* being a new genus) – its only cave adaptation is the small eyes (Stock, manuscript).

Three other hypogean species, not restricted to this cave, were also found: the collembola (*Entomobryidae*) *Pseudosinella ashmoleorum* Gama and *P. azorica* Gama (see Oromí *et al.*, 1990) and the centipede *Lithobius melanops orotavae* Latzel (see Eason and Ashmole, manuscript).

11. Gruta do Chocolate (Plate 12; Figure 5, lava tube 14)

Location: Pau Velho, Biscoitos (Terceira) Elev: 250 m; UTM: 4781/42924; Length: 109.7 m; Height: 0.50-6.20 m; Width: 0.40-3.60 m.

Gruta do Chocolate is a small but beautiful lava tube located in the Pau Velho lava flow (1761).

The entrance, a small aperture of 40 by 40 centimeters, is made through a secondary gallery which is partially obstructed by earth and roots. The first part of the cave has a reddish coloration up to one third of its height, probably as a consequence of oxidation.

We think that the occurrence of three superimposed tubes is a consequence of the bent tendency of the ground where the cave was formed. Therefore, the main gallery was subjected to several strangulations caused by materials that obstructed the flow of the lava. A new superimposed tube formed once the lava flowed again.

The first of the galleries is formed by a drainage tube through a hollow in the main "sink"type tube. It is a narrow, low tube with an aa type floor. The walls and ceiling are rich in remelt structures. There is also a formation (miniature of a lava tube) that shows how a lava tube can arise. Over the first gallery there is another, extending the main tube. A third gallery occurs over the second and reaches the cave entrance.

Forty meters upstream there is a large lava rock recovered by the lava flow. The passage at this site is difficult and has to be traversed by crawling over pahoehoe lava. Higher upstream there are yellow-

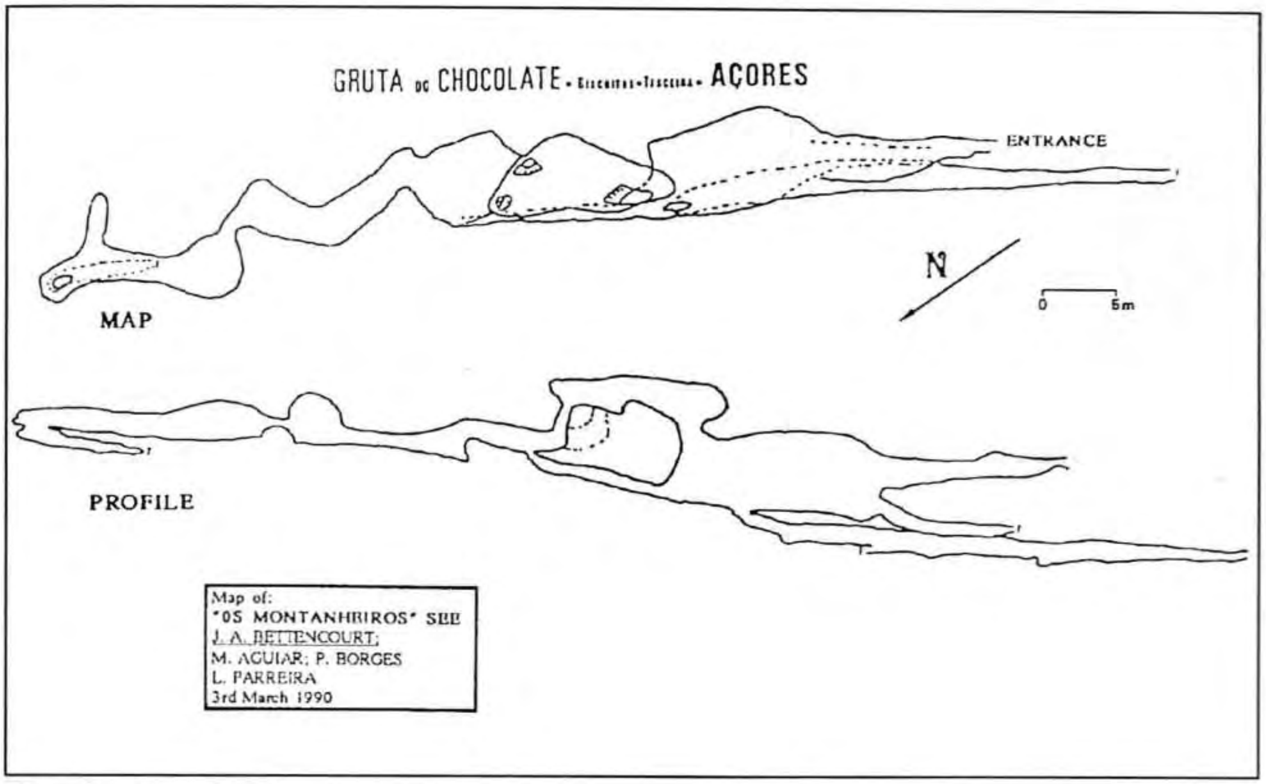

Plate 12 – Gruta do Chocolate.

ish formations, probably silica, covering the lava structures.

Fauna: Unknown.

São Miguel

12. Gruta de Água de Pau (Plate 13; Figure 6, lava tube 4)

Location: Água de Pau (São Miguel); Elev: 2 m; UTM: 6295/41752. Length: 323.1 m; Height: 0.20-2.60 m; Width: 0.80-6.60 m.

This lava tube was mapped during the recent Biospel-90-S. Miguel Expedition of Os Montanheiros.

This is a small, somewhat braided lava tube cave located only two meters above sea level and covered by some 70 meters of overburden (Oromí and Borges, in press). There are also two levels of galleries – a lateral entrance near the ceiling, 40 meters from the main entrance, being the access to the second gallery.

There are two main galleries that intercept each other. The main galleries have lateral benches in some parts, covered with rocks collapsed from the ceiling and walls. On the floor there are large blocks of lava. On the walls there are rod stalactites and blisters (remelting stalactites). The secondary gallery has very low passages and some crawlways. The floor is pahoehoe and the ceiling is covered by stalactites (lava-drops).

The tube is interrupted by a collapse of the roof. Before reaching this point another large amount of collapsed rocks makes progress very difficult.

Fauna: The fauna of this cave was studied during the biospeleological expedition directed by N.P. Ashmole and P. Oromí (1989). The general results of this study are still unpublished, but one troglobitic species of ground beetle collected in this cave was recently described, *Thalassophilus azoricus* Oromí and Borges (see Oromí and Borges, in press). The type material consisted of 14 specimens (10 of them collected by Borges in 1990), but two more individuals were collected by one of us (F. Pereira) during the Biospel-90-S. Miguel Speleological Expedition of Os Montanheiros to the island of São Miguel.

So far it is the only eyeless ground beetle known from the Azores; it is a relict and paleoendemic species (Borges and Oromí, in press).

This cave should be protected.

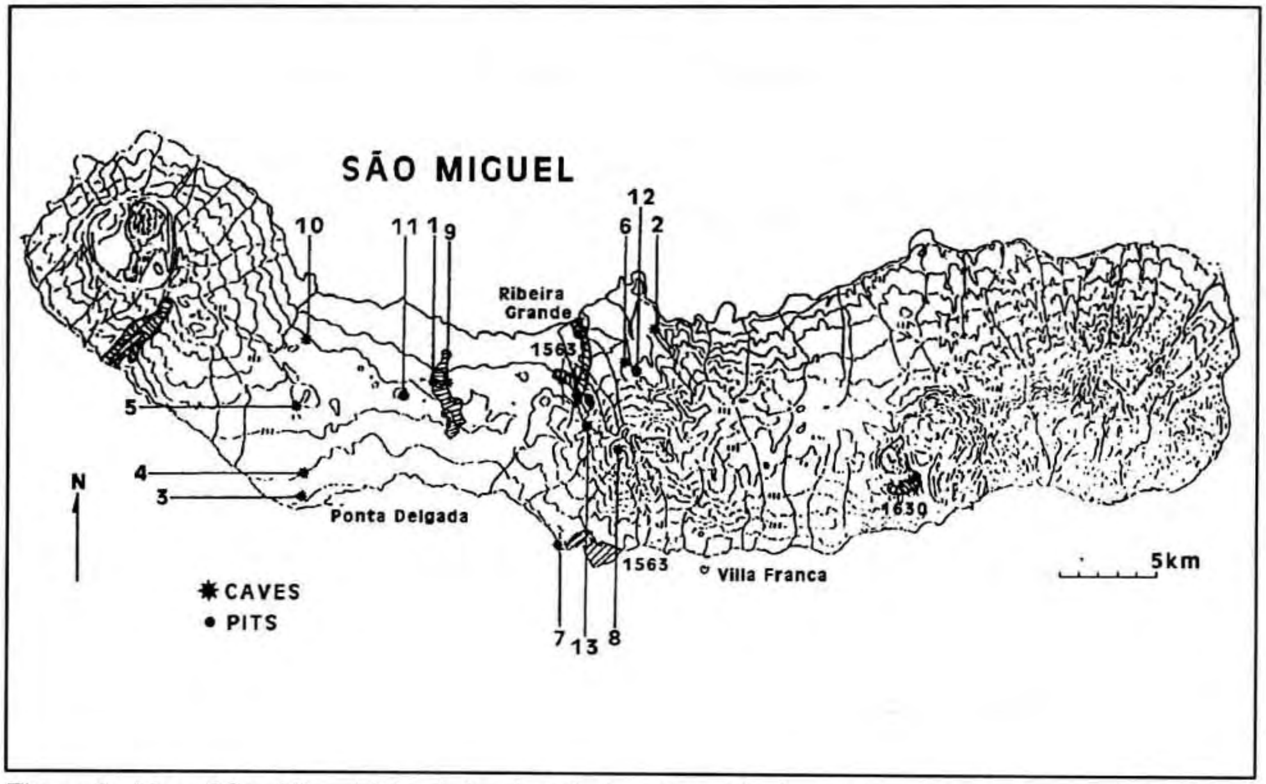

Figure 6—Map of São Miguel Island showing the location of the lava tubes and pits (see also Table 3)

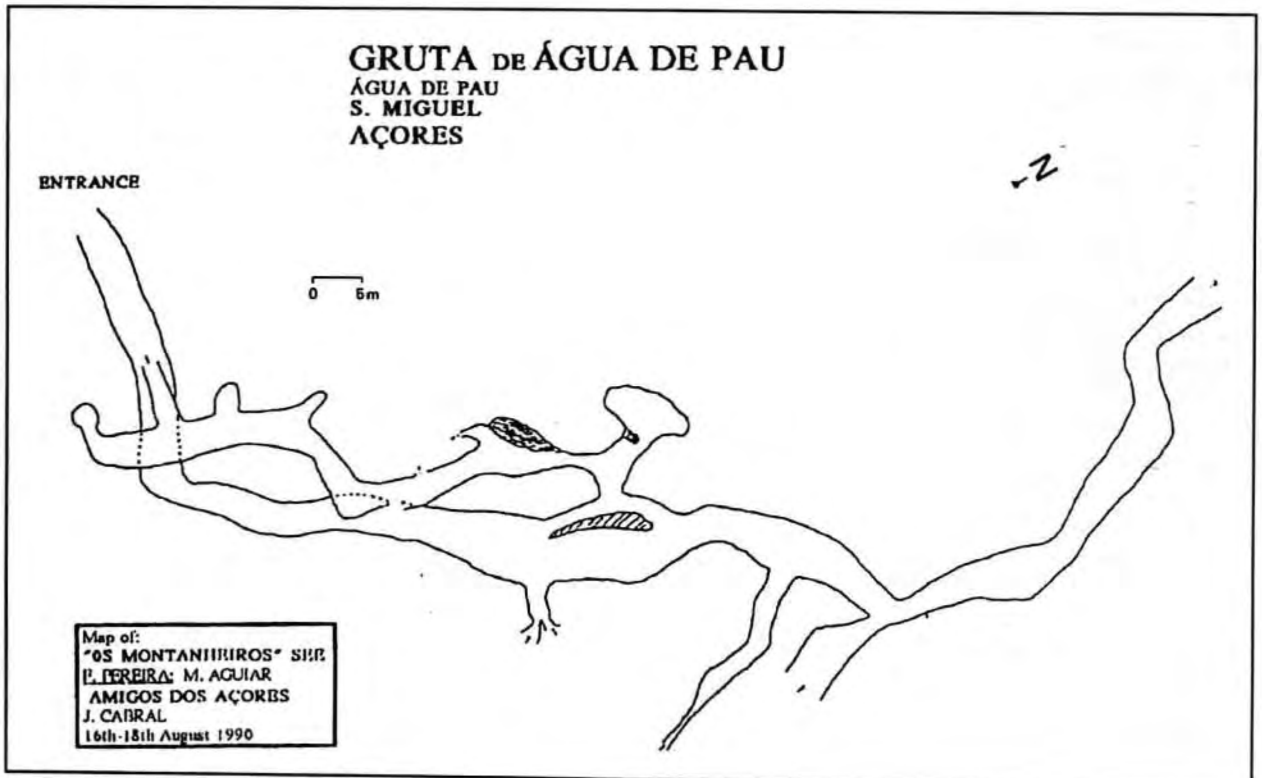

Plate 13—Gruta de Água de Pau.

13. Gruta do Esqueleto (Plate 14; Figure 6, lava tube 5)

Location: Lagoa do Fogo road, Ribeira Grande (São Miguel); Elev: 250 m; UTM: 6311/41843; Length: 188.2 m; Height: 0.30-9.50 m; Width: 1.00-12.50 m.

As with the previous one, this lava tube of large dimensions was mapped during the Biospel-90 S. Miguel Speleological Expedition of Os Montanheiros to the island of São Miguel.

It is located in the lava fields of the Serra de Água de Pau volcano. The entrance is a consequence of the collapse of a lateral part of the wall and roof at about 40 meters from the beginning of the lava tube.

The initial part of the cave, the largest one, is well preserved. There is a lid-type wall, probably the stopping point of a lava flow posterior to the tube formation. The walls have marks of several lava levels. In the ceiling there are many melt-stalactites.

Unfortunately the major part of the cave is very much spoiled. This is due to the collapse of great blocks of basalt from the ceiling and walls. Some vestiges of small stalactites and preliminary lava can still be seen. The tube ends with a collapse of the roof. Probably this cave was destroyed by earthquakes and the land movements they caused.

Fauna: A biospeleological expedition directed by N.P. Ashmole and P. Oromí (1989) visited this cave. The general results of this study are still unpublished.

14. Gruta do Pico da Cruz (Plate 15; Figure 6, lava tube 6)

Location: Pico da Cruz, Ponta Delgada(São Miguel; Elev: 273 m; UTM: 6217/41830; Length: 98.5 m; Height: 0.60-2.90 m; Width: 0.85-5.40 m.

This is a simple unitary or throughway lava tube (see Halliday and Larson, 1983) and was mapped during the Biospel-90 S. Miguel Speleological Expedition of Os Montanheiros to the island of São Miguel.

It is a narrow, low lava tube with an ovoid configuration in all its length. The entrance consists of two holes, quite near each other, that are a result of a collapsed vault. We think that the lava flow of the Pico da Cruz volcano is the origin of this lava tube.

Five meters before the end of the tube it becomes narrower and lower with a great slope. Fifteen meters after the main entrance there is a "sink"

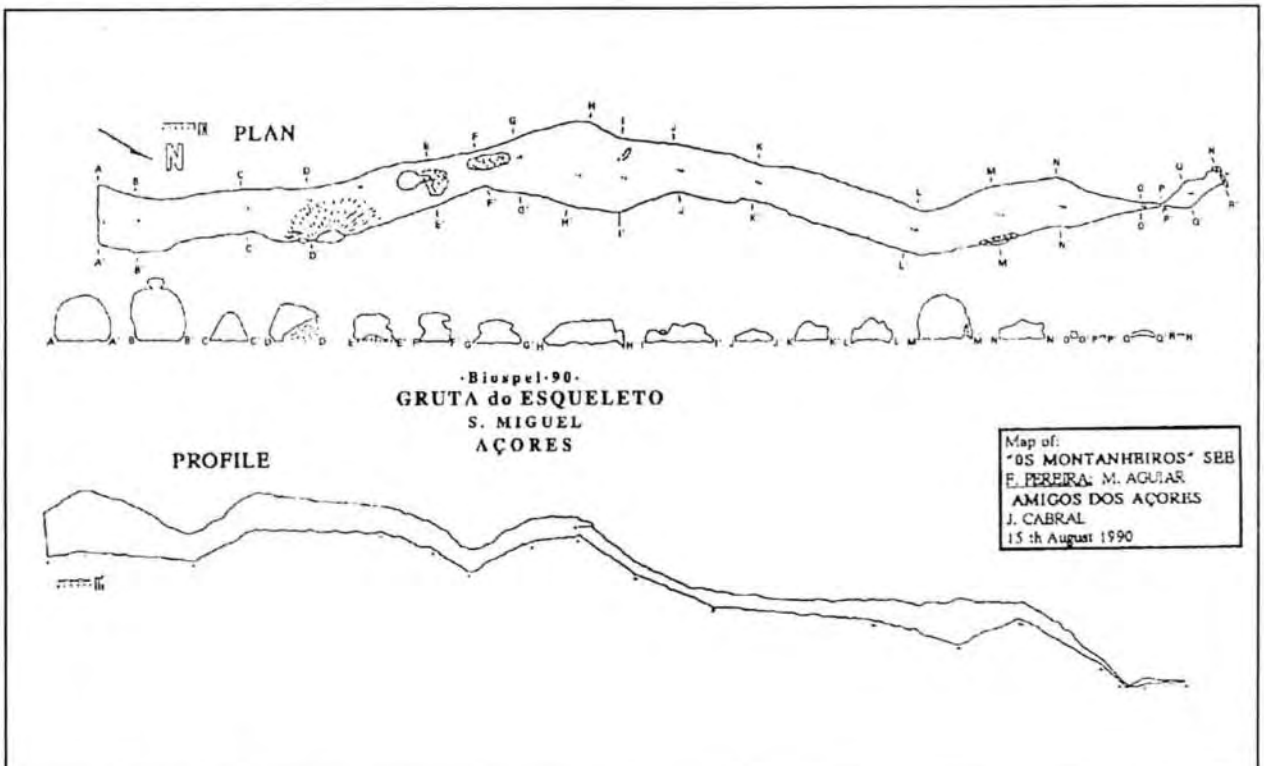

Plate 14 – Gruta do Esqueleto.

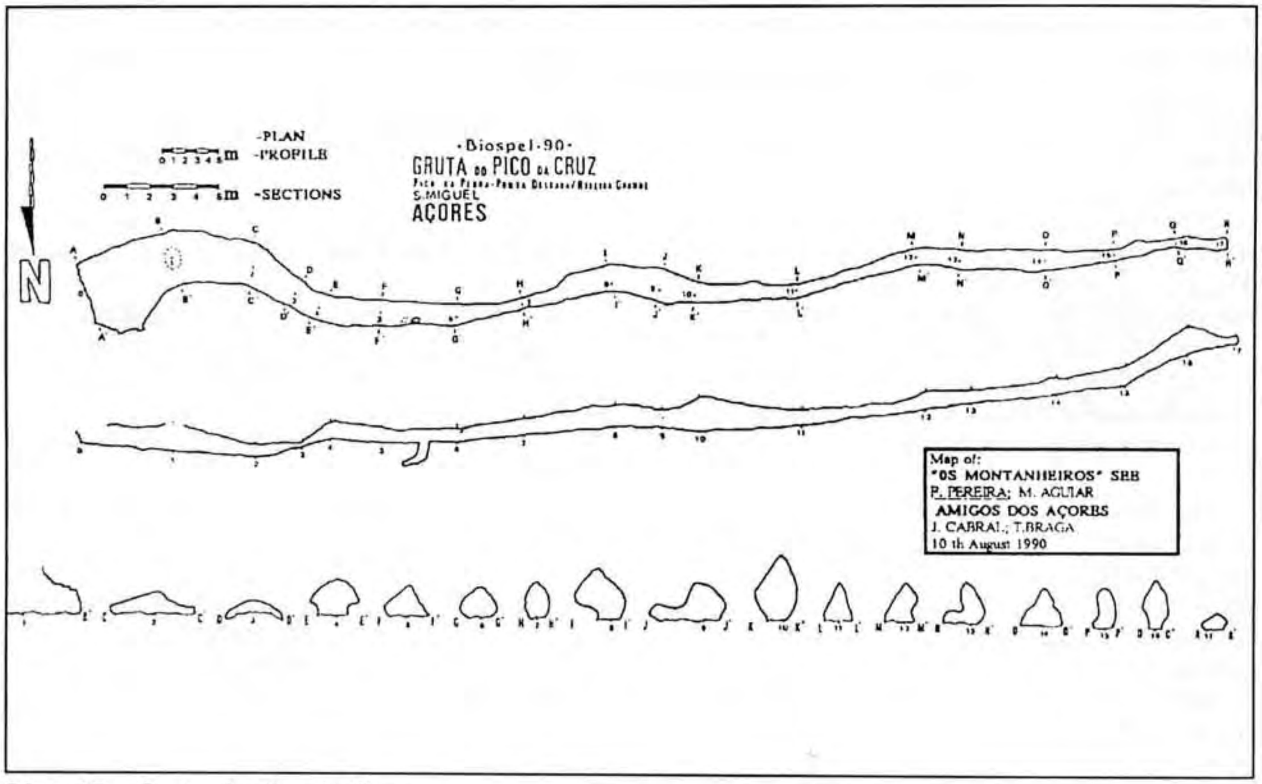

Plate 15– Gruta do Pico da Cruz.

that begins a secondary small tube under the main gallery. The levels of drainage are evident in the walls where we can also see signs of draining.

Due to its proximity to the high ground and the speleleometric data, this cave must be a secondary lava tube originated by a small lava flow. This situation contrasts with other bigger lava flows originating from that volcano. Nearby there are several sinks showing the occurrence of other cavities that were destroyed by land movements.

Fauna: A biospeleological expedition directed by N.P. Ashmole and P. Oromí (1989) visited this cave. The general results of this study are still unpublished.

15. Algar da Batalha (Plate 16 and 17; Figure 6, pit 8)

Location: Fajã de Cima, Ponta Delgada (São Miguel); Elev: 240 m; UTM: 6198/41837. Length: 51.9 m; Depth: 9.5 m; Height: 0.40-3.30 m; Width: 0.50-5.70 m.

Mapped during the recent Biospel-90-S. Miguel Expedition of Os Montanheiros, this pit is associated with a lava tube. The lava that flowed in the tube rose through the roof forming a pit and a secondary tube that ended in a low, crawling gallery.

The upper level is 33.7 meters long, 0.50 to 3.20 meters wide, and 0.40 to 2.30 meters high. The lower level is 18.2 meters long, 2.90 to 5.70 meters wide, and 0.90-3.30 meters high. The entrance is a hole 1.40 by 0.90 meters and 9.5 meters deep.

Fauna : Unknown.

Santa Maria

16. Furna das Pombas (Furna Velha) (Plate 18; Figure 7, littoral cave 1)

Location: Vila do Porto (Santa Maria); Elev: 0 m; UTM: 6663/40900; Length: 337 m; Height: 0.50-14.50 m; Width: 0.40-12.50 m.

This cave was mapped during the recent St. Maria-90 Expedition, being a littoral cave of marine erosion located on the south cliff of Santa Maria near the aeolic park of Vila do Porto.

Inside the cave there are layers of fossiliferous sandstone and two basalt veins, with horizontal prismatic disjunction. Fifty meters after the main entrance, buried in the sand that covers the floor, we found a calcite speleothem. The wall in this

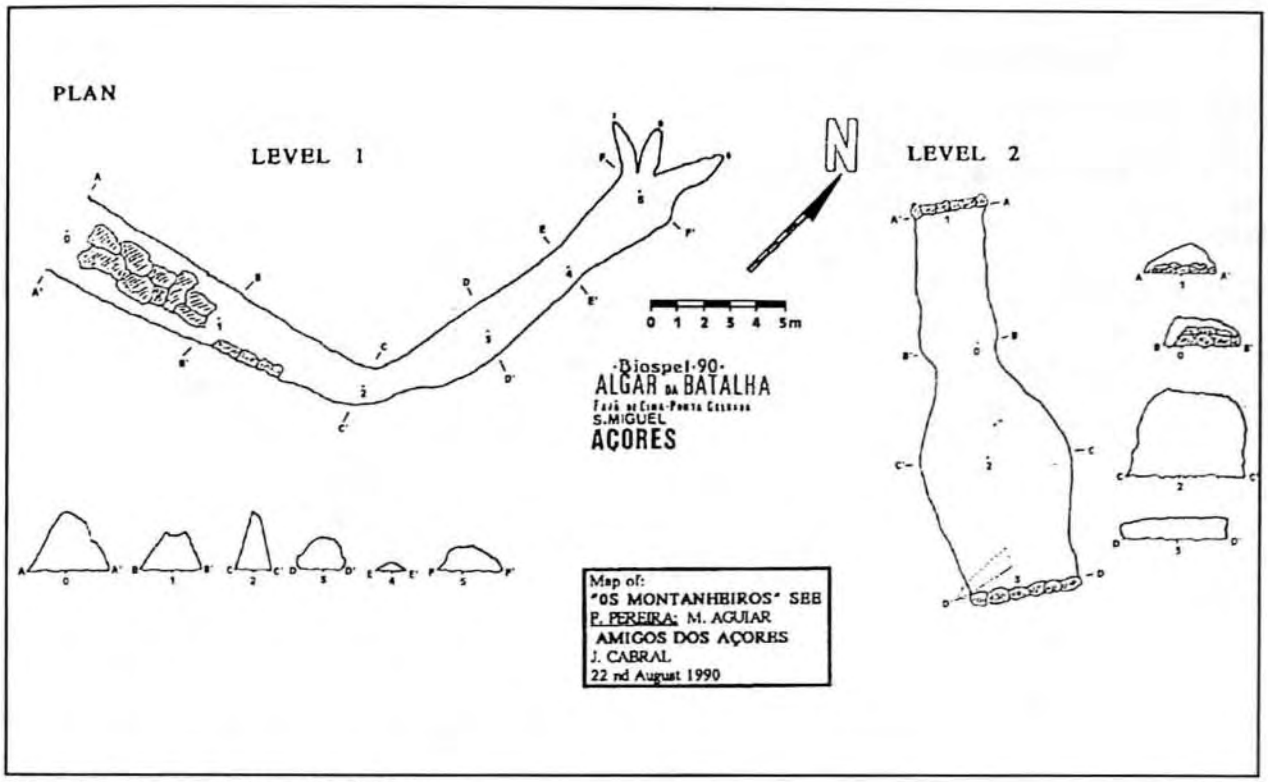

Plate 16 – Algar da Batalha (Plan).

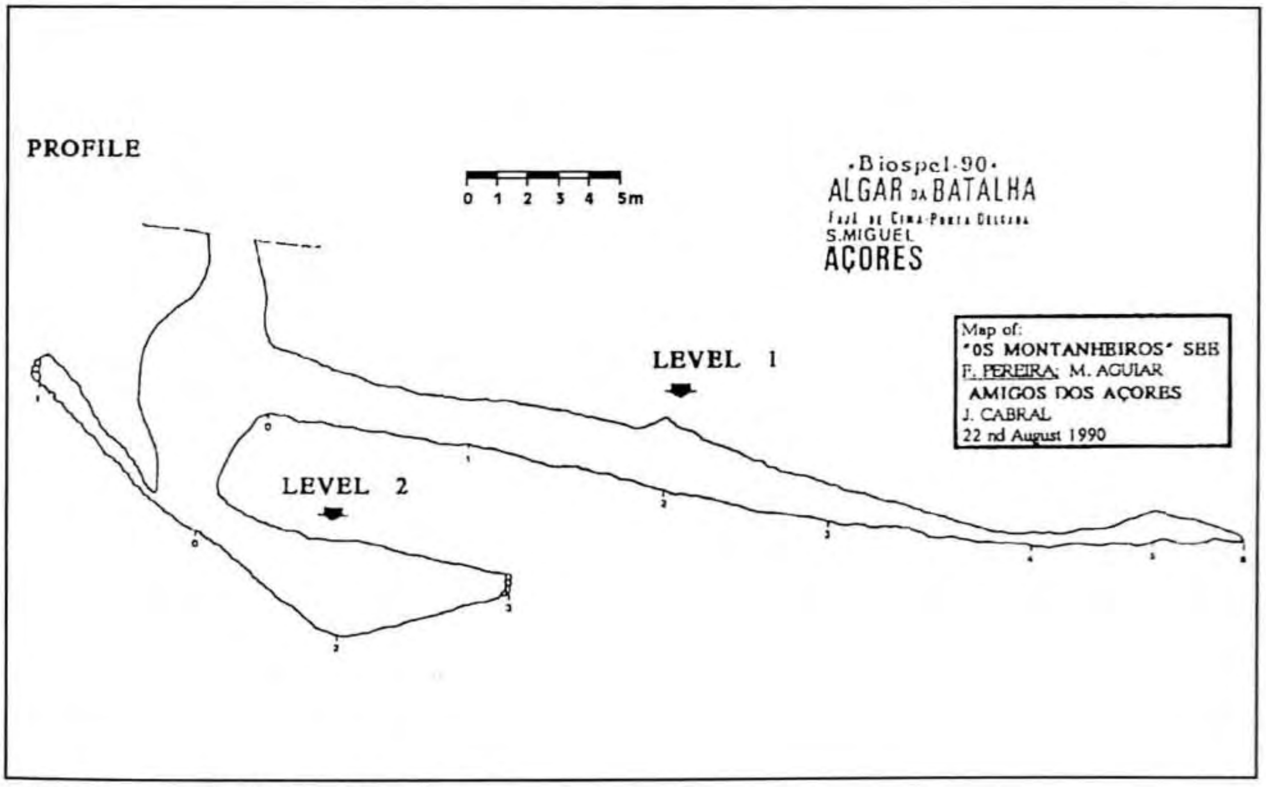

Plate 17 – Algar da Batalha (Profile).

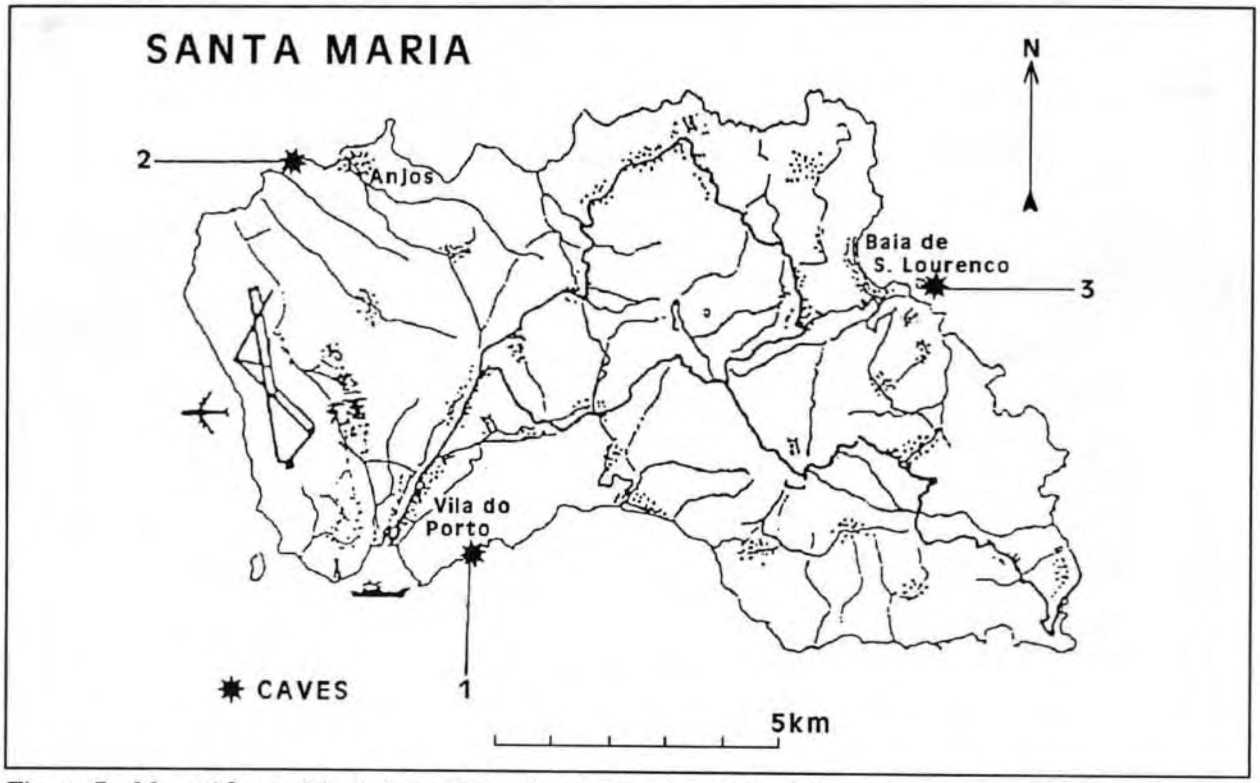

Figure 7—Map of Santa Maria Island showing the location of the littoral caves (see also Table 3).

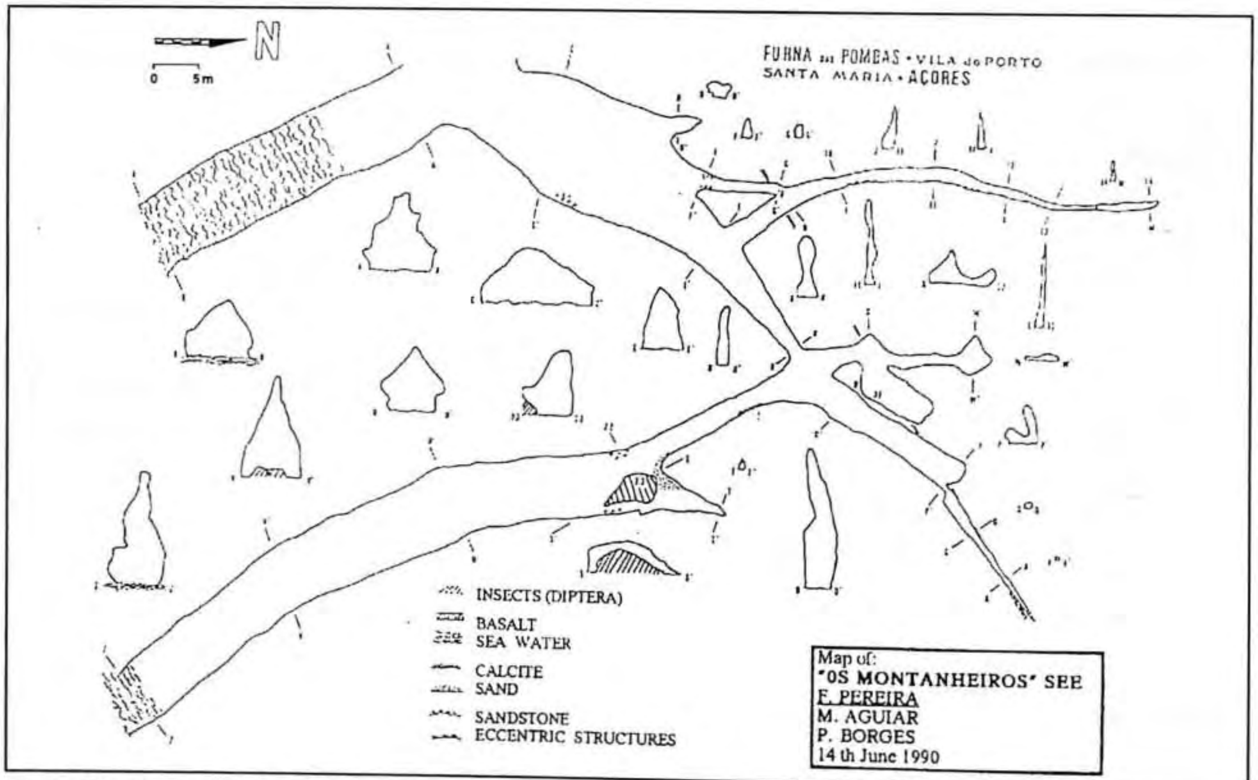

Plate 18—Furna das Pombas.

locality is covered by a layer of calcite from the ceiling to the floor.

Fauna: A biospeleological expedition directed by N.P. Ashmole and P. Oromí (1989) visited this cave. The general results of this study are still unpublished.

17. Furna dos Anjos (Plate 19; Figure 7, littoral cave 2)

Location: Anjos (Santa Maria); Elev: 10 m; UTM: 6639/40969; Length: 117.85 m; Height: 0.65-8.60 m; Width: 0.44-11.20 m.

As with the previous one, this cave was mapped during the recent St. Maria-90 Expedition, being also a littoral cave of marine erosion located in a cliff to the west of Anjos. The cave is located in a basalt vein and we had the information that a rock exploration occurred on it. It has a relatively large chamber at the entrance that elongates itself into a tunnel which bifurcates just before the end.

Fauna: A biospeleological expedition directed by N.P. Ashmole and P. Oromí (1989) visited this cave. The general results of this study are still unpublished.

Conclusions

The most interesting Azorean island from the vulcanospeleological point of view is Pico. This island is dominated by the Pico volcano, a tall basaltic cone (2,351 meters high). The western two thirds of the island form a conspicuous lava field of recent age (Anonymous, 1980c).

All the main volcanic lava tubes on Pico are situated in pahoehoe basaltic lava flows (Forjaz, 1963). They are built by very fluid lavas under special conditions. Such a type of cave is very common, appearing in other Azorean islands also (e.g. Terceira).

On Pico there are several historical lava flows (see Figure 4), areas with a great concentration of lava tube caves and pits. The Mistéro of S. Luzia (1718) is the Pico lava flow with a larger number of lava tubes (see Figure 4 and also Table III). Probably some of them are remains of a single longitudinal tube. In the Mistério of Silveira (1720) there is a remarkable lava tube, Gruta do Soldão (1,150 meters long), a simple unitary or throughway type lava tube (see Halliday and Larson, 1983) that is very well preserved.

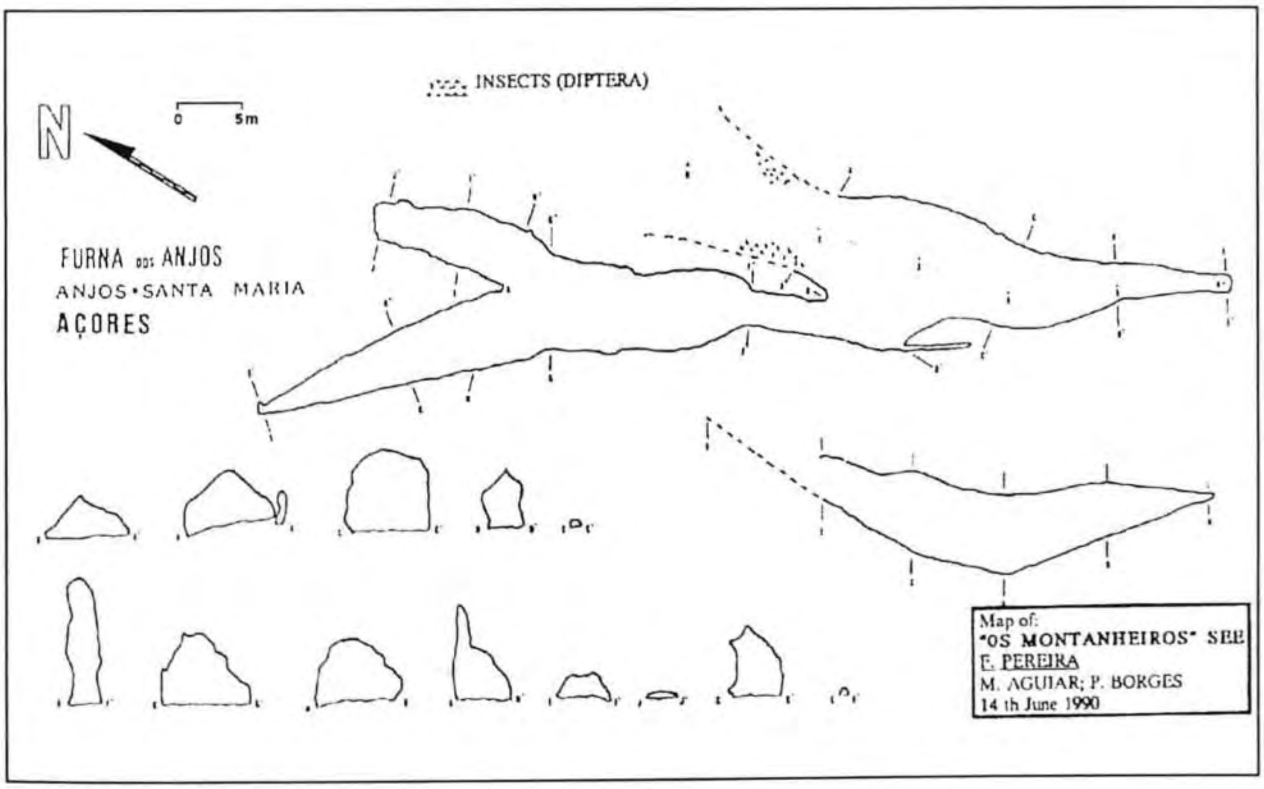

Plate 19 – Furna dos Anjos.

Several levels of drainage registered on the walls by lateral benches (*bancadas*) are commonly found in many caves from Pico and also Terceira and São Miguel. However the best example of this is in Gruta das Torres (Pico), with approximately 11 different levels of drainage.

Up to now 28 lava tubes and eight pits are known from Pico, but as a consequence of the laborious work of the amateur speleologist A. Garcia (Pico, Madalena) more will probably be discovered soon.

The cavernicolous fauna of Pico is very rich and diversified. Much work on ecology and evolutionary ecology can be done here in the future.

With respect to the caves and pits that occur on it, Terceira is without any doubt the second most interesting Azorean Island, after Pico. On this island there are several areas with caves of great interest (see Figure 5). The Pau Velho lava flow (1761) is probably the area with the most interesting caves from this island (see lava tubes 5, 6, 13, 15, 18, and 20).

Until now, three speleological sites have been identified in the Pau Velho lava flow (1761) on Terceira Island: Balcões (20), Galeria Queimada (5), and Caldeira (13). One of them, Balcões, is made up of more than one cave (Balcões, Pau Velho, Branco Opala, Chocolate), located between altitudes of 240 and 400 meters. It is quite probable that other caves, still unknown, will be found in the area.

Montserrat and Romero (1983) mapped Balcões and Pau Velho. During the field surveys (helped by Os Montanheiros) most of the other lava tubes situated in the lava flow mentioned above were visited and mapped in the last few years.

Balcões is the second longest lava tube in the Azores, 2,713 meters long. The caves cited before vary from 87 to 640 meters, with several galleries, rooms, and halls as beautiful as in Balcões.

Two of the caves already explored and mapped, the Galeria Queimada and Gruta do Chocolate (see Plates 10 and 12 respectively) have very diversified formations and may illustrate the importance of the speleological sites of the Pau Velho lava flow.

These caves have a moderate importance from the entomological point of view, because most of them are covered by pastures and there is some mud infiltration. Nevertheless, the relict cave carabid *Trechus terceiranus* Machado could be found in Balcões and Caldeira lava tubes (Borges and Oromí, in press).

On Terceira there is also Algar do Carvão, a remarkable volcanic chimney developed as a show cave since 1988.

As a consequence of the constant effort of Os Montanheiros, most of the main lava tube caves and pits from Terceira are already listed, however this speleological group has not yet been able to find the "magnific" pit described by Fouque (1873) (300 meters deep).

The hypogean fauna of Terceira is not so diversified as that of Pico, even though some remarkable troglobitic species occur in Terceira's lava tubes and pits.

On São Jorge there are two lava tubes (Beira and Leão) and two pits (Bocas do Fogo and Montoso) of great interest, not only because of their speleological structures but also because of their unique fauna. Algar do Montoso is a remarkable volcanic chimney (see plate 9) still poorly studied.

Faial has small and unimpressive lava tubes but with striking endemic hypogean arthropods on it. Furna Ruim is an exception with the third biggest vertical drop of the Azorean pits (55 meters).

On São Miguel all of the main caves are located in the recent part of the island, the center plateau. Most of them are small and very much destroyed. In spite of that, their fauna is worth noticing, probably because of the ancient age of the island (four million years) (Abdel-Monem *et al.*, 1975).

Santa Maria is the oldest island of the archipelago (eight million years) (Abdel-Monem *et al.*, *op. cit*) without recent lava flows. It has only littoral caves of sea erosion (e.g., Anjos and Pombas).

Graciosa is still poorly studied, but on this island the beautiful Furna do Enxofre occurs, with a large lake at the bottom and *solfataras*.

On the smallest of the two eastern islands, Corvo, there is the record of one cave, presently closed.

Beautiful stalactites (lava-drops) and some stalagmites of many types and forms cover the ceiling and floor of the Azorean caves making them excellent objects of admiration and study.

After this work the number of known caves and pits from the Azorean Islands are: Corvo (1;0), Flores (0;0) , Faial (3;1), Pico (28;8), Graciosa (16;1), São Jorge (7;5), Terceira (20;6), São Miguel (10;3) and Santa Maria (3;0).

Islands like Faial, Graciosa, and Santa Maria need a lot of field work for a better inventory. Others like Pico, Terceira, and São Miguel are in an advanced stage of knowledge but in spite of that there is still much speleological work to be done.

Pico is doubtless the Azorean island where more speleological surprises may show up. The Gruta das Torres is a good example of it. Presently the biggest lava tube known from this archipelago, it was only discovered very recently (1990).

Conservation Aspects

Cave ecosystems provide a unique habitat for evolutionary and ecological research. Because of that, all the caves where there is fauna adapted to the subterranean environment should be protected from all types of injuries (see Table III; and also Oromí *et al.*, 1990, Oromí *et al.*, in press, Borges and Oromí in press). These Azorean caves with biological interest are: Anelares, Cabeço do Canto, and Furna Ruim from Faial; Montanheiros, Soldão, Henrique Maciel, Capucha, Arcos, Gruta dos Esqueletos from Pico; Beira and Algar das Bocas do Fogo from São Jorge; Balcões, Coelho, Caldeira, Agulhas, Madre de Deus, Algar do Carvão from Terceira; Água de Pau and Esqueleto from São Miguel.

But the Azorean caves have other values, and we should preserve them for their geological or educational interest. In protecting them we are protecting much scientific and recreational patrimony.

Unfortunately some Azorean caves (e.g., Furna do Cabrito, Furna D'Agua-Terceira) were closed and modified by construction by the government for protection of water resources. Others, like the once beautiful Gruta do Camelo (Terceira) is now completely destroyed, for the same purpose.

On the other hand, many of the Terceira lava tubes are visited by tourists and the population in general which is good. However a great amount of trash can be found on the floors of these caves (e.g., Natal, Balcões, Agulhas). Os Montanheiros has recently cleaned up Grutas do Natal and Agulhas. On Pico and São Miguel the entrances of some lava tubes and pits are currently used to dispose of domestic animals (e.g., Gruta do Galeão) or as garbage and offal dumps (e.g., Gruta do Galeão, Gruta da Rua do Carvão, Gruta da Merda, and so on).

Some lava tubes (e.g., Natal and Agulhas) and pits (Algar do Carvão) from Terceira are under the management of Os Montanheiros speleological group from Terceira (Azores). The peculiar features and dimensions of these caves and the remarkable scenic aspects of the Algar do Carvão make Terceira Island unique in the Azores. Some support for carefully supervised tourism is being implanted by Os Montanheiros with the help of Secretaria Regional de Turismo e Ambiente (Environmental and Tourism Regional Secretary).

We recently found the hypogean relict beetle from Terceira, *Trechus terceiranus* Machado in the Algar do Carvão, showing that a rational tourist exploration won't harm the fauna of caves (pit in this case).

Nevertheless we should like to point out that, in some cases, if the habitat of a peculiar species is changed, the species is doomed to disappear. For example, the *Trechus montanheirorum* Oromí and Borges lives only at the entrance of the Gruta dos Montanheiros (Pico) (see Borges and Oromí, in press). In this case we think that its habitat must not be changed, and in consequence, no cement or other related products should be used for the construction of a better access than the existing wooden staircase.

As already noted by Halliday (1981) the Azores are islands of unusual speleological interest. They have some remarkable volcanic chimney caves (e.g., Algar do Carvão, Algar do Cabeço Bravo, Algar do Tambor, Furna Ruim, and Algar do Montoso) and lava tube caves (e.g., Balcões, Chocolate, Queimada, Agulhas, Torres, Montanheiros, Frei Matias, Soldão, and perhaps still others). Therefore all the lava tubes and pits of these islands should be protected.

There are several solutions for this. The top priority for the conservation of the caves and their fauna is to conduct accurate speleological and biological inventories on all islands in order to establish conservation priorities. Simultaneously it is also urgent to learn more about the ecology of the Azorean cave species so the protection measures will be effective.

Acknowledgements

We were able to carry out the field work thanks to the support of Secretaria Regional de Turismo e Ambiente, Bombeiros Voluntários da Madalena (Pico), Bombeiros Voluntários das Velas (São Jorge), Bombeiros Voluntários da Ribeira Grande (São Miguel), Bombeiros Voluntários de Ponta Delgada (São Miguel), Bombeiros Voluntários de Angra do Heroísmo (Terceira), Câmara Municipal da Horta (Faial), Câmara Municipal da Madalena (Pico), Câmara Municipal da Ribeira Grande (São Miguel), Câmara Municipal de Ponta Delgada (São Miguel), Câmara Municipal de Angra do Heroísmo (Terceira), Instituto Nacional do Ambiente,

Serviço Regional de Protecção Civil dos Açores, Ministro da República da Região Autónoma dos Açores, Departamento de Biologia da Universidade dos Açores, Departamento de Ciências Agrárias da Universidade dos Açores and Força Aérea Portuguesa.

Our trips to the 6th International Symposium on Vulcanospeleology (Hawaii, 1991) were made possible by the support of Secretaria Regional de Educação e Cultura (SREC), Direcção Regional dos Assuntos Culturais (DRAC), Fundação Luso-Americana para o Desenvolvimento, Instiuto Nacional de Investigação Científica (INIC), Junta Nacional de Investigação Científica e Tecnológica (JNICT) and Câmara Municipal de Angra do Heroísmo.

We would also like to express our gratitude for the field help that we received from our companions of Os Montanheiros: M. Alves, J. Bettencourt, L. Bettencourt, J. Botelho, R. Gabriel, P. Oviedo, L. Pimentel, F. Silva, João Silva, Jorge Silva, J. Sousa, O. Teixeira; and also J.A. Castro, J.V. Castro, J. Miratela, M.A.V. Pereira, M. Rosário, and V. Sousa (Pico); F. Silvano and Cmdt. Soares (São Jorge); T. Braga, J. Cabral, G. Hayes, J. Nunes, and A. Belchior (São Miguel); D. Pombo (Santa Maria); and especially A. Garcia (Pico) for his noteworthy and laborious work in discovering and locating the lava tubes and pits on Pico.

Our vertical caving instruction was done by one of us (F. Pereira) who made a course of one month (February 1988) in La Laguna (Canaries) with the orientation of L. Esquivel, J. Hernandez, A. Medina and I. Zamora, and with the support of the National Geographic Society, Câmara Municipal de Angra do Heroísmo and Serviço Regional de Protecção Civil dos Açores.

Our biospeleological instruction was done by another one of us (P. Borges) during the biospeleological expedition carried out to the Azores directed by N.P. Ashmole and P. Oromí and supported by the National Geographic Society, USA, in July through August 1989.

We would also like to thank R. Gabriel (Azores University) for her help in the improvement of the English text.

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Lava Caves of São Miguel Island, Azores

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Abstract

The Azores Archipelago is located in the north Atlantic at the triple junction of the Eurasian, African, and North American plates and is formed by nine volcanic islands aligned on a west-northwest to east-southeast trend.

At São Miguel, the largest island, nine lava caves and pits have already been identified, some of them being open volcanic conduits. Several smaller lava tubes are also known. The majority of these caves are found at the "Picos Volcanic Complex," a volcanic unit of about 50,000 years formed by several scoria cones and associated lava flows.

In the present paper some of the features of these lava caves are presented. Among these features we refer to their shape, size, local setting, small associated structures (levées, flow marks, benches, and stalactites), and their probable origin. The importance of a detailed study of the lava caves as well as their future use are also referred.

The Azores archipelago is particularly plentiful in lava tubes, above all owing to the abundance of lava flows of a basaltic nature (basalt and hawaiite) where plenty of structures of the pahoehoe type are to be found.

Considering the small area covered by the Azorean Islands, their speleological wealth is comparable to any other volcanic region in the world, due to the number of existing caves and to their particularities (Oromí *et al.*, 1988).

In spite of the fact that to date there is no detailed account of the existing caves in the island of São Miguel, the geological and geomorphological conditions of the island allow one to foresee an important speleological wealth. However, in the sixteenth century, the local historian, Gaspar Fructuoso, when describing the coast of Ponta Delgada, refers to volcanic caves to the west of the city: "Beyond, a short distance to the west of the Fortress, there is a point called Pits Point because there are two entrances to caves there and on entering these it is possible to walk a long distance under the ground, inside them. It seems that a stream of volcanic stone flowed in former times, of which there is no record."

More recent historical references, above all of an informative character, refer mainly to the "Pit" (cave) of Rua Formosa, now Rua de Lisboa (Walker, 1886; Silva, (?); and Bryan, 1963) and a cave situated "about three or four miles northwest of Ponta Delgada" (Webster, 1821).

From 1988, on the initiative of the Amigos dos Açores ecological association, a bibliographic listing and an exploration of the caves and pits in the island of São Miguel was started. At the moment there are 22 known volcanic caves and four artificial cavities.

In 1989 the first scientific expedition of a biospeleological nature took place, a joint venture of the Universities of La Laguna (Canary Islands) and Edinburgh (Scotland) which explored about 20 caves. In 1990, with the participation of the Amigos dos Açores, Os Montanheiros, and the University of the Azores (Departments of Geosciences and Agrarian Sciences) the field work of the Biospel-São Miguel project took place, having as its main

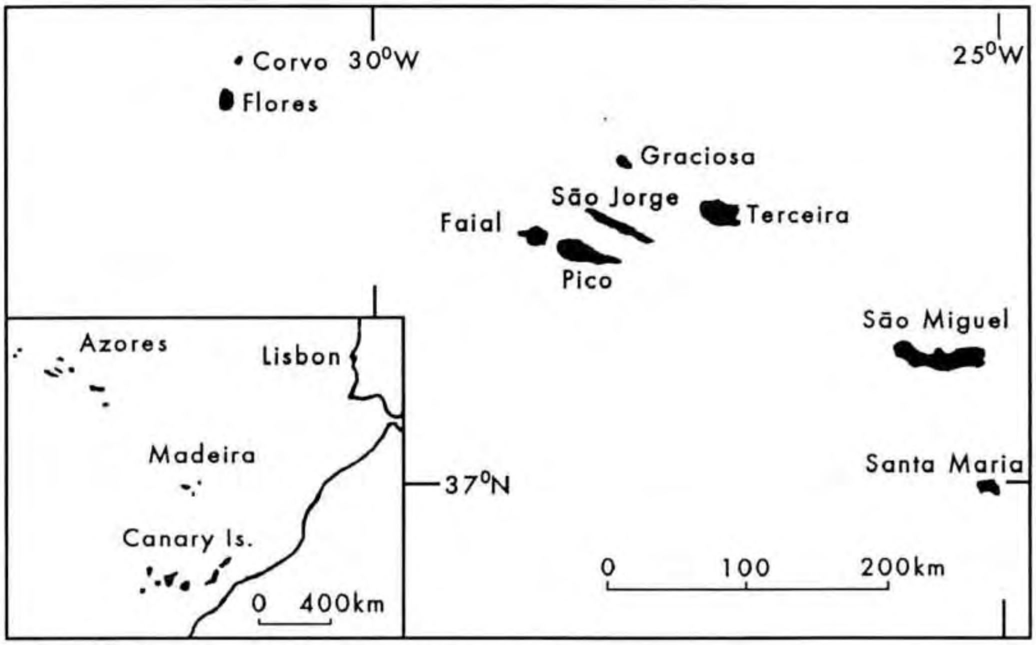

Figure 1 – Location of the Azores Archipelago.

objective the mapping, photographing, listing of geological characteristics, tourism possibilities, and possible stratagems for the preservation and protection of the caves and pits of São Miguel.

Figure 2 – Main tube of Agua de Pau Cave, covered with secondary deposits (white colored). (Photo by João Nunes)

With the present paper, as a follow up of that project and the field work which took place in 1991, we hope to fill in a gap existing in the vulcanospeleological bibliography of the island of São Miguel, present some of the results obtained, and give a general perspective of future activities.

The Azores Archipelago

The Azores Archipelago is made up of nine islands of volcanic origin situated in the middle of the North Atlantic, between latitude 37° to 40° north and longitude 25° to 31° west (Figure 1). Aligned in a general west-northwest to east-southeast trend, the Azores Islands evidence a very special geotectonic setting at the triple junction of the Eurasian, African, and North American lithospheric plates.

The Azores are a very active seismic region where volcanic phenomena are common. On the Islands of São Miguel, Terceira, São Jorge, Pico, and Faial, as well as in the surrounding ocean, several volcanic eruptions have occurred since they were settled in the first half of the fifteenth century. All the Azores Islands, with the exception of Santa Maria (the oldest), present one or more quaternary stratovolcanoes, often with a caldera (Booth *et al.*, 1978). On the other hand there are in the archipelago more than a thousand scoria cones, frequently aligned along faults and responsible for the emission of several flows of basaltic nature.

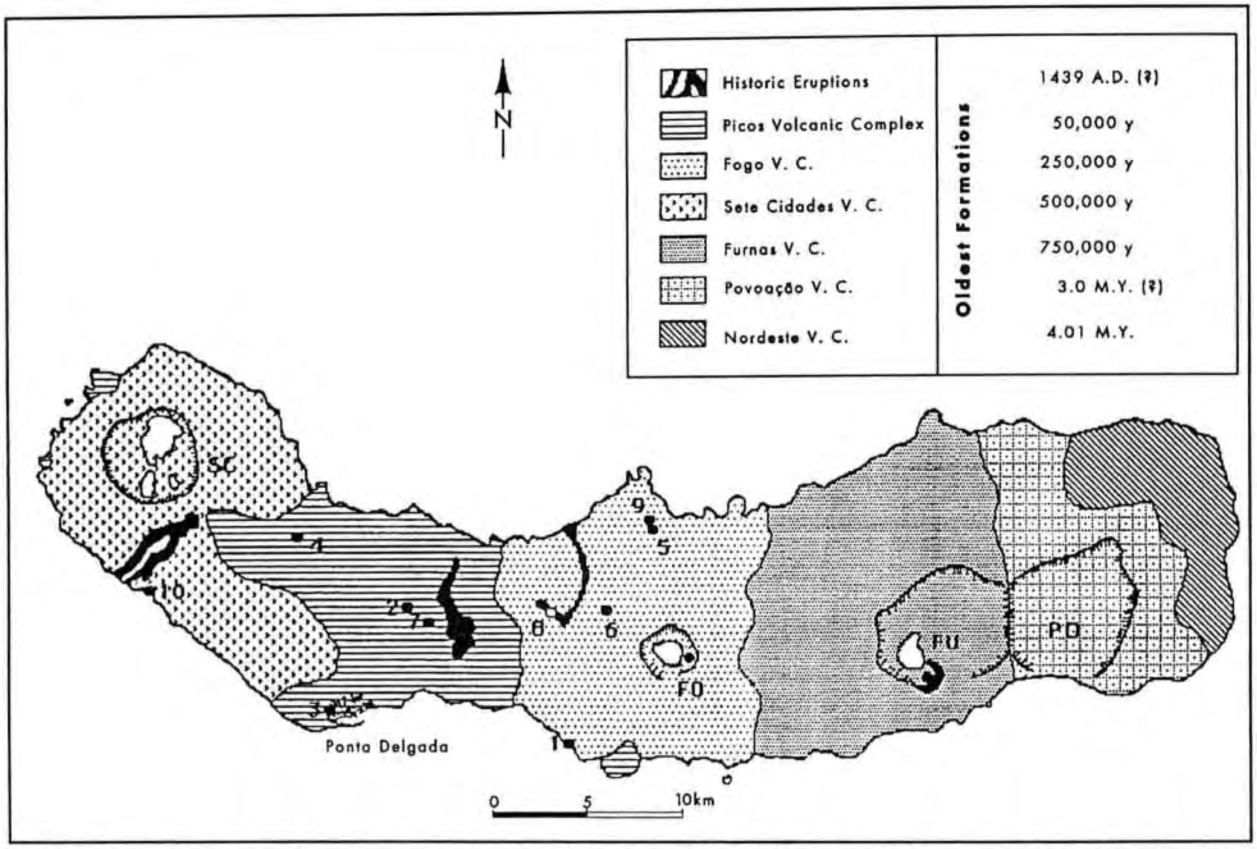

Figure 3 — Location and geological setting of São Miguel volcanic caves. Volcanostratigraphic sketch by Forjaz, 1984 and 1985; in: Queiroz, 1990. SC = Sets Cidades, FO = Fogo, FU = Furnas, PO = Povoação.

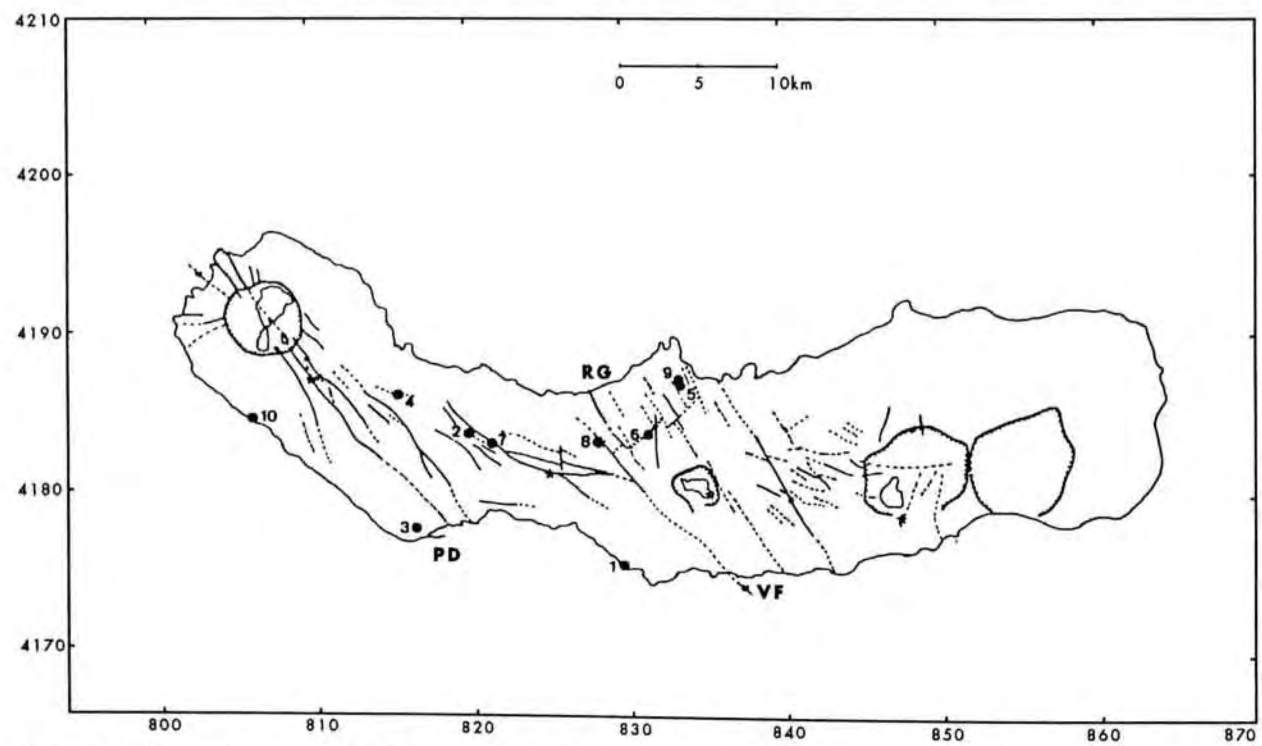

Figure 4 — Tectonic map of São Miguel island (Forjaz, 1986) and lava cave locations. PD = Ponta Delgada,

Summary Table of São Miguel Caves Main Features						
Name	C = Cave P = Pit	Geographic Coordinates	Altitude (m)	Total Length (m)	Geological Setting	Age (years)
1-Água de Pau	C	37°42'55" 25°31'48"	15	323	F.V.C	>>6,500?
2-Batalha	C/P	37°47'27" 25°38'25"	245	52/9.5	P.V.C.	4,000-4,600
3-Carvão	C	37°44'14" 25°40'51"	20	>980	P.V.C.	>4,600?
4-Enforcado	C	37°48'49" 25°41'36"	235	185	P.V.C.	<4,000
5-Escadinhas	C	37°49'03" 25°29'00"	135	31	F.V.C	4,990
6-Esqueleto	C	37°47'23" 25°30'29"	210	188	F.V.C	4,790
7-Pico da Cruz	C	37°47'06" 25°37'22"	260	98.5	P.V.C	<4,000
8-Pico Queimado	P	37°47'08" 25°32'45"	285	37	Hist.	1563 A.D.
9-Ribeirinha	C/P	37°49'14" 25°29'04"	150	54.5/5	F.V.C	4,990
10-Feteiras	C	37°48'06" 25°47'51"	35	22	SC.V.C.	≈20,800

F.V.C. = Fogo Volcanic Complex; P.V.C. = Picos Volcanic Complex; SC.V.C. = Sete Cidades Volcanic Complex; Hist. = Historic Eruptions.

The Island of São Miguel

The island of São Miguel, the largest (747 square kilometers) and the most densely populated in the Azores, has three active stratovolcanoes with calderas (Furnas, Sete Cidades, and Fogo) and a long record of explosive eruptions (Figure 3). The eastern part of the island, of extinct volcanism, includes the Volcanic Complex of Nordeste, where the oldest rocks in the island exist and are about four million years old. The Volcanic Complex of Povoação is composed of a stratovolcano with a caldera (the biggest in the island), very much affected by erosion.

During the last thousand years, several basaltic eruptions have taken place in the region known as "Picos Volcanic Complex," an area extending between the volcanic massifs of Sete Cidades and Fogo (Booth *et al.*, 1978 and Forjaz, 1986). It is composed of about 200 scoria cones (built during strombolian eruptions), aligned mostly along faults in generally northwest to southeast and east to west directions, and associated lava flows (Figure 4). The basaltic nature of the lava flows (mostly the aa and pahoehoe type) and the relative youthfulness of the formations (2,000 years) make this region particularly plentiful in lava tubes. In fact, more than 60% of all the known caves and pits in the island of São Miguel are situated in this area.

Volcanic Caves in São Miguel Island

In the present paper there are some notes concerning about ten of the caves and pits in São Miguel Island according to their size, geomorphological situation, and existing structures. In Figures 2 and 3 the location of these caves is shown while in Table I their main features are summarized.

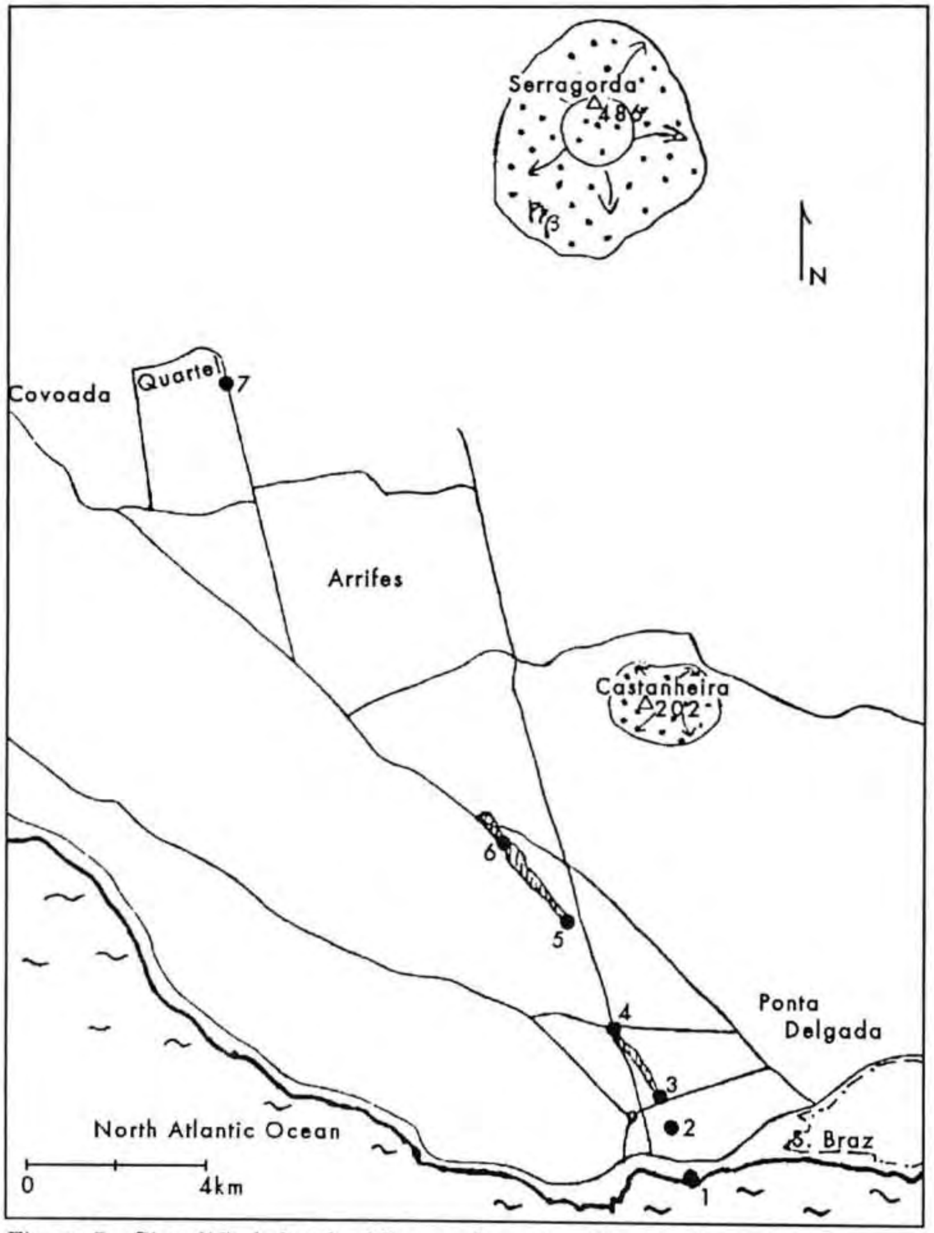

Figure 5—Simplified sketch of Carvão Cave. 1 = Point indicated by Frutuoso, 2 = Alcohol/sugar factory, 3 = Tobacco factory, 4 = Carvão Street, 5 = residence of Mr Belchior, 6 = Residence of Mr Madeira, 7 = Military barracks. Indicated also are the location of two scoria cones and the explored sections of the cave (hatched line).

Agua de Pau Cave

This cave, the second longest, has a general east to west direction and most of it can be walked through standing upright. The two branches into which it is divided upslope are obstructed by big falls which prevent going beyond them. In the secondary tubes, with a very low roof about 60 centimeters high and a level floor, there are beautiful formations of cone-shaped fusion lava stalactites. Also to be seen are various long extensions of benches, witnesses of ancient lava flow surfaces.

The entrance to the cave is almost at sea level through a nearly circular opening about two meters in diameter. The flow shows layered lava and in the area around the cave it is possible to observe some buckling in the lava flow and lesser tubes, sometimes totally filled in. Owing to its difficult access, the cave is little visited and so is relatively unspoiled.

Batalha Pit

Having an oval opening situated in a pasture, the Batalha pit has a lava tube about three meters from the surface. This pit is situated east of the Picos de Lima scoria cone, which is placed on an active geological fault with a northwest to southeast direction (Figure 4). A couple of lateral ridges can be observed on the surface at a bearing of N155°E, as a result of the collapse of the central part of the lava flow.

The geomorphology of this area, local information, and a note written by Luis Ataíde (1951) lead to the conclusion that other caves and/or pits exist in this locality. This writer refers to a visit to one of them in 1909 and to "underground chambers full of animal bones and live owls."

Recently it was not possible to carry out a more detailed study of it due to the nauseating smell caused by dead animals inside, probably thrown down there

Figure 6—Carvão Cave, the most important known tunnel on São Miguel Island and a potential tourist site. In this section the cave is almost five meters high and two levels of benches can be observed. (Photo by João Nunes)

by the farmers. The entrance of this pit is in urgent need of protection to avoid its total destruction.

Carvão Cave

This is the best known cave in São Miguel. Already in the sixteenth century the historian Gaspar Frutuoso, in his "Saudades da Terra" refers to the existence of lava caves west of Ponta Delgada. Emigdyo da Silva, in his work, "São Miguel in 1893" considers it "the most remarkable of the volcanic caves in the Azores" and refers to it in the following terms: "the cave of Ponta Delgada is over one kilometer in length, so far as is known. It comes out by the sea after passing under the alcohol factory in Santa Clara, coming in a north to south direction."

Halliday (1981) explored the southern section and estimated its length to be about 400 meters. During the Bioespel expedition, Os Montanheiros explored about 980 meters of this cave, most of it more than five meters wide.

Besides the extensions, historical writings, and the existence of other sections—fallen in, blocked up, or simply of impossible access—there are indications that Carvão Cave must be much longer (Figure 5). As can be seen in Figure 5, the cave, following a north-northwest to south-southeast direction, extends for more than 20 kilometers from the coastline to the village of Arrifes. Halliday (1981) refers to the existence of a cave the entrance of which was near the military barracks in the village of Arrifes. It appears to be an up-slope portion of a system including Carvão. According to the author this cave might be the one described by Webster (1821).

An important feature of the Carvão cave is the fact that the visited up-slope portion ends in a chamber over ten meters wide (Cabral, 1990), completely blocked, possibly as a result of filling in (see Figure 5). So it is possible to suggest the continuation of the Carvão Cave further to the northwest, as suggested by Halliday (1981) and also to the cave mentioned by Webster (1821). If this were the case, the Carvão Cave would be the most important underground structure in the archipelago, being over five kilometers in length.

Owing to its size, a great variety of structures can be observed such as flow marks, burst bubbles of lava, branching galleries, superimposed channels, long extensions with benches of rare beauty, and at several steps. On the roof there are many fusion lava stalactites and other irregular deposition-type stalactites, sometimes over the former.

Drainage work has greatly affected this cave, where garbage is thrown in as well as the overflow of water. These latter affect mostly the flatter extensions depositing sand and clay which silt them up. The Carvão Cave, commonly known as the "Algar do Carvão," is therefore an important lava tube in the island of São Miguel and the Azores. A detailed study of it should be urgently carried out including a variety of specialities.

Enforcado Cave

Figure 7– Enforcado Cave with a general shape of an inverted funnel. The floor shows levée structures. (Photo by João Nunes)

This is a cave composed of three extensions separated by falls caused by the clearance of land when it was turned into pasture. With a total length of about 185 meters and an average height of two meters, it shows a roof generally in the shape of an inverted funnel and the floor, seemingly aa, shows levées.

The Enforcado Cave, with an alignment N138°E, is situated in a geological structure defined by the scoria cones and spatter cones of the Pico do Cedro and Pico do Enforcado, responsible for extensive lava flows. The fault so defined is considered as one of the best examples of fissure eruption in the island of São Miguel (Booth *et al.*, 1978).

Escadinhas Cave

Escadinhas Cave is a small lava tube near the surface following a N40°E direction. It is situated in the graben of Ribeira Grande (Forjaz, 1986) and to the west of Pico da Multa, a very altered scoria cone.

The very irregular and scoriaceous roof shows a plastic collapse in its central part, while the floor shows characteristics of aa lava, over which it is extremely difficult to walk.

Esqueleto Cave

This is a volcanic tube, the exploration of which involves some risk, owing to enormous piles of rocks fallen from the roof – falls which have reached the surface, leaving four openings.

In spite of these difficulties, Esqueleto Cave, owing to its size, easy access, and existing structures (such as levées and flow marks) is a place worth visiting.

Pico Da Cruz Cave

This cave is situated on the Picos Volcanic Complex and along the northwest to southeast tectonic alignment defined by a group of scoria cones (Figure 4), In this area there is a reference to two pits over 20 meters deep which could be the result of the withdrawal of lava from a fissure (Booth *et al.*, 1978).

The main features of this cave are its funnel shaped roof and very narrow walls. Seemingly very solid and resistant, this is one of the most interesting of the speleological heritage in the island of São Miguel and is still in a good state of preservation.

Pico Queimado Pit

Pico Queimado Pit is a pit about 30 meters deep to be found in a parasitic spatter cone of Pico Queimado, situated on its northwest slope. It is an open volcanic conduit that had formed a vent in the historic basaltic eruption of 1563, which gave rise to a very fluid lava flow. This lava flowed along two distinct branches, one to the northwest and another to the northeast (Figure 3).

To southeast of the pit there is a tension fracture about one meter wide, more than five meters long and six meters deep. Developing in a N140°E trend, it is to be found in the continuation of the multiple craters of Pico Queimado and in the orientation of the active faults mapped in the area (Forjaz, 1986).

Ribeirinha Pit

Situated very close to the Escadinhas Cave, this pit has an opening about eight meters in diameter.

At the bottom of the pit, about ten meters deep, there is a small cave. There is historical and geological evidence of other volcanic caves in this area, where the pits may result from the withdrawal of lava from existing faults.

Unfortunately it has been used as a dump for waste and garbage so that its state of preservation leaves much to be desired.

Feteiras Cave

This is probably the oldest of the known caves in the island of São Miguel and one of the few situated in the Sete Cidades Massif in the western part of the island. In spite of its small size, 22 meters long, and average height of one meter more or less, it has an interesting particularity: about half of its length consists of two superimposed galleries as a result of the joining of two levées. Its up-slope termination was filled by a lava flow after its formation.

Some hundred meters to the west there is a lava flow which came from Picos das Ferrarias (Queiroz, 1990) and which, according to some authors, is considered to have taken place during the first half of the fifteenth century (Figure 3). However, the lava flow where Feteiras Cave is to be found is a much older flow and corresponds to the last effusive local phenomena. In fact, the superior formations are composed of explosive materials, specially trachytic pumice and basaltic pyroclasts (*lapilli* and ash). Below the cave are other lava flows sometimes with very small lava tubes.

Conclusions

On account of their scientific importance and potential tourist interest, the natural caves justify the passing of regional legislation to protect them and energetic measures for their recovery. It is also necessary to promote campaigns for the preservation of the caves and pits in the island of São Miguel, an integral part of the regional landscape heritage.

After legally protecting Carvão Cave and carrying out the necessary and urgent work of cleaning up, it will be possible and desirable to include the cave in the tourist attractions of the island of São Miguel, following an order of controlled and duly guided visits. It is equally urgent to protect the openings of the remaining caves to avoid their deterioration.

Acknowledgements

This present work was possible thanks to the support given by Drs J.P. Constância and G. Hayes to whom we are extremely grateful.

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Graciosa Caldera Lava Lake and Associated Lava Caves, Graciosa Island, Azores

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The Azores archipelago is located in the Atlantic Ocean and is formed of nine volcanic islands divided into three different groups according to their geographic position: eastern, central, and western.

The geostructural environment of the Azores Plateau, defined by the 2,000-meter bathimetric curve, is dominated by the confluence of the American, Eurasian, and African lithospheric plates. This tectonic feature is responsible for a remarkable seismovolcanic activity from which the Capelinhos eruption (Faial Island, 1957/58) and the January 1, 1980 earthquake (epicentral location 30 kilometers west of Terceira Island, Magnitude 7.2) are the most recent catastrophic events.

Graciosa belongs to the central group and is located in the Terceira Rift, a fracture zone with an approximately northwest to southeast trend, thought to be the present eastern branch of the Azores triple junction. The main faults in the island also show a dominant northwest to southeast pattern with the central graben being the most important tectonic structure.

The island is composed of three distinct geomorphological units: (1) the central massif – dominated by the heights of Serra das Fontes, Serra Dormida, and Serra Branca – corresponds to the oldest volcanic complex, strongly faulted and almost completely covered by recent basaltic activity; (2) the northwest platform consists of several superimposed aa and pahoehoe lava flows erupted from different cinder and spatter cones; finally, (3) The Graciosa Stratovolcano that rises in the southeastern end of the island with a small caldera on the summit. In this volcano the deposits related to hydromagmatic activity (surges and lahars) represent an important portion.

The caldera of Graciosa Stratovolcano lies along the northwest to southeast direction with a maximum axis of 1.6 kilometers and an average depth of 200 meters. The structure resulted from the coalescence of two or three smaller craters during a complex evolutionary process.

One of the latest episodes connected with the stratovolcano evolution comprised an important intracaldera effusive activity. At that time a lava lake was formed probably in the southeast part of the caldera and successive lava level changes resulted in several stages of overflow. This process gave rise to superimposed lava flows on the caldera floor, some of which generated lava tube structures.

When the lake level reached approximately 240 meters, lava overrode the caldera rim. Related to this stage, a lava tube was developed on the northwest volcano slope which was an important path for the lava flow that covers the present Luz region to the south. Another lava flow reached the sea on the north coast.

The end of the eruption seems to be connected with the sudden lava lake collapse leaving a veneer on the caldera walls. A lava cave located at the southeast caldera bottom and controlled by northwest to southeast and northeast to southwest faults can be interpreted as a preferential drainage place during this final phase.

Acknowledgements

Thanks are due to Prof. J. Guest and Prof. A. Serralheiro for their suggestions. We are also grateful to the Câmara Municipal de Santa Cruz and the Serviço Regional de Desenvolvimento Agrário for logistic support. The field work on Graciosa was provided by the Universidade dos Açores and the Centro de Vulcanologia of the Instituto Nacional de Investigação Científica.

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Vulcanospeleological Pseudokarst in Micronesia: an Overview

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In 1984 the Pacific Basin Speleological Survey embarked upon a project to compile a preliminary listing of the known caves in the island nations of the Pacific Basin. Previous American, Australian, French, and British work in Melanesia and portions of Polynesia was a matter of record so Micronesia was selected as the focus of the Pacific Basin Speleological Survey's working area. Pohn Pei, Kosrae, Chuuk, and Yap States of the Federated States of Micronesia; Agrihan, Pagan, Saipan, and Rota Islands in the Commonwealth of Mariana Islands; the Territory of Guam; and the Republic of Belau were visited. Extended expeditions to these areas in 1984, 1986, and 1989 have found a small but significant sampling of volcanic speleological features to be investigated.

Pohn Pei Island

On the island of Pohn Pei rock shelters up to 50 meters wide and deep and 30 meters high have formed in vertical cliffs in the middle elevations of the island. These shelter caves have their origin in the differential weathering of breccia beds intercalated with massive basaltic flows. Small rock shelters, formed either by collapse of basaltic rock outcrops or failure of lava tube segment roofs and containing large amounts of rock art, have been found on the uppermost slopes of the island. Some of these sites are prominent in indigenous people's religious beliefs. In the walls of construction material quarries where Pohn Peians have removed both columnar basalt "logs" and crushed rock for

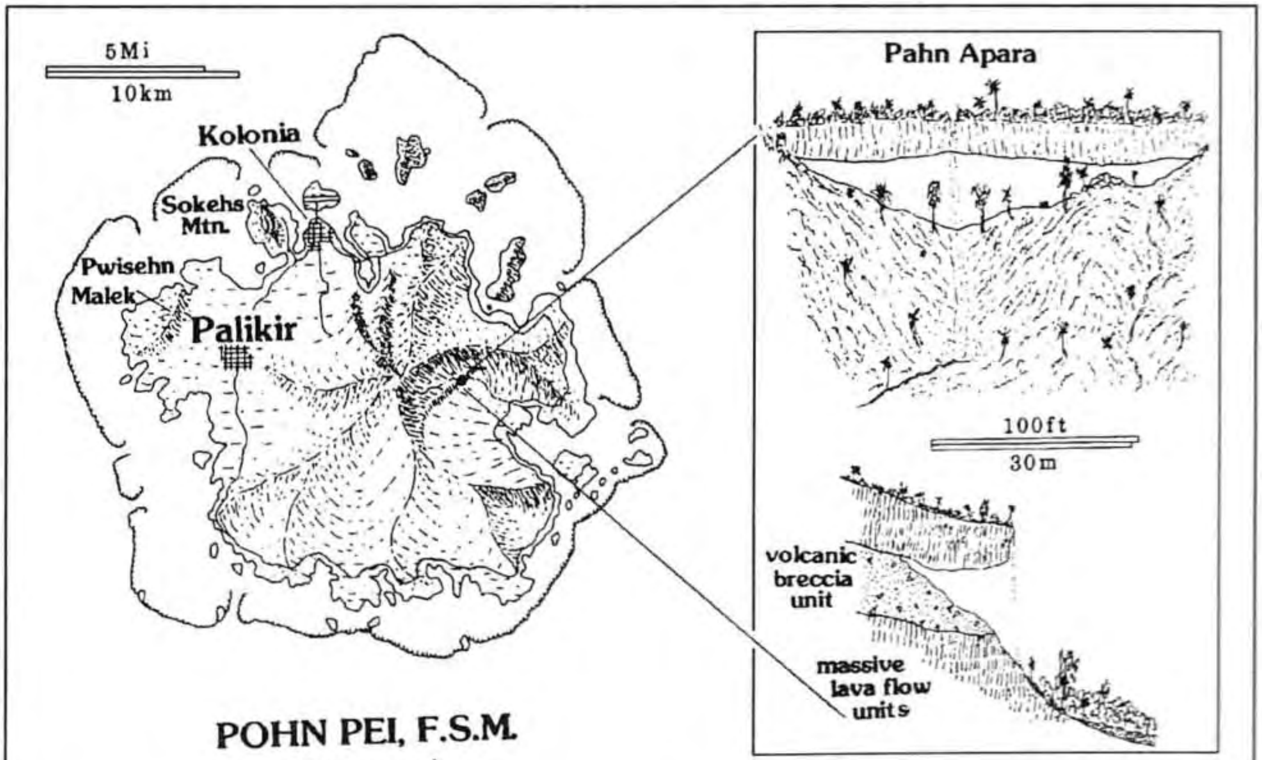

Figure 1—Pan Apra Cave, Pohn Pei. The map of the Island shows the location of Pan Apra Cave (left), a frontal view (upper right), and cross section (lower right) of the cave. Noted both the easily weathered basaltic breccia into which the cave has been eroded and the massive basalt flow unit that forms the cave's roof.

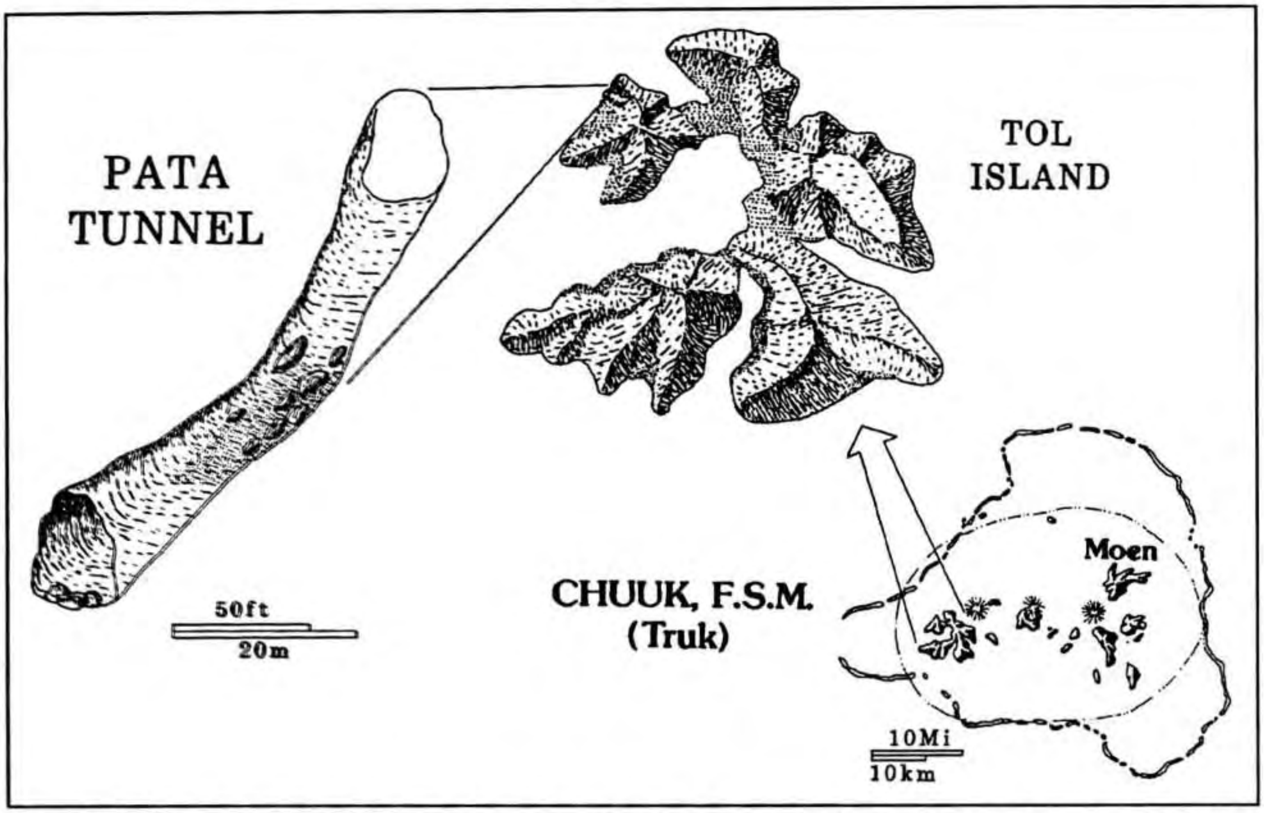

Figure 2—Chuuk (Truk) Island consists of an eroded triple-vented volcano (lower right). On the western island of Tol (top center) is the 61-meter- long Pata Tunnel (left).

over 800 years, many large, lava-filled tubes are exposed. On the lower slopes of the volcanic island are many outcrops of olivine basalt showing kluftkarren development. The origin of these solution forms is poorly understood but may be due to the fact that silicate minerals are unstable in the presence of water high in dissolved carbon dioxide and organic acids common in warm, humid climates.

Kosrae Island

Kosrae State has at least one large lava tube developed in olivine (?) basalt in the middle slopes of the central massif. The cave is approximately ten meters in diameter, is floored with deep deposits of both bird and bat guano, and extends for an unknown distance. Two large colonies of both sac-wing(?) bats and cave-dwelling swiftlets occupy the cave.

Chuuk Islands

In the main island grouping of Chuuk State several volcanic pseudokarst features are found. On the Pata Peninsula of Tol Island a 61-meter-long and 10-meter-diameter lava tube in an 8.2-million-year-old olivine basalt lava has been utilized by local inhabitants for many hundreds of years. A local legend attributes the origin of the tube to industrious sea turtles assisting an imprisoned local chief. The Japanese Army also used the cave as a munitions bunker during World War II. On the upper slopes of the island, two 4.6-million-year-old melilite nepheline basalt and nepheline basalt lava flows are surfaced with a meter-high kluftkarren field as a result of the extreme—up to ten meters deep—weathering common to these islands.

Yap Island

There are reports of small sea caves several tens of meters long eroded into the western shores of Yap, Rumung, and Map Islands in Yap State of the Federated States of Micronesia. These have formed in basalt and andesite flows of Cretaceous age. The volcanic rocks were metamorphosed by subduction to a unique suite of garnet-bearing green schists and amphibolites which were subse-

quently exposed by up-thrusting along the Palau-Yap-Mariana trench.

Caroline Islands

The islands of Saipan and Rota in the Commonwealth of the Northern Mariana Islands, the Territory of Guam, and the Republic of Belau (Palau) are largely comprised of elevated Miocene to Recent reefal limestones. These islands, however, also have areas of exposed Paleocene to Eocene volcanic basement rock which has been important to both the local development of karst terranes and as sources of cultural materials for the indigenous peoples of Micronesia. Intercalated basaltic and andesitic lavas and tuff beds in many of these carbonate terrains have channeled ground water which produced solution caves. These beds also allow perching of the local water table, thus producing flashy springs, some of major magnitude. Volcanic agglomerates also are the hosts to many small sea caves in the littoral zones of Guam, Saipan, and Belau. These volcanic rocks have been important sources of tough rock from which the Chamorro, Yapese, Kosraean, Chuukese, Pohn Peian, and Belauan peoples fashioned tools and carved a great variety of megalithic sculptures over the last 3,500 years. Farallon de Pajaros (Uracas), Maug, Asuncion, Agrihan, Pagan, Alamagan, Guguan, Sarigan, and Anatahan Islands in the Northern Mariana Islands are Miocene to Holocene volcanos. All have reported lava tubes and other non-solution caves but little is known of their extent or contents.

Agrihan Island

Agrihan Island is a Quaternary volcano of basaltic and andesitic composition. As recently as 1917 volcanic activity included lava flows down the slopes of the central volcano but little is known of the extent or contents of the resulting lava tubes.

Pagan Island

Pagan Island is the only island in the northern "inner arc" Mariana Islands which has a well known volcanic history. It is a Late Miocene to Holocene composite volcano. Major eruptions in 1872, 1909, 1917, 1923, 1925, 1929-1930, and 1982 have been recorded. While most of the basaltic to andesitic lavas have been erupted as aa flows or pyroclastic deposits, there are moderate-sized areas of pahoehoe flows. In these flows on the west, east, and especially the south flanks of Mount Pagan are concentrations of caves of differing types. Lava tubes up to ten meters in diameter; collapse trenches over 13 meters deep; eruptive fissures, vents, and hornitos deeper than 20 meters; and many 1.5-meter-diameter surface tubes have been reported. Some tubes have been utilized repeatedly with tubebearing younger flows emanating from the older tubes' mouths. Only one series of tubes, however, has been correlated with a documented eruption – that of the February to May 1925 eruption of Mount Pagan. During this eruption, an olivine augite basalt pahoehoe flow descended the west slopes of Mount Pagan at 4:00 A.M. on March 11 and formed a series of lava tubes. Many of these caves are still active fumaroles, emitting hot air and steam. The extent and composition of secondary deposits in these and the other known older tubes are unknown;

Figure 3 – On Pagan Island are many lava tubes formed during the 1929 eruption. This tube is approximately a meter high and three meters wide. (U.S. Geological Survey photo)

Figure 4—Charmaine Legge looks into the outlet of Waterfall Cave on the southeast side of Luta (Rota) Island. This large karst spring is perched on a thin bed of andesitic volcanic rock.

however, inferences of sulfur and carbonate deposits are found in the literature.

Inland from many of the steep, rocky headlands are areas of fissure caves up to ten meters deep formed by separation of basalt blocks from the headlands and resulting slow seaward creep. Along the east and northwest coasts of Pagan are deep sea caves formed by littoral excavation of loose clinker. The caves have roofs and floors of massive basalt flow units.

The constant volcanic activity, civilian and military construction during the 1941-1945 Japanese occupation, and 1950s U.S. Marine and Navy war games activities have all but erased evidence of Pagan Island's earliest inhabitants, thus we know nothing of their utilization of the island's caves. The Spanish and German occupiers of the island left little record of their activities but we do know that they mined sulfur from various sites in the inner crater of Mount Pagan. The Japanese mined the same(?) deposit as well as deposits discovered near the summit of the south cone of South Volcano during 1917 and 1934. The amount of sulfur obtained was small, the labor considerable, and both operations were abandoned. During the 1982 eruption of Mount Pagan, inhabitants of Lagona Village sought shelter in lava tubes for several days until evacuated by ship. Only incidental observations of spelean biology have been made. Reports of large populations of cave-dwelling insectivorous and fruit-eating(?) bats have been made as well as of forest-dwelling flying foxes.

Rota Island

The island of Rota, in the Marianas, derives its water supply from a large karst spring perched on the island's andesitic basalt pile. A small cave in agglomerate has developed at the island's Sabana District summit. Other deposits of fine-grained andesite and andesitic basalt exposed on the southeast coast were utilized as sources of stone for tools.

Saipan Island

On the island of Saipan in the Sabana Dan Dan area are small soil pipe caves which have developed in tuffaceous siltstones and sandstones of the Eocene Hagman Formation. In the Eocene andesitic volcanic rocks of the Hagman Formation exposed on the Hagman Peninsula are several small caves at sea level. Deep fissure caves in up to ten-meter-square creeping blocks of tuffaceous sandstone and conglomerate are also present. Other small sea and fissure caves in the Hagman sandstones and conglomerates are located along the sea level areas of Punta I Naftan. Andesite and dacite from the Eocene and Eocene(?)

Figure 5—The original Chamorros inhabitants of Saipan Island utilized both the basalt bed rock to fashion tools (right) and the weathered basalt clay-rich soils to construct pottery (left). These pieces from Cave of the Sinking Waters are approximately 1,000 years old.

Densinyama, Hagman, and Sankakuyama Formations were locally quarried for tool making.

Guam Island

On the island of Guam are several areas of badland topography including small soil pipe caves developed in tuffaceous shale of the Eocene to Oligocene Alutom Formation. Along the southwest coast of the island are small sea level caves developed in the basalt and basalt breccia of the lower Miocene Umatac Formation.

Palau Islands

In the northern volcanic islands of the Republic of Belau short sea level caves have developed in Eocene to Oligocene basaltic andesite, andesite, and dacite flows and breccia of the Babeldaop, Aimeliik, and Ngeremlengui Formations. Large slabs of andesite also furnished material for the extensive megalithic sculpture tradition and for tools used in the islands.

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Caves In Cheju Island, Korea

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Cheju Island is a volcanic island formed at the end of the Tertiary period. Geological strata of the island include the Seoguipo Formation (end of the Cenozoic era), sedimentary rocks of the Seongsan, Whasoon, and Shinyangri Formations (Quatenary period), and basalt, trachyte, and other volcanic rock and debris. Most of the layers are basalt. Those layers in the Pioseonri, Mt. Hanla, Cheju, Hahyeri and Shiheungri areas are basic and of low viscosity, and are closely related to the distribution of lava tube caves. The lava caves of Cheju Island are in basalts with low viscosity and alkali. About 60 are known to have been investigated. About 100 are known.

Most of the caves of Cheju Island are located near villages and have been a part of the life of villagers. Some of them are separate parts of lava tube systems. In these systems, the caves at higher elevations tend to be larger than those at lower elevations. Two major groups of volcanic caves exist on the island: the Manjang cave area in the northeast, and the Sochon cave area in the Hanlim region.

The Manjang cave area includes Songdang Cave, Dockchon, Sagul Cave, Kaenaegi Cave, Pocknamoo Cave, Pocknamoo mit Cave, Boojong Cave, Waful Cave in Chocheon, Immemerru Cave, Gonaiesl Cave, Yooktigie Cave. The Socheon cave area includes Hyopjae Cave, Jorong Cave, Sanhyong Cave, Large Chokit Cave, and Hwankeum Cave.

The temperature of magma extruding from the ground here was about 900° to 1,200° Celsius. The surfaces soon cooled but the inner parts of the flows remained molten for long distances. When they evacuated themselves, lava tube caves remained. This occurred extensively on Cheju Island.

Features of Cheju Island Caves

The volcanic caves of Cheju Island have scientific and other values because of their size, distribution, density, topography, and natural features. Some are among the longest in the world, and some of their natural features are exceptional. Among these features are the following:

Lava rod or column

These features are formed by molten lava cascading into a cave passage which previously had cooled. The most notable is 1,000 meters upslope from the main entrance of Manjang Cave. It is 7.6 meters high and is the largest in the world.

Lava ball

Lava balls are formed by solidification of aggregated lava in a stream of lava.

Lava bridge

Lava bridges are formed when the top of the lava flowing in a lava tube cave crusts and solidifies sufficiently to leave a floor of lava suspended from the walls.

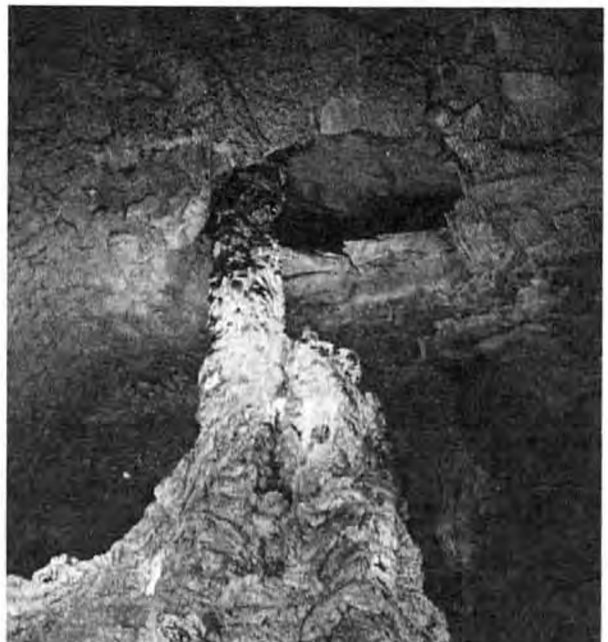
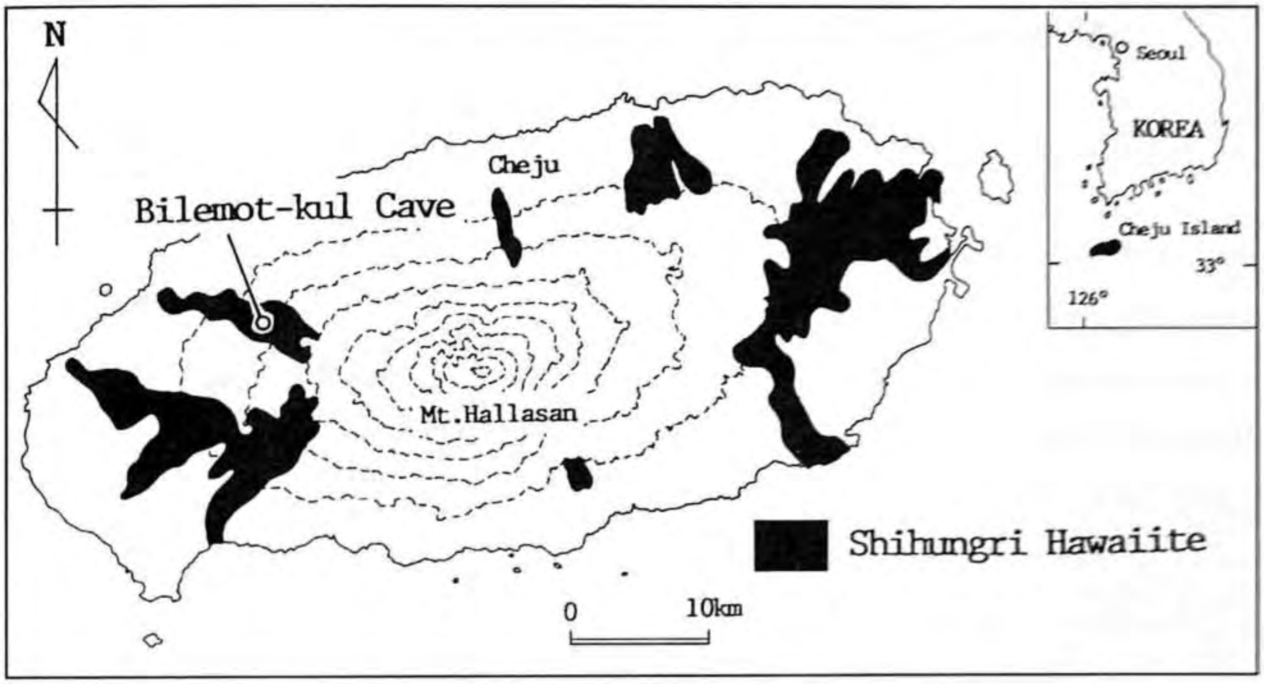


Figure 1—A double lava column, 7.6 meters high, cascading from a small upper level passage into the main passage of Manjang Cave. The right hand section is hollow.



Lava stalagmite

Lava stalagmites form from the piling-up of droplets of lava dripping onto a solid floor where they accumulate in a pile of solidified drops.

Lava stalactite

In some locations, hot lava solidifies when dripping from walls or ceiling like an icicle, forming lava stalactites.

Mini-Cave in Cave (Tube in Tube)

After formation of a lava tube cave, sometimes another lava stream flows along its bottom and produces a mini gaseous cave inside the original cave. This is called cave in cave or tube in tube.

Silica rod or column

Rarely, secondary silica stalactites develop in lava tube caves and extend to the bottom of the cave, forming rods. Those of Cheju Island are some of the most notable examples in the world.

Silication

Sometimes silicic acid in the liquid phase is deposited on the cave wall by gas. This is called silication.

Gas balls

Sometimes hollow droplets are attached to the wall or ceiling of a cave during lava flow. Originally they contained concentrated gases and are called gas balls. Gas balls on the floor are formed by incomplete extrusion of gas in the lava flow.

Ropy lava

Sometimes the weight of low-density lava on cave walls presses it downward in a wavy form. This is called ropy lava.

Lava ledge

Lava ledges are formed by solidifying of the top outer edges of flowing lava in a lava tube cave.

Meteorology of Cheju Island Caves

The temperature of Cheju Island caves is about 12° to 16° Celsius. The inner zones are almost at a constant temperature all year, although the entrance area temperatures differ considerably.

Biota in Cheju Island Caves

The lava tube caves on Cheju Island are young. Thirty species of animals are known only from caves, with one troglobite (*Epanerchodus clavisetosus*). Fifty-one surface species have been identified in caves here. Only three species are aquatic.

Mineralogy of Bilemot-Kul Cave in Cheju Island, Korea

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Introduction

Cheju Island is located the southernmost part of Korea, between 126°10′ to 126°57′ east longitude and 33°12′ to 33°34′ north latitude. It is composed mainly of alkali basalt lava flows, minor pyroclastic rocks, hyaloclastics, and numerous parasitic scoria cones of early Pliocene to Quaternary age.

After the 5th International Symposium on Vulcanospeleology held in Cheju Island in November 1988, the writers visited Bilemot-kul Cave for an investigation of speleo-minerals.

Bilemot-kul Cave

The entrance of Bilemot-kul Cave opens in Eum 2 Ri, Aewol Eub, Buk Cheju Kun, 33°24′01″N, 126°24′08″E. This cave is developed in the Sihungri lava (hawaiite) where the lava flowed against a ridge of the Pyosonri lava and stagnated. The narrow entrance barely allows a person to go through but leads to grand halls and an extremely complex cave system with branching and crossing horizontally and vertically. There is even a spiral passage between upper and lower parallel caves. The main cave is 2,917 meters long but the length of the complex branch cave system is 8,832 meters making the total length 11,749 meters.

Mineralogy

The mineralogy of the specimens was determined by X-ray powder diffraction analysis using a Shimazu Seisakusho Ltd. X-D 3A unit equipped with a copper tube and nickel filter and scanning microscope scrutinies using a JEOL JSM T-20.

The $<2\,\mu m$ size, suction collected, handpicked specimens were oriented on the glass slides with acetone.

Analytical results for specimens were as follows: Carbonates (calcite, trona), Phosphate (taranakite), Silicates (albite, opal, quartz), and Sulfate (gypsum).

Albite, (Na, Ca)(Si, Al)$_4$O$_8$. This mineral may be crystallized under syngenetic conditions.

Calcite, $CaCO_3$. Calcite speleothems occur as thin white crusts which are sublimates.

Gypsum, $CaSO_4 \cdot 2H_2O$. This mineral is a common speleo-mineral in volcanic caves, and occurs as white wall coatings which are sublimates.

Opal, $SiO_2 \cdot nH_2O$. Composed of amorphous silica, opal is a common speleothem (anthodite) in this cave.

Quartz, SiO_2. The mineral quartz is a syngenetic product in high temperature conditions. A 28-centimeter long siliceous pillar was found in this cave.

Taranakite, $(K, NH_4)Al_3(PO_4)_3(OH) \cdot 9H_2O$. In lava caves, taranakite occurs as a result of reactions between water leached through bat guano and the clayey cave deposits; the phosphorus and ammonium derived from the bat guano and the aluminium from the clay.

Trona, $Na_3H(CO_3)_2 \cdot H_2O$. The sodium and carbon dioxide gas for the mineral trona are derived from alkali basalt lava flows erupted from deeper (high pressure) igneous activity.

As to the origin of speleo-minerals in Bilemot-kul Cave, there are two main mechanisms: (1) Syngenetic (rock forming) and (2) Epigenetic (biochemical) processes.

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Volcanic Caves in Bulgaria

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Introduction

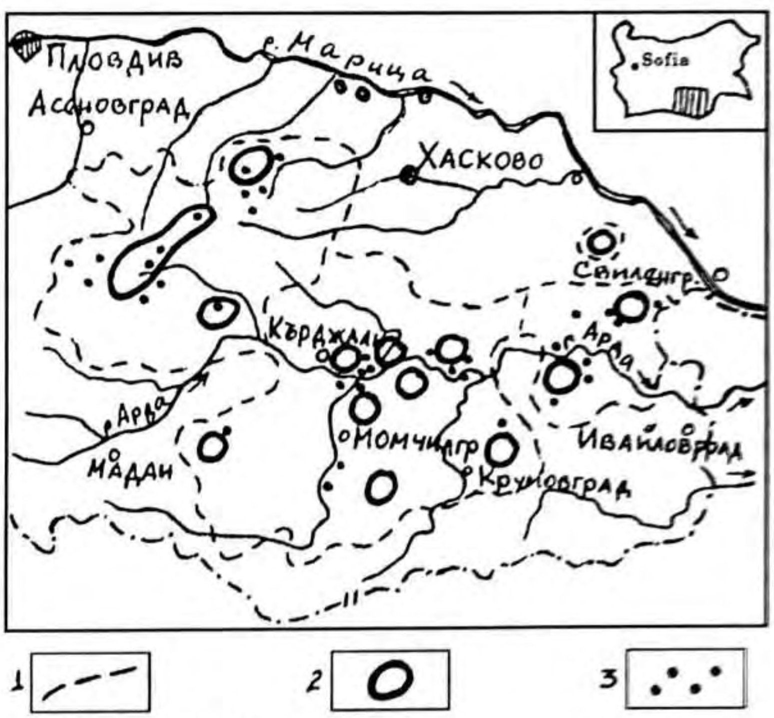
The largest area of the Balkan Peninsula covered with volcanic formations is in the eastern margin of the Rhodope Massif. Its area is about 3,600 square kilometers. The Rhodope paleovolcanism is one of the best known volcanic structures in Europe (Boyanov, 1961). During the Lower and Middle Oligocene, the eastern Rhodope underwent vigorous volcanic activity, with several stages at the bottom of a warm, shallow sea and partly above sea level (Tzankov and Spassov, 1968). The volcanic activity had several phases with simultaneous action of two magma sources. It was cyclic and possessed many central and unstable volcanic structures. Andesites, latites, trachytes, trachyandesites, dacites, rhyolites, tuff, and agglomerates are represented. Repeated deposits of submarine volcanics with marine sediments have undergone elevation of 2,000 to 2,500 meters (Tzankov and Spassov, 1968).

Within the eastern Rhodope paleovolcanics are three secondary structures:

1) Northeast Rhodope structure. This includes the prototypical "Borovichki" volcanic massif and a wide lava flood in the Metchkovetz, Dragonia, and Sini-vruh hills.

In this structure is a large ring-shaped volcanic structure (Dragoinovo) with a diameter of 16 by 19 kilometers (Spiridonov and Rivera, 1978).

2) Southeast Rhodope structure. This embraces a part of the middle drainage of the Arda River and a part of the southeast of the Rhodopes massif, with major volcanic constructions of several paleovolcanoes: Irantepenski, Dambalashki,



1. Граници на Източнородопската вулканична област
2. Палеовулкански структури (Paleovolcanic structures)
3. Вулкански пещери (Volcanic caves)

Yurkidendagski, Kardjaliyski, Perpereshki, Sveteileysky, and some smaller examples.

3) Madjavoro structure. This embraces the eastern part of the Rhodopes along the middle drainage of the Arda River. It includes the Madjarovo paleovolcano.

Some specialists use slightly different boundaries, but the differences are trivial (Boyanov, 1961; Galabov, 1937; Ivanov, 1960).

Many caves exist in this paleovolcanic area. They differ in size, morphology, and genesis. Until about 25 years ago, it was believed that such caves did not exist in Bulgaria, or, on the other hand, it was believed that such caves were of no interest to speleology (Trahteev and Georgiev, 1968).

In the past 25 years, more than 80 caves have been found in this area, thanks to research of members of the Aida Cave Club in the town of Haskovo. Since 1977 their research has followed a program of research on volcanic caves of the Bulgarian Federation of Speleology (Kolev, 1987).

Origin of Volcanic Caves in the Rhodopes

The Rhodope volcanic caves are the result of primary volcanic processes plus a series of exogenic and endogenic processes. Their origin and morphological characteristics are determined by specifics of the Rhodope paleovolcanism, characteristics of sedimentation, some post-volcanic processes, and several weathering processes: lateral erosion, denudation, suffosion, and thermal erosion.

In the specialized speleological literature there are several generic and morphological classifications of volcanic caves (Maksimovich, 1975). Basically there are two types of volcanic caves: primary and secondary.

Primary caverns are those formed during emptying of lava. These are lava tubes, lava pits (shafts or vertical conduits), gas bubbles, and caverns beneath lavafalls. In the Rhodopes, the last two types are common. Usually they have smooth walls and vaulted roofs. Some are enlarged by processes of physical weathering, suffosional undermining, lateral erosion, or other processes. Primary cavities served as a base for development of the larger caves. This is the origin of such caves as Prilepnata Peshtera (Bat Cave) and Gumburdek (Ringing Cave) in the middle Arda region; Kaleto II, III, IV in the region of the ring structure of Dragoinovo; and the caves near Madjarovo and on Sheinovetz Peak.

An example of a lava tube cave is Kaleto I on the slopes of a paleovolcano near Mostovo Village. This cave is about 30 meters long and up to four meters in diameter. Its ceiling is covered with lava pendants up to five centimeters long and with crystal gypsum druses up to five millimeters long.

Caverns beneath lavafalls are formed during the successive emptying of two lava streams. For example, Golymata Peshtera, with a total length of 51 meters, was formed by the emptying of a lavafall over previously cooled lava. In the middle Arda region, the caves called Topal Kadirovata Doupka and Malkata Peshtera have the same character. They are formed in a rhyolite canopy. Lateral erosion modified them.

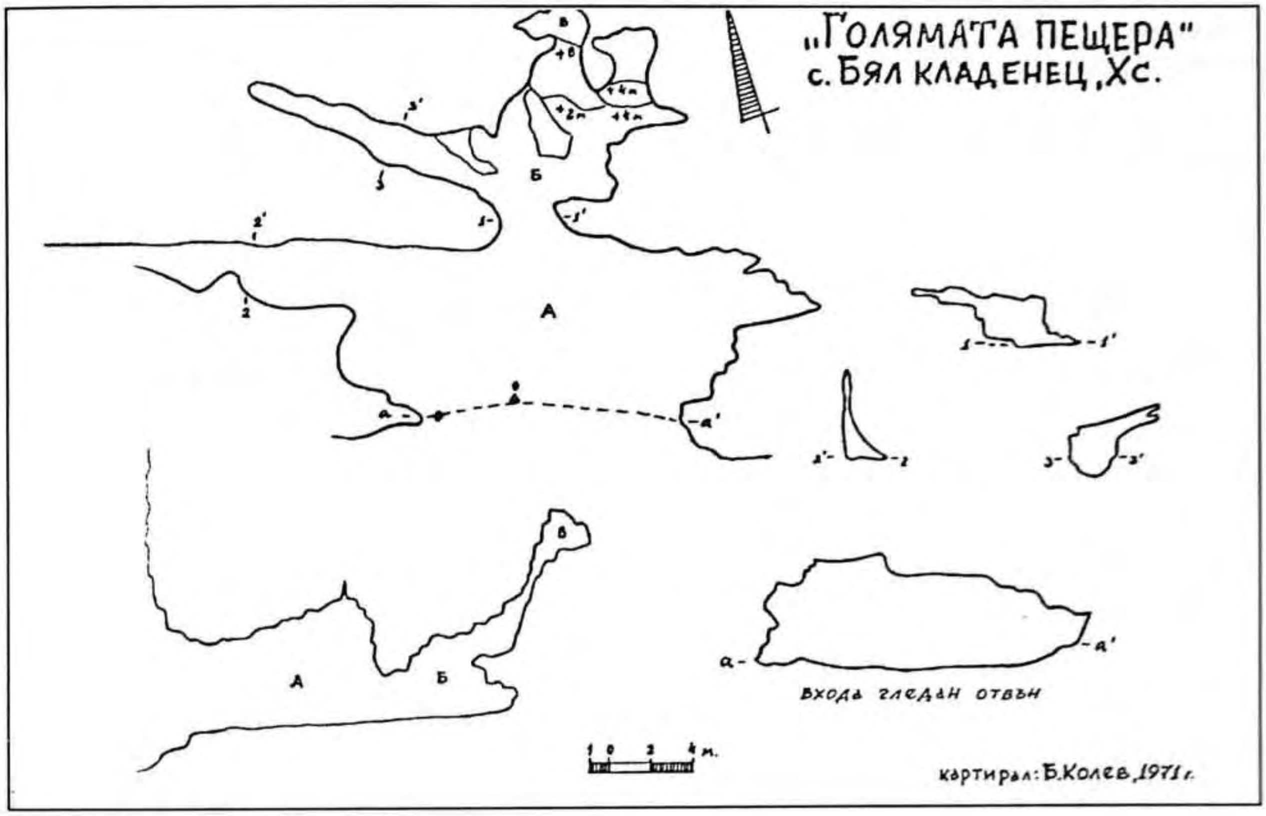
Secondary volcanic caves include all the caverns formed in lava and tuff, tuffite, and pyroclastic rocks by weathering and from falling water. In the Rhodopes there are several types:

1) Suffosion-erosional. These are mostly in tuff and are small. Suffosion and erosion are the main genetic factors. Examples are the cave near Dobrovoletz Village and the cave called Ogledalnata (passage) near Golobradovo Village.

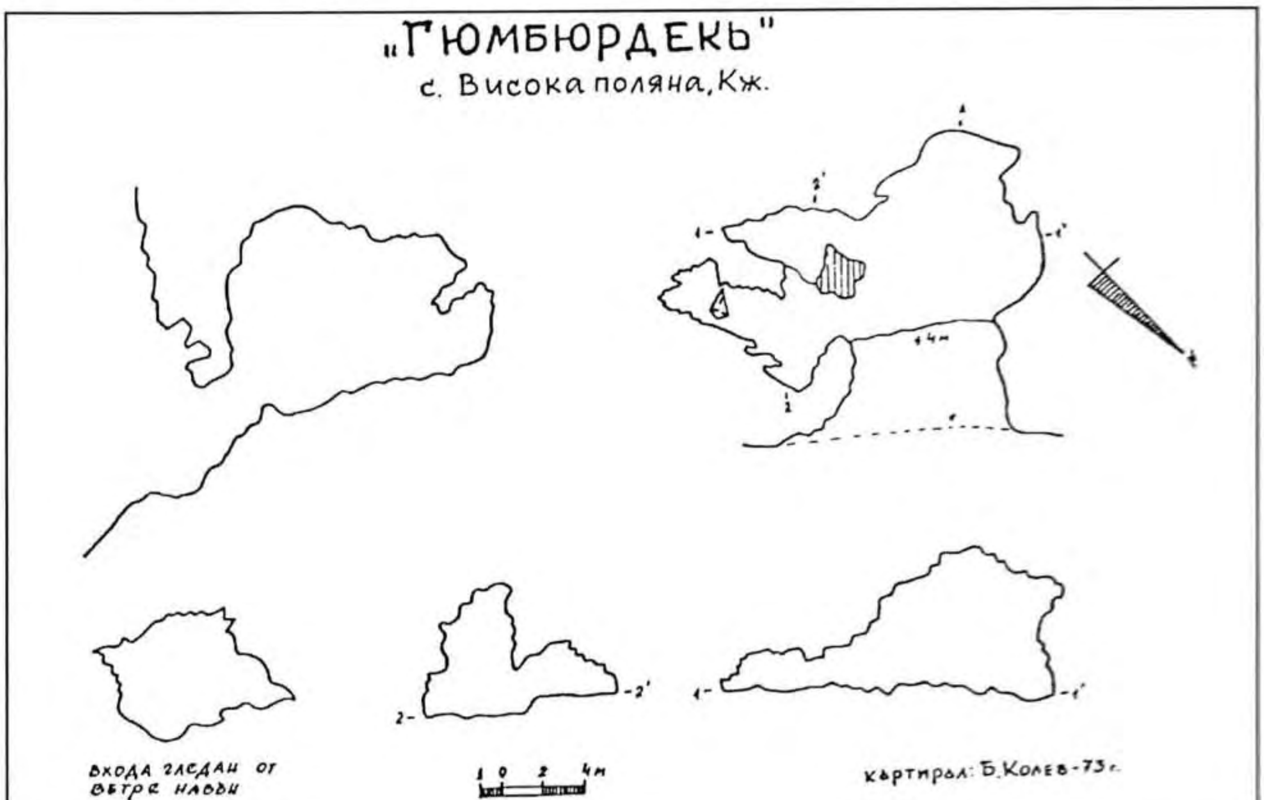
2) Lateral erosion. These comprise most of the volcanic caves of the Rhodopes. They are formed by lateral erosion in the valleys of the great rivers. They are found chiefly on contacts between the hardest lava rocks and underlying tuffs, tuff-breccia, lava breccia, and other pyroclastic rocks. They mark old lateral levels of the river. These include Vichegradskata, Podskalna 1 and 2 Caves, caves in the middle Arda region near Mostovo Village, and caves near Studen Kladenetz Gorge.

3) Denudo-erosional. These are caves formed in subvolcanic bodies (massifs), uncovered by denudation of the volcanic massifs. This is the genesis of most of the caves in the northeast Rhodopes structural depression and in the Dragoino ring structure, such as Jultata Peshtera, Probitiya·Kamak, Myurekovata Peshtera, Lipovitza, and so on.

4) Gravity-erosional. These are formed in blocky fissured volcanic rocks by supplemental enlargement and hollowing by erosion and other weathering processes. This is the character of



Golymata Cave (B. Kolev, 1971)



Gumburdek (B. Kolev, 1973)

Golyamata Peshtera near Nochero Village, Ivanov Kamak near Sarnitza Village, and others.

5) Rock bridges and arches. These are formed mainly in pyroclastic rocks as a result of lateral erosion and flowing surface waters, and are in valleys of the great rivers. They include Duptchen Kamak and Hobota in the middle Arda region and Probitya Kamak (Kolev, 1987).

The pattern of distribution of caves in the Rhodopes is not uniform. Twenty-six are known in the northeast Rhodope structure, 44 in the southwest structure, and 14 in Madjarovo. They are especially numerous in the valley of the Arda River and along the valleys of its tributaries, on the slopes of the Dragoinovo ring structure, around the crater of Madjarovo paleovolcano, and on high elevation denuded surfaces.

Secondary Minerals in the Volcanic Caves

Of the 227 cave minerals known (Shopov, 1989), 18 are known only in volcanic caves. Those of the Rhodopes are classified as follows:

1) Volcano-weathering. These are formed as a result of weathering of volcanic rock. This group includes gypsum, allophane, gibbsite, soda, and thermonatrite. Gypsum is represented by crystals two to five millimeters long on the ceiling of most of the caves. According to Hill and Forti (1986) it is the most common mineral of volcanic caves. Allophane is represented by a crust 50 centimeters long and 10 centimeters thick in Gyumburdek Cave. Gibbsite is represented by pale yellow porous sediments lavishly impregnated with soda and thermonatrite in Prilepnata Cave (Shopov *et al.*, 1987; Shopov, 1988). This is the second recorded observation of thermonatrite and third of soda in caves.

2) Volcano-guanogenic. These minerals are formed by the action of guano on the volcanic rocks, including acetamide, newberryite, and purpurite. Small quantities of acetamide are found in sediments of Prilepna Cave together with soda and thermonatrite (Shopov, 1988) and determines their brown color. This is the first recorded occurrence of this mineral in caves (Shopov, 1989). Newberryite and purpurite form a rose-colored crust in Gumburdek Cave. They are formed as a result of interaction of bat guano with the cave walls which

Prilepnata Cave

are the source of magnesium and manganese. This is the second recorded occurrence of purpurite and the fifth of newberryite in caves.

All the cited minerals were determined by x-ray diffraction analysis. Their further analysis will be published separately.

Other Interests

These caves also are of biospeleological interest. Troglophiles familiar to karstic biospeleologists are most common. In Prilepnata Cave in the middle Arda are about 1,200 individuals of the big horse-shoe nosed bat, *R. ferrumeguinum*.

Some of these volcanic caves are also important archaeologically. Vichegradska Cave was inhabited during the neolithic period and bronze age (Djambasov, 1958; Mikov, 1933). Some others were used for cultural purposes and for sanctuary by ancient Thracians, for Christian sanctuaries, and for shelter by the local population during the Middle Ages (Kolev, 1983).

Summary

Volcanic caves in Bulgaria have many interests and require multidisciplinary study. The dry climate and the presence of bat guano has resulted in the formation of several rare cave minerals.

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The State of Speleological Investigation of Volcanic Voids in the U.S.S.R.

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Abstract

In the U.S.S.R. there are many mountainous systems where, in various geological times, active volcanic processes took place. The evidence of this activity is provided by the presence of a variety of volcanic deposits. Caves developed in these deposits are of secondary origin and resulted from epigenetic processes such as denudation, erosion, suffosion, and man's activity. Caves developed in volcanic rocks are usually small in volume and numerous in number.

Volcanic caves proper formed as the result of volcanic activity are associated with areas of Quaternary eruptions (Caucasus) and recent volcanic activity (Kamchatka, Kurile Islands). Caves formed in the processes of outflow and gas escape in the lava (tube-like and sphere-like caves) have been revealed in the above regions. The largest lava caves, approximately 500 meters long, have been described in Kamchatka. It is worth mentioning in this connection that the study of lava caves in the U.S.S.R. is at the initial stage and we are looking forward to discovering new and most interesting caves.

In the general genetic classification proposed by the author jointly with V.N. Dubljansky, volcanic caves are referred to volcanogenetic subclass of endogeneous class of underground voids. Volcanic subclass includes three types of voids: explosive, extrusive, and geyser.

The Fajanita Cave (La Palma, Canary Islands): A Volcanic Cavity Originated by Partial Draining of a Dike

La Cueva de La Fajanita (La Palma, Islas Canarias): cavidad volcanica originada por el drenaje parcial de un dique*

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Abstract

The probable genetic process of a volcanic cave contained in a basaltic dike is pointed out. The eruptive fissure, which became a dike after solidifying, was partially drained when the inner lava flowed down, thus originating the cave.

Resumen

Se describe el posible proceso de génesis de una cueva volcánica desarrollada en el interior de un dique basáltico. Su origen ha sido interpretado como consecuencia del drenado parcial de una grieta eruptiva, al descender la lava que recorría su interior debido a un defecto de masa y a la acción gravitatoria.

Description of the cave

As shown on the map (Figure 5), the small branches of Fajanita Cave (cueva de la Fajanita) are vertical. Basically, the cave consists of a main gallery 250 meters long with its second half inside a buried volcanic cone.

The cavity opens to the outside through one entrance only, situated almost in the base of a high cliff, with a steep gradient (35°). After a short horizontal passage, it starts to descend, gently at the beginning and abruptly at the end.

In the less collapsed walls, grooves and small lava stalactites similar to the ones formed in typical lave tubes can be seen. This indicates that still liquid lava flowed inside the gallery.

The second half of the cave is inside a buried cinder cone where the dike became thicker.

Genesis

When a new emission vent opens in an eruptive fissure at a lower level than a previous one, it can create a remarkable decrease of the push or pressure that can cause a descent of the still fluid lava through the laminar conduit. The final result of this draining effect can be a totally or partially empty dike, or even a pit, under the mouth of the volcano.

* Este estudio se ha beneficiado en parte de la ayuda proporcionada por el proyecto concedido al GIET de la Universidad de La Laguna "Catalogo de cavidades volcánicas de Canarias," subvencionado por la Direcciân General de Medio Ambiente del Gobierno de Canarias. El segundo autor (J.L.M.) contá con ayudas del Excmo. Cabildo Insular de La Palma y de la Federación Territorial Canaria de Espeleología.

This phenomenon took place in Fajanita Cave. Today, scarcely 270 meters remains of what could have been a complex net of vertical labyrinths caused by the drainage of the dike.

Introducción

En la campaña de prospección y catalogación de cuevas realizada por el Grupo de Investigaciones Espeleológicas de Tenerife en la Isla de la Palma durante 1987, se localizó una cavidad de morfología muy distinta a la de las restantes de la isla. Su formación se interpretó como consecuencia del drenado parcial de un dique casi vertical. Este origen se aparta en cierto modo de las hipótesis actuales sobre la formación de cuevas volcánicas (Wood, 1977; Ollier, 1983; Ogawa, 1986) y quizás debido a que se presenta de forma bastante inusual, no se había tenido en cuenta en las clasificaciones de cuevas volcánicas existentes (Montoriol-Pous, 1973; Martín *et al.*, 1985).

Por otro lado, el presente descubrimiento contribuye a incrementar la importancia espeleológica de la Isla de la Palma, ya de por sí sobresaliente debido a lo espectacular de algunas de sus especies cavernícolas. En efecto, entre su fauna se encuentran el dermáptero *Anataelia troglobia* y el anfípodo *Palmorchestia hipogaea*, unos de los pocos troglobios conocidos en todo el mundo en sus respectivos ordenes (Martín *et al.*, en prensa).

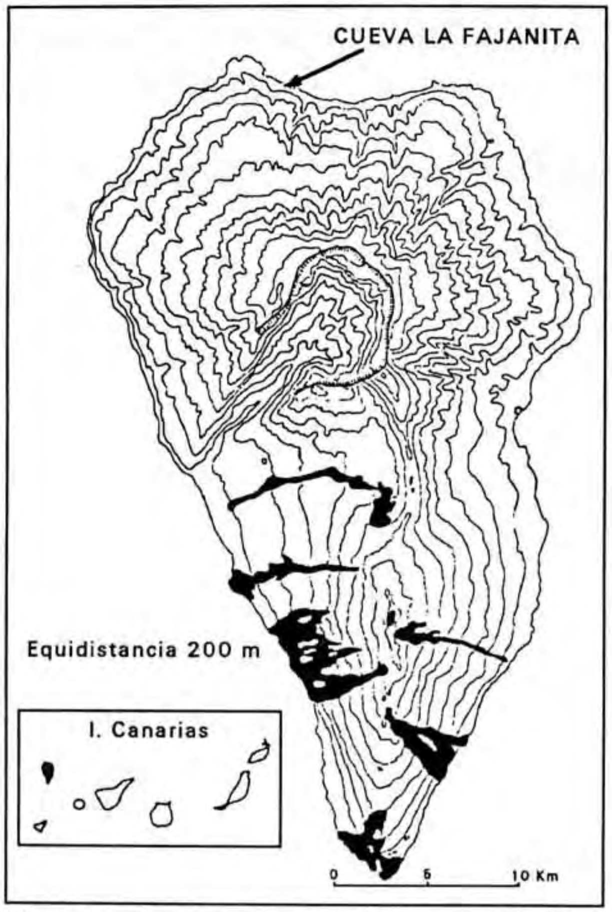

Figura1 – Situación geografica de la cavidad. En negro se representan las coladas históricas.

Figure 1 – Location of Fajanita Cave. Historic lava flows of La Palma are shown in black

Rasgos geologicos de la isla de La Palma

La Palma, situada en el extremo noroccidental del Archipiélago Canario es una de sus islas más jóvenes, con una antigüedad que no sobrepasa los dos millón de años (Nuez, 1985).

Su principal accidente geológico lo constituye una enorme caldera de erosión de unos 40 kilómetros cuadrados que se conoce como Caldera de Taburiente y que ocupa la zona central de su mitad norte. En los flancos exteriores de esta depresión, y en disposición radial hacia la costa, se encuentran profundos barrancos (Figura 1). La mitad sur, por el contrario, se muestra menos erosionada, en parte por ser aquí donde en los últimos milenios acaecieron varias erupciones volcánicas. Precisamente, en el extremo sur de la Palma tuvo lugar en 1971 la última erupción volcánica registrada en el Archipiélago Canario, la del Volcán Teneguía.

Pueden distinguirse tres unidades características: el complejo basal, las series antiguas, y las series recientes (Hernandez-Pacheco y Nuez, 1983).

Las series antiguas se han subdividido en cuatro categorias en función de sus distintas edades y constitución (Coello, 1987). La cueva objeto de nuestro estudio se encuentra en la serie antigua tres, que comprende toda la pared de la Caldera de Taburiente y el borde posterior hasta la costa norte, con algunos afloramientos intermedios de las series antiguas uno y dos, en fondos de barrancos.

La serie antigua tres parece corresponder al ciclo efusivo subaéreo más importante de la Isla. Esta serie estaría formada por un apilamiento de coladas, aglomerados y piroclastos basálticos, traquibasálticos y tefríticos (Coello, *Op. cit.*).

Figura 2. En la primera mitad, el dique es muy estrecho, contrastando con el final donde adquirió un gran espesor.

Figure 2 – The first stretch is very narrow in contrast with the second half.

Figura 3. En la parte superior de la imagen aparece una galería ascendente.

Figure 3 – An ascendent gallery appears at the top of the figure.

Las capas están atravesadas por una red de diques con un espesor de 0,5 a 2 meteros, predominando los de tipo basáltico y rumbo nordeste, aunque también los hay de orientacitón norte, norte-nordeste y oeste. Hay muy pocas dataciones sobre la edad de estos diques, siendo los más jóvenes de una edad entre 0,5 y 1 millón de años (Feraud, 1981). Esta fecha se correspondería con la mencionada etapa de intensa actividad efusiva de la serie antigua tres. En el interior de uno de estos diques verticales en la costa norte de la isla se formó la cueva que nos ocupa.

Descripción de la cueva

Tal como se representa en la Figura 5, las pocas ramificaciones de la Cueva de la Fajanita son en vertical. Está constituida en esencia por una galería principal de unos 250 metros de longitud,

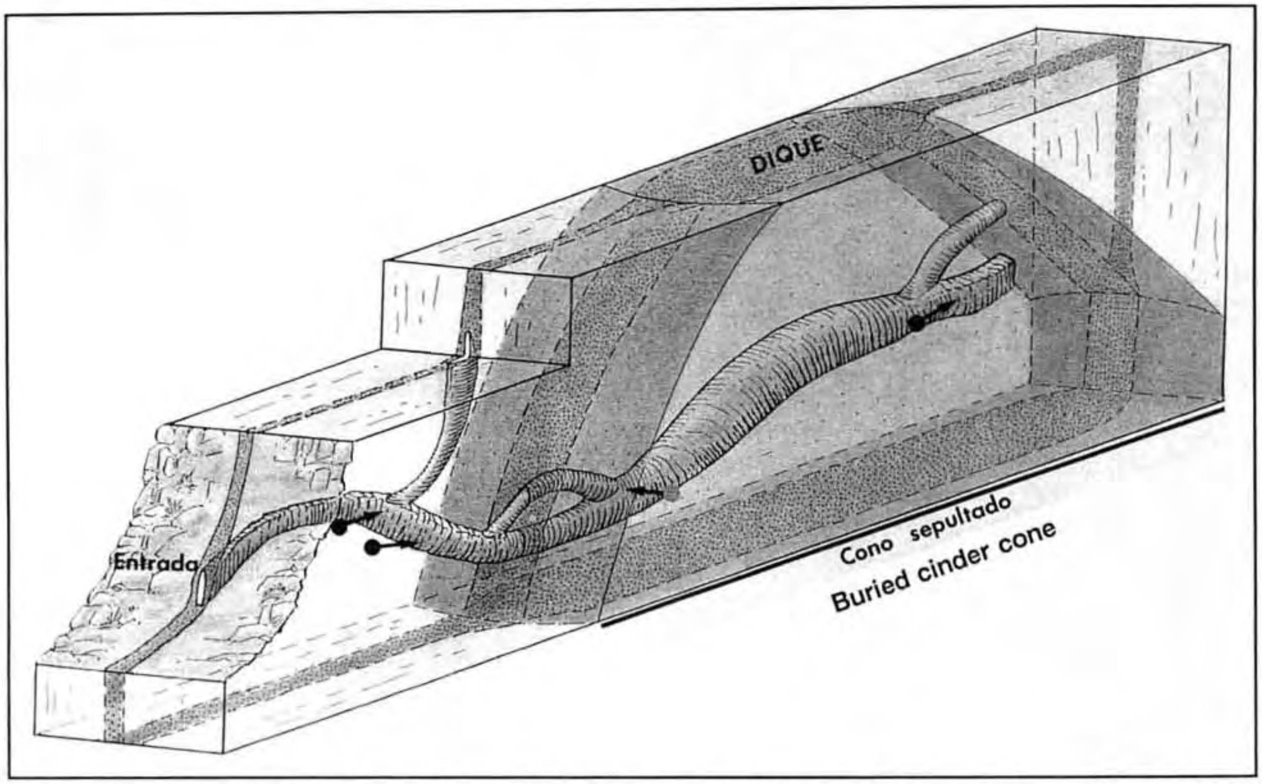

Figura 4—Esquema de al disposición espacial de al cavidad. La entrada se encuentra en la base de un acantilado costero.

Figure 4—Perspective view of the cavity. The entrance is situated at the base of a coastal cliff.

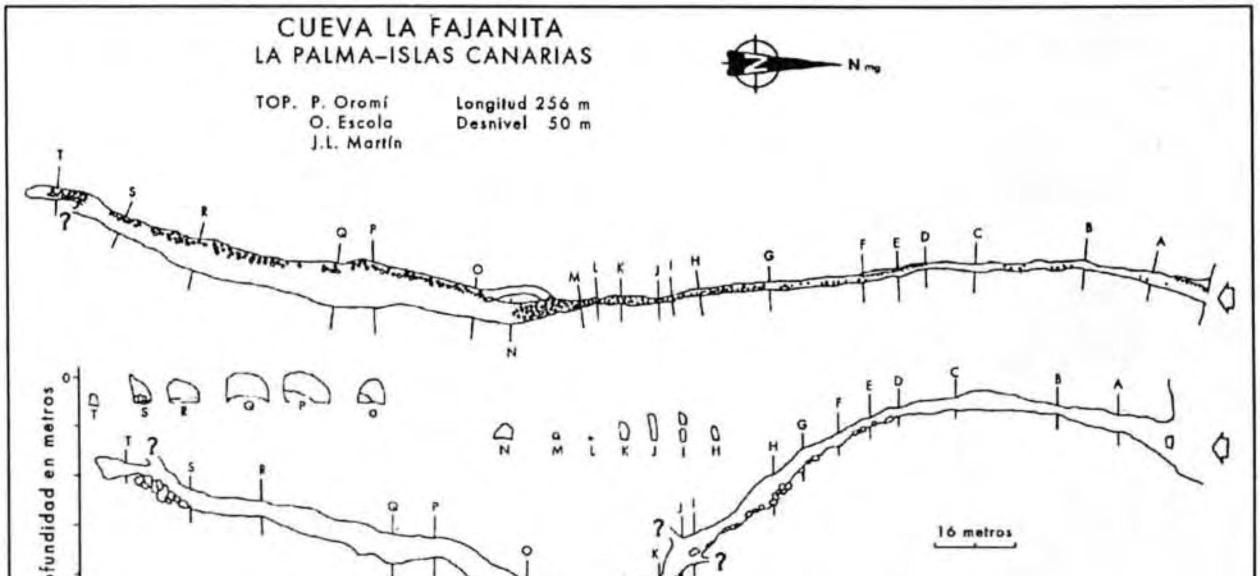

Figura 5—Topografía de la Cueva de La Fajanita.

Figure 5—Map of Fajanita Cave.

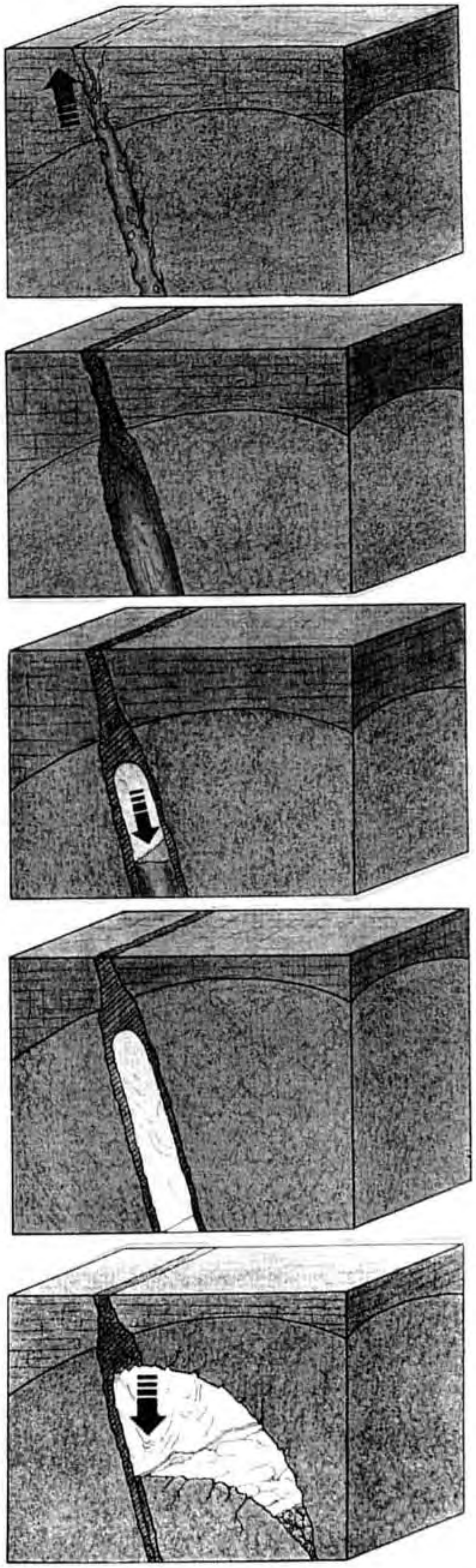

Figure 6—Schematic sequence of the widening of the dike in the buried cone and the later collapse of the final hall.

A. During the development of the eruptive fissure, the lava is injected into a buried volcanic cone carrying fragments of scoria and lapilli away and thus becoming much thicker. The difference of the thickness can be appreciated comparing Figures 3 and 6.

B. The magma cools slower in the thicker parts of the dike.

C. When the pressure decreases, the magma that was still liquid descended by gravity, leaving the dike partially empty.

D. As the dike is inclined and empty, a part of the buried cone remains without support and collapses.

E. The collapse widens the cave considerably.

encontrándose la segunda mitad inmersa en un cono volcánico sepultado.

Esta cavidad se abre al exterior por una sola boca, casi en la base de un potente acantilado, con una fuerte rampa de unos 35°. Despues de un corto trayecto horizontal, comienza a descender, primero pausadamente y luego de una forma más brusca. La inclinacitón media en esta zona es de unos 45°, aunque a veces la pendiente alcanza los 80°. Aproximadamente a unos 180 metros de la boca y después de descender unos 50 metros en vertical, se alcanza el punto más profundo. En todo este tramo de grandes pendientes las paredes del tubo se muestran consolidadas sólo en algunos lugares, mientras que en otros están bastante desgajadas.

En los tramos donde los desplomes han sido más intensos, los derrubios se acumulan en el suelo, siendo más abundantes sobre todo en las partes más profundas verticalmente. En estos segmentos es posible apreciar a ambos lados de la cueva la existencia de coladas horizontales que fueron atravesadas por el dique en el momento de su formación.

Donde las paredes apenas han sido derruidas se aprecian estrías e incluso pequeñas estalactitas de lava similares a las de los tubos volcánicos clásicos, lo que evidencia el discurrir de la lava aún bastante líquida por el interior de la galería.

En todo el tramo de cueva desde la boca hasta el lugar más bajo, las secciones transversales son por lo general más altas que su anchura y de dimensiones reducidas (Figura 2), pero a partir de aquí, su morfología cambia ostensiblemente (ver Figura 5). Este punto coincide con un estrechamiento debido al acúmulo de derrubios provenientes de las galerías a ambos lados.

En adelante y casi hasta el final, la cueva asciende con una pendiente media de unos 20° y las paredes están bastante derruidas, sobre todo en su lado izquierdo, lo que permite el afloramiento de los materiales encajantes en los que se inyectó el dique (Fotos 3 y 4). Se trata de piroclastos de fuerte tonalidad rojiza que al ser fácilmente disgregables han permitido el desplome de extensos bloques y el consiguiente ensanchamiento de la galería principal (Figura 6), originando secciones transversales – al contrario que en la primera parte de la cueva – más anchas que altas, que superan a veces los siete metros en ambas medidas.

Cerca del final de la cavidad, las paredes aparecen de nuevo bien consolidadas y la amplitud de la galería vuelve a disminuir configurando una sección transversal semejante a la de la primera parte de la cueva (Figura 8), pero más ancha,

Figura 7 – Punto donde comienza la parte inmersa en el cono sepultado.

Figure 7 – The second half is inside a buried cinder cone, where the dike became thicker.

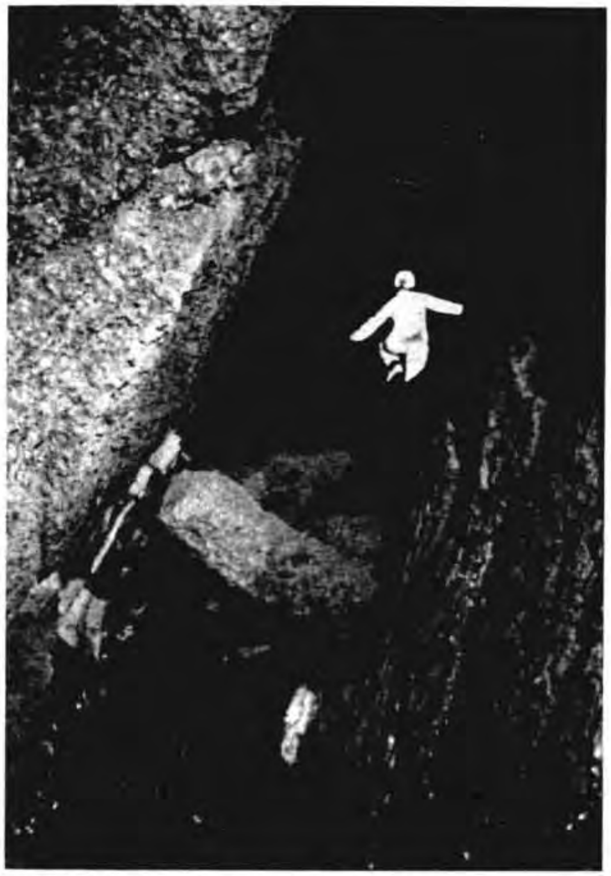

Figura 8—En el segmento final se coservan ambas paredes del dique hueco adheridas a las escorias y lapilli del cono volcánico sepultado.

Figure 8—Last segment of the cave. The walls of the empty dike are attached to the cone's cinder.

posiblemente debido a un mayor grosor del dique en esta zona.

Las pocas ramificaciones existentes determinan una disposición esencialmente vertical en la estructura tridimensional de la cueva, como es lógico al haberse constituido en el interior de un dique volcánico casi vertical. Algunas de estas ramificaciones no se exploraron debido a la dificultad de acceso, pero en cualquier caso, evidencian una cierta complejidad en la estructura de la cueva similar a la de los tubos volcánicos clásicos, pero estos últimos obviamente con una disposición básicamente horizontal.

Génesis de la cueva

Desde las profundidades en que se generan los magmas basálticos, el fluido asciende aprovechando alguna debilidad o fractura de la corteza. La propia presión del magma va propagando esta grieta hasta que alcanza la superficie, lugar donde se produce la primera boca eruptiva. Pero la lava puede seguir empujando dentro de la grieta a kilómetros de distancia y llegar a la superficie en otros lugares, produciendo nuevos puntos eruptivos que estarán alineados entre sí.

Si los puntos finales se encontraran a una cota sensiblemente inferior a los iniciales, estos quedarían sin el suficiente empuje o presión, pudiendo llegar incluso a cesar por completo el aporte de magma. Como consecuencia, si la lava que llena la grieta eruptiva permaneciese líquida en su totalidad al menos en las partes más gruesas del conducto, podría descender por gravedad dejando semivacía la grieta por la que antes ascendía con violencia. El resultado final puede ser una red laberíntica vertical producto del drenaje de la lava.

Esta cueva tiene además la particularidad de que en su segmento final, la grieta eruptiva se desarrolló en el seno de un cono volcánico sepultado, por lo que adquirió un mayor grosor al ser más fácil, en este material disgregado, arrastrar fragmentos. Por otro lado, al ser mucho mayor el espacio vacío en esta zona, y tener el dique una cierta inclinación, se produjo un enorme desplome que afectó a todo este sector (Figura 6 y 7), salvo los metros finales de la cavidad (Figura 8).

Agradecimientos

Agradecemos la colaboración de O. Escolá y P. Oromí en el trabajo de campo para la elaboración de la topografía de la Cueva la Fajanita. Además debemos hacer una mención especial al apoyo mostrado por la Dirección General de Medio Ambiente en la Isla de la Palma, y en concreto a la persona de C. Alba por todas las facilidades proporcionadas durante las campañas de prospección espeleológica en esta isla. Por último vaya nuestro agradecimiento a las instituciones que contribuyeron económicamente a la realización del estudio así como a Helga G. Court y A. Hernández-Pacheco por sus respectivos comentarios críticos al presente artículo.

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Volcanic Caves in El Hierro Island, Canary Islands, Spain*

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Abstract

The complete catalogue of volcanic caves from El Hierro Island (Canaries) is presented. The total number of caves known up to today is 35, of which 27 are lava tubes, 7 are pit caves and 1 is a pit-tube. The unpublished maps of 10 caves are shown as well as a brief commentary about their more relevant geological and biological features.

Introduction

El Hierro Island, with an area of only 278 square kilometers and maximum age of between one and three million years (Abdel-Monem *et al.*, 1972), shows a great number of caves of volcanic nature. This is mostly due to the youth of the lava flows spread all over the insular area (only a few thousand years) together with the basal character of the materials of which they are made.

Background

Among the caves of El Hierro Island, one, called "Cueva de Don Justo," is outstanding for its great length. It, with its 6,315-meter total length, has motivated the presence in the island of several speleological expeditions.

The first report we have about speleological exploration in the island is dated from 1961. In that year a local speleological group – surely the first one in the Canary Islands – called "Grupo Herreño de Espeleologóa, Montañismo y Escalada" (GHEME) was established. Even though its work was never published, the members of this group achieved the first exploration and mapping of the Cave of Don Justo.

More recently, in the year 1974, the Department of Crystallography and Mineralogy of the University of Barcelona and the Group for Underground Exploration of the Club Muntanyenc from Barcelona started with the mapping of this cave (anonymous, 1975; Montoriol-Pous and De Mier, 1977). In the year 1976 the Speleological Exploration Team of the Exploration Center of Cataluña visited it again. In 1978 another exploration by the same catalan group together with the Speleology Branch of the Exploration Society of Malaga, finished the survey of this cave (Montoriol-Pous *et al.*, 1979).

At that time, only five caves of the island were known to speleologists: the above mentioned, three more of the subaerial type discovered during 1974's exploration (Montoriol-Pous and De Mier, 1980), and an old report about the "Cueva

* This work has been completed in the field of the research project called "Scheme of Preparation of a Caves Catalogue in the Canary Islands. I. The Western Islands: La Palma, El Hierro and La Gomera" given to the Department of Animal Biology (Zoology) of La Laguna University by the Canarian Executive Power's General Administration of Environment, November 1986.

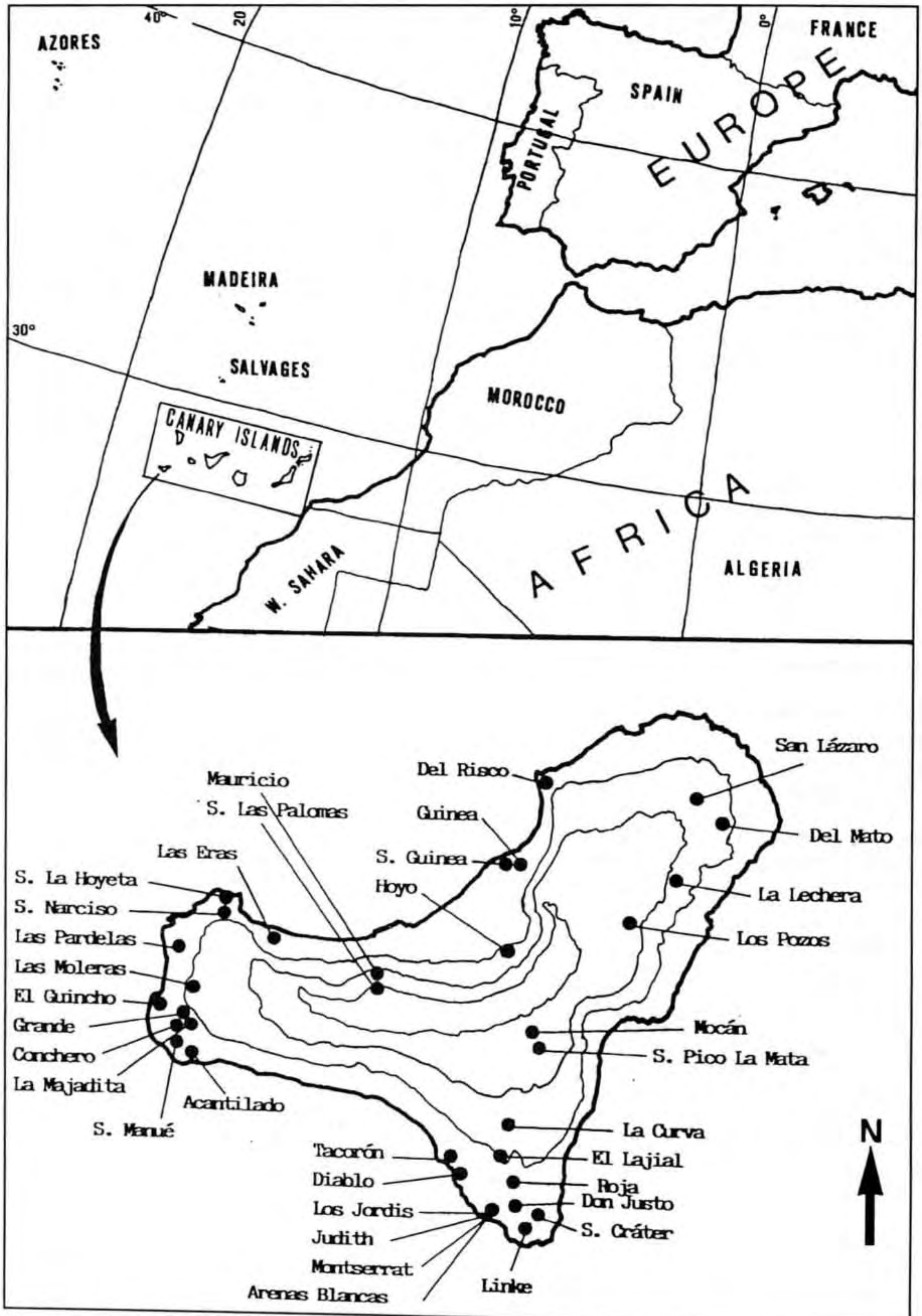


Figure 1 – Location of volcanic caves in El Hierro Island (Canaries - Spain).

del Hoyo" at the beginning of this century (Fernandez Navarro, 1908). Nevertheless, the information we had about the island showed a greater quantity of lava tubes. For this reason we decided to complete various explorations in order to increase the speleological chart of El Hierro and also biological studies, so as to demonstrate whether or not cave fauna is possible inside these tubes.

For this purpose, the Group of Speleological Researchers of Tenerife (GIET), from the University of La Laguna, has made two trips to the island during the months of April and May 1984, which resulted in the study of 16 caves. This work was published in the II Regional Symposium of Speleology which took place in Burgos (Spain) in 1984 (Martín et al. 1985a, Socorro, 1985) and in the 9th International Congress of Speleology, which took place in Barcelona, Spain, in 1986 (Socorro, 1986). Afterwards, the authors went on with this work during various visits to the island (May 1985; May, December 1986; March, April, and November 1987) the results of which are the basis of this report.

Results

For the time being, as a result of these last explorations, 35 caves are known, spread all over El Hierro. Among them, seven are of the volcanic pit type, the biggest being the "Sima de Las Palomas" with a depth of 75 meters. Among the 28 lava tubes known, the longest one is the already mentioned Cave of Don Justo, the third volcanic tube of Canary Islands and one of the longest of the world.

Table I shows the caves known to date, with data of interest such as location, length, whether there is a map or not, interest, and degree of preservation. In some cases, the interest is purely a geological one, while in others it is outstanding botanical and zoological outlooks (Martín *et al.*, 1987). Some caves are of archaeological value since they have been used during historical periods by the "bimbaches" i.e. primitive inhabitants of the island. Others are of paleontological value, since inside can be found remains of bones of big vertebrate species now extinct (Izquierdo *et al.*, 1989). The location of each cave is shown in Figure 1.

Report of the Caves Studied

Following is the topographic study completed in the caves of Linke, El Mocan, Los Pozos, Taco-ron, La Curva, and Roja and the pits of Guinea, Crater, Las Palomas, and Pico La Mata, with a brief description of each cave and comments about the fauna found inside.

Cave of Linke

Location: La Restinga (Frontera)
UTM: 28BR067635
Length: 290 meters

Description: The cave is situated at 800 meters on the east side of Mount Prim, between a lot of small ovens ranked up to the coast. Its only entrance is at an altitude of 150 meters above sea level, it is tight and of a trigonical shape. The hole gives access to an ascending tube 60 meters long and another descending tube of approximately 300 meters. There is a lot of dust inside, such a quantity that the numerous lava stalactites buried in the ground can hardly be seen.

Biology: The cave shelters species peculiar of the underground environment of the island. Some of them, such as the earwig *Anataelia lavicola* Martín and Oromí or the cockroach *Loboptera ombriosa meridionalis* Martín and Izquierdo, are essential to the ecosystem of the Cave of Don Justo, which is within one kilometer.

Cave of Mocan

Location: El Pinar (Frontera)
UTM: 28BR037694
Length: 214 meters

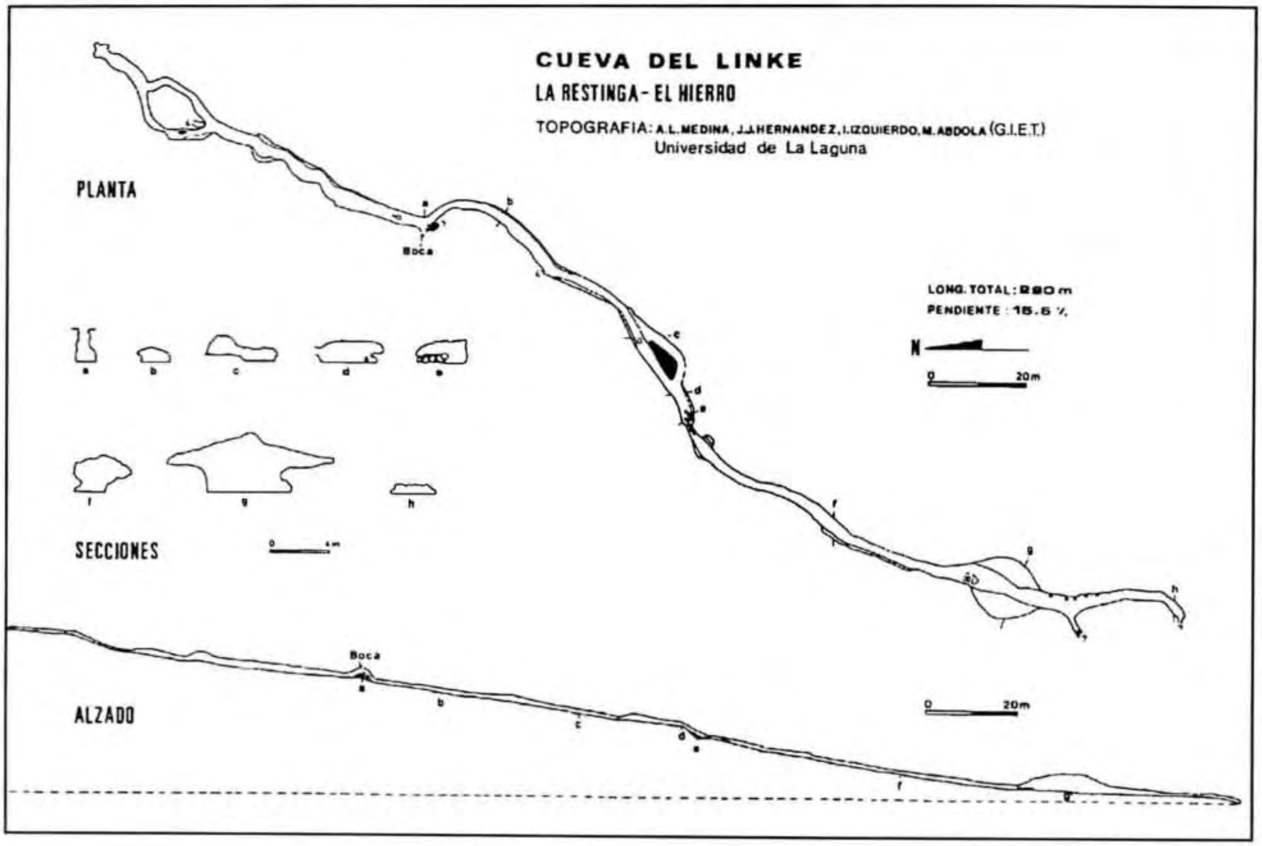
Description: A lava tube with only one entrance on the upper end at a height of 1,100 meters above sea level. The tube, of an average height of seven meters, is large throughout all its length. In the middle area there is a small split in the roof, where a beam of light can find its way through. The appearance of the cave shows that it is often frequented since varied rubbish is found inside.

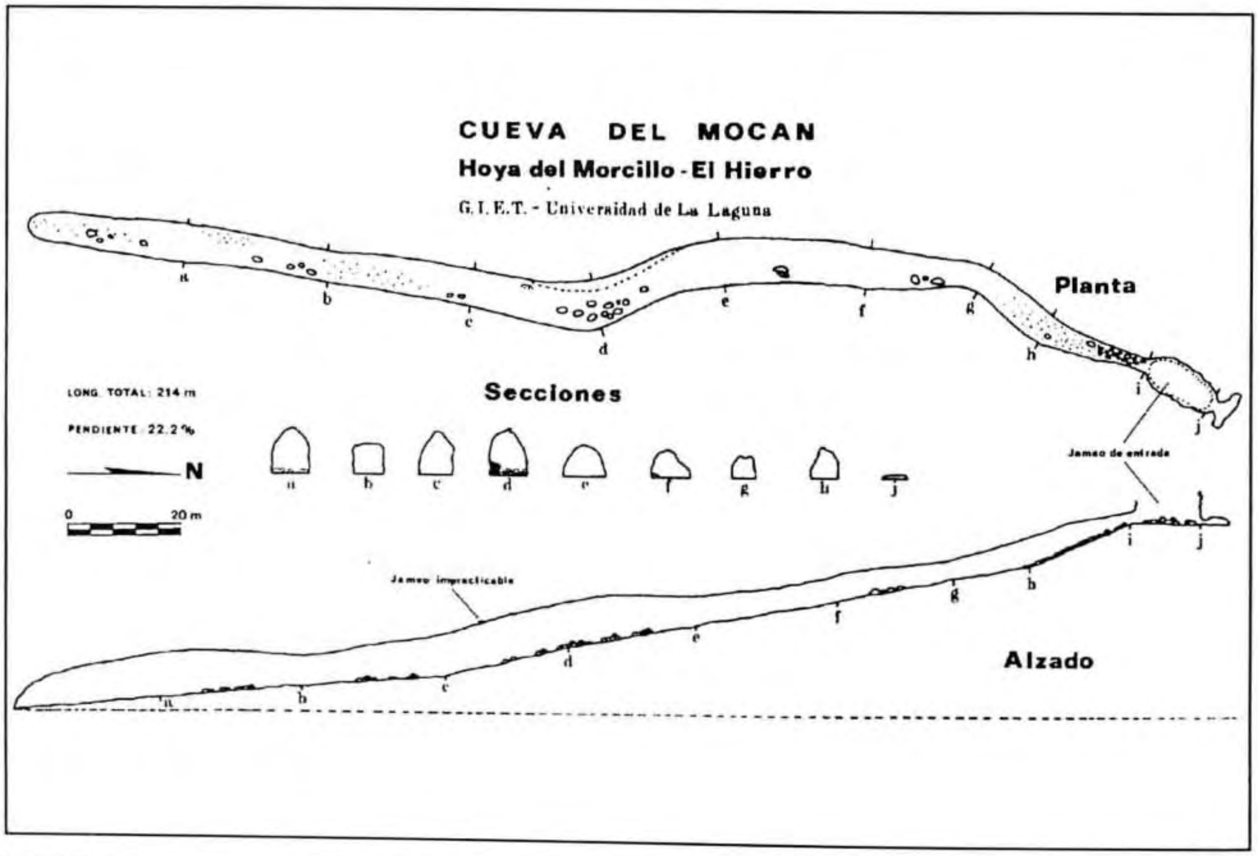
Biology: The invertebrate fauna seems to be very poor. The discovery of subfossil remains of giant lacertids stands out.

Caves of San Andres or Los Pozos

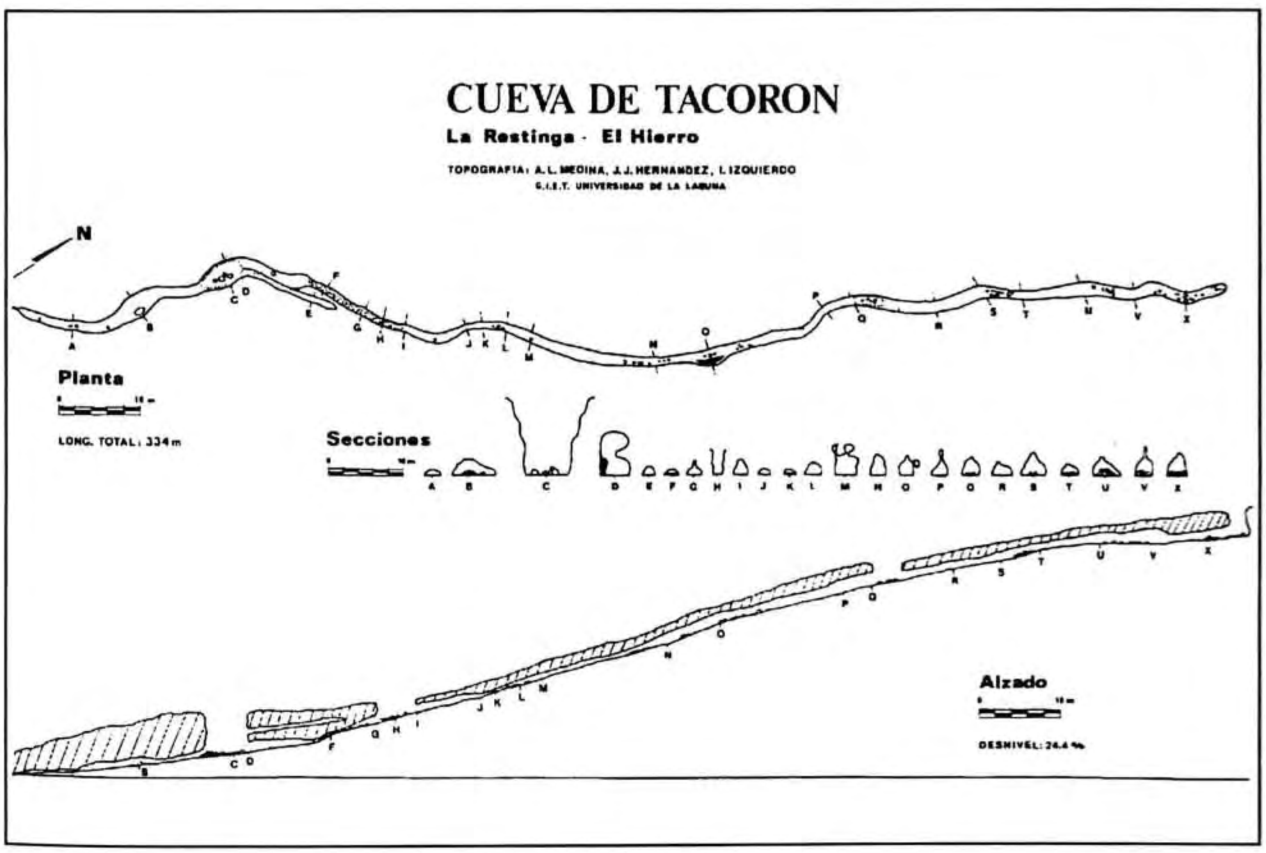
Location: San Andres (Valverde)
UTM: 28BR082741
Length: 390 meters

Description: This is a small area of three ranked caves, with a total of five entrances situated at an elevation of 1,000 meters. The extreme west entrance is a closed oven eight meters deep that can only be entered with ropes. The middle


CUEVA DEL LINKE
LA RESTINGA - EL HIERRO
TOPOGRAFIA: A.L.MEDINA, J.J.HERNANDEZ, I.IZQUIERDO, M.ABDOLA (G.I.E.T.)
Universidad de La Laguna
PLANTA
Boca
LONG. TOTAL: 290 m
PENDIENTE: 15.5 %
N
0 20m
SECCIONES
Boca
ALZADO
0 20m


CUEVA DEL MOCAN
Hoya del Morcillo - El Hierro
G. I. E. T. - Universidad de La Laguna
Planta
LONG. TOTAL: 214 m
PENDIENTE: 22.2 %
N
0 20 m
Secciones
Jameo de entrada
Jameo impracticable
Alzado


N
CUEVA DE LOS POZOS
SAN ANDRES (EL HIERRO)
TOPOGRAFIA: A.J. HERNANDEZ, A.L. MEDINA, I. IZQUIERDO, M. ABDOLA
(GIET) UNIVERSIDAD DE LA LAGUNA
PLANTA
ALZADO
SECCIONES


CUEVA DE TACORON
La Restinga - El Hierro
TOPOGRAFIA: A.L. MEDINA, J.J. HERNANDEZ, I. IZQUIERDO
G.I.E.T. UNIVERSIDAD DE LA LAGUNA
N
Planta
LONG. TOTAL: 334m
Secciones
A B C D E F G H I J K L M N O P Q R S T U V X
Alzado
DESNIVEL: 24.4 %

Cave	Locality	Length (m)	Map	Interest	Preservation
Sima de Marciso	Arenas Biancas	-29	Yes	Geol	Good
Sima de La Hoyeta	Arenas Biancas	-26	Yes	Geol	Good
Cueva Las Pardelas	Lomo Negro	180	Yes	Geol/Zool	Acceptable
Cueva Cuaclo Las Moleras	La Dehesa	170	Yes	Zool/Archaeol	Acceptable
Cuava Grande de Orchilla	Pta de Orchilla	85	No	Archaeol	Acceptable
Cueva del Conchero	Pta de Orchilla	80	No	Archaeol	Acceptable
Cueva del Guincho	Pta de Orchilla	20	No	None	Acceptable
Cueva La Majadita	Pta de Orchilla	50	No	None	Acceptable
Sima de Manué	Pta de Orchilla	-15	No	Geol	Acceptable
Cueva del Acantilado	Pta de Orchilla	401	Yes	Geol	Good
Cueva de Judith	La Restinga	120	Yes	Geol	Good
Cueva de Los Jordis	La Restinga	46	Yes	Geol	Good
Cueva Monserrat	La Restinga	114	Yes	Geol	Good
Cueva de Arenas Blancas	La Restinga	95	No	None	Acceptable
Cueva del Linke	La Restinga	290	Yes	Geol/Zool	Good
Sima del Cráter	La Restinga	-36	Yes	Geol	Acceptable
Cueva de Don Justo	La Restinga	6,315	Yes	Geol/Zool	Good
Cueva Roja	El Lajial	300	Yes	Geol	Good
Cueva de Tacorón	El Lajial	334	Yes	Geol/Zool	Acceptable
Cueva del Lajial	El Lajial	??	No	Geol/Zool	Good
Cueva de La Curva	El Pinar	141	Yes	Zool	Aceptable
Sima Pico la Mata	El Pinar	-23.5	Yes	None	Acceptable
Cueva El Mocán	El Pinar	214	Yes	Tourist	Acceptable
Cueva de Los Pozos	San Andrés	390	Yes	Zool	Acceptable
Cueva La Lechera	Isora	??	No	None	Acceptable
Cueva San Lázaro	Echedo	~100	No	None	Acceptable
Cueva del Mato	Valverde	20	No	None	Acceptable
Cuevas de Guinea	Frontera	30	No	Archaeol	Aceptable
Sima de Guinea	Frontera	57 (-8.7)	Yes	Zool/Tourist	Good
Cueva del Hoyo	Frontera	247	Yes	Geol/Zool	Good
Sima Las Palomas	El Golfo	300 (-75)	Yes	Geol/Zool/Bot	Good
Cueva de Mauricio	El Golfo	193	Yes	Zool/Geol	Good
Cueva Las Eras	Sabinosa	80	No	None	Acceptable
Cueva del Diablo	La Restinga	20	No	Tourist	Acceptable
Cueva del Risco	Frontera	40	No	None	Acceptable

Table 1 – Relation of all volcanic caves known to date in El Hierro Island (Canaries).

cave has two entrances and is 26 meters in total length. The extreme east cave is the biggest with two entrances and a total length of 350 meters. At that point the cave presents a high degree of wetness and shows a great adduction of organic material from the outside. There are ponds some meters long and the stratum is made of muddy deposits.

Cave of Tacoron

Location: El Lajial (Frontera)
UTM: 28BR032642
Length: 334 meters

Description: This is a volcanic tube with four entrances all along its length, located at 500 meters above sea level. It presents a pronounced slope due to the dip of the soil on which it formed. From the lower entrance a small gallery starts upwards until reaching the upper level, about 20 meters long. The four entrances are not the usual type of collapse but seem to have originated during the geological formation of the tubes. Its morphology shows the ups and downs of the lava flow, which seems to demonstrate that the holes were genuine lava drains.

Biology : The presence of the earwig *Anataelia lavicola*, also to be found in other caves of the lowlands, is interesting.

Cave of La Curva

Location: El Pinar (Frontera)
UTM: 28BR069667
Length: 141 meters

Description: This is a small lava tube, located at a height of 400 meters, beneath the road leading to Taibique. It presents two overlapped tubes, the upper one with only 40 meters of length. At its lower end the cave is obstructed by landslides.

Biology: In spite of its short length, the cave shows a great biological wealth. Inside, both humidity and temperature are high and the cave has many roots covering the floor and walls. The fauna found includes the cockroach *Loboptera ombriosa meridionalis*, a small troglobitic Fulgoroid (Cixiidae), and another Fulgoroid belonging to the family Meenoplidae, possibly *Meenoplus canavus* Rename and Hoch, also found living in the Cave of Don Justo (Hoch and Asche, 1988).

Roja Cave

Location: El Iajial (Frontera)
UTM: 28BR043642
Length: 300 meters

Description: This cave is only a hole, just on the crater of Mount Julan at a height of 350 meters. This hole takes one to a tube of great magnitude which shortly divides into two branches. The one from the right goes gradually downward. It reaches a 70 percent slope at some points, and then continues level until its deepest point. The branch to the left is tighter, with scarcely any dip until is gets to a point where the tube changes into a real volcanic cavern of about 12 meters depth. As we step downward, it enlarges and grows so as to form a big vault with layers of different colors on its walls.

In some stretches of the cave one can observe how the basaltic plaques have fallen from the walls showing a pyroclastic stratum of the lapilli type. This stresses the point that the lava flows that originated Roja Cave excavated under the material covering the surface of the area, which in that particular case is a large stratum made of pyroclastic materials.

Pit of Guinea

Location: Guinea (Frontera)
UTM: 28RB047756
Length: 57 meters (-8.7 meters)

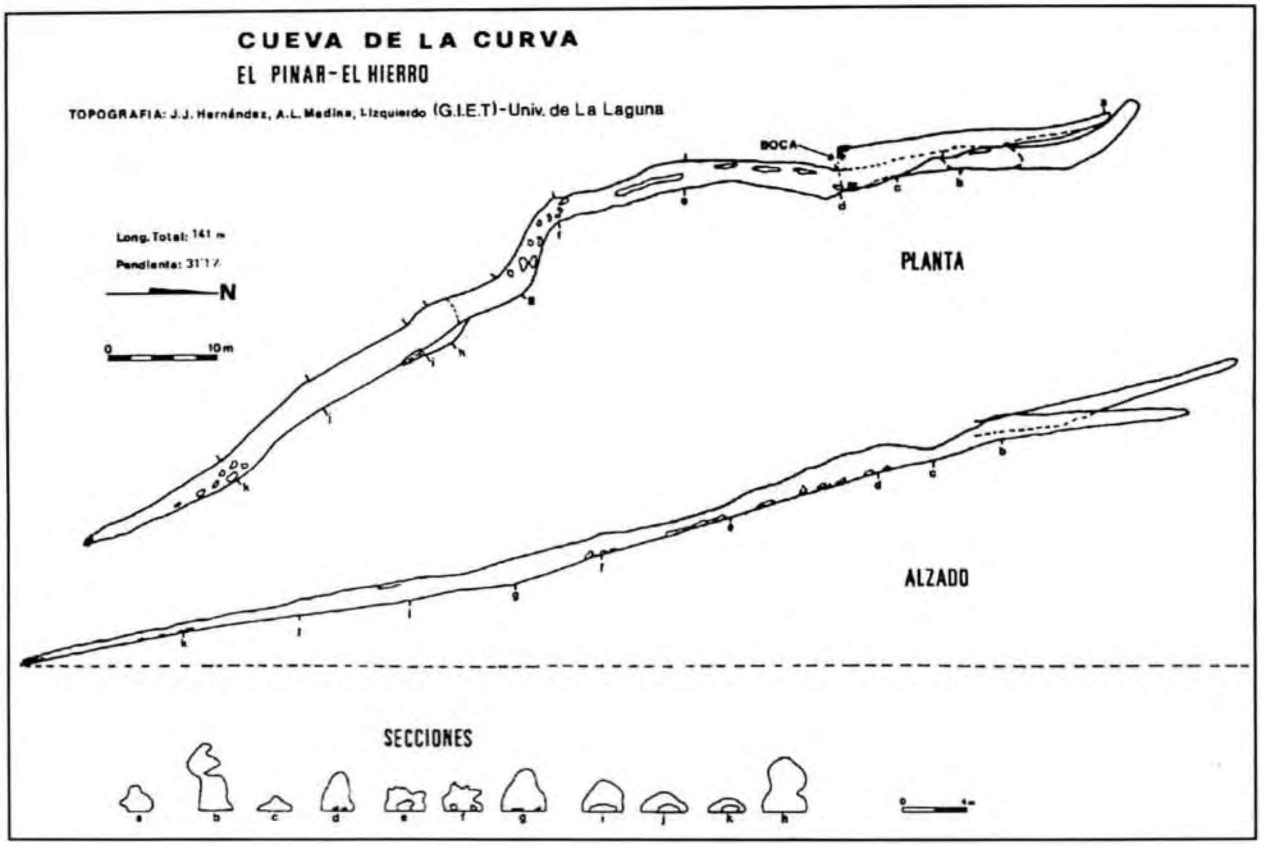
Description: A small lava tube belonging to the Guinea's Cave area, at an elevation of 95 meters. Ropes are necessary to enter since the only entrance is collapse of the roof of a big cavern 8.7 meters high. From there starts a large tube 57 meters long, running southeast to northwest. There is an important deposit of clay covering the whole cave and even closing both ends of the tube.

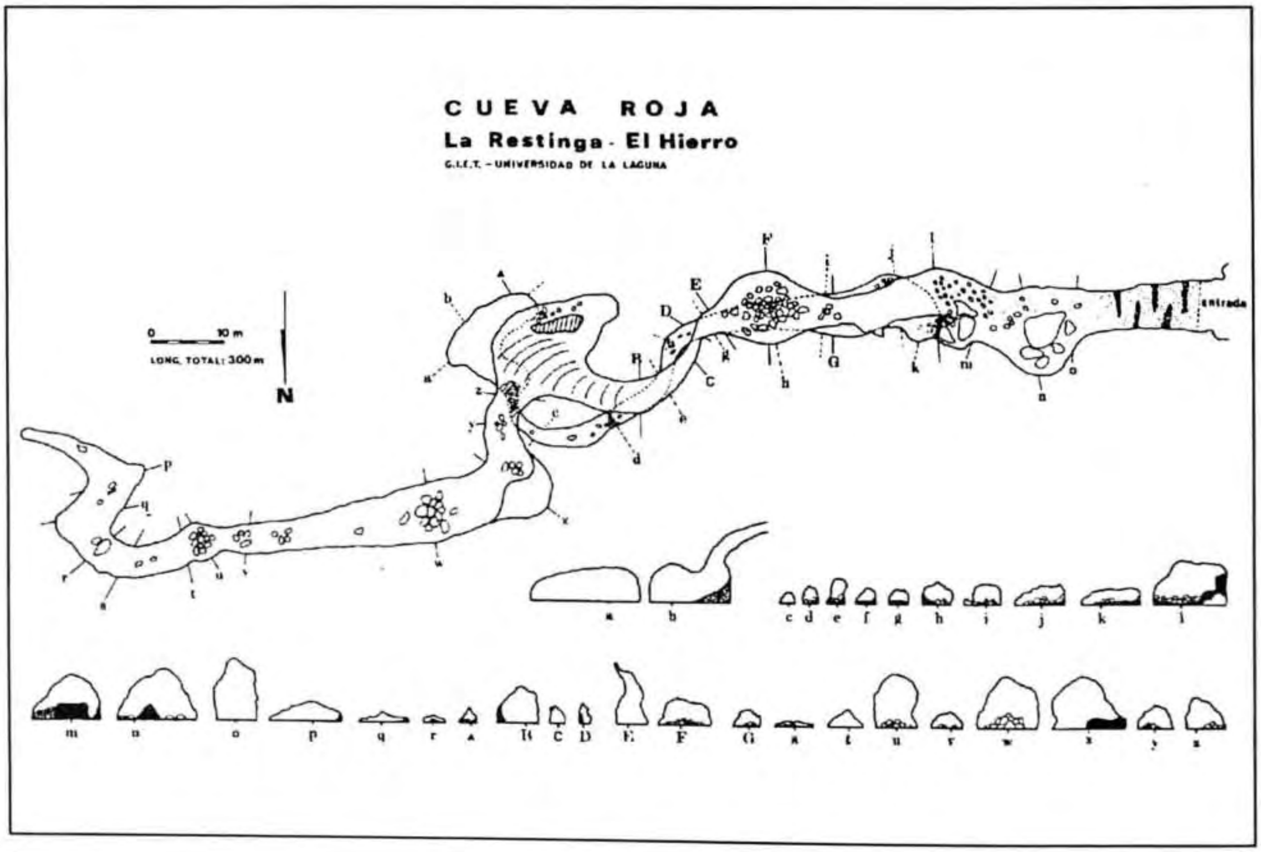
Biology: Outstanding is the presence of Curculionidae beetles of the group *Paratorneuma*, spiders belonging to the Linyphiidae and Dysderidae families, and other species of springtails, gastropods, woodlice, and so on. Bones of lizards and goats can be observed which proves a former communication with the outside, now disappeared, since the entrance hole existed only a few days before our exploration. It is possible that the clay deposit on the inside could have a paleontological interest.

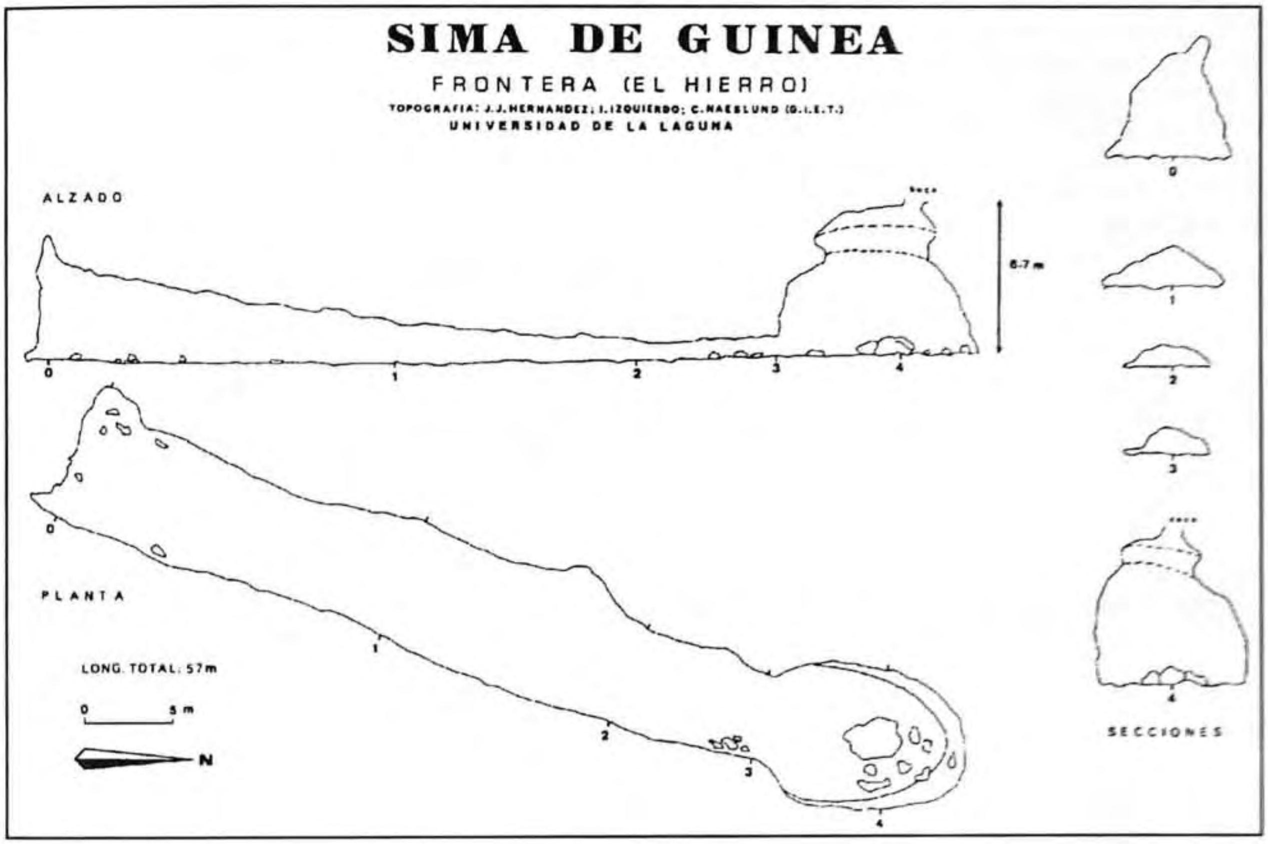
The Crater Pit

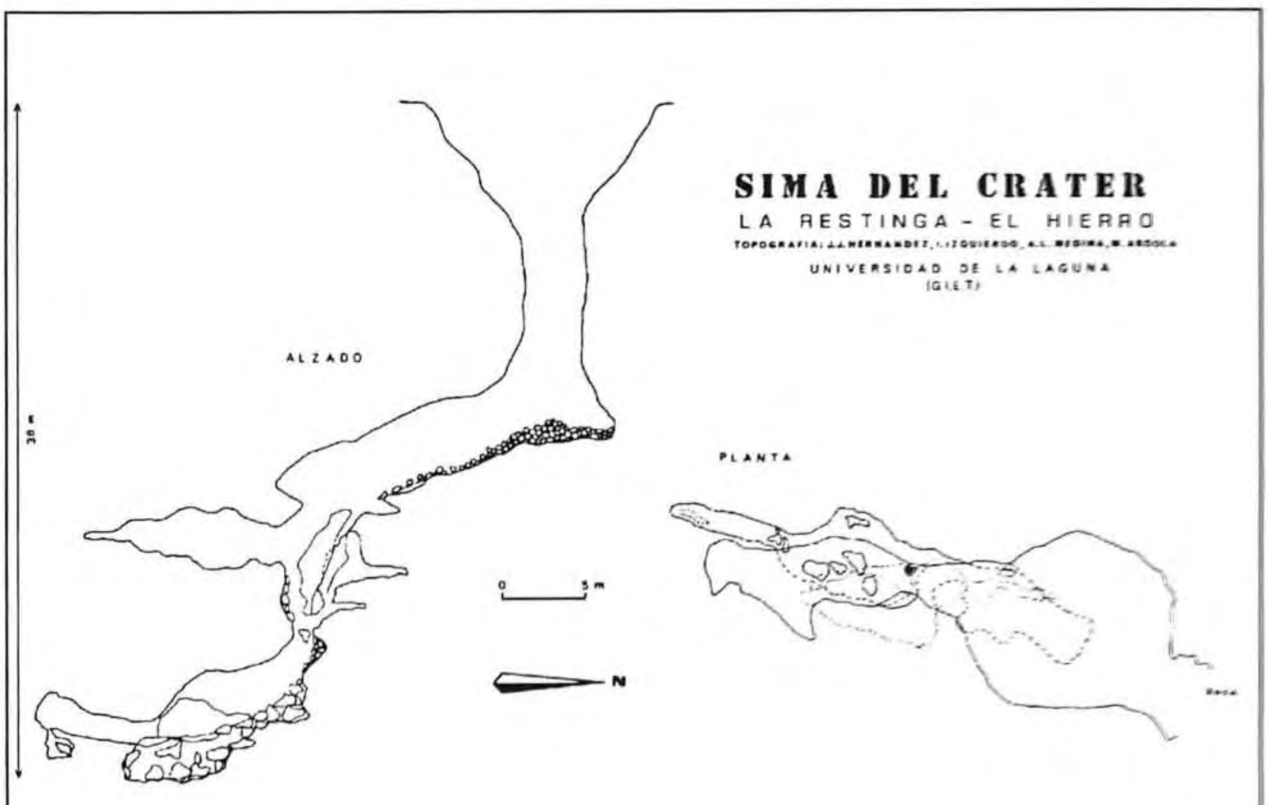
Location: La Restinga (Frontera)
UTM: 28BR068636
Depth: 36 meters

Description: The pit, located at an elevation of about 800 meters, is northeast of Mount Prim


CUEVA DE LA CURVA
EL PINAR-EL HIERRO
TOPOGRAFIA: J.J. Hernández, A.L. Medina, I.Izquierdo (G.I.E.T)-Univ. de La Laguna
BOCA
PLANTA
ALZADO
SECCIONES
Long. Total: 141 m
N
0 10m


CUEVA ROJA
La Restinga - El Hierro
G.I.E.T. - UNIVERSIDAD DE LA LAGUNA
0 10 m
LONG. TOTAL: 300 m
N
entrada


SIMA DE GUINEA
FRONTERA (EL HIERRO)
TOPOGRAFIA: J.J.HERNANDEZ; I.IZQUIERDO; C.NAESLUND (G.I.E.T.)
UNIVERSIDAD DE LA LAGUNA
ALZADO
6-7 m
0
1
2
3
4
PLANTA
LONG. TOTAL: 57m
0
5 m
N
SECCIONES


SIMA DEL CRATER
LA RESTINGA - EL HIERRO
UNIVERSIDAD DE LA LAGUNA
(G.I.E.T.)
ALZADO
PLANTA
0
5 m
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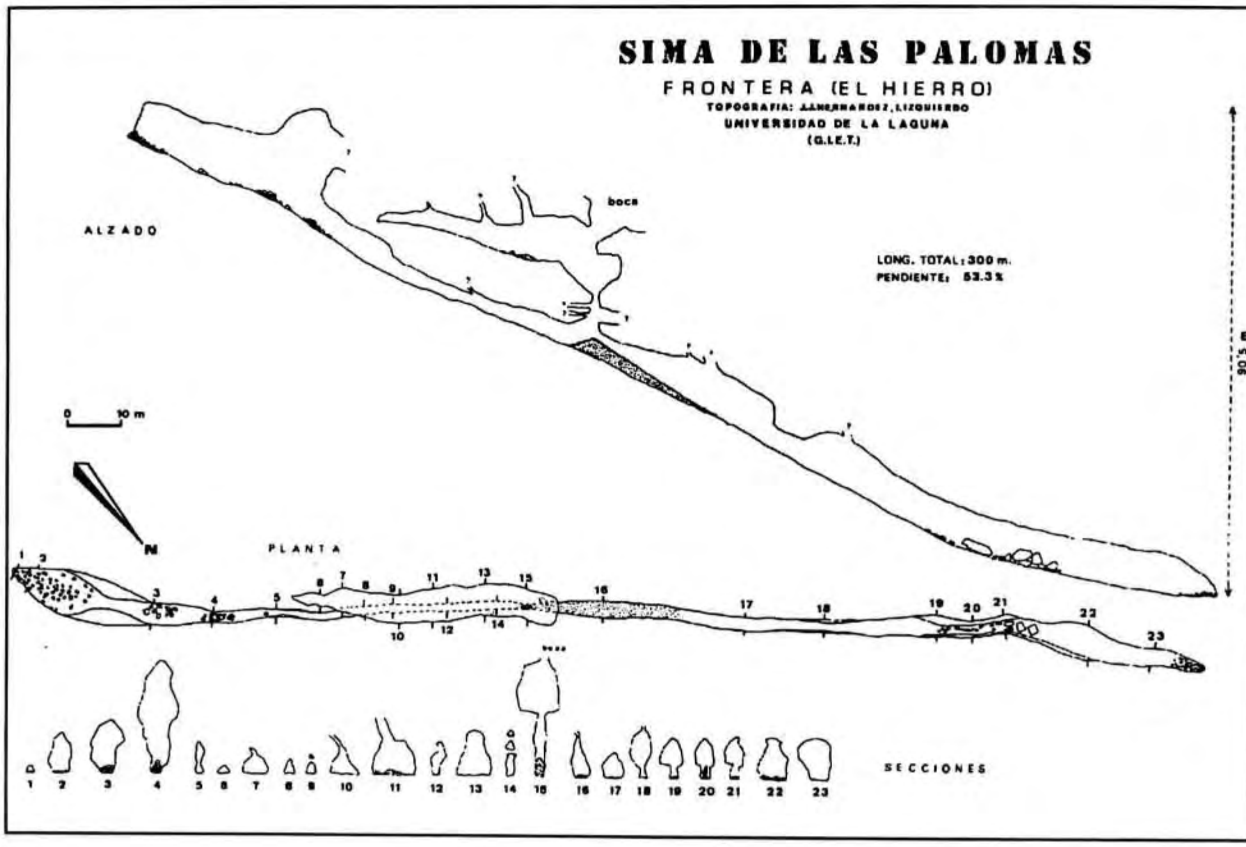
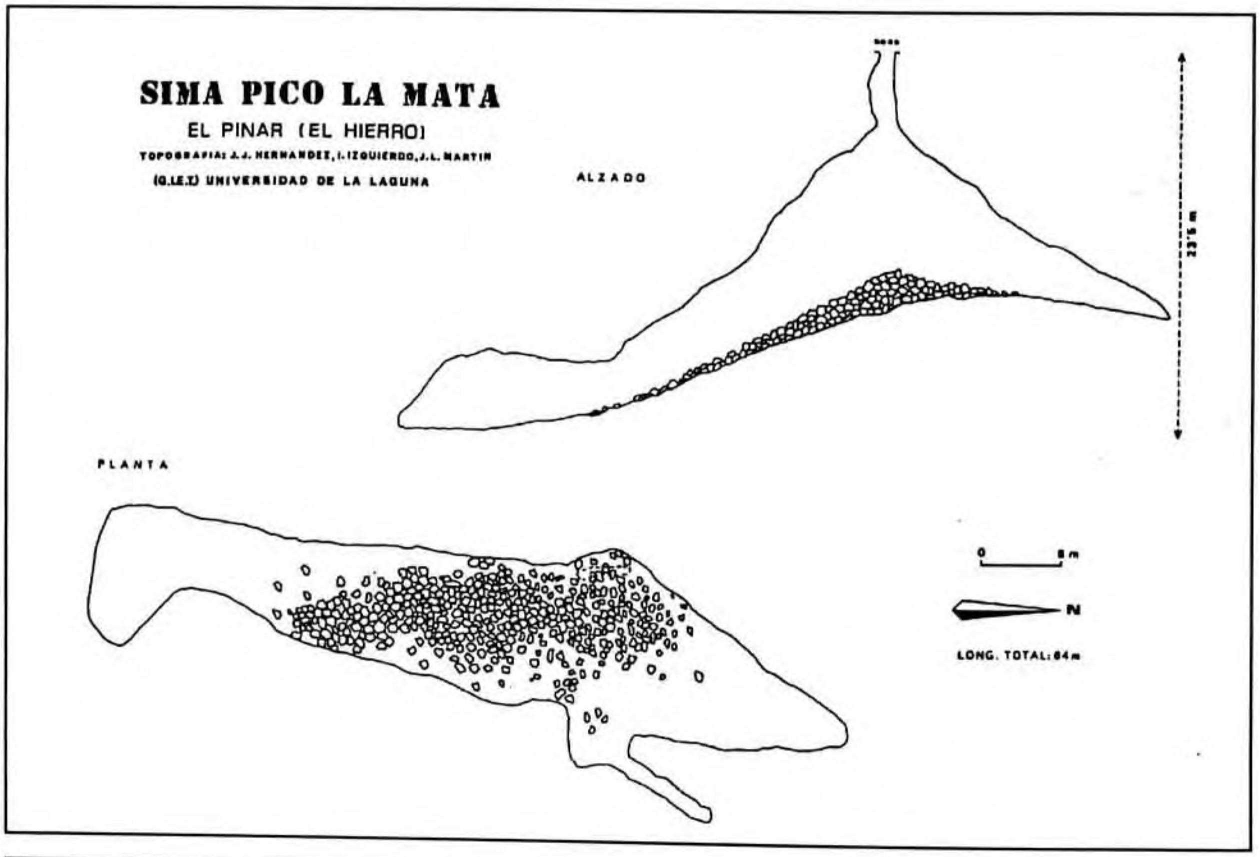

SIMA DE LAS PALOMAS
FRONTERA (EL HIERRO)
TOPOGRAFIA: J.J. HERNANDEZ, I. IZQUIERDO
UNIVERSIDAD DE LA LAGUNA
(G.I.E.T.)
boca
ALZADO
LONG. TOTAL: 300 m.
PENDIENTE: 53.3%
90'5 m
0 10 m
N
PLANTA
SECCIONES


SIMA PICO LA MATA
EL PINAR (EL HIERRO)
TOPOGRAFIA: J.J. HERNANDEZ, I. IZQUIERDO, J.L. MARTIN
(G.I.E.T.) UNIVERSIDAD DE LA LAGUNA
boca
ALZADO
23'5 m
PLANTA
N
LONG. TOTAL: 64 m

and near the sea cliff where an aggregate of small ovens and craters can be observed. The eruptive chimney of one of them is the entrance to the cave. The hole is about four meters in diameter at the access of the first pit of eight meters depth, with approximately the same diameter as the hole. In this area there are lots of blocks fallen from outside and from the walls. Further away there are two more pits of four and seven meters. They are much smaller than the entrance one and lots of scours and slips obstructing the way down force one to find his way between fitted blocks.

Biology: There are remarkable and various remains of living vertebrates such as goats, rabbits, sea gulls, and others. As occurs in many pits, it is used as a nesting place by numerous pigeons.

Pit of Las Palomas

Location: El Golfo (Frontera)
UTM: 28AR986721
Depth: 75 meters

Description: This is an amazing and frighting cave located in the slope of the Tanganasoga volcano. Its entrance, whose vertical diameter forms a descending slope of 45 percent, gives way to a small oven from which three overlying tubes go in the same direction and with same declivity as that of the slope. The lower tube can reach heights of 15 meters. This is one of the deepest volcanic pits of the archipelago and in its birth the typical mechanism of lava tube formation was merged with the latter melting of the overlaying tubes (Martín *et al*., 1985a).

Biology: There are lots of pigeons' nests *(Columba liva gmelin)* on the floor of the upper tube. In the vertical wall of the entrance there is much pigeon guano and a rich, recently investigated arthropod fauna (for example, the rove-beetles *Sepedophilus tenuicornis* Lind, and *Omalium ocellatum* Woll).

Pit of Pico La Mata

Location: El Pinar (Frontera)
UTM: 28BR057690
Depth: 23.5 meters

Description: This cave is located at about 900 meters above sea level. It presents the characteristic form of a typical chimney of the Canarian volcanic pits: it has a diameter larger at the bottom (50 meters) than at the entrance (2 meters). From the entrance there is a free drop of 13.5 meters to the top of a pile of blocks which have fallen from the outside. From here on, the cave runs about six more meters until it reaches the deepest point. It does not seem to be very old since its walls are not very damaged and are full of lava stalactites. The piling up of the blocks fallen from outside is not very important, since just underneath the lava flows of the primitive stratum can be seen. The external structures peculiar to an eruptive hole, are very well preserved.

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Þríhnúkargígur*

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The most northeasterly of the Þríhnúkar (Three Peaks) is a hollow volcanic cinder cone (Figure 1) that erupted in about the time of the settlement of Iceland (784 AD) (Jóhannesson and Sæmundsson, 1989). It is 36 meters high and stands on the highland edge about 20 kilometers southeast of Reykjavík, at an altitude of 550 meters. In the top of the cone is an opening – underneath is a tremendous volcanic chamber, side passages, and vent. On the southwest slope is a small crater that emitted a small flow of about 200 square meters to the south. Also to the southwest, 150 to 200 meters from the main vent, are four small craters that spewed a small lava flow of about one hectare to the east.

Figure 1 – The most northeast Þríhnúkar, a hollow volcanic cone.

This was a small fissure eruption that soon centered itself in the cinder cone on the northeasterly part of the fissure. The lava covers about 38 hectares (94 acres) and is estimated to be five meters thick. It totals about two cubic hectares [*sic*] (Jónsson, 1978) and is rather small. The lava is rich with plagioclase dots and is easy to distinguish from the older Þríhnúkar lava that only has some small olivine dots (Jónsson, 1978; Einarsson). About one kilometer to the northeast are some craters in the same line that spewed forth a bigger lava, estimated at 200 hectares (495 acres) (Jónsson, 1978). This lava is also very plagioclase rich (Jónsson, 1978; Einarsson) and the eruption there may very well have taken place at the same time.

What makes the peak unique is the volcanic chamber and the volcanic vents that have emptied themselves without collapsing. The cinder cone, the tremendous chamber, and passages underneath are singular in their kind in the world for their depth and size, so far as I know. (Note: I just recently learned of a bigger chamber on the Azores. It is not much bigger and not as deep. I am not quite sure which one is more voluminous.)

The opening in the top of the cone is four by four meters. The vertical drop to the bottom of the underlying chamber is 121 meters. The vent widens from four by four meters at the top to eight by 15 meters at 50 meters in depth. From 35 to 55 meters in depth is a narrow parallel side vent to the northeast (0.5 to 1.5 meters in diameter) which, in cross section, is shaped like the handle of a jug. At 60 meters depth the vent widens suddenly to the northeast and measures about 15 by 40 meters. Above the northeast end of the widening is a large chimney that is clearly connected with a crater bowl 10 meters northeast of the entrance opening. From 60 meters down is a tremendous chamber about 150,000 cubic meters in volume. The center of the chamber is 121 meters below the surface. The diameter at this point on the bottom is 48

*Poster exhibit, text from the *York Grotto Newsletter*, Vol 28 No 3, pp 45-51 © 1991.

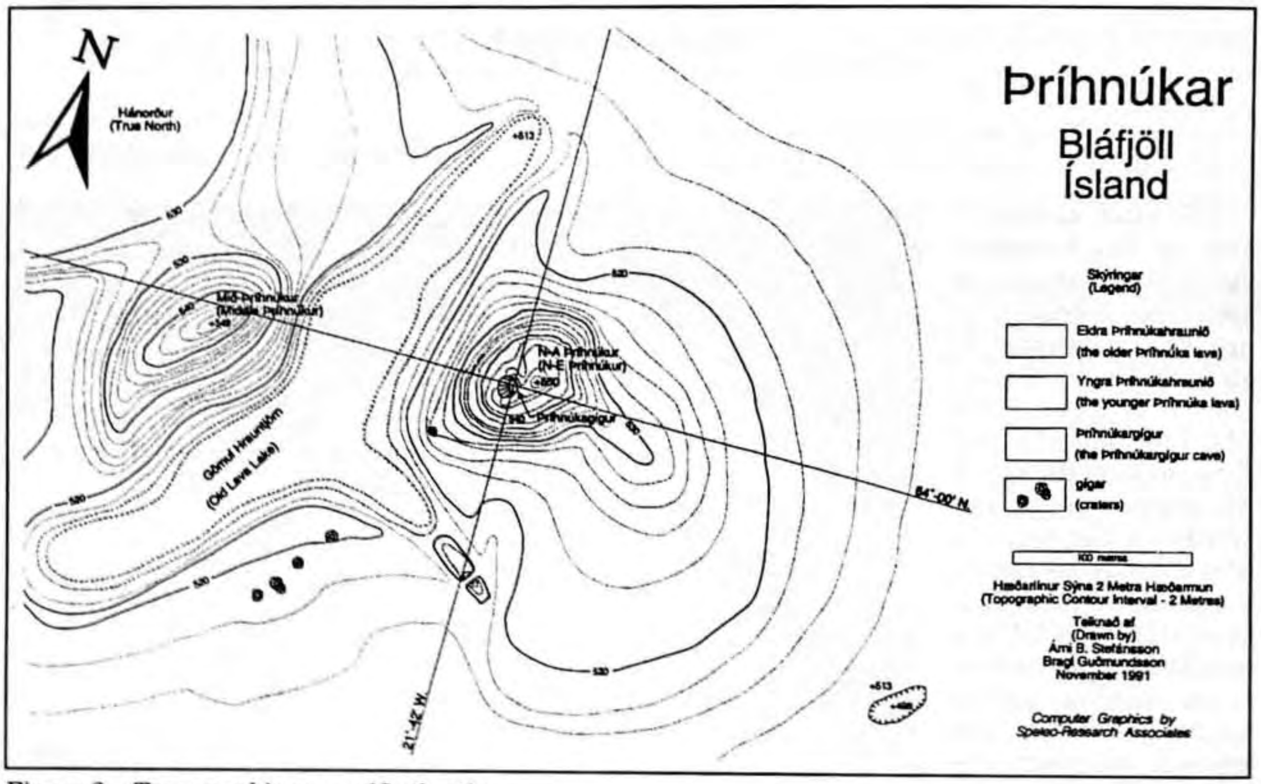

Figure 2—Topographic map of Þríhnúkar.

Figure 3—Ready to descend the 121-meter drop.

meters southeast to northwest and 65 meters southwest to northeast. Down to the southwest is a passage sloping 50° downward for 115 meters. The total depth of the vent is 204 meters. At 175 meters depth there is a chimney 45 meters high shaped like an elongated bulb. The lowermost diameter is 2.5 by 2.5 meters; the maximum diameter at 25 meters height is four by five meters. This vent seems to be the feeder of the small crater in the southwest slope of the main crater. The feeder chimneys for the craters 150 to 200 meters southwest of the main crater must be deeper than we were able to penetrate.

The original lava coat is on the walls from the surface down to minus 75 meters on the southeast and northwest walls, but tongues of lava coat extend down to minus 90 meters on the southwest and northeast walls. It looks about 40 to 50 centimeters thick at the edge where the lower part is broken off. This coat is, for the most part, a long-rippled matte gray glassy lava from the surface down to minus 50 to 60 meters. In and around the big chimney at minus 60 meters the walls are covered with frothy red lava sputter that has dripped down into an abundance of rather pretty little stalactites. The original lava coat is also on the walls of the chimney that rises from the southwest passage. At the broken lower edge it is 10

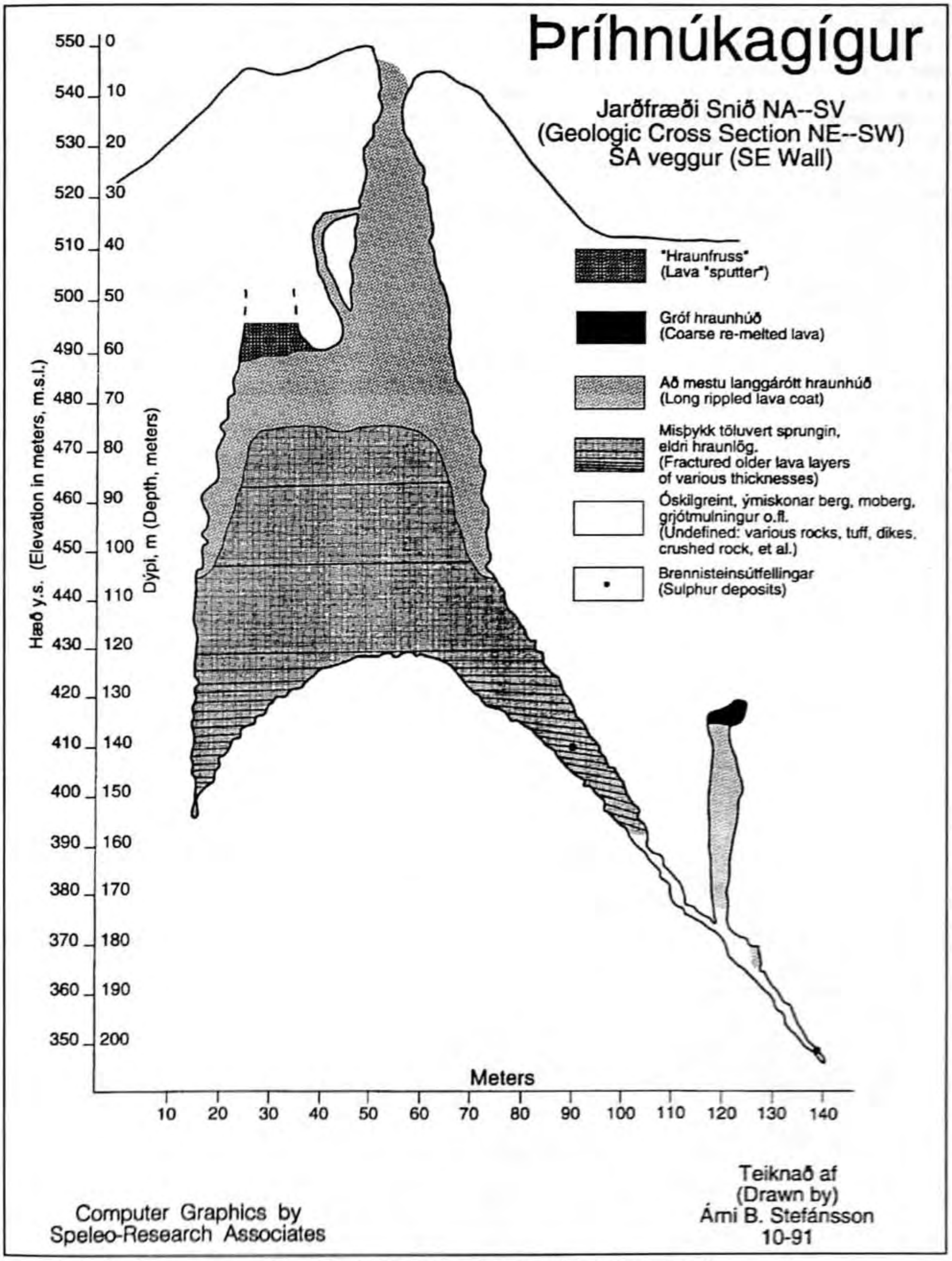

Figure 4—Geologic cross section of Þríhnúkagígur showing the southeast wall.

to 30 centimeters thick. The coat is similar to the coat in the main vent. At 40 meters in height in this chimney there is a circular sill. Above that the lava has a quite different, much coarser re-melted glassy appearance with yellow deposits. The sill is apparently the setting edge of the molten lava that must have stayed there for some time. It is probable that after the upper part of this vent closed the gas pressure from the gases emitted from the molten lava withheld this setting edge. Nowhere else was a setting edge to be seen.

This points to a continuous drainage of the lava down from the vent to a point deeper than we were able to penetrate, how quickly is hard to say. Lastly, there was some lava spatter on the southeast wall in the southwest passage at 185 to 190 meters depth—the same kind as found around the chimney at minus 60 meters.

The walls of the main chamber, from 75 to 125 meters depth, consist of three quite cracked old (probably the last interglacial period) lava layers 15 to 25 meters thick. No "in-between" layer could be seen, but the boundaries were fairly distinct. Between minus 125 and 150 meters there are also old lava layers, but much thinner (one meter at minus 125 meters and 5 to 10 centimeters at minus 140 meters). On the lowest part of the northwest wall is a thick (15- to 20-meter) lens of compressed volcanic ash thinning out down to the southwest and northeast, possibly the root of the most westerly Þríhnúkar (tuff).

The bottom of the chamber is a saddle formed from rock breakdown from the walls. The breakdown is higher against the southeast and northwest walls because the main collapse is from the long sides of the fissure and therefore higher on these walls, but lower to the southwest and northeast. The rock on the bottom and on the walls is colored with some hematite (brown-red-yellow). This indicates considerable heat in the chamber for some time and, from the look of the rock, the main collapse took place during this early phase. The rock contracts on cooling so the main collapse takes place during the cooling phase, like in most lava caves. On the driest place on the walls of the southwest passage at minus 145 meters and minus 200 meters depth, there were some small, one-centimeter-thick sulfur deposits. This is unusual for a lava cave and speaks for considerable dryness at these places.

The tongues of original lava coat down on the southwest and northeast walls of the main chamber are the convex ends of a fissure. This fissure was probably 10 to 15 meters wide and 60 meters long at minus 100 meters. In an originally narrow fissure the lava concentrated on this part. The subsequent wideness must be from the erosion of the long sides by the erupting lava. The main collapse is from the less stable long sides and therefore the circular form of the chamber. If we could try to imagine, from the size of the fissure with elongation down to the southwest, just how deep the original lava has sunk, it must be 300 meters or deeper.

That this was a fissure eruption is also confirmed by the fact that one can see the original dike on the northeast wall, from the bottom up to the lava coat tongue at minus 90 meters, and down from the lava coat tongue on the southwest wall, in the ceiling of the southwest passage, in the southeast edge of the chimney at minus 175 meters, and continuing on in the ceiling of the southwest passage as far as we could go to the minus 204 meter depth, in all unbroken for about 190 meters. The direction of the fissure and all its formations is southwest to northeast like the main fissure system in Iceland.

Figure 5—Looking up the chimney.

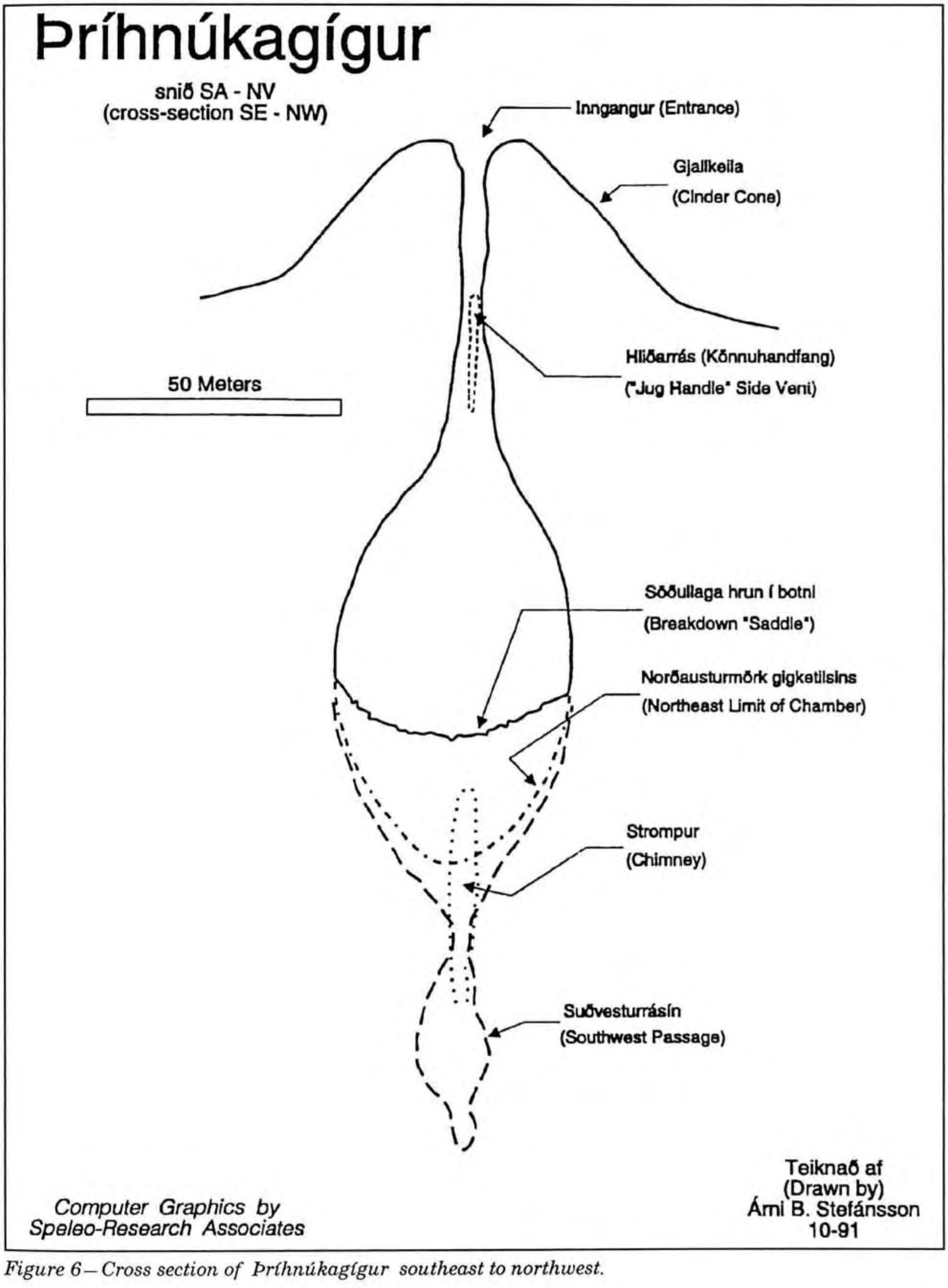

Figure 6—Cross section of Þríhnúkagígur southeast to northwest.

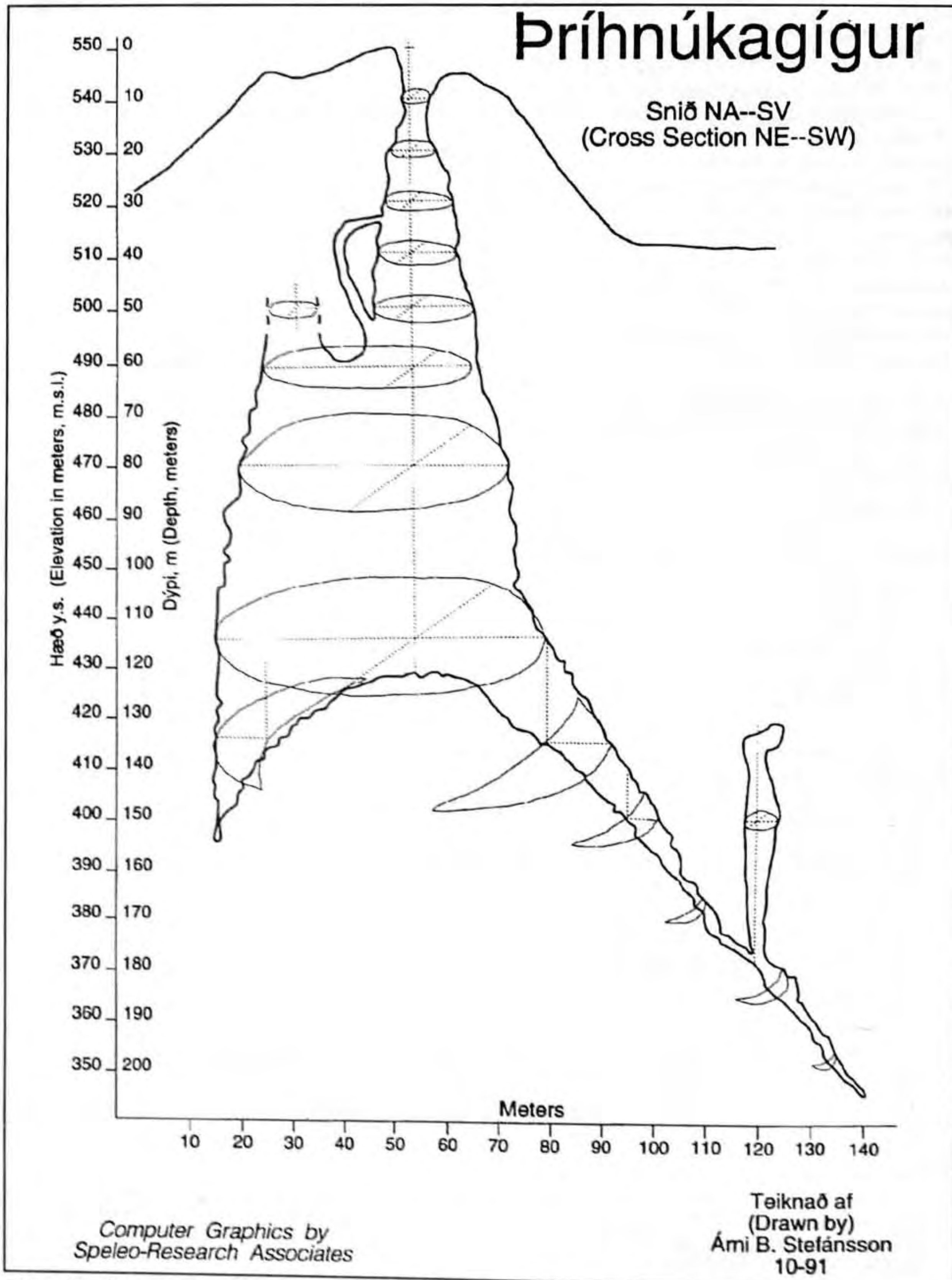

Figure 7—Cross section of Þríhnúkagígur northeast to southwest.

The surface temperature ranged from -10° to -3° Celsius. The temperature at the bottom of the big chamber was 4° Celsius and at minus 204 meters it was 5° Celsius. Temperature of ground water in these areas is 4.8° Celsius (Sæmundsson).

There was a slow northerly breeze, increasing during the day (April 6, 1991), and it was dry. The breeze pulled air from the vent, so conditions for photography were superb. Often it is quite humid and foggy down in the hole.

The measurements were made with compass, tape, clinometer, and a five-meter-long stick. It was a long way to the walls in the chamber and to the ceiling in the first part of the southwest passage, so there is some guesswork there. The depth of the chamber was plumbed with a nostretch nylon line that was subsequently measured with a tape. The total depth is probably within ±two to three meters.

There is a lot of work behind these results. We would like to thank all of those who helped us and the firms that supported us with equipment, Skátabúðin Reykjavík and Jóhann Rönning h/f Reykjavík (Hitachi Agency) and the rescue squads of Reykjavík and Kópavogur.

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Contribution to the Vulcanospeleology of the Galapagos Islands*

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Abstract

During April and May 1990 and March and April 1991 the Museo de Ciencias Naturales of Tenerife (Canary Islands) carried out two expeditions to Galapagos Islands, within the framework of the Project "Galápagos: Patrimonio de la Humanidad," on the occasion of the Fifth Centennial of the Discovery of America. We present here the first results of the speleological research, consisting of the location and topography of seven new caves—two pits in Isabela Island (Cerro Grande and Las Torres) and three lava tubes and two pits in Santa Cruz Island (Elena, La Micona, and Casajo Caves and pits known as La Pirámide and Pozo de Los Gemelos). Among these Cueva del Casajo is really notable; with its length of three kilometers it is undoubtedly the longest lava tube of the Archipelago. We present the maps of these caves, as well as information about their geomorphology, state of preservation, location, and means of access. A list of all Galapagos volcanic caves known to date (a total of 50 caves) is shown and an up-to-date speleological view of this archipelago is discussed.

Introduction

Stretching across the middle of the Pacific Ocean, 972 kilometers off the coast of Ecuador, there lies an extraordinary island group covering some 8,000 square kilometers. It is made up of 19 islands, 42 islets and 26 rocks (Figure 1).

The islands extend over an area of some 320 kilometers from east to west and a bit less from north to south. They connect with South America via the Carnegie underwater ridge and with Central America by means of the Cocos underwater ridge. Their volcanic nature gives the islands a beautiful and varied landscape, where hundreds of slag cones, a multitude of basaltic lava flows, and spectacular sunken calderas predominate.

Since Darwin's visit to these islands in 1835 they have truly become a milestone in the historical evolution of scientific thought. The special geological nature of these islands as well as their extraordinary vegetation and fauna (especially vertebrates) has always attracted the attention of a great number of researchers.

However, despite all this interest, the abundant volcanic caves that exist on the islands and the enigmatic subterranean wildlife have been, until

*This study is part of the project called "Galápagos: Patrimonio de la Humanidad," carried out by the Museum of Natural Sciences of Tenerife, under the direction of Dr. Juan José Bacallado Aránega, with sponsorship of the Island Council of Tenerife, the Tourism and Transportation Council of the Canarian Government, and the Commissions, both National and Canarian, established to participate in the activities that will take place in commemoration of the Fifth Centennial of the Discovery of America.

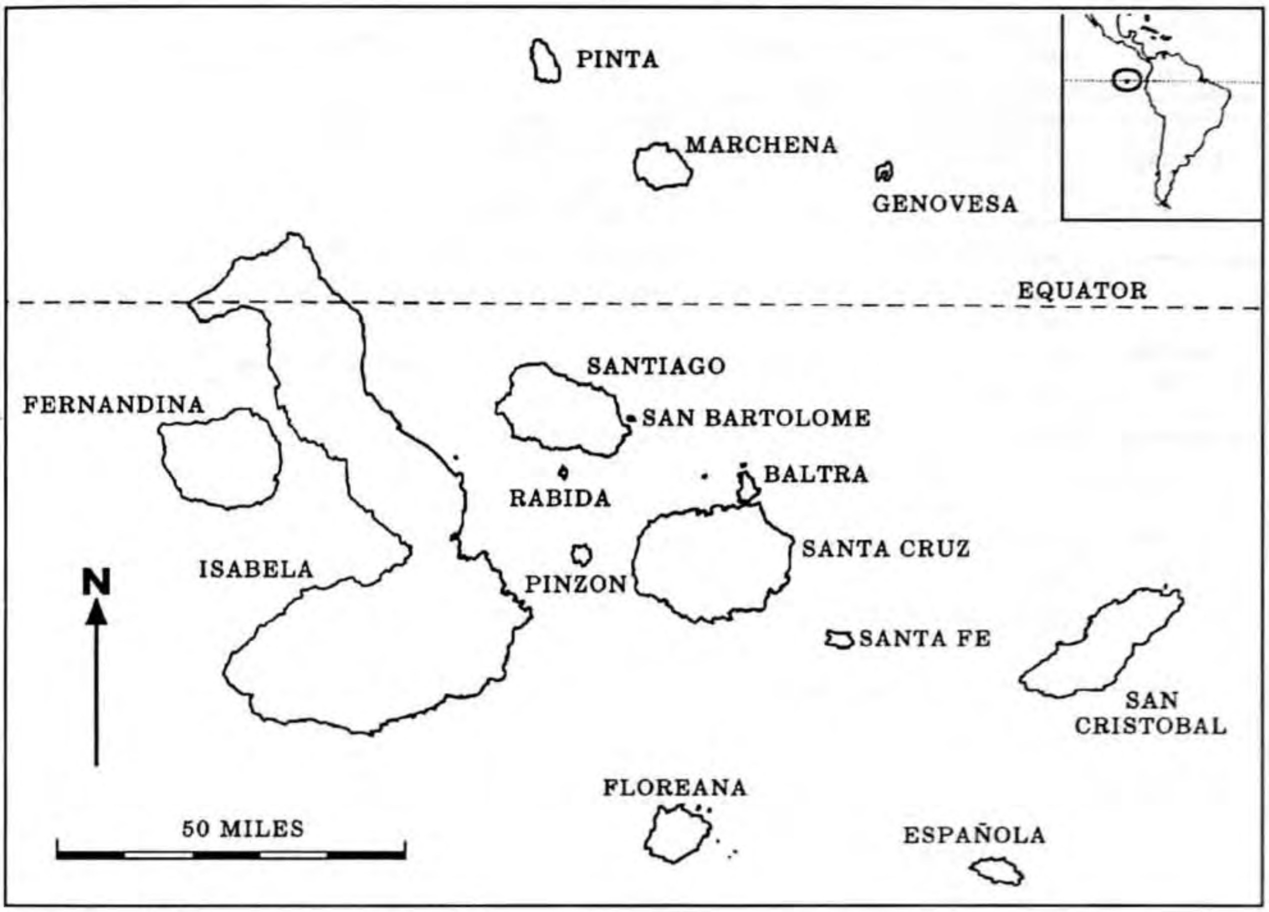

Figure 1 – The main Galapagos Islands.

just a few years ago, unknown to the international scientific community.

This study represents an attempt to provide more knowledge about the interesting vulcanospeleology of these islands, which hold many surprising secrets yet to be revealed.

Background

Although Darwin cited the existence of certain caves on the island of San Cristobal (Darwin, 1845) during his visit to the Galapagos, we believe that it was the "Mission Scientifique Belge aux Galapagos" in 1962 that deserves the honor of being recognized as the pioneer of speleological studies on these islands. The first contributions to speleology coming from these islands were made by G. Stoops and P. De Paepe, who participated on this expedition and who published two brief reports in 1965 (Stoops, 1965; De Paepe, 1965) about a cave located near Puerto Ayora (Island of Santa Cruz) and which is unmistakably known today as Kübler Cave.

In 1970 the Hungarian speleologist, Denes Balazs, mapped this cave as well as another cavity, named after him, located near Bellavista (Santa Cruz). Five years later his studies were published (Balazs, 1975). It was in this year that an expedition called "Galapagos '75" was undertaken, the first Spanish speleological expedition to be carried out on these islands and whose results have been reported in three publications, about the islands of Floreana (Montoriol-Pous and Escola, 1975), Santa Cruz (Montoriol-Pous and De Mier, 1977) and Isabela (Montoriol-Pous and Escola, 1978).

Later that year, in July and August 1982, the "Sociéte de Spéléogie et de Préhistoire des Pryrénées Occidentales (SSPPO)" embarked on an expedition, "Ecuador 82," in which caves were catalogued in continental Ecuador as well as on the Galapagos Islands (SSPPO, 1982). This is the first general catalog of caves of the Galapagos Islands. It mentions a total of 38 cavities.

By 1985, Doctors Stewart and Jarmila Peck from Carleton University (Canada) initiated, in

Island	Cave: Main name	Cave: Other names	Length (m)	Biol. Work	Geol Work	References
Santiago (3)	Cueva Bucanero I	Pozo de la Bahía de los Bucaneros I	567	No	Yes	27
	Cueva Bucanero II	Gruta de la Bahía de los Bucaneros II	?	No	Yes	27
	Cueva del Cráter de Sal		~350	Yes	Yes	27,(*)
Isabela (5)	Cueva de Sucre		355	Yes	Yes	14,16,27,(*)
	Cueva de Macas		92	Yes	Yes	14,16,27,(*)
	Cueva de La Cadena		114	Yes	Yes	14,16,27,(*)
	Simas de Las Torres		-46	No	Yes	(*)
	Simas de Cerro Grande		-20	No	Yes	(*)
Floreana (5)	Cueva de Post-Office Superior		38	Yes	No	12,16,27,(*)
	Cueva de Post-Office Inferior	G.32	202	Yes	Yes	12,16,27,(*)
	Cueva del Pinzón	Finch Cave	110	Yes	Yes	26,(*)
	Cueva de La Lechuza	Barn Owl Cave	60	Yes	Yes	26,(*)
	Cavidades de la Bahía de las Cuevas	Cueva de Los Piratas	16;10;4	No	Yes	12,27
Santa Cruz (35)	Cueva de Andrés		205	No	Yes	16,25,27
	Cueva de Iguana	G. de la Est. Darwin	100(-12)	Yes	Yes	16,25,27
	Cueva de Raúl Aguirre		115	No	Yeso	13,16,27
	Cueva de Gallardo	Cuevas de Bellavista nº1 & nº2. Los Túneles	2,250	Yes	Yes	1,13,16,27,(*)
	Cueva de Sra. Colombia	C. de Jorge Sevilla	47	Yes	Yes	16,27
	Cueva de Gilberto Moncayo		590	Yes	Yes	16,27,(*)
	Cueva de Kübler	G.12	852	Yes	Yes	1,4,13,16,27,28
	Grieta del Pozo de Puerto Ayora		50(-15)	Yes	No	16
	Grietas de Bahía Tortuga		30(-10)	Yes	No	9,16,27
	Grietas en el camion por Bahía Tortuga		12(-10)	Yes	No	16,27
	Grieta de Lentenech		28(-5)	No	Yes	13,16,27
	Cuevas de la Finca Kastdalen	Cueva de Tres Pisos	1,500+500	Yes	Yes	16,(*)
	Cueva de La Curva		80	No	No	16
	Cuevita de Las Cyatheas		18	Yes	No	16
	Cueva de Huesos		750	Yes	Yes	16
	Cuevas de Fincas Vargas		20	Yes	No	16
	Cuevas de la Finca Devine		~100	No	No	16,23,(*)
	Cueva de La Miconia		276	No	Yes	(*)
	Cueva de Elena		677	Yes	Yes	(*)
	Sima de La Pirámide		-44	No	Yes	(*)
	Cueva 2 km al S de El Chato		500	Yes	No	16
	Cueva de Tres Entradas		400	Yes	No	16
	Cuevas de Cerro Banderas		1,000	Yes	No	16
	Cuevitas al SW de Cerro Banderas		15	Yes	No	16
	Sima del Pozo de Los Gemelos		-64	Yes	Yes	16,(*)
	Cueva sin nombre		~60	No	No	16,(*)
	Cueva del Cascajo		3,010	Yes	Yes	(*)
	Cueva del Monte Cascajo		~100	No	No	25,27
	Grieta de la Punta de Las Palmas		-12	Yes	No	22,27,29

Island	Cave		Length (m)	Biol. Work	Geol Work	References
	Main name	Other names				
Santa Cruz (cont)	4 cavidades en Zona Naranja		?	No	No	1,25,27
	Cueva al N de El Chato		?	No	No	25
	Cueva del Caballo	C. de Cheval: G.36	?	Yes	No	8,27
	Cueva de Rovalino	Cueva de Castro	50	No	Yes	27
	Agujeros de Agua	G.26	?	Yes	No	9,27
	Cueva de Miguel Arias		~ 1,000	No	Yes	(**)
San Cristóbal (2)	Pozos de Hundimiento		-15	No	No	1,3,27
	Cueva de Cerro Pelado		?	No	No	(#)

Table I—All volcanic caves currently known on the Galapagos Islands: Spanish names are used, as caves are known by inhabitants of the islands. (*) Caves visited by us during the expeditions of 1990 and 1991. (**) Pat Whelam personal communication (#) Oral communications from SPNG on San Cristóbal.

collaboration with the Charles Darwin Research Station, a project, still being carried out, for the study of the biology and distribution of the cave-dwelling and soil anthropods of the Galapagos.

In 1986 the initial results of their studies were published (Peck and Peck, 1986a) in which 30 cavities were cited and in which interesting information was given about cave locations, biological characteristics of certain caves, and unpublished maps drawn by Chris Vanbeveren in 1985. In 1986 the American paleontologist, David Steadman, published a study on vertebrate fossils of the island of Floreana (Steadman, 1986), in which he shows maps of various caves on this island. His studies on vertebrate fossils found in the interior of the lava tubes have permitted him to discover unknown caves which are cited in his paleontological studies (Steadman, 1981, 1982; Steadman and Ray, 1982).

Biospeleology

The first biological study of the subterranean fauna of these islands was carried out by N. and J. Leleup of the Belgian Royal Museum of Central Africa, who in 1965 spent six months on the Galapagos Islands, collecting and studying cryptozoic wildlife. These authors found ten species in underground waters, in cracks of rocks, in the soil, and in caves (Leleup, 1967, 1968). Among the interesting finds made by these Belgian scientists on the expedition was an eyeless fish *Caecogilbia galpagoensis* Poll and Leleup, as well as several albino crustaceans (Van Mol, 1967; Poll, 1976). The samples taken by Leleup came from only three caves, and this suggested indirectly that there existed a terrestrial troglobite fauna on the islands. Leleup thought this wildlife to be a relict fauna from immigrants of the Pleistocene period (Leleup, 1976).

The presence of this fauna has not only been confirmed but has been considerably increased thanks to the recent work by S. and J. Peck (Peck and Peck, 1986b, 1986c; Peck and Shear, 1987a, 1987b; Campbell and Peck, 1989). According to the latter authors, the total number of species of cryptozoic anthropods comes to 56, of which 21 (37.5%) have been found inside caves (Peck, 1990).

Results

According to the specialized literature that has been consulted, as well as our own field research, the total number of volcanic caves currently known on the Galapagos Islands is 50. Their distribution on the various islands is quite diversified, which reflects – besides the speleological richness itself of each island – more importantly, the different degree to which each one of them has been studied. In this way, the island of Santa Cruz, perhaps that which has had the most human activity, shows a total of 35 cavities, Floreana 5, Isabela 5, Santiago 3, and San Cristobal 2 (Table I).

Most of these caves are horizontal lava tubes (although many of them have an abundance of vertical extensions in their interior, which form passages to other tubes located at different levels). The rest are vertical pits, formed sometimes by the reflux of lava in the interior of volcanic chimneys, and other times by the fracturing of the earth as a consequence of seismic movement.

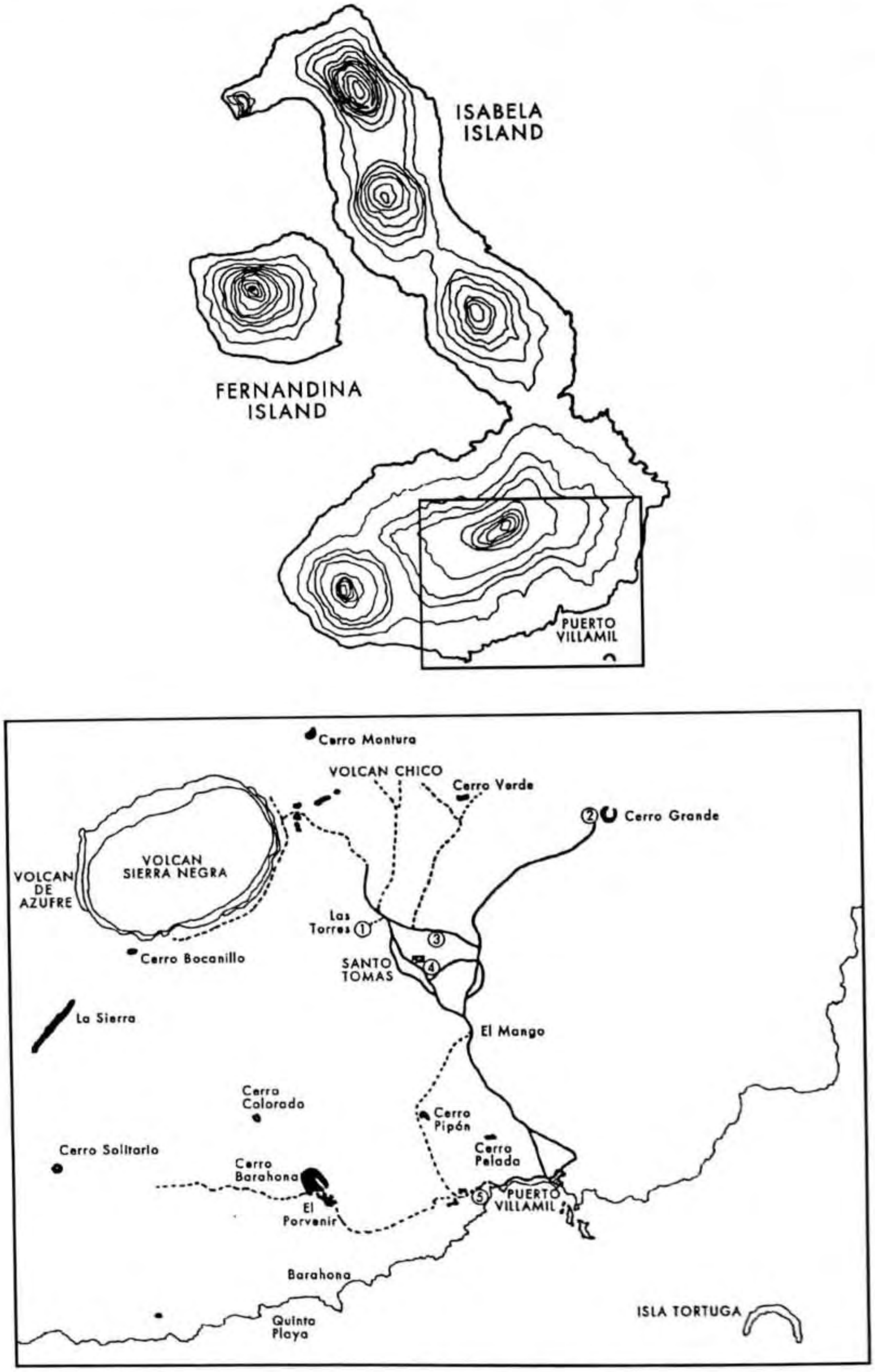

Figure 2—Location of known caves on Isabela Island. 1=Pits of Las Torres. 2=Pits of Cerro Grande. 3=Macas Cave. 4=Sucre Cave. 5=La Cadena Cave.

The field study carried out during the expeditions of 1990 and 1991 has led to the location and mapping of six previously unknown caves (Pits of La Piramide, Cerro Grande and Las Torres and the Elena, Miconia and Cascajo Caves) in addition to two caves previously mentioned in other writings but which had never been mapped (Pit of Pozo de Los Gemelos and Kastdalen Cave).

The following pages describe these eight findings with information about the location, access, related fauna, and state of preservation of each one.

1. Isabela Island (Figure 2)

There were only three small caves whose existence was known on this large island. The contacts established in Puerto Villamil with Sr. Arnaldo Tupiza, the current representative of the Galapagos National Park Service on Isabela (SPNG), has allowed us to locate two groups of pits that were until then unexplored (Figure 2).

1.a. Pits of Cerro Grande (Figure 3)

Unlike the Las Torres pits, the pits of Cerro Grande are part of a large crack or facture in the ground, caused by seismic movement. They are located near the Cerro Grande, to the northeast of Santo Tomas (Figure 2). The largest of these pits do not exceed 20 meters in depth and, similar to the next case, their narrowness makes them extermely difficult to explore.

1.b. Pits of Las Torres (Figure 4).

This is a group of small pits that have a maximum depth of 46 meters and a minium depth of 25 meters. They start at the emission tubes of small eruption vents, known as Las Torres and are lo-

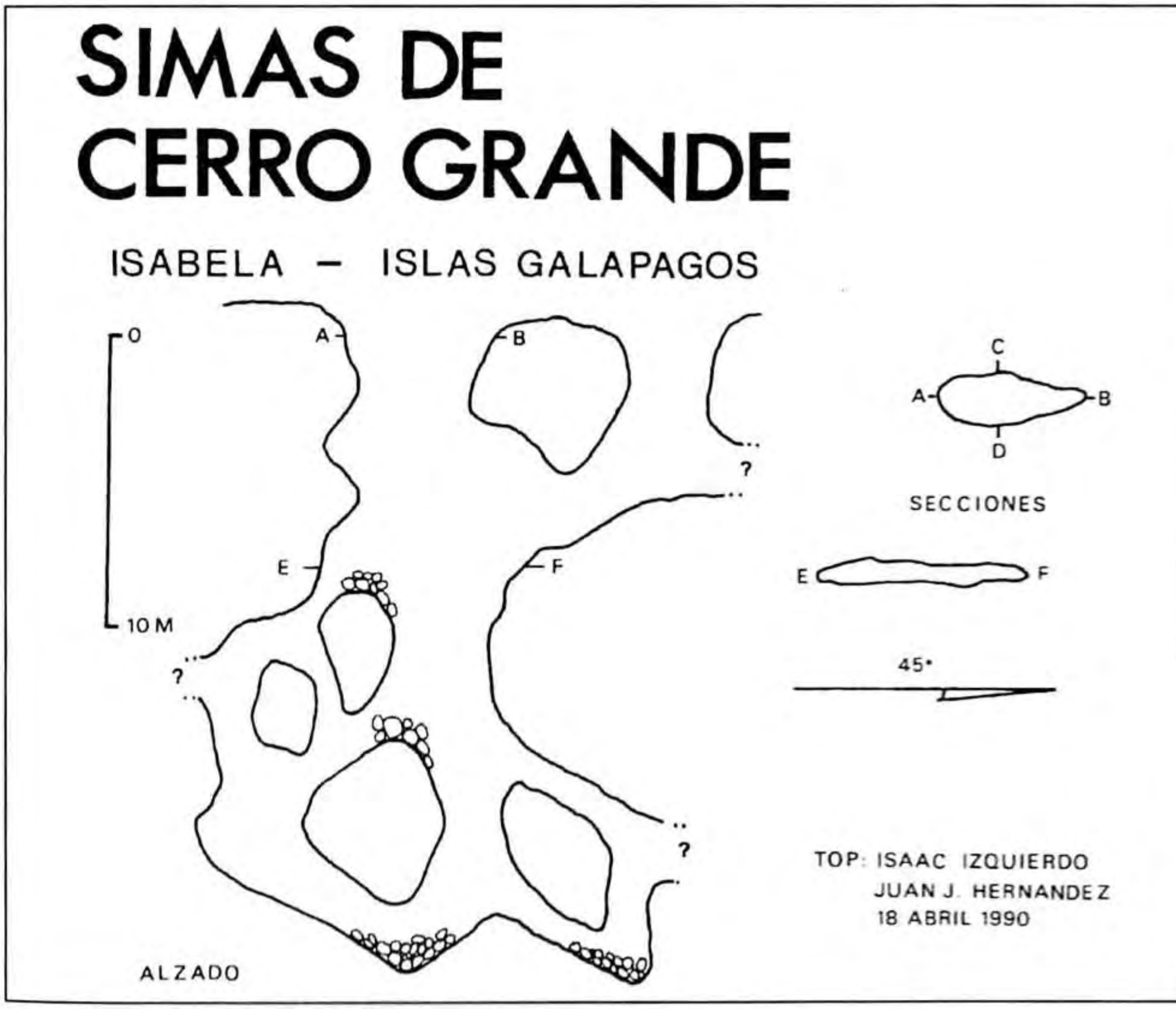

Figure 3 – Pits of "Cerro Grande."

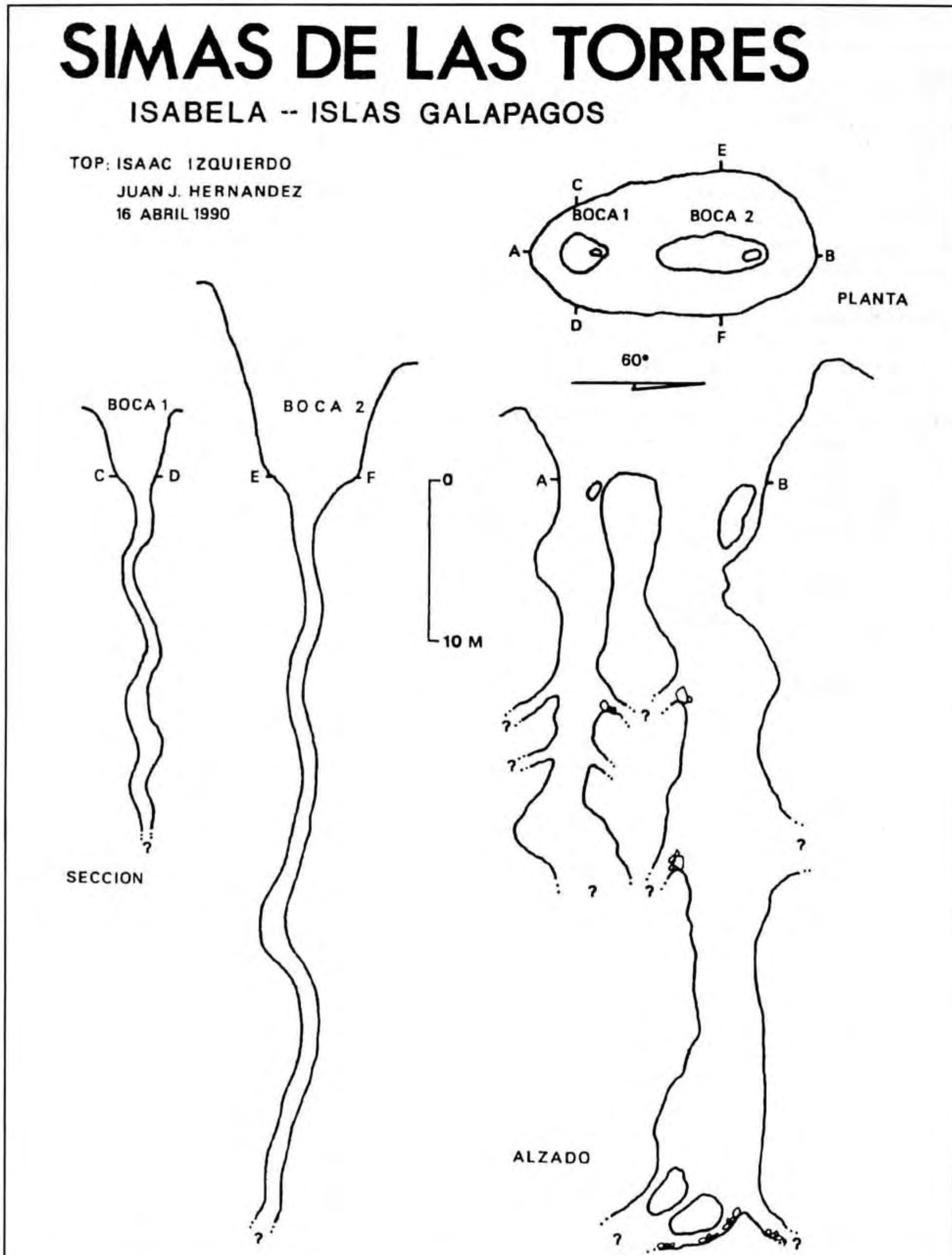

Figure 4—Pits of "Las Torres."

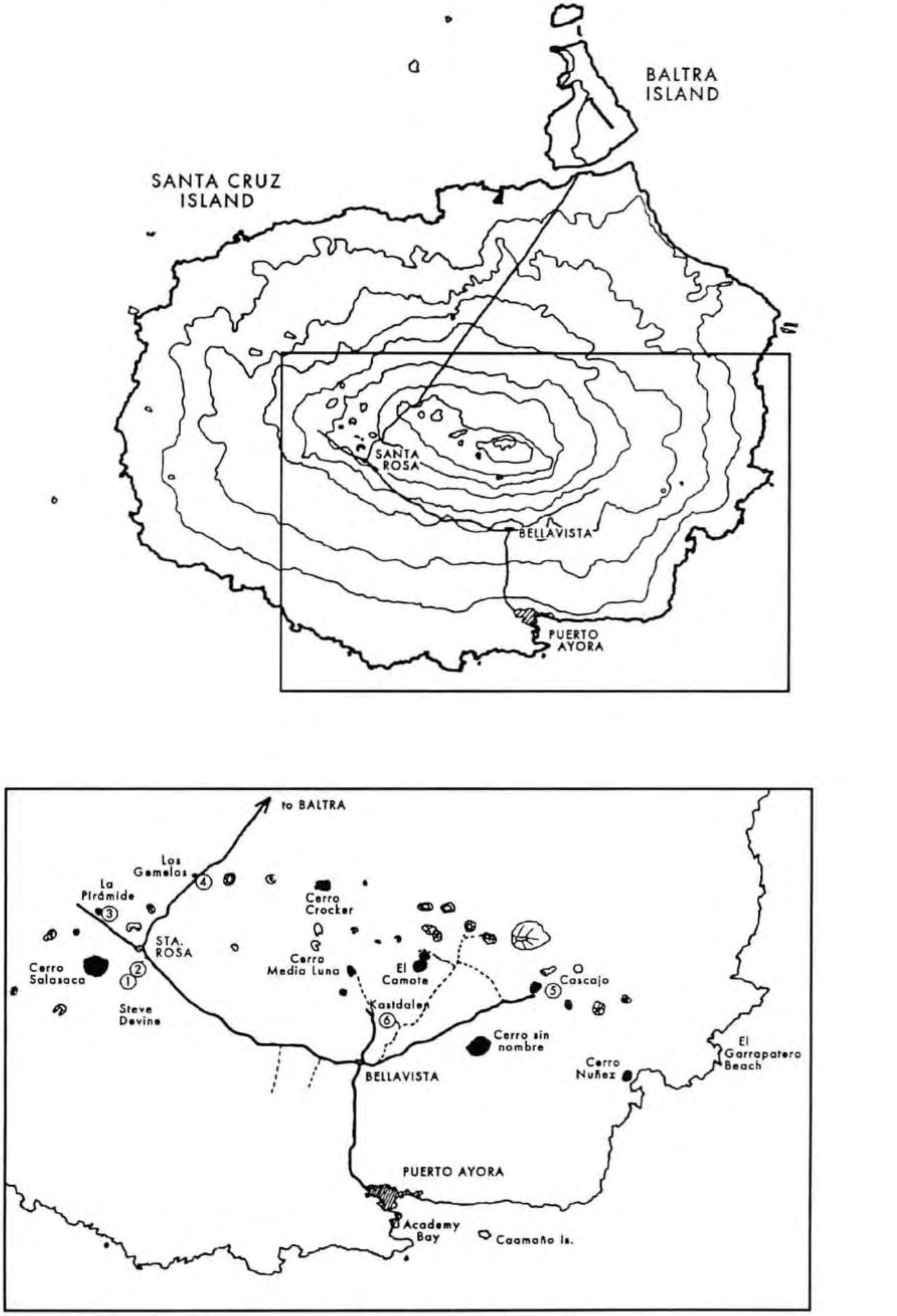

Figure 5 – Location of caves mapped by us on Santa Cruz Island.

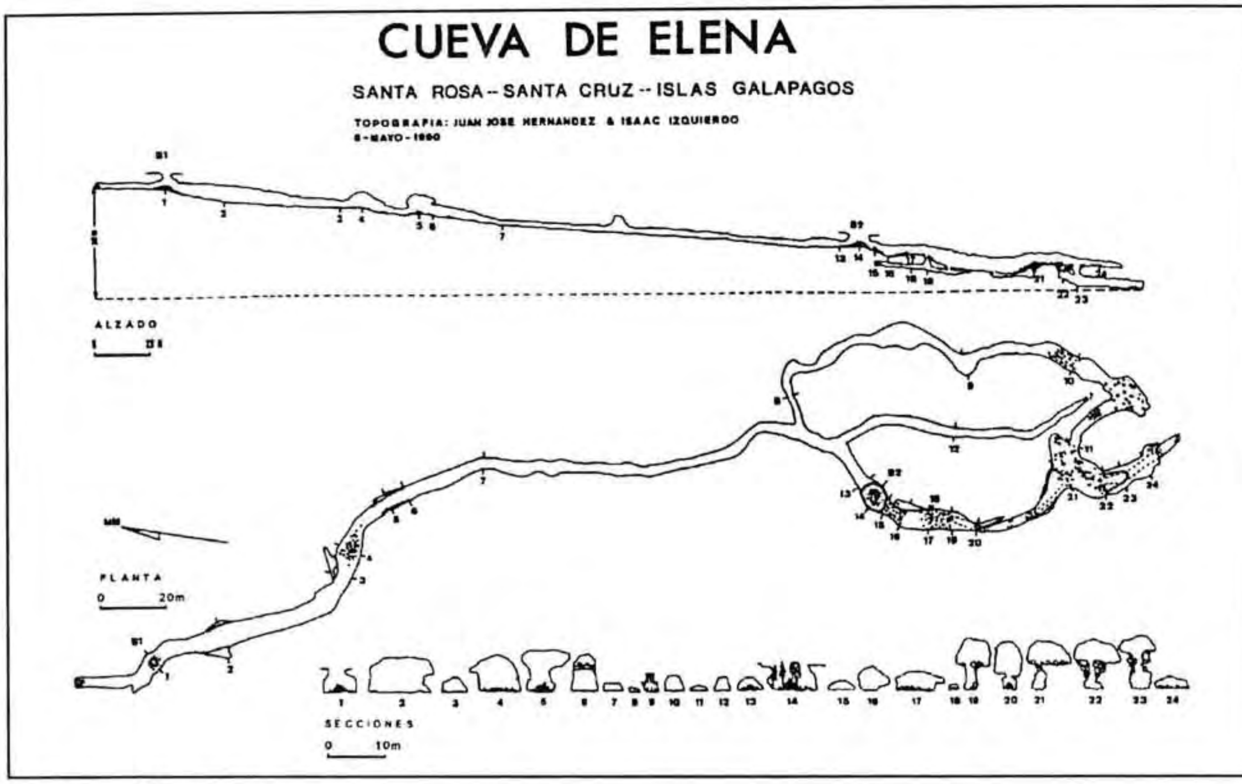

Figure 6—Elena Cave.

cated between the agricultural area of Santo Tomas and the south side of the Sierra Negra Volcano. There are extremely narrow passages that extend between the two pits. Generally these pits are in the form of long, narrow cracks, with an average width of one meter. Entering these caves is not only difficult because of their narrowness but also quite dangerous due to the constant threat of rock slides. There exists a large number of bone remains, especially of galapagos (*Geochelone*), which have fallen inside.

2. Santa Cruz Island (Figure 5)

2.a. Elena Cave (Figure 6)

Located on the property of Steve Devine, in the agricultural area of Santa Rosa, Elena Cave is 677 meters in length, with two accesses for which a small climb is required to enter. This cave displays a curious form of geomorphology, a type of labyrinth in its lower extreme. The difference between the upper and lower part of its slope is around 38 meters and some of the larger passages reach heights of up to 10 meters. It also exhibits some lava stalactite formations as well as small overlapping tubes.

Inside the cave the temperature is around 23.6° Celsius and the relative humidity is high (90 to 95%). The fauna which have been collected, and are still being studied, seems to be quite interesting. In the interior of the passageways lives the only species of Galapagos troglobitic rove beetle (*Pinostygus galapagoensis* Campbell and Peck); an undetermined pseudoscorpion associated with decomposing roots, spiders (Pholcidae and Linyphidae), millipedes (diplopods Polydesmidae), the amblipigy *Charinus insularis* Banks, depigmented woodlice, the blind earwig *Anophthalmolabis* sp., and so on.

The cave receives virtually no visitors and it is in an excellent state of preservation.

2.b. La Miconia Cave (Figure 7)

This small tube, 276 meters in length, is also located on the land of Steve Devine, not far from the previously mentioned cave. This cave displays a uniform, linear arrangement, with two entrances, one at the upper extreme and the other in the middle, where the cave becomes quite narrow. The difference between each end of the slope is 24 meters. This cavity is apparently of little biological interest.

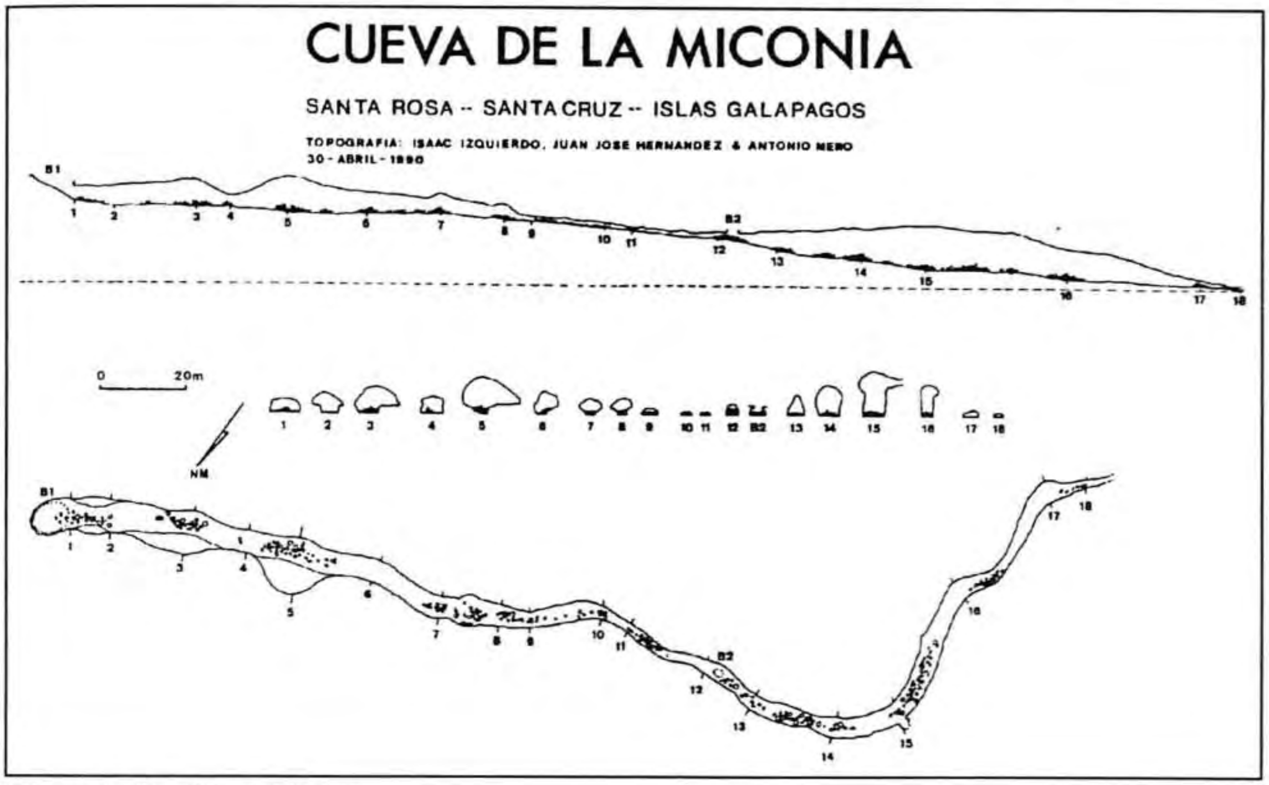

Figure 7— "La Miconia" Cave.

2.c. Pit of La Piramide (Figure 8)

This pit, also located in Santa Rosa (Salasaca), is an emission tube located at the very center of the crater of "La Pirámide" giving it a curious geomorphology. This pit features a hollow pyramid-like monolith which projects out of the ground, making almost 11 meters of its 44 meters of total depth surficial. Below the ground level the pit drops to 33 meters shooting off in three directions into large openings. Bone remains of giant rice rats can be found in the deepest opening, but it appears that the cave does not offer anything of much interest in the way of fauna. Given its difficult access, the cave is not visited and its good state of preservation has been maintained.

2.d. Pit of Pozo de Los Gemelos (Figure 9)

The Pozo de Los Gemelos is a well-known place on Santa Cruz Island and one of the important tourist attractions. It consists of large sunken calderas located on both sides of the road that goes from Puerto Ayora to Baltra, approximately 2.5 kilometers northeast of the Santa Rosa crossing. Between these two large calderas, some ten meters from the southwest corner of the one furthest to the east, there is a well or pit with an almost circular mouth of some ten meters in diameter. This diameter is reduced to form an almost cylindrical chimney of some two to three meters in diameter, widening again at its lowest height and bifurcating into two opposite openings. Although this cave is found just between two large collapses in the area, it does not seem to have originated in this way. The walls along the chimney, and in the two lower openings, have a perfectly visible lava layer, which makes one suppose that this acted as an exhaust tube for molten lava material. According to our information, we were the first to explore this pit.

The cave is about 560 meters above sea level and its total depth is 64 meters, with a vertical drop from its mouth of 52 meters. The exterior temperature was 32.3° Celsius, while at the deepest end of the pit it falls as low as 29° Celsius.

From a biological point of view, there were several surprising discoveries: eyeless harvestmen (currently being studied), small depigmented polydesmid diplopods, symphyla, springtails, two-pronged bristle tails, and ants. Crane flies were especially abundant at the lower end.

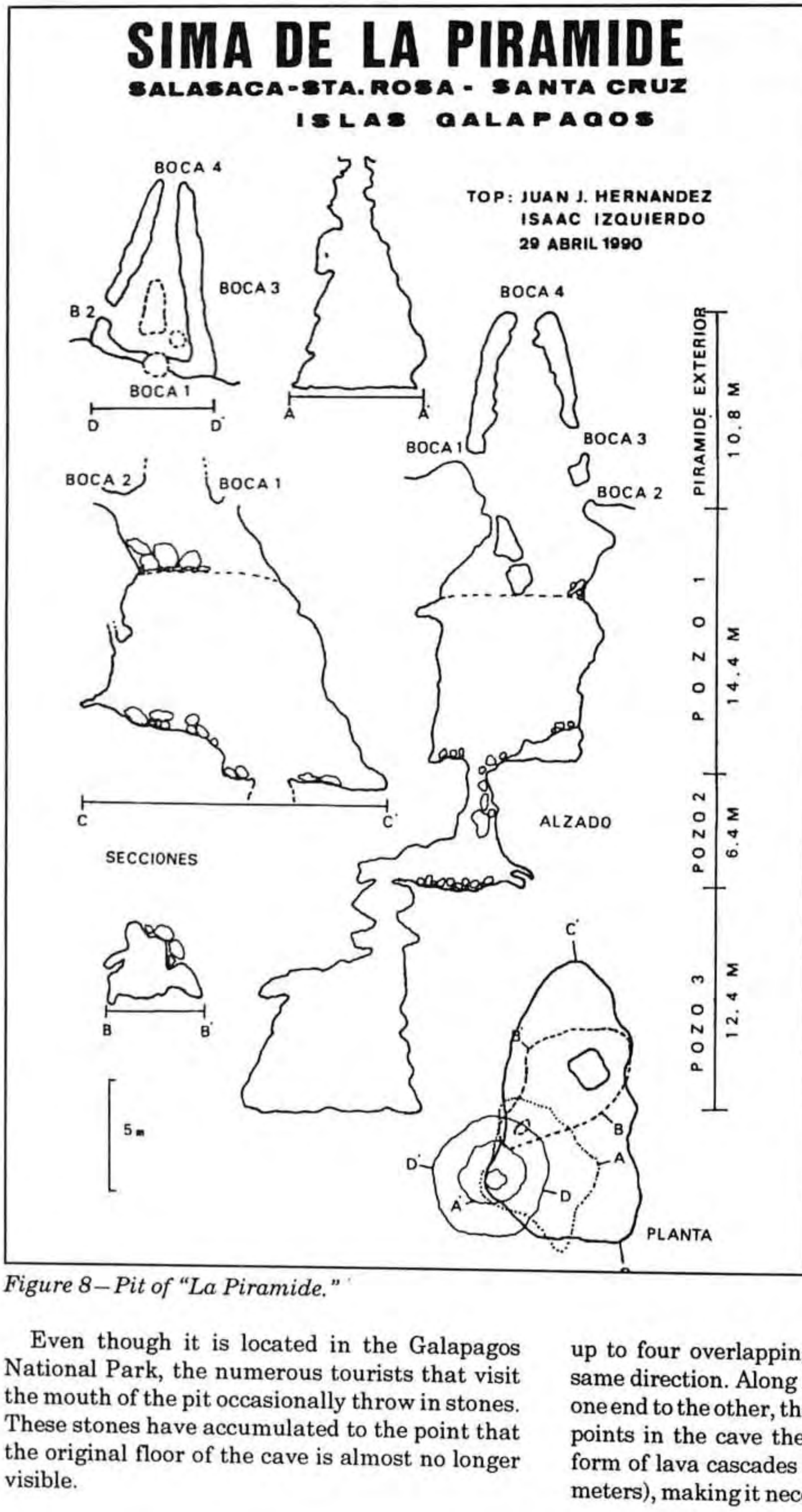

Figure 8—Pit of "La Piramide."

Even though it is located in the Galapagos National Park, the numerous tourists that visit the mouth of the pit occasionally throw in stones. These stones have accumulated to the point that the original floor of the cave is almost no longer visible.

2.e. Cascajo Cave

(Figure 10)

This is a large cave located some 700 meters (15 minutes on foot) east of Mount Cascajo, about eight kilometers from Bellavista. In the rainy season, the area around the access to the cave is usually flooded, forming large overflowing pool which makes it difficult to enter. However, a detour from the foot trail which goes to El Garrapatero beach from Mount Cascajo could be an alternate route. Since this interesting cave is practically unknown to most of the inhabitants of Santa Cruz, we show in Figure 11 one of the accesses to the cave (to entrance number 5 at 230 meters altitude), where Wilfrid Urive from Bellavista guided us. He is a good contact to find the cave.

From a speleometric point of view this is without a doubt the most important volcanic cave of the Galapagos Islands. Its 3,010 meters of length makes it the longest known lava tube of all these islands (and perhaps in all of South America). It is a large lava tube with a uniform, linear arrangement, there are practically no lateral ramifications and in some areas there are up to four overlapping tubes, all oriented in the same direction. Along its 2,007-meter length from one end to the other, there are 14 skylights. At some points in the cave there are unlevel areas in the form of lava cascades (the maximum being seven meters), making it necessary to use rope to get over

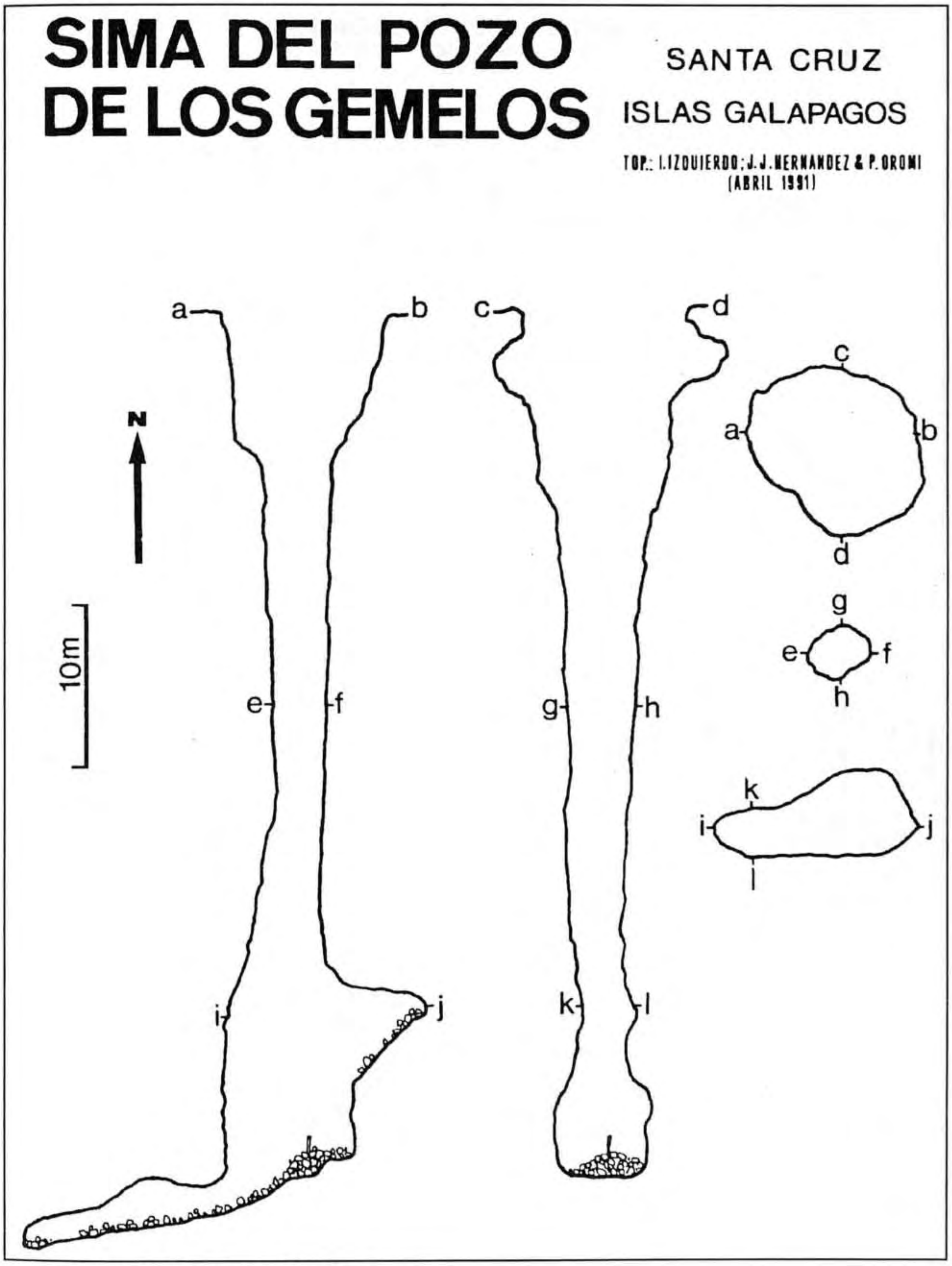

Figure 9 – Pit of "Pozo de Los Gemelos."

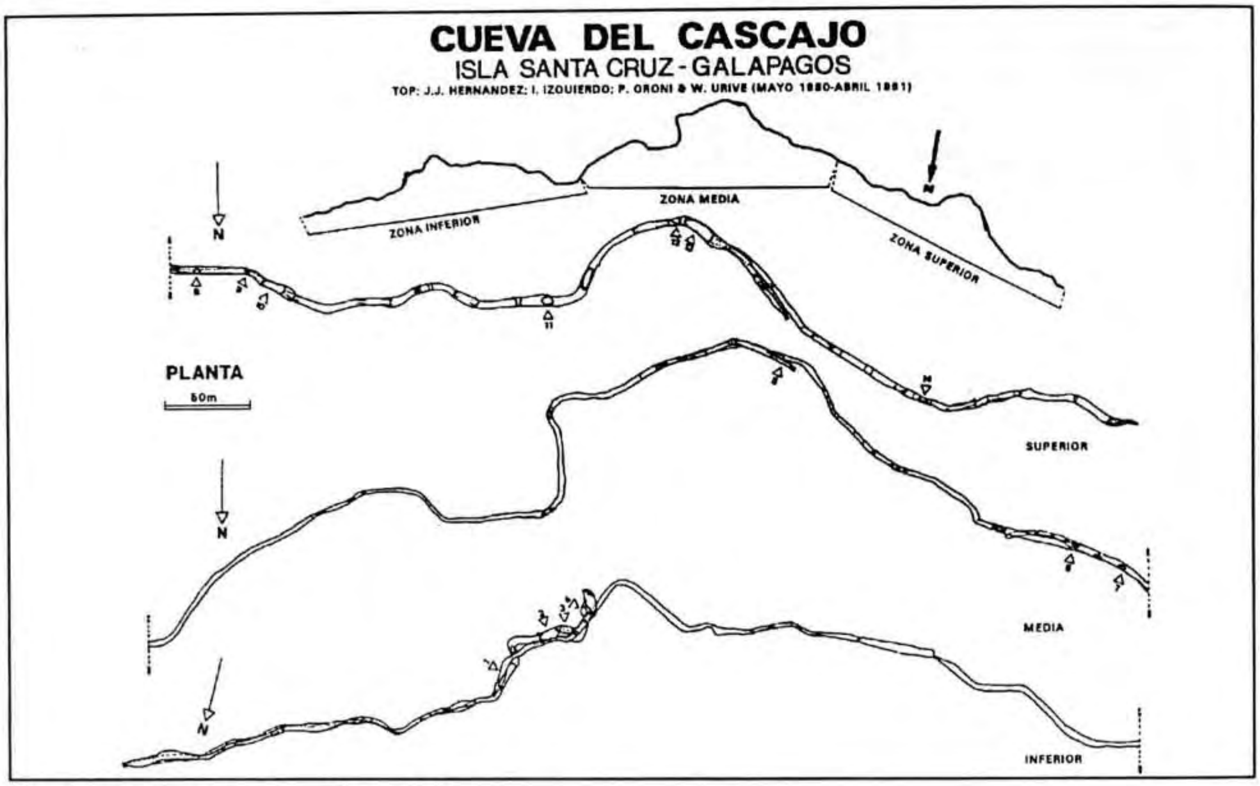

Figure 10 – Cascajo Cave. Ground plan.

them. In many of these skylights it is not unusual to see a Galapagos Barn Owl (Tyto alba) nesting. The large quantity of bone remains of the extinct Giant Rat of Santa Cruz (Megaoryzomys curioii) is surprising, and there are also remains of land iguanas, galapagos, and various types of birds. In this way, Cascajo Cave represents an important paleontological deposit which should be studied.

The invertebrate fauna is unquestionably rich and varied. In the first sampling the presence of spiders (Pholicidae and Linyphidae) was detected, along with the amblipigy *Charinus insularis*, depigmented millipedes (dipolopods Polydesmidae), centipedes, Symphyla, depigmented woodlice, springtails, cockroaches, two-pronged bristle tails (Diplura, campodeids), ground beetles (*Calosoma*), tenebrionids and curculionids beetles,

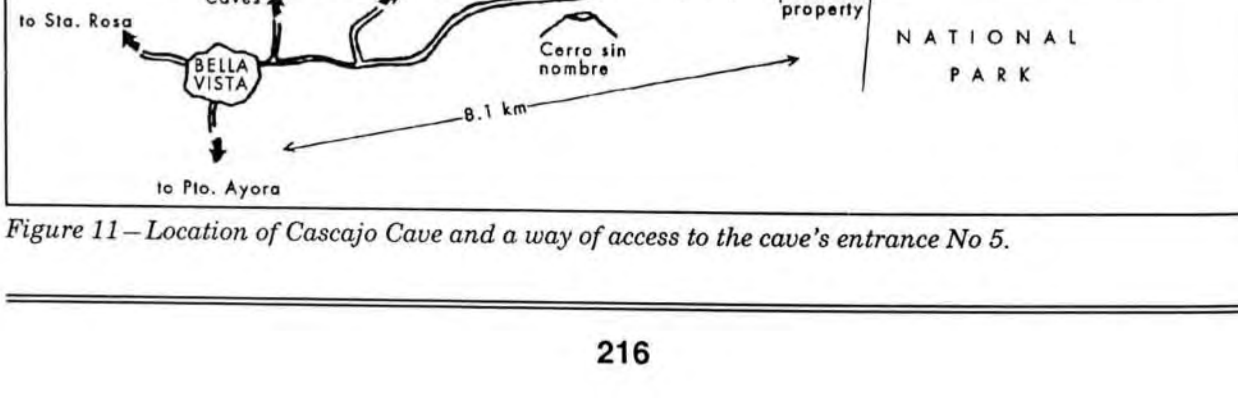

Figure 11 – Location of Cascajo Cave and a way of access to the cave's entrance No 5.

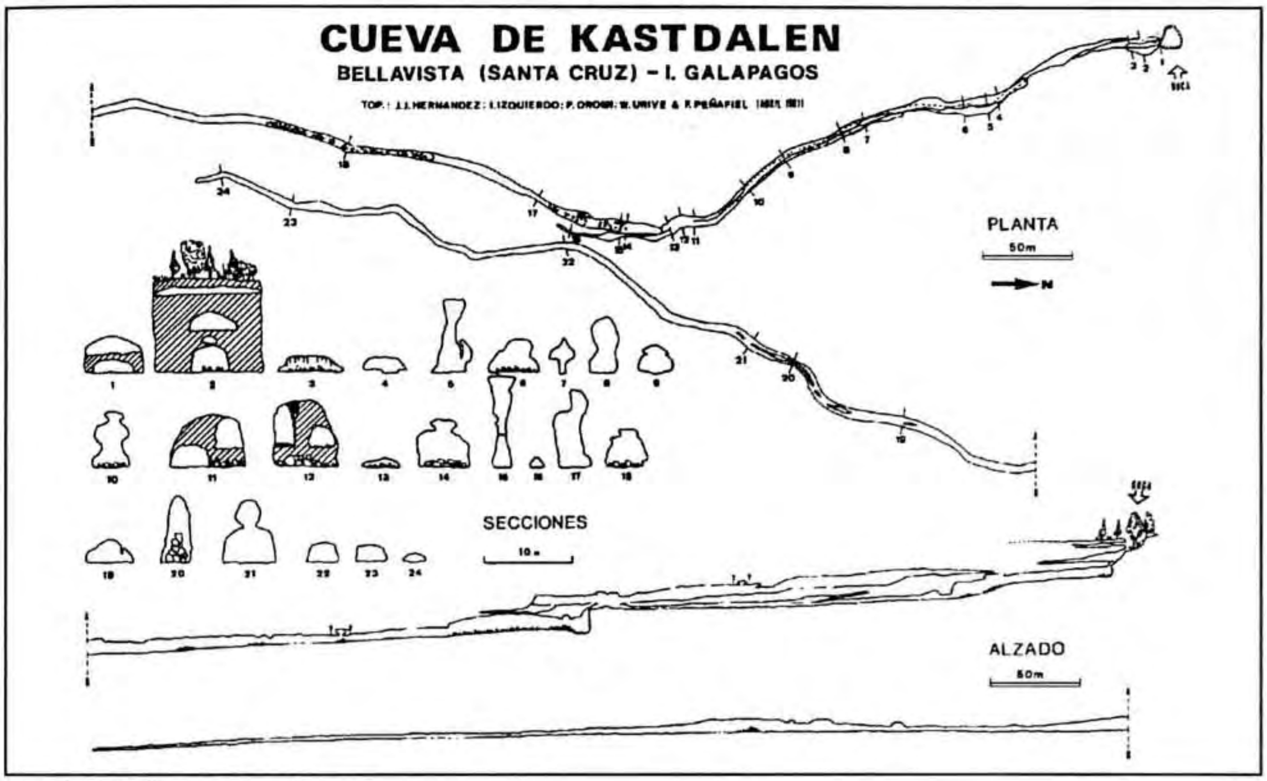

Figure 12—Kastdalen Cave.

lepidopteras, dipteras (Phoridae, Sciaridae, and Tipulidae), ants, and so on. Of special interest is the discovery of a new species of a troglobite curculionid beetle, belonging to the genus *Anchonus*.

Due to its great length this cave extends under private land and also into areas of the National Park. It receives practically no visitors and it is not unusual to find at its entrances the remains of livestock (mostly cows) which have fallen in.

2.f. Kastdalen Cave (Figure 12).

This cave is located on Kastdalen Farm, some two kilometers northeast of Bellavista at an altitude of approximately 300 meters above sea level. As it is well described in Peck and Peck (1986a), it consists of a series of four entrances to sections of the large lava tube. These sections do not communicate underground and, although they haven't been mapped, they are estimated to have a total length of some 500 meters (Peck and Peck, 1986a). Our work was centered on the entrance at the southeast end, which gives access to three overlapping tubes of which the lowest one has yet to be studied, due to the difficulty presented by its vertical access. Its entrance looks exactly like what it is, a large lava tube, measuring 1,500 meters long.

Although Kastdalen Cave extends towards the big Cave of Bellavista, it does not connects with it. The part of the cave that is perhaps the most interesting has a vertical fall of some 12 meters which makes it necessary to use a rope for its exploration. The last section, which is very easy to move through, features white mineral deposits of simple composition, covering the ceilings, walls, and floors. This tube had already been explored by Chris Vanbeveren in 1985, but given its difficult access, it remains practically undamaged.

These lava tubes have unquestionable biological interest. Peck and Peck (1986a) had already found, in the curved sections of the northwest sector, an interesting troglobitic fauna made up of harvestmen, *Galanomma microphtalma* Juberthie, and pholcid spiders (*Corysocnemis* spp.) among others. Our samplings topped off these finds with the presence of slugs, eyeless spiders (Gnaphosidae), woodlice, the silverfish *Nicoletia meeinerti* Silvestri, earwigs, ants, click beetles, and so on.

Speleology In The Galapagos

The volcanic caves on the Galapagos Islands are truly a natural heritage. Their special geomorphology is of great geological interest because through them the constitution and dynamics of their interior formation can be studied. Biologically, they are of even greater interest since inside of them live very special animal communities, in which many of the species are totally dependent on the evironmental conditions of the subterranean ecosystem.

Sometimes these cavities can also represent important paleontological deposits since the remains of animals which no longer exist have been preserved in their interior for thousands of years. In many cases we only have these bone remains to lead us to the knowledge of their existence.

The peculiar cryptic fauna that live in these caves, and in general the entire network of subterranean spaces, is extremely interesting from an evolutionary point of view, given the simplicity of the ecosystems in which they develop. There is no doubt that this is just the beginning of the study of the cryptozoic animals on the Galapagos, and judging from the finds that have been made in the lava tubes of the Azores, Canary, and Hawaiian Islands (Oromí *et al.*, 1990; Hernandez *et al.*, 1986; Martín *et al.*, 1989; Howarth, 1972, 1982) there are still many cryptic species which have yet to be discovered on those islands, although the role of these species is already starting to become understood in the functional dynamics of island ecosystems.

We are fortunate to be able to say that today the Galapagos caves are in an excellent state of preservation. In some cases the steepness of the entrances to the caves is what has stopped visitors from coming and therefore an optimum state of preservation has been maintained. In other cases this has been simply due to ignorance of their existence. Nevertheless, the population of the Galapagos is growing sharply, and the number of tourist-visitors is progressively increasing each year.

All this has already meant more interest on the part of the colonists who live in the agricultural area of Santa Cruz to use the lava tubes that exist on their land for tourist purposes. With an infrastructure that leaves much to be desired, part of the Bellavista Cave is being utilized for this purpose under the name "The Tunnels." Other landowners are beginning to request reports on the tourism viability of the caves. In some cases these caves have tremendous biological and paleontological interest and, though they are not located within the limits of the Galapagos National Park, they should be preserved at all cost. We therefore urge that these natural resources located on the Galapagos Islands be completely catalogued, in order to carefully organize their use (tourist/didactic and scientific) and that the appropriate organizations plan the territory properly, considering the natural value that these caves represent.

Acknowledgements

The authors wish to thank Dr. Stewart Peck (Carleton University, Canada) for the valuable information he made available about the mapping and location of many of the caves. We would also like to thank the Charles Darwin Research Station, and especially Pat Whelan, Fionnuala Walsh, and Sandra Abedrabbo for their invaluable collaboration during our stay on the Galapagos. The Galapagos National Park Service for the authorization granted to us, and especially Sr. Arnaldo Tupiza for his great assistance in the work on Isabela Island. To P.N. Ashmole and N. Ashmole for their colaboration in the field work. To our good friend, guide, and collaborator Wilfrido Urive and the kind staff of the Hotel Galapagos for their hospitality and those unforgettable good times we shared with them.

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Theoretical Biological Conservation and Management Topics


5683

Lava Tubes in the Solar System

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Abstract

All of the major planets and satellites have been visited by spacecraft except Pluto and its moon, Charon. Results show that volcanism is important in the surface evolution of nearly all planets, although the type of volcanism varies considerably. The inner solar system is dominated by basaltic volcanism and lava tubes or channels have been identified on Mars, Moon, and possibly Mercury. The other solar objects of geologic interest, the satellites of major planets, consist of mixtures of ice and rock. Unusual styles of volcanism include eruptions of sulfur, water-slush, or methane ices, some of which form flow channels as seen in spacecraft images. Depending upon their rheological properties, these materials may also form tubes.

Venus is the last terrestrial planet to be explored geologically. It has often been described as the sister planet to Earth because of its similarity in size, density, and proximity in the solar system. Because Venus is completely shrouded by dense, hot clouds, its surface is hidden from view by conventional cameras. Its geological diversity is currently being revealed by the U.S. Magellan mission. Launched in 1989 and beginning operation in August 1990, this mission involves a sophisticated radar imager that is systematically mapping the surface of Venus at a resolution better than 100 meters. Preliminary results show that volcanism dominates many areas. Thin flows hundreds of kilometers long are seen, many of which originated from calderas, small pit craters, or fissures. Some of the flows were clearly emplaced through lava channels, parts of which are discontinuous and suggest roofing to form lava tubes.

Introduction

With the flyby of the Voyager 2 spacecraft past Neptune in the fall of 1989, the geological reconnaissance of the Solar System is nearly complete, with parts of all major planets and satellites photographed except for the Pluto-Charon system. Analysis of photogeological results for solid-surface planets and satellites shows that the principal processes in surface evolution are impact cratering, surficial processes (such as landslides and weathering), tectonic deformation, and volcanism. Impact cratering and surficial processes effect the planet from sources external to the planet; volcanism and tectonic deformation result from internal processes and are primarily manifestations of heat loss from the interior.

Most of the larger planets and satellites and some of the smaller satellites of the outer planets show evidence for volcanism. Dark regions on the Moon, called maria, are known to be of volcanic origin; similar plains regions seen on Mars and Mercury are also the result of eruptions. Radar images of Venus obtained from the Magellan mission show huge mountains and vast plains that are of volcanic origin. Many of the satellites of Jupiter, Saturn, Uranus, and Neptune exhibit smooth plains that are the consequence of liquid materials erupted from their interiors onto the surfaces to form plains that mantle older terrains.

The Moon

Mapping shows that mare lava flows cover about 17% of the surface of the Moon. The total volume of volcanic rock, however, probably constitutes less than 1% of the crust, with most of the material being composed of impact-produced brecciated rocks. Nonetheless, mare lava flows dominate the near side of the Moon and contain a variety of

volcanic features and flow structures (Wilhelms, 1987). Samples of the Moon returned by the United States Apollo program and the Soviet unmanned Luna series have shown that the mare lavas are composed of basaltic rocks. Although very similar to basalts on Earth, they tend to be more titanium-rich and were erupted more than one billion years ago. Estimates of the viscosities of the lavas at the time of their eruption show that they were extremely runny, having the consistency of motor oil at room temperature.

In December 1990, the Galileo spacecraft flew past the Moon and returned the first new information for the far side in more than two decades (Belton et al., 1992). The data revealed the presence of numerous iron-rich deposits in the highland terrain that constitutes most of the far side. Many of the areas showing this distinctive signature appear to be mare deposits that have been mantled by impact generated debris. Mapping the location of these areas, termed "cryptomaria," is showing that volcanism on the Moon is more extensive than previously considered.

Figure 1—Mosaic of photographs taken by the Apollo 17 astronauts from orbit around the Moon, showing the southwestern part of Mare Imbrium. Some of the flows seen here can be traced more than 1,000 kilometers north (toward top) from vent areas south of the area shown here. Initially, the flows were fed through lava channels and lava tube systems (NASA AS 17-155-23714 to 23716).

Although most of the lava flows on the Moon were emplaced as vast flood lavas which generated huge pools of molten magma, some of the flows, particularly in the later stages of eruption, were emplaced through open rivers of lava or through closed systems of lava tubes (Figure 1). These ancient lava channels and partly collapsed lava tubes are seen today as lunar sinuous rilles (Figure 2) like lava tubes and channels found on Earth, with many lunar sinuous rilles exceeding 100 kilometers in length and 1 kilometer in width. Despite the differences in scale between the lunar and terrestrial features, the mechanics of eruption, flow emplacement, and lava tube formation are considered to be similar based on the assumption that it is the rheological property of

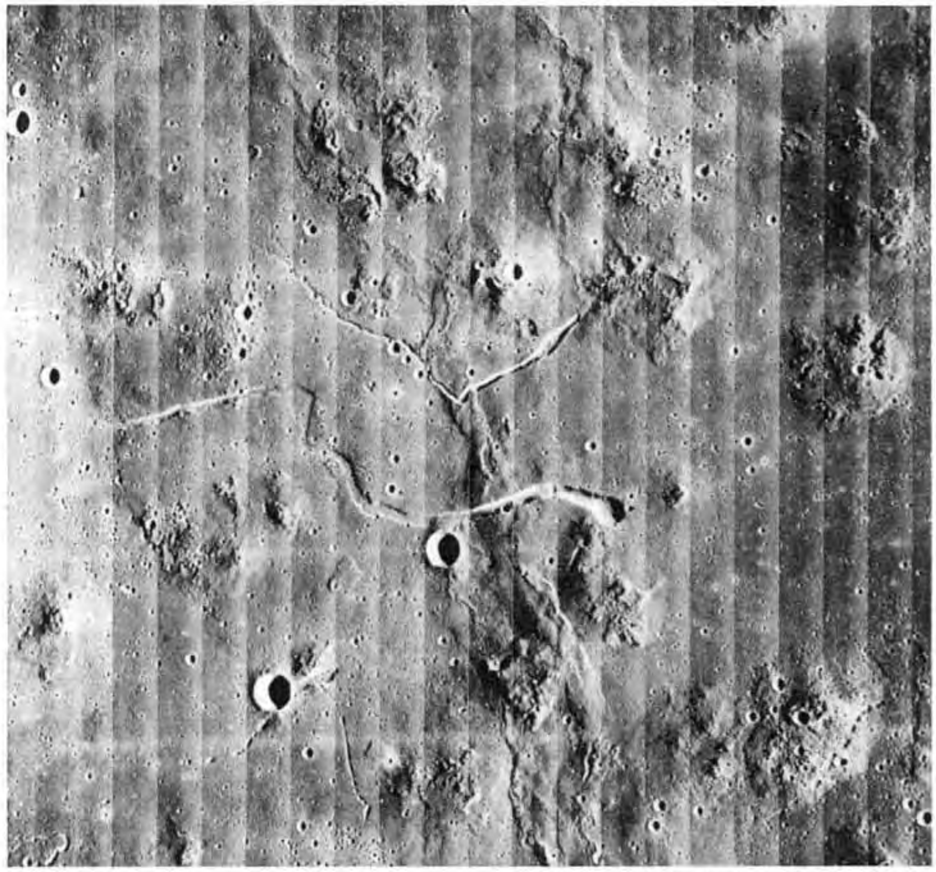

Figure 2—Lunar Orbiter (robotic spacecraft) image of the lunar Marius Hills region, showing several sinuous rilles and partly-collapsed lava tubes (lower left) that emplaced lavas in the mare regions (NASA LO V-M-213, sun illumination from the right, north to the top, areas shown is about 60 kilometers by 55 kilometers).

the lava and the style of eruption that lead to the formation of lava tubes and channels.

A current debate for lunar sinuous rilles centers on the role of erosion by flow through tubes. Some planetary scientists suggest that the sinuous rilles are primarily the consequence of erosion by flowing lava, while others maintain that they are predominantly constructional features.

The only lunar sinuous rille visited on the surface of the Moon was the Hadley Rille, located on the eastern margin of the Imbrium basin on the lunar near side (Figure 3). The Apollo 15 mission landed on lava plains between the rille and the Apennine Mountains to the east. Samples collected by the Apollo astronauts show that the lavas that spilled from the bank of the rille are basaltic. Photographs taken of the interior walls of Hadley Rille show distinctive horizontal layers that are typical of those seen in the relatively thin lava flow units associated with most lava tubes and channels on Earth. Recent work by Spudis et al. (1988) indicates a complex geologic history for the development and evolution of Hadley Rille.

The Moon was the first extraterrestrial planetary object examined for volcanic features and much of what is known about lava tubes in the Solar System context has been derived from the study of lunar sinuous rilles. Hadley Rille and dozens of similar features show that many of the lava flows on the Moon were emplaced through unitary lava tubes and channels. Mapping their origin and tracing their pathways enable eruptive vents to be identified. These mapping projects contribute to the understanding of lunar surface history.

Mars

More than half a dozen spacecraft have been sent to Mars over the past two decades and a tremendous wealth of information has been returned from the red planet. Most of the information has come from the United States Mariner 9 and Viking missions, both of which operated during the 1970s (Carr, 1981). More than half of the surface of Mars is seen to be covered with volcanic materials of one form or another (Figure 4; Greeley and Schneid, 1991). Although information on the composition of the volcanic flows and deposits is very limited, x-ray fluorescence measurements obtained by the Viking lander spacecraft, multispectral remote sensing observations of the surface, and various geophysical models all suggest that the predominant rocks are basaltic. However, some models also incorporate ultramafic materials, such

Figure 3—Apollo 15 mapping camera photograph of the Hadley Rille (115 kilometers long) and the Apollo 15 landing site ("A"); "H" marks the mountain block that is part of the ancient lunar crust. Sun illumination is from the left, north is to the top (NASA AS 15-414).

as komatiitic lava flows. Komatiitic lava flows are characterized as magnesium-rich and were common in the early history of the Earth. Studies suggest that they were extremely fluid and flowed as fast-moving, turbulent masses. This characteristic poses intriguing problems in the consideration of lava tube and channel formation, and komatiitic lavas are being studied by planetary scientists for comparisons with features seen on Mars and Venus.

Although the most impressive volcanic features on Mars are the enormous shield volcanoes, such as Olympus Mons and the other volcanoes of the Tharsis region, various plains-producing lava flows compose most of the surface area of the volcanic materials. Many of the lava flows that built both the shield volcanoes and the plains were emplaced through lava tubes and channels, as shown in Figure 5. In these high resolution images, obtained from the Viking Orbiter spacecraft, open channels and roofed channel segments are clearly visible. Some of the volcanoes, such as Alba Patera, are enormous structures covering thousands of square kilometers and are composed of individual lava flows fed through extensive tube and channel systems.

The Mars Observer mission, to be launched by the United States in 1992, will carry an array of instruments to provide new and important information on the geology of Mars. Of particular interest for the study of lava tubes and channels is the imaging system that will be capable of obtaining pictures with a resolution of ~1.5 meters for any place targeted on the surface of the planet. In addition, the Thermal Emission Spectrometer will obtain measurements that will allow the compositions of the martian lavas and other volcanic deposits to be assessed.

In 1994, the Soviets are scheduled to launch an ambitious mission to Mars that will include not only measurements made from orbit, but also small simple probes that will land in at least four different locations. A high priority target for one lander is a young volcanic terrain. The goal is to obtain

in-situ measurements of the composition of the lava flows and high resolution images from the surface. At the same time, a German built, high-resolution camera will obtain stereoscopic images from the Soviet orbiter. Images from this system will enable photogrammetric measurements and construction of topographic maps over lava tube systems and volcanic terrains.

The information to be obtained from the American and Soviet missions has the potential for making significant contributions to the study of martian lava tubes. Data on lava compositions, images of collapsed tube segments and possible tube entrances, and topographic information will aid in understanding the formation and evolution of the martian surface. Mars remains one of the most important planets for understanding the evolution of the inner Solar System.

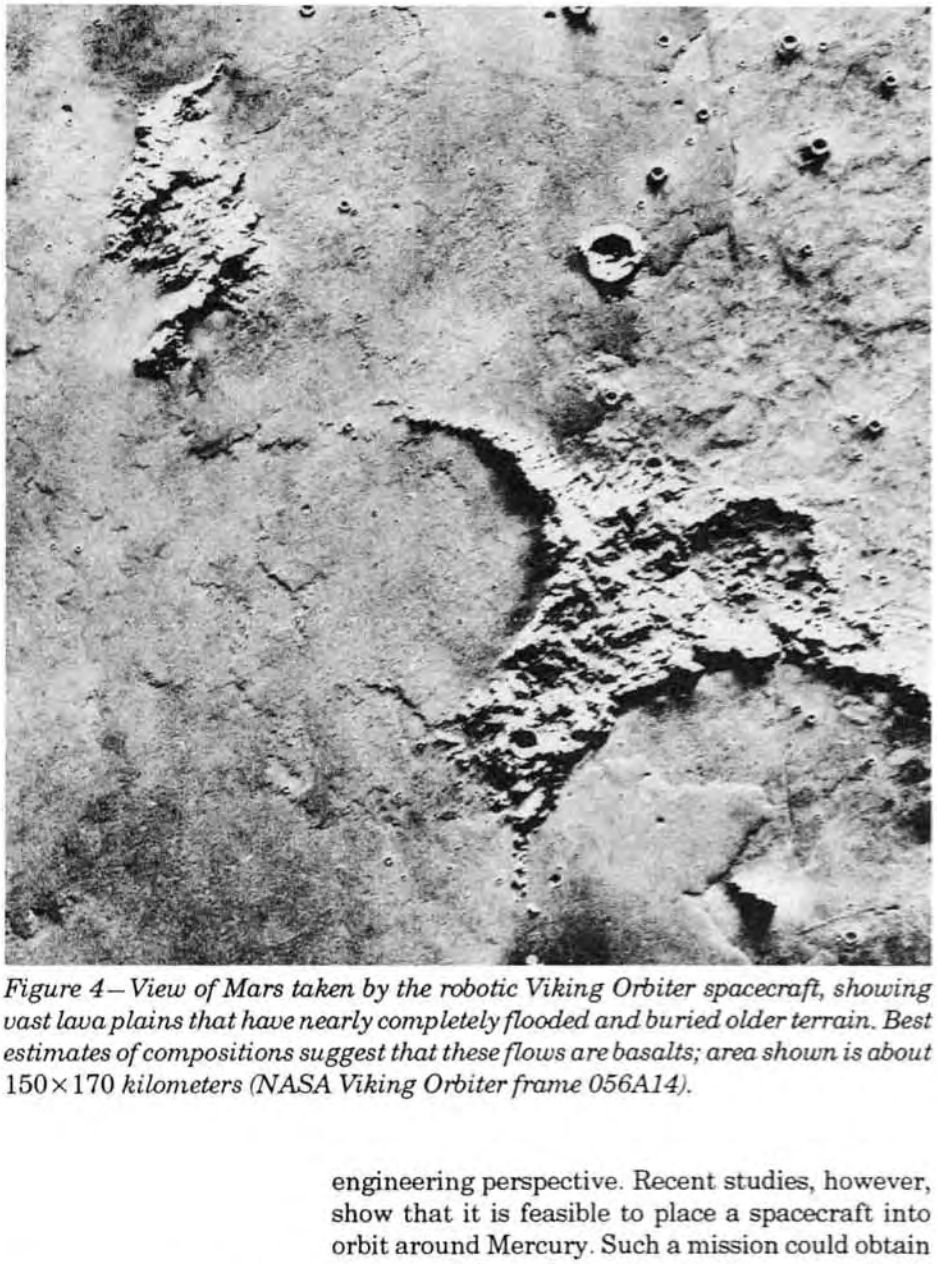

Figure 4—View of Mars taken by the robotic Viking Orbiter spacecraft, showing vast lava plains that have nearly completely flooded and buried older terrain. Best estimates of compositions suggest that these flows are basalts; area shown is about 150×170 *kilometers (NASA Viking Orbiter frame 056A14).*

Mercury

The only geological information available for Mercury came from the Mariner 10 spacecraft that flew in the early 1970s and observed about half the surface. Photographs of Mercury and limited remote sensing information show various smooth plains that are significantly younger than the rest of the surface of the planet (Greeley, 1987). It is only by circumstantial evidence, however, that these areas are considered to be volcanic, and the types of features, such as sinuous rilles seen on the Moon and Mars, generally are not seen on Mercury.

For many years an advanced mission to Mercury was deemed impossible or very difficult from an engineering perspective. Recent studies, however, show that it is feasible to place a spacecraft into orbit around Mercury. Such a mission could obtain not only high resolution images for suspected volcanic areas of the surface, but also to observe the other 50% of the planet which remains totally unknown at this time.

Venus

Venus has been called the sister planet of Earth because both planets are nearly the same size and density, and occupy the same general location in the Solar System. Venus, however, is completely enveloped in clouds and its surface is not visible to conventional cameras. The clouds, composed of droplets of sulfuric acid, create a greenhouse ef-

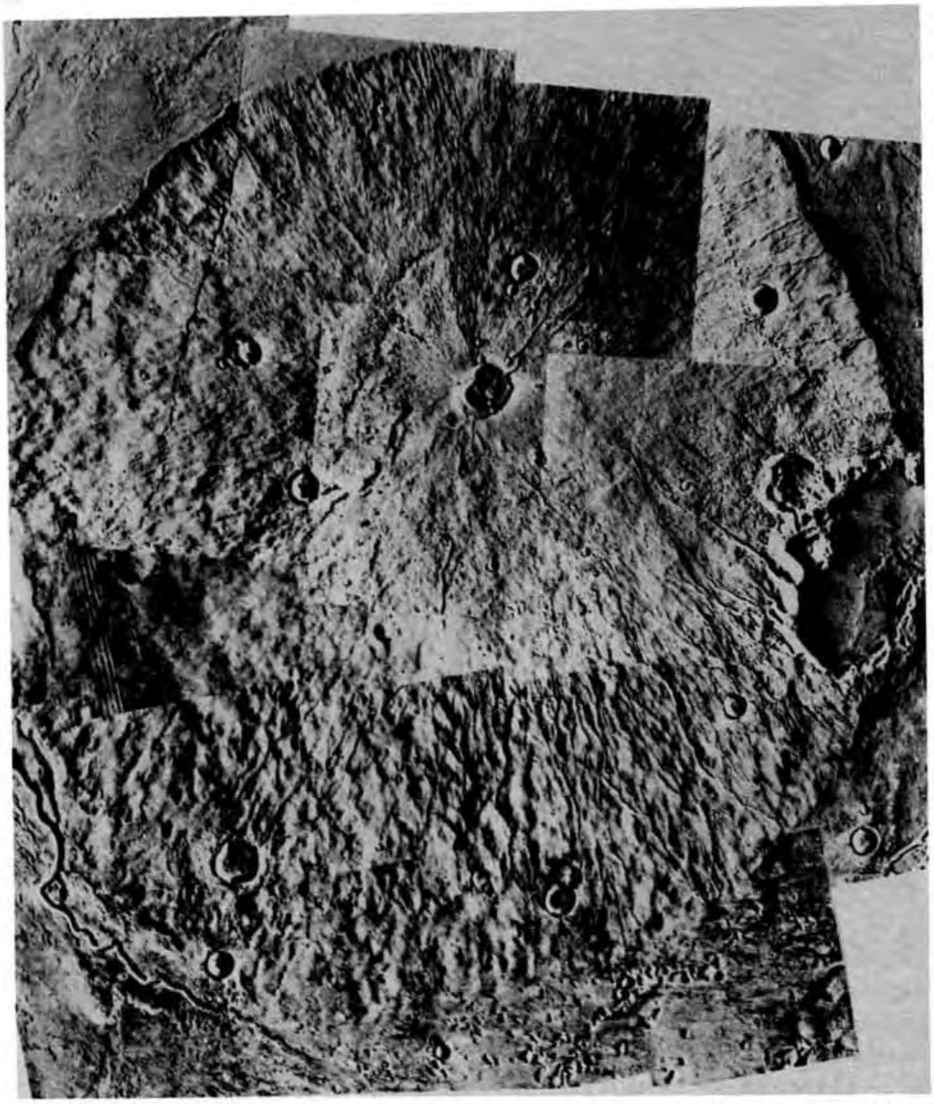

Figure 5—Mosaic of images of the Martian volcano, Hecates Tholus. This shield volcano is more than 200 kilometers across and is composed of hundreds of individual flows, many of which were emplaced through lava tubes and channels. Segments of collapsed tubes are visible as radial patterns around the summit caldera (NASA Viking Orbiter mosaic).

fect, causing the surface temperatures to rise to 450° Celsius, or in excess of the melting temperature of lead.

Venus is the last of the inner planets to be explored geologically. Although the Soviets have landed in more than a dozen locations on the surface and returned information on local rock types (indicating primarily basaltic compositions), the global perspective of the planet has only recently been obtained by the Magellan spacecraft. Launched by the United States and placed in orbit in 1990, Magellan carries a radar mapping system that returned the first high resolution (~75 meters/pixel) radar images of the surface from orbit. Magellan data have revealed Venus to be a geologically diverse planet, dominated by volcanism and tectonism (Saunders and Pettengill, 1991).

Like Mars, Venus exhibits both central volcanoes including shield structures hundreds of kilometers across, and vast plains formed by the accumulation of countless lava flows (Figure 6). Venus exhibits a wider variety of volcanic landforms than Mars, and includes domes that appear to be composed of viscous, pasty lavas and hundreds of fields of cinder cones.

Among the puzzling volcanic features revealed by Magellan are numerous channels, some of which are nearly 7,000 kilometers long. Preliminary analysis reveals several different types of channels, most of which are inferred to be of volcanic origin. One category includes long, narrow channels that have a constant width; they also show breached channel segments where lava flows have spilled onto the surrounding terrain. Although analyses are only preliminary, it is likely that many of the flows were fed through systems of lava tubes, either directly from vents, or as feeder systems from the channels.

The great length of the channels on Venus poses interesting problems for volcanology. Although it is conceivable that conventional flows, such as those composed of basalt, may account for the formation of the channels, other, more exotic lava compositions are also being considered. For exam-

Figure 6—Radar image of the Lada region of Venus taken by the Magellan spacecraft, showing a series of lava flows, some of which were emplaced through channels and networks of lava tubes; area shown is about 550×630 *kilometers (NASA P-38088).*

ple, sulfur compounds are known to exist in the atmosphere of Venus and it is conceivable that some of the flows could be composed of sulfur. Carbonatite is a rare type of lava found in some places on Earth and also has been suggested to exist on Venus. These flows erupt at very low temperatures and, in the Venusian environment, carbonatite and sulfur flows would never solidify, but would continue to flow so long as there was a slope.

The analysis of Magellan images will require many years of study by geoscientists and the wealth of data is only now being realized. As is true for the Earth, Moon, and Mars, study of the volcanic features must include assessment of lava tubes and channels in the emplacement of the extensive lava flows.

Outer Solar System Satellites

The Jovian planets—so named for their resemblance to Jupiter—include Saturn, Uranus, and Neptune as well as Jupiter. All are enormous gaseous planets composed predominantly of hydrogen and helium and lack solid surfaces. Although they are not amenable to geological study, they all have solid-surface satellites, many of which exhibit extensive geological modification.

Jupiter's four large moons were first discovered by Galileo in the early 1600s. They include two objects—Ganymede and Callisto—that are about the size of Mercury, but which have low densities, suggestive of water-ice compositions. The other two moons, Io and Europa, are about the size of Earth's Moon and have densities suggestive of rocky material. Two Voyager spacecraft returned extensive data on the Jupiter system and revealed the first evidence for active volcanism in the Solar System outside of Earth. Voyager images show that eruptions are taking place constantly on Io, with pyroclastic material raining down on the surface nearly everywhere. In addition, high resolution Voyager images show countless flows emanating from enormous calderas. Spectral reflectance data suggest that sulfur is present on the surface of Io and it has been proposed that some of the flows may be composed of liquid sulfur. Although rare and of limited extent, sulfur flows have been observed on Earth and contain small tube-like features. If such features can form at larger scales on Io, they would be important in transporting liquid sulfur lava long distances in the frigid (-140° Celsius) environment of the outer Solar System.

Jupiter's Europa and Ganymede; Saturn's Enceladus, Tethys, and Dione; and Uranus' Miranda are all ice-rich satellites that show large, smooth plains areas. These areas lack abundant superposed impact craters and are considered to be geologically young. The plains are thought by most planetary scientists to have formed by the eruption of slushy ice onto the surface as a consequence of interior heating and melting of ice. Fracture systems seen in association with some of the plains probably served as eruptive conduits to the surface. In some cases, the fractures are ancient features

that formed in response to large impact events. In other cases, the fractures appear to have formed in response to internal activity and crustal deformation. Such internal activity and the eruption of liquids onto the surface of some small moons was a surprise to most planetary scientists. Prior to the exploration of the outer Solar System, the degree of internal activity was considered to be a function of planetary mass—large planets would contain more radioactive elements and hence generate more heat and magma. Small objects, such as 500-kilometer-in-diameter Enceladus, were thought to be far too small to generate sufficient heat to melt rocks or even ice. The discovery of active volcanoes on Io (and on Neptune's moon Triton) caused a reassessment of these ideas, and it was recognized that factors other than radioactive heating can generate magma and lead to active volcanism. For example, Io resides in an orbit between Jupiter and another moon, Europa. As such, it is constantly subjected to gravitational tides that push-pull its crust. Frictional heat generated by this tidal stressing is more than adequate to melt parts of Io and to drive the volcanism observed today.

Unfortunately, most images of the outer planet satellites are of low resolution and primarily provide only a reconnaissance of their surfaces. Details of the styles of emplacement and history of the materials that flooded onto the surfaces of these objects must await better data to be obtained on future missions. For example, the Galileo mission, launched in 1989 and currently on its way to Jupiter, will be in orbit around this giant planet for some 20 months beginning in late 1995. During that time it will make repeated passes of the Galilean satellites and obtain images of 10 to 100 times better resolution than the Voyager images. In addition, tentative approval has been given for a joint NASA European Space Agency mission named Cassini. Like the Galileo mission to Jupiter, Cassini will involve a spacecraft placed in orbit around Saturn and will observe not only the giant planet and its rings, but it myriad satellites as well.

Summary

Solar System exploration has demonstrated that volcanism is an important geological processes on the terrestrial planets—Earth, Moon, Mars, and (possibly) Mercury—and on many of the satellites of the outer Solar System. While basaltic volcanism dominates most of the terrestrial planets, exotic (by Earth standards) compositions, such as ultramafic komatiites, sulfur, and carbonatite lavas, may also be found. Lava tubes and flow channels play an important role in the emplacement of many of the lava flows seen on the terrestrial planets. Understanding the origin and evolution of these flow features is critical to the derivation of the evolution of the planets where they are found.

Outer planet satellites include volatile elements such as sulfur, ice, and methane. Understanding the mechanics of eruption and emplacement of volatile and ice-rich materials must await future exploration by spacecraft such as Galileo and Cassini planned for later in this decade and extending into the next century.

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Nomenclature of Lava Tube Features

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Abstract

In the past 75 years, works including well over 1,000 different names and phrases for features of lava tubes have been published. Inasmuch as there are only about 100 lava tube features arguably deserving distinction, that is far too many to go around. The excess consists of synonyms (the majority), ambiguous modifiers, oxymorons, conjectures, innocent misuse, double talk, and efforts to convey dimensions with terminology. While much of the redundancy is simply personal preference, sometimes without regard for the literature, certain characteristics of lava tubes generate more than their share of confounding terminology. This paper will focus on those aspects, the most troublesome of which is the matter of segmentation which even has political implications. Pitfalls are pointed out and suggestions offered for improving lava tube terminology.

Introduction

Prior to the early 1960s, U.S. literature regarding lava tubes was scanty and fragmentary. There are few excellent monographs about individual lava tubes—even fewer about groups of lava tubes—by and large, writers were more concerned with processes of volcanism other than lava tubes. For example, the fundamental connection between lava tubes and the emplacement of lava far removed from a vent escaped notice by all but a few. Except for the ubiquitous "lavacicles,"—named in 1923 but not successfully defined then or since—individual features of lava tubes were regarded as little more than curiosities. One of the first works to describe lava tube features in a comprehensive way was *Lava Beds National Monument: Outline of Geology*, by Lewis and Anderson, in 1936. Even though never published, several of the terms introduced therein are in use today.

In the early 1960s, with the advent of organized caving in the northwestern United States (where lava tubes outnumber other types of caves), exploration and description of them quickened. In 1963 description of lava tubes began in earnest with publication of *Caves of Washington*, by William R. Halliday. In this book, Halliday introduced a groundwork of lava tube terminology, most of which is still in use today.

Since then the number of recognized, significantly different features has increased modestly and steadily as new discoveries were made, but the increase in terminology has been exponential. The habit of naming lava tube features after well known, everyday objects, without reference to morphology or genesis has created confusion. One person's curb is another's shoulder, another's bench, still another's apron, *ad infinitum*. Some terms such as "formation," "lavacicle," "dripstone," "original," and "balcony" have been so indiscriminately and unsystematically used that they are meaningless unless qualified. Furthermore, premature classification of features based on the study of a single lava field, even a single lava tube, produced theories and terms which, while conforming perfectly with the observations, conflict with observations of other lava fields and tubes.

Many terms currently in use were adapted from the much older family of terms used to describe features of solution caves, and rightly so. There are many directly interchangeable terms, e.g. collapse, coralloid, pillar, and sink. Many terms for depositional features have the same meaning regardless of cave genesis. However, some terms are not interchangeable, and a special problem is that many primary lava tube features so resemble their calcite cousins that they are often called speleothems. This is unfortunate, because there is an important distinction to be made, e.g. mineral stalactites (speleothems) form in both lava tubes and solution

caves, but stalactites composed of lava form only in lava tubes. A speleothem is a secondary mineral deposit formed in a cave, and cannot be composed of lava, some say, since it has a variable composition of many minerals.

Over 1,000 different terms and phrases for features of lava tubes have been published in the last 75 years. There are only about 100 lava tube features arguably deserving distinction. The excess consists of synonyms (the majority), ambiguous modifiers, oxymorons, conjectures, innocent misuse, double talk, and efforts to convey dimensions with terminology. Among the excess are the following:

Misuses:

"projected" when "inferred" is meant.

"linear" when "elongate" is meant – a surprisingly common misuse.

confusing "roof collapse" and "ceiling collapse."

"channel", when "river" or "stream" is meant.

"hydraulic" when "hydrostatic" is meant.

"upper tube" when "upper level" is meant

"cross section" when "profile" is meant, and vice versa.

"ice cave" when "glaciere" is meant (or "cave containing ice" if preferred)

"perennial ice cave" when "cave with perennial ice" is meant.

"permanent ice" when "perennial ice" is meant. There is no such thing as permanent ice.

"remelt" (or remelted) when there is no way of knowing if remelting occurred.

Redundancy and Reiteration:

hot molten lava.
molten liquid.
cupola in roof.
vertical pit
downstream flow [of molten lava]
excessive use of "lava" as an adjective

Oxymorons:

segmented cave
collapsed channel
loose cinder, loose welded cinder, loose clinker
ceiling stalactite
underground lava tube, underground passage

Conjectures:

Former skylight, covered-over skylight.

Non Sequiturs:

partial natural bridge
secondary speleothem.
pre-lava
aa-pahoehoe transitional
filled skylight

Ambiguous Terms:

physically connected
map view.
old skylight.

"Intact" or "original" are often used but rarely qualified. Either term presupposes some condition that should be specified.

Problem Areas

Segmentation.

Lack of broad agreement regarding segmentation of lava tubes and systems increasingly spawns confusion about the nature of openings into lava tubes. A case could be made that there are only two kinds of openings: skylights, which are considered too small to segment a tube, and all other openings which do. This proposition is supported by Curl's argument (1965) that all definitions of a cave which have ever been offered include the notion of rock overhead.

The principal aspect of segmentation, that of individual caves isolated from the tube or system by collapse, is troublesome. It directly affects the number of individual caves in a given province, a matter of some significance now that a U.S. Federal Cave Law requires that lists of caves be generated. It also directly affects the position of a given cave in long-cave lists, a matter of virtually no significance. Perhaps nothing illustrates the lack of a segmentation protocol more than the occasional use of the term "segmented cave."

Speleothems.

"Speleothem" is a generally accepted, but frustrating term that differentiates an icicle formed in a cave from one formed under a highway bridge – and rests on the insecure definition of a cave. A good example of a term run amok. On the one hand, some speleologists contend that a mineral deposit formed in a mine, and morphologically and chemically identical to one found in a cave, is not a speleothem. On the other hand, there are those who would lump all mineral deposits, regardless of where found, including many rheologically-formed lava features, under the speleothem umbrella.

Openings.

The terms skylight, entrance, and opening are often used at the expense of truly descriptive terms. An "entrance" is not a lava tube feature. Neither is an "exit." Both terms refer to a use of an opening, and often convey a false impression of the opening. For example, there are three openings into Ape Cave, in the Mount St. Helens National Monument. All three are skylights, and they do not segment the tube, yet only one is called a skylight. The other two are "entrances" – it would make as much sense to call them "exits" – because that's where visitors go in and out.

Flow Features.

There is an entire class of forms created when lava freezes – lava flowstone, lava stalactites, lava stalagmites, and other things that resemble speleothems but aren't – for which there is no attractive general term. "Rheologically formed" is an obvious candidate, but it is such a mouthful. "Primary" would be, it seems, appropriate, but as presently construed "primary" includes collapse features that occurred while lava was flowing. "Flow feature" is appropriate but by no means enjoys universal use.

Recommendations

- Use existing terms when possible. Borrow from solution cave nomenclature if appropriate. For example, a speleothem may be found in any type of cave. Sinks, pillars, sand castles, stalactites, stoping, and so on are common to solution caves as well as lava tube caves. The glossary accompanying this paper includes most former usage, but nothing will substitute for searching the literature.
- Terms should not be used to denote dimensions: for example, one writer uses tubelet for little tubes.
- If a term has to be manufactured, try to make it as expressive of the morphology and composition of the feature as possible. Avoid using names of everyday, commonly encountered objects, or names of persons living or dead.
- Use lava as an adjective only to distinguish from similarly-shaped features of different composition in other types caves. Excessive use of lava, pahoehoe, and basalt – as adjectives – is uncalled for in regard to lava tubes.
- Don't allow point of view to influence terminology: For example, skylights (there's that term again!) are usually seen as skylights from inside the cave, but often as pits when viewed from the surface.
- Don't confuse roof and ceiling.
- Avoid speculative terms or speculative use of terms, e.g. "remelt." Most of what has been called remelt was certainly fluid at one time, but examples that can be positively identified as remelt are few and far between.

Glossary of Vulcanospeleology

The following Glossary of Vulcanospeleology was culled from over 1,000 terms found in the works of about 100 different authors. The reference list is by no means exhaustive – it gives only references to pertinent works rich in terminology. Those works in turn provide reference to much other literature pertaining to lava tubes.

I have included features apt to be associated with lava tubes, and some having similar meaning regardless of cave type, and avoided redefining anything in other geologic senses. Though not specifically relating to lava tube features, the following terms are included because they are not universally understood and often misused: ceiling, cross section, map length, plan view, profile, roof, traverse length, and others. "Lava" is frequently used as an adjective to avoid conflicts with morphologically similar forms (principally speleothems) found in other kinds of caves.

Aka (Also known as): These are the other 900-odd names for the same thing, as nearly as I could discern. Many of these terms are clearly synonyms, but equally as many have not even approached common usage. Many have been used only once, and then not clearly defined. I expect that some readers will be unhappy because their favorite term(s) were not listed prominently. Please let me know. If this glossary does no more than narrow the focus on lava tube nomenclature, I will consider it time well spent.

The illustrated glossary (see references) should be available by the time this paper is published. It includes photos of nearly all the principal features, and an alphabetized list of all terms, cross referenced to the source literature.

Glossary of Lava Tube Features

Abbreviations used: Aka = Also known as, Cf = compare with, e.g. = for example, i.e. = that is, Syn = synonym.

AA. A type of lava flow with a rough, jagged, spinose, clinkery, and generally irregular surface. Fully developed aa is unusual inside lava tubes. Pronounced ah ah, as in father. Etymol: Hawaiian. An expletive of pain when walking barefoot on such lava. Cf: cauliflower aa, pahoehoe.

ALCOVE. A relatively small recess in the wall of a lava tube. Cf: cupola. Aka: balcony, lateral pocket.

AMBERAT. A varnish-like deposit composed primarily of the residue of rat urine. It ranges in color from clear yellow through red, brown, mahogany to jet black. It has been reported only in dry caves. Etymol: Resembled amber, smelled of rats. Type material from Sheep Canyon Cave, Montana. Aka: ratite.

APRON. A top surface that slopes down inward from a lava tube wall. Aka: sloping alcove, sloping apron, sloping lava bench, sloping lava ledge, sloping-top bench.

BENCH. A bank along the side of a lava tube. Distinction between benches, shelves and levees isn't always clear. In general, benches are essentially rectangular in cross section, and join both floor and wall; levees are usually attached to the floor and separated from the wall, but may be attached to the wall at considerable distance above the floor; shelves are attached to the wall and overhang. Cf: curb, terrace. Aka: balcony, basalt bank, "B" type lava ledge, bench line, flow bench, flow ledge, flow level, flow shelf, lateral lava shelf, lateral ledge, lava terrace, lava tunnel terrace, ledge, lining curb, perched balcony, perched lava bench, shelf, shoreline, shoulder, side walk, spatter bench, terrace, tide bench, tide mark.

BLISTER CAVE. A lava blister that can be entered by a human.

BLOCK RAMPART. A ridge or wall of loose blocks adjacent to or surrounding a collapse sink or collapse trench; the remnant of a tumulus which collapsed back into the lava tube from which it came. Cf: pressure ridge. See also: raised-rim crater. Aka: elevated rim, hydraulic rampart, rampart, tilted rampart.

BOTRYOID LAVA STALACTITE. A cluster of short, branching lava helictites that resembles a bunch of small grapes. Aka: grape type lava stalactite, knotted string stalactite.

BRANCH TUBE. (or simply "branch") (a) Either of the branches at a fork of a lava tube. (b) The place where a tube forks. See also: distributary tube, effluent tube. Aka: bifurcate, branched, once-branched, secondary lava tube, side passage, subordinate tube.

BREAKDOWN. A general term for broken pieces of a lava tube's roof or walls – the product of collapse – applied to individual blocks, accumulations and various structures resulting from re-incorporation of loose pieces in fluid lava. See pillar, rafted breakdown. Aka: basalt rubble, breakdown block (a single piece), breakdown rock, collapse block, collapse breccia, collapsed roof block, collapse rubble, pre-lava [*sic*] collapse breccia, rubble.

BREAKDOWN FLOOR. A cave floor that is mostly covered with breakdown.

BREAKDOWN JAM. An accumulation of rafted breakdown lodged in such a way as to plug a tube. Identity may be totally masked by lining(s), especially on the upstream end, but individual pieces often remain discernible at the downstream end. Cf: lava seal. Aka: breakdown plug, breakdown seal, floor jam, jam of jostled pahoehoe blocks, jam of rafted blocks, lava ball, lava block jam, lava-carried breakdown pile, plug.

BRIDGE. A remnant of a lava tube roof no wider, measured parallel to the tube axis, than the width of the tube it spans. Aka: arch, balcony, lava bridge, lava span, natural bridge, span.

BULBOUS LAVA STALACTITE. A lava stalactite that is significantly thicker at the bottom than at the top. Known examples appear to be small, hanging lava toes. Aka: bulbous pendant, lava stalactite, push out lava stalactite.

CAULIFLOWER AA. A type of lava transitional between pahoehoe and aa, the surface of which consists of closely-spaced lumps that range from about 5 to 30 cm across, that are **firmly bonded** to the underlying lava. The outer skin of the "floret" is typically knobby, bumpy, or even spiny. Cauliflower aa is quite common in lava tubes on the surface of lava falls, floors, levees and tongues, and often entrains rafted breakdown, broken crusts, lava stalagmites, and anything else that fell on it prior to congealing. It is frequently modified on a broad scale

with billows and ropes. Gradational to clinker (loose pieces). Cf: aa, clinker, spiny pahoehoe. Aka: aa-pahoehoe [*sic*] transitional, clastolith, clinker, clinkery pahoehoe, clinkery pahoehoe ripple, frothy pahoehoe, granular, granularly surfaced pahoehoe, pahoehoe to aa surface, scraggy veneer, spiny pahoehoe, tesselated, transitional pahoehoe-aa.

CAULIFLOWER AA FLOOR. A lava tube floor which is predominantly cauliflower aa. Aka: clinkery floor, klinkery ripple.

CAVE. "A naturally occurring void, cavity, recess, or system of interconnected passages which occurs beneath the surface of the earth or within a cliff or ledge . . . and which is large enough to permit an individual to enter . . ." (Federal Cave Resources Protection Act of 1988). Federal law notwithstanding, there is no commonly accepted definition of a cave. For example, one popular elastic definition requires that the cave extend beyond the twilight which, by definition is virtually undefinable. See also (the limitations of): lava tube cave. Aka: cavern.

CAVERNOUS WEATHERING. Chemical and mechanical weathering which results in disintegration of lava tube linings, and associated cliff-like surface features, in semi-arid regions. The usual result is a range of features remarkably similar in appearance to speleogens in solution caves, and some peculiarities like hollow breakdown blocks. Limited study to date indicates that the phenomena is the "cavernous weathering" described in Bates and Jackson (1987) – also known as "fretwork weathering" or "honeycomb weathering." The cavities so produced, including hollow boulders, are known as "tafone" (ta-fo'-ne). Aka: differential weathering, groundwater erosion, lava weathering, salt replacement weathering, subterranean weathering, weathered form.

CEILING. The upper inside surface of a lava tube or multiple level thereof. Cf: floor, roof. Aka: back.

CHOCKSTONE. A lava block, or mass of consolidated debris, caught in a passage constriction. Subsequent modification by continued lava flow often obscures the origin, e.g. chockstones are often the nucleus of a pillar. Aka: lava ball, meatball, perched lava ball.

CLINKER. Small (usually less than one foot in diameter), loose fragments of lava with rough, jagged surfaces. Clinker is commonly found on the floor and behind linings of lava tubes. It is a primary feature and should not be confused with pieces of breakdown which have fractured surfaces and may be either primary or secondary. See also: clinker floor. Aka: autobrecciated lava, flow breccia, flow-top breccia, loose clinker [*sic*].

CLINKER FLOOR. A floor on which clinkers predominate.

COLLAPSE. The mechanical failure of parts of a lava tube to withstand gravity. Collapse, like many other modifications, may be primary or secondary. See also: breakdown, collapse sink, collapse trench, stoping. Aka: breakdown, cave-in, caving, post-volcanic (roof) collapse, rockfall, unraveling.

COLLAPSED LAVA POND. A shallow surface depression with gently dipping sides, resulting from drainage of a lava pond. Typically the pond crust settles gently downward leaving a relatively even basin broken only by tension cracks. Aka: sag, sag basin, shallow collapse basin.

COLLAPSE SINK. An essentially circular, usually steep-sided, surface depression resulting from collapse into an underlying cavity, e.g. a lava tube. Cf: collapse trench. Aka: breakdown, collapse basin, collapse depression, collapse hole, collapse pit, jameo.

COLLAPSE TRENCH. An elongate, usually steep-sided and sinuous, surface depression resulting from collapse of a lava tube roof. Cf: trench. Aka: breakdown, breakdown trench, broken surface tube, caved-in trench, collapse depression, collapse pit, jameo, lava tube collapse depression, rift, surface trough.

COLUMN. (a) A speleothem formed by joining of a stalactite and corresponding stalagmite. Rare in lava tubes. (b) A lava stalagmite reaching the ceiling. Only two examples of the latter have been described (Halliday, 1967; Ogawa, 1980). Cf: pillar. Aka: mitertite, pillar, stalacto-stalagmite.

COMPOUND [features]. An adjective denoting a series of similar features. Multiple benches, flow lines, and levees are commonly found overlapping, in stair step fashion, and may be termed compound [features], e.g. compound benches. Aka: "C" type lava ledge, multiple levees, set of steps, stair step, successive lava marks, successive level marks.

CONTRACTION CRACK. A narrow, elongate crack caused by contraction of lava as it cools. Contraction cracks are abundant in lava tubes,

usually limited to a single flow unit, and vary in width from microscopic to several centimeters, the wider often found in floor units of considerable thickness which cooled slowly. Aka: cooling crack, contraction fissure, contraction fracture.

CONULITE. The compacted and/or mineralized lining of a drip hole in sediments. Conulites impregnated, and lined, with calcite have been identified, but other minerals seem suitable as well. When exposed by erosion of the surrounding unconsolidated material they are strikingly apparent. Aka: antistalagmite, mud cup, splash cup.

CORALLOID. A general term for a nodular, globular, botryoidal, or coral-like speleothem. Commonly found on projections of the ceiling, wall, or floor where a nucleus for growth is provided and evaporation is enhanced. Siliceous and marginally calcareous coralloids have been identified in lava tubes, mostly in semi-arid regions. A wide range of colors has been noted. Aka: cave coral, cave grape, concretion, coral, coral lava, coralloidal opal, globulite, knobstone, lava coral, lava lace, opal coral, pisolitic concretion, popcorn. (A variant in which spines of lava project beyond the speleothem is known as lava lace.)

CROSS SECTION. The outline of something cut off at right angles to an axis, in the speleological context, the transverse outline of a cave, stalactite, etc. at a specified point. Cf: profile. (Some of the adjectives used to describe the cross section of lava tubes are: arched, bell-shaped, bulging, ceiling channel, channeled, circular, cutbank, dome-shaped, double tube, elliptical, figure-8, flat-roofed, gable-shaped, gothic (arch), hemispherical, horizontally oval, hourglass, irregular, keyhole, moorish dome, multistoried, multi-tiered, mushroom, oval, overcut, semi-circular, shell-shaped, skull-shaped, stacked, triangular, undercut.)

CRUST. (a) The hardened exterior of a body of lava. Inside lava tubes, crusts form where heat loss is greatest, typically near openings to the surface. See also: lower level roof. Aka: balcony, initial roof stratum, tube-in-tube. (b) A form of speleothem. Crusts are unusual in lava tubes, except for gypsum crusts in lava tubes in arid locales.

CUPOLA. A recess in the ceiling of a lava tube. Possible origins of a cupola are: a cavity created by collapse, inflation of the roof by gas or lava pressure, or the roofed-over site of a former tube overflow. See also: rise chamber. Cf: alcove. Aka: breakdown dome, ceiling dome, covered skylight [*sic*], dome, filled skylight [*sic*], former skylight [*sic*], old skylight, overflow dome, roofed-over skylight [*sic*], standpipe chamber.

CURB. A low, narrow bench. Aka: curb lining, lining curb, small flow edge ridge.

CUTBANK. The concave wall of lava tube meander bend that is frequently the site of a recess or alcove eroded by an impinging lava stream. Cf: slip bank. Aka: meander cutbank.

CUT-OFF BRANCH. A lava tube cut off by collapse, plugged with congealed lava, or left hanging above subsequent flows in a main tube. Cf: perched tube. Aka: former branching, once-branched, once-interconnected.

DEFLATED FLOOR. A floor crust which collapsed following withdrawal of underlying lava. Cf: inflated floor.

DIP-LAYERED STALACTITE. A lava stalactite composed of highly vesicular, concentric layers, apparently resulting from repeated inundation by fluid lava. They are rare because of the special conditions required for their formation. Cf: spatter stalactite. Aka: candle-dip stalactite, coarse lavacicle.

DISTRIBUTARY TUBE. A lava tube flowing away from a main tube that does not return (as a re-entrant tube). Cf: effluent tube. Aka: branching secondary tube, divergent branch, egressive branch, feeder tube, major distributary, minor lava tube.

DRAINBACK. An opening through which a lava tube overflowed onto the surface, usually distinguishable by obvious patterns of lava flowing back into the tube. Other indicators are the absence of fractured surfaces around the lip of the opening and/or patches of red, oxidized linings adjacent to the opening. Aka: drainback feature, influx, lava retreat, roof rupture, skylight.

DRIBLET SPIRE. A smaller type of hornito built of imbricating clots of lava feebly rather than violently ejected. Large examples in Idaho (Greeley, 1971) averaged 12 feet in height and 5 feet in diameter. Hornitos can be much larger. Aka: driblet cone, lavacicle, small rootless volcano.

DRIP HOLE. A vertical hole eroded by dripping water. Dripping water creates drip holes in sediments, soluble rocks, and mineral deposits. Drip holes that penetrated mineral deposits to

erode underlying bedrock have been described. In sediments they are usually tapered, with a roughly circular transverse cross section. They may be slightly tilted, or considerably elongated in transverse cross section as a result of prevailing air movement on dripping water. See also: conulite. Cf: sand castle. Aka: drill hole, drip cup, drip-drilled mud pit, drip-formed depression, splash cup, splash hole.

DRIP LINE. The line defined on a cave floor at an opening where surface water drips from overhanging rocks. Because overhangs are vulnerable to erosional processes—especially ice wedging—the drip line is often marked by a wall of recently-fallen blocks. The drip line is also a valuable reference point for surveying and resolution of segmentation dilemmas.

DRIPSTONE. A speleothem precipitated from dripping water, abundant in solution caves but unusual in lava tubes. Cf: flowstone, lava flowstone.

EFFLUENT TUBE. A lava tube flowing away from a main tube. Cf: distributary tube. Aka: divergent branch, egressive branch, side tube.

ELEPHANT'S FOOT STALACTITE. A lava stalactite which had its growth terminated on an obstruction later removed. Seldom more than a few centimeters long because they usually occur between separated roof linings. Cf: tubular lava stalactite. Aka: club foot pendant.

ENTRANCE (Cave). An opening into a cave large enough to admit a human. Natural entrances to lava tubes are either residual openings or are created by collapse to the surface. Aka: collapse entrance.

FALSE FLOOR. A lower level roof (usually a crust) over an underlying passage too small to enter. Aka: hollow floor, secondary floor, subsidiary floor, tube-in-tube.

FESTOON. An arcuate fold or ridge formed by gravity-induced slumping and wrinkling of lava flowstone. Festoons are common on lava tube walls. Cf: ropy lava. Aka: arcuate plications, drapery of lava dripstone, festooned ropy pahoehoe, wrinkle.

FILLED LAVA TUBE. A segment of a lava tube that is filled with hardened lava, as a result of failure to drain or invasion by a subsequent lava flow. Aka: reactivated system.

FLOOR (lava tube). The lower inside surface of a lava tube or multiple level thereof. (For example, the top surface of a lower level roof dividing levels of a multilevel tube is a floor.) Cf: ceiling, roof. Floors may be the completely exposed, aa-congealed surface of the last lava to flow in the tube or covered with debris, like clinkers, breakdown, fragments of plates and linings, or composites thereof. Such coverings range from an occasional piece to elongate entrainments several feet thick, often rafted along, conveyor-belt fashion. Infrequently, floors are covered to some degree with sand (usually tephra), sediments and other deposits, especially near openings to the surface. The character of aa-congealed floor surfaces depends on whether the lava was moving or quiescent when it congealed, and its state of transition from pahoehoe to aa. Surfaces range from very smooth pahoehoe (as smooth as a sidewalk) to, rarely, full-blown aa. Cauliflower aa predominates. On a broad scale, patterns revealing movement are common regardless of the surface, e.g. billows, ropes, contraction cracks (as well as tension cracks), levees, tube-in-tube, and so on. See also: breakdown floor, cauliflower aa floor, clinker floor.

FLOW FEATURE. A collective term for features formed by movement of molten lava. Aka: rheogenetic feature.

FLOW LINE. An elongate projection or groove along the wall or floor, too small to significantly affect the tube's cross section. Flow lines along the wall typically mark interruptions of receding lava flow and often accumulate in stair-step fashion (see compound). Ordinarily they are gently dipping down-tube, reflecting the lava stream's hydrostatic grade, but standing waves may reverse the dip locally. Dips up to 15 degrees have been noted. Cf: strandline. Flow lines on the floor typically demarcate currents, eddies, and zones of shear in the flow. Aka: bathtub ring, curbing, "D" type shelves and ledges, flow crest line, flow mark, former lava level, frozen shore line, high lava mark, high stand, horizontal ridge, lateral flow groove, lateral line, lava mark, longitudinal deposit, miniature lava bench, minor ledge, multiple lateral groove, shear, stripe, shoreline, temporary surface level, tide mark, wall groove, wall ridge.

FLOWSTONE. A speleothem deposited by flow of water films, common in limestone caves. In lava tubes, ice flowstone in massive accumulations is common but rarely do other minerals accumulate (as flowstone) in excess of films or coatings. Cf: dripstone, lava flowstone.

FLOW UNIT. A successive but essentially contemporaneous layer or unit of lava constituting a single larger flow. Each unit represents a separate surge or sheet of liquid lava, all of which are part of the same eruption. Thickness ranges widely, from centimeters to several meters.

FORMATION. (a) A geological term for the basic or fundamental unit by which rocks are grouped in geologic mapping. (b) Any kind of a distinctive or unusual natural feature arising from processes of deposition, molding, or erosion, hence it has been indiscriminately applied to many of the fascinating features of caves. Aka: decoration.

FUMAROLE. A gas vent, sometimes associated with spattering of lava. Cf: hornito.

GLACIERE. A French word for subterranean ice. It was tentatively proposed by Balch, in 1900, as a term for a cave – in rock – that contains ice. (Not to be confused with "glacier cave" which is a cave in a glacier.) Cf: ice cave. Aka: cave of perpetual ice, cave of transient ice, freezing cave, freezing cavern, ice cave.

GLAZE. A thin, smooth, vitreous surface commonly found on lava tube features, especially on lava flowstone. Some researchers believe that convection and radiant heat from the lava flow alone are enough to glaze even hardened basalt. Others believe glaze is, to some degree, remelt but could only occur in a blast-furnace-like atmosphere augmented with burning gases. Aka: flash glaze, glassy surface, remelt glaze, sheet of glassy lava, thin lava veneer.

GROOVED LAVA. Grooves, striations, and gouges produced by movement between bodies of lava, of which at least one is still plastic. Aka: ceiling groove, dragged (lava), drag mark, flow groove, scratch marks, striation.

GUTTER. A trough-like, elongate depression between a levee, or tongue, and adjacent wall, the bottom of which may be lower or higher than the medial floor. Cf: lava channel. Aka: flow channel, lateral gutter, lava channel, shear, slot, trough, wall gutter.

HORNITO. A conical structure built up by clots of fluid lava ejected through an opening in the crust of a lava flow . Common on the roof of a lava tube and occasionally found on floors. Usually retains the central conduit. Cf: driblet spire, fumarole, rootless vent. Aka: agglutinate spatter cone, blow hole, blowout, blow pipe, chimney, driblet cone, entrance, fumarole, pneumatogenetic explosive cave, rootless spatter cone, rootless volcano, secondary spatter cone, secondary vent, spatter vent, small volcano, spatter cone, spatter cone pit, volcano without roots.

ICE CAVE. A cave in ice. The term is, however, commonly applied to any type of cave that contains ice. See: glaciere.

ICE HORIZON. A sharp, thin, rimstone marking a former ice stand line in a lava tube. They are seldom more than a film, and typically so inconspicuous that they are only apparent on more or less uniform surfaces at eye level.

INFLATED FLOOR. A floor crust ruptured by injection of lava beneath it. Typically, the crust splits near the center and along the walls, creating plates tilted upward in a form resembling a pressure ridge. Cf: deflated floor. Aka: arch, bread loaf ridge, floor inflation, heaved-up blocks.

ISLAND. An obstruction (usually a piece or raft of breakdown) "run aground" on the floor of a lava tube, surrounded and often modified by passing lava flow. Aka: bubble, concentric, depositional concentric, lava ball, splash ring. Cf: rafted breakdown.

KIPUKA. An island of older rock surrounded by younger lava.

LAVA. A general term for a molten extrusive, most commonly applied to surface flows from a volcanic vent, also for the volcanic rock that solidifies from it.

LAVA BLISTER. A hollow, surficial swelling of the crust of a lava flow, puffed up by gas from within or beneath the flow. Blisters range from tens of centimeters to several meters in diameter. Blisters noted on lava tube floors range in diameter from a few millimeters to tens of centimeters. They have a thin, vitreous skin, and may be empty or filled with nested layers of frothy lava. They may be found singly or in wall-to-wall accumulations, making non-destructive passage virtually impossible. See blister cave. Aka: blister, gas blister, lava bubble, pneumatogenetic expansion cave.

LAVA CAVE. A general term for any cave within lava, regardless of how formed. See also: cave, lava tube, lava tube cave.
Aka: volcanic cave.

LAVA CHANNEL (or simply "channel"). A long open trough, on or in a lava flow, occupied or formerly occupied by a lava stream. Commonly, channels bounded by levees – or walls built up of congealed overflows, splashes, and spatter –

are perched above adjacent surfaces. Channels inside lava tubes are typically much smaller and closely follow the tube centerline. Cf: gutter. Aka: channel, contraction valley, feeder channel, gutter, lava brook, lava gutter, lava river, open lava channel, river, shoot [*sic*], trough.

LAVACICLE. A general term that has been applied to nearly anything that protrudes into a lava tube, even stalagmites. It is ambiguous unless qualified. [The word originated with Phil Brogan, a prolific writer about Oregon's natural history, who applied it to both stalactites and stalagmites. It is first known to have appeared in print in 1923 (as "lava-cicle"), in Ira Willams' "The Lava River Tunnel," in reference to the tubular lava stalactites which were once abundant there.]

LAVA DAM. A levee across a lava tube. Aka: dam.

LAVA FALL. A precipitous drop in the floor of a tube over which lava flowed. Aka: cascade, dam, fall, lava drain, rapids.

LAVA FLOWSTONE. A fluid layer of lava on the boundary surface of a lava tube. Commonly, a fluid layer remains when an intratubal stream of lava recedes. A fluid layer may be acquired by remelt, or may be deposited by spatter. Also, a general term for lava forms resulting from its flow. Cf: dripstone, flowstone. Aka: dripstone, lavacicle, dribble, drip lava, film of liquid lava, flow of film, flowstone, lava dripstone, lava formation, lava speleothem, liquid lining film, primary drip, skin of lava, solidified drips of once fluid lava, vertical flow lines.

LAVA HELICTITE. A cylindrical – often partially tubular – extrusion, usually contorted and jointed but sometimes linear, unaffected by gravity. Many resemble tubular lava stalactites – with which they occur in combinations – in all respects except that they are not gravity-controlled. Most emerge abruptly from the host surface, apparently extruded in response to gas pressure, and may grow at either end. Ranging in size from tiny, five-millimeter-diameter, twig-like branches up to the familiar diameter of tubular lava stalactites. They emerge from all kinds of linings, other helictites, stalactites, and even from fractured surfaces. Aka: eccentric, eccentric stalactite, erratic, irregular tubular lavacicle, lavacicle, worm, worm stalactite.

LAVA LAKE. A standing body of usually basaltic fluid lava in a volcanic crater or depression. The term applies to solidified and partly solidified stages as well as to the fluid, active lava lake.

LAVA ROSE. A broad, low form resembling the bloom of a rose. There are two distinct types which, while similar in appearance, originate quite differently.

(a) Extruded Roses are created by successive, concentric extrusion and rupture of lava bubbles, the result resembling a rose bloom. Averaging about eight centimeters in diameter, they seldom exceed five centimeters in height. Like lava bubbles, they are uncommon and extremely fragile. Aka: minicano.

(b) Stalagmite Rose. The blunt, cup-shaped top of a lava stalagmite, flattened by the impact of relatively large clots of lava falling from considerable height, the result resembling a flower bloom. Also resembles a small driblet spire but lacks the central conduit. Aka: lava puddle, pancake lava stalagmite, puddle, rose cicle.

LAVA SEAL. A point where a lava tube is completely blocked by congealed lava Cf: breakdown jam. See also: filled lava tube, lava sump. Aka: intrusive lava seal, lava fill, lava plug, plug, sump, viscous plug.

LAVA SPRING. Lava welling up into a tube, typically on the downstream side of a lava sump. Aka: upwelling, upwelling source of lava.

LAVA STALACTITE. A stalactite consisting of a molten or solidified mass of lava. All lava stalactites originate in the molten state. Some harden, without modification, from the liquid. Others are distorted externally (by gas currents) or internally (by vesiculation) prior to hardening. Still others accumulate layers of lava flowstone or spatter. Transverse cross sections range widely, from circular (See teat stalactite) to extremely elongate (See rib). See also: botryoid lava stalactite, bulbous lava stalactite, dip-layered stalactite, elephant's foot stalactite, pipe stem stalactite, shark tooth stalactite, soda straw stalactite, spatter stalactite, teat stalactite, tubular lava stalactite. Aka: accreted form, cicle, basaltic ornamentation, common stalactite, drip cicle, drip lava stalactite, drip decoration, dripstone stalactite, festoon, glaze stalactite, lava candle, lavacicle, lava drip formation, lava drip, lava cicle, lava formation, lavacicle stalactite, lava speleothem, lavatite, ornamentation, primary ornamentation, remelt stalactite, solidified drips of once fluid lava, speleothem, stalactite of basalt, stalactitic

droppings of lava, syngenetic basalt stalactite, tapered stalactite. Cf: stretched lava projection.

LAVA STALAGMITE. A vertically oriented accretion of droplets and dribbles of semi-solid and solid lava, occurring in a wide variety of shapes and sizes ranging from broad, low lava roses rising barely above the floor, to giants over two meters high. They are initially associated with a ceiling or wall structure which dripped (a low point, stalactite, etc.), but usually the host surface moves or is overridden, causing a numerical disparity between stalactites and stalagmites. See also: column. Aka: basaltic ornamentation, common drip stalagmite, cored form, driblet spire, drip accreted stalagmite, drip-formed stalagmite, drip mound, drip stalagmite, floor cicle, globular lava stalagmite, lavacicle, lava formation, lavamite, lava speleothem, little people, little people formations, multiglobular stalagmite, ornamentation, pancake lava stalagmite, primary ornamentation, speleothem, stalagmite lavacicle.

LAVA STREAM. A body of lava flowing in a lava channel.

LAVA SUMP. A local depression in the floor where lava drained from a lava tube. Although most lava sumps are lava seals at the down-tube end of a lava tube segment, occasionally they occur elsewhere, for example where lava drained into a lower level. Aka: inverted siphon, inverted spoon, lava fill, lava siphon, siphon, siphon plug, solidified lava sump.

LAVA TOE. A bulbous mass of lava in tough, seemingly elastic skin which emerges from the crusted front of a relatively slow-moving pahoehoe flow, and is a primary means of expansion of pahoehoe lava flows. Toes vary widely in size, up to several meters. Coalescence of toes is thought to be a primary means by which distributaries of lava tube systems advance. Toes inside lava tubes are not common and limited in size.

LAVA TREE. A lava tree mold that projects above the surrounding surface.

LAVA TREE MOLD. A cavity inside a lava flow formerly occupied by a tree engulfed by the flow. Many, perhaps most molds are substantially altered as the tree burns. Frequently the mold preserves the craze pattern of burned wood in minute detail. Occasionally tree molds are exposed inside lava tubes. Cf: lava tree.

LAVA TUBE. A conduit formed of hardened lava, on or within a lava flow through which lava flows to an advancing flow front, also a cavernous segment of the conduit remaining after flow ceases. Only two variants, surface tube and tube-in-tube are literally tubes. Cf: cave, lava cave, lava tube cave, lava tube system. See also: branch tube, cut-off branch, distributary tube, effluent tube, filled lava tube, main tube, master tube, perched tube, re-entrant tube, surface tube, tributary tube, unitary tube. Aka: basalt cave, drain pipe of solid lava, lava cave, lava tublet [*sic*], lava tunnel, rheogenetic surface cave, true lava cave, tublet [*sic*], tunnel, volcanic flow drain. A lava tube may be active (carrying fluid lava), abandoned (see primary), filled with solid lava (did not drain), reactivated (invaded by a subsequent eruption), or filled to some degree with deposits like sand or water.

LAVA TUBE BOXWORK. Pairs of intersecting blades projecting from tube ceiling or walls which appear to be of two possible origins. (a) Preferential remelting on or adjacent to contraction cracks. Related to melt-out pocket. See also: remelt. (b) Preferential cavernous weathering adjacent to contraction cracks. Aka: boxwork.

LAVA TUBE CAVE. (Or simply "lava tube.") A specific lava tube, or segment of a lava tube that qualifies as a cave. (Distinction between individual lava tube caves is complicated by progressive collapse creating new openings to—or segmenting—known caves, and incremental discovery, but most of all by lack of consensus about the effect of segmenting features. For example, the usual type of opening, a collapse, often creates more than one opening and the question arises: is the sink a part of a single cave, or does it separate two caves? The International Union of Speleology has suggested a partial resolution: if the sink's largest dimension measured horizontally exceeds its depth, the tube is segmented, resulting in multiple caves. All parts of a segment which can be traversed by an individual, without passing through a segmenting sink, constitute an individual cave. (International Union of Speleology, 1979.) Aka: lava-tube cave, lava tube system, open tube.

LAVA TUBE SLIME. A relatively thin layer of moist, algae-like, sometimes gelatinous material that locally coats the walls and ceilings of lava tubes. Limited study indicates that a major

component is bacteria of one sort or another, which account for the wide range of colors reported. Under certain conditions the slime becomes hydrophobic causing water beads to form, and rendering the surface highly reflective—the white or silvery appearance often reported.

LAVA TUBE SYSTEM. A distributive network of lava tubes that is characteristic of tube-fed pahoehoe flows, and the principal means by which such flows are so widely and thinly spread. While systems range in complexity from unitary tubes to complicated networks of parallel, overcrossing and re-entrant tubes, they are usually broadly dendritic in pattern, with an identifiable master tube. For obvious reasons, in-depth study of lava tube systems is virtually limited to inactive examples. An inactive lava tube system is a series or network of lava tube caves, collapse trenches, and other characteristic features, all of which, it is reasonably certain, are part of contemporaneous flow units. (Characteristic features, roughly in order of their probability from proximal to distal extremities of a system are: collapses, hornitos, skylights, rootless vents, tumuli, and pressure plateaus.) Aka: axial conduit network, axial tube system, braided complex, braided pattern, chain of collapse trenches, chain of large lava tubes, conduit system, distributary pattern of channels, distributary system, interconnected system, internal artery system, lava cave system, lava distributary system, lava tube, line of breakdowns, line of large feeder tubes, line of major breakdowns, major cave system, major lava tube, master drainage system, master lava tube system, repeatedly branching, rift, set of lava tubes.

LAYERED LAVA. Successive thin flow units and near-surface zones of vesiculation within the thin flow units. Commonly associated with a leveed channel or semitrench. Aka: lamina, multi-lamination.

LEVEE. (a) Surface. A retaining wall of hardened lava along the side of a lava channel or lake, built up incrementally by successive overflow, overthrusting of lava crusts or blocks, or spatter. (b) Intra-tubal. A free-standing lateral remnant of a lava tongue or flow caused by cooling along the edges and subsequent evacuation. The outer surface is usually rough and blocky (cauliflower aa); the inner surface is smoother but usually grooved, striated and marked with flow lines, and the upper edge is sometimes crenulated. Typically levees lean inward and occasionally opposing levees arch over to join, forming a tube-in-tube. If there is a space (gutter) between it and the wall, it is a levee. Levees may be found at considerable distance above the floor. Gradational to tube-in-tube. Aka: arched ledge, coffin, cornice, crust, free-standing wall, gutter rim, kerb, lateral ridge, pull-off curb, rail, railroad track, sheared-out curb, sheared wall, spatter bench.

LINING. A layer of hardened lava left against the interior surface of a lava tube by intermittent flow. Linings may be fused to the host surface, mechanically locked in place by conformity or intermittently separated by air, clinkers, or zones of shear. Lining thickness is widely variable, ranging from millimeters to meters, and not necessarily uniform or complete. Lining is a primary feature: collapse, for example, may be primary or secondary. Curbs, benches, scrolls, and terraces are linings. Cf: crust. See also: lining plug, lining shut. Aka: accretionary layer, accretionary lining of lava plaster, ceiling lining, cemented, chilled margin, concentric shelling, crust, detachment laminae, dripstone, floor lining, laminae, laminations of the wall, lateral coating, lateral crust, lava coating, lavacicle plaster, lava lining, lava plaster, onion skin layer, peeled off wall lining, peeling accretionary wall, peeling wall, peeling wall of lava plaster, plaster, plastered, selvage, sheet of glassy lava, shell, skin, skin of basalt, tube wall lining, veneer, wall coating, wall lining.

LINING PLUG. An obstruction formed of successive linings that completely blocks a lava tube. Aka: plug, solid basalt of concentric rings, successive tube-in-tube, tube-in-tube.

LINING RUPTURE. Local detachment of a lining, usually limited to the near-tube strata. A recess formerly occupied by a patch of lining blown away by the pressure of exsolving gas, so weakened by vesiculation and/or remelt as to no longer withstand gravity, or exfoliated by differential shrinkage (spalled). Aka: blowout, blowout pocket, broken gas bubble, bubble, burst blister, burst bubble, gas blowout, peeling dripstone, peel-off, peel-off of dripstone plaster, peel-off of thin lava plaster, pull-down patches, pulled-out, pulled-out bubble, pull-off, pull-off patch, pull-out, pull-out patch, ruptured blister, ruptured bubble, ruptured lining, ruptured wall lining, sag.

LINING SHUT. Massive, opposing accumulations of linings on the walls of a lava tube which have joined to separate the tube horizontally. See also: lower level roof. Aka: initial roof stratum, partition, selvage.

LOWER LEVEL ROOF. A partition dividing a lava tube horizontally into multiple levels. Some incipient forms, often heavily modified by subsequent flow, are crusts, shelves, lining shuts, and tube-in-tubes. See also: bridge. Aka: balcony, cave-in-cave, ceiling, crust, double deck, false ceiling, false floor, false roof, horizontal division, internal balcony, internal roof, lava floor, lining partition, lower balcony, lower tube ceiling, multiple subsidiary roof level, new roof, overhang, partition, roof bench, roofing-over partition, roofing partition, roof of the lower level, secondary crust, secondary roof, septum, subsidiary roof level, successive floor, tube-in-tube, upper balcony, upper deck, upper floor.

MAIN TUBE. (a) A lava tube which supplies lava to all other downstream tubes and branches. (b) The largest of branch tubes. Note that a main tube is not necessarily a master tube. Aka: main cave, main distributary channel, main feeder tube, main lava feeder channel, main passage, major artery, major feeder tube, parent lava tube, trunk passage.

MAP LENGTH. The length of a cave derived using its vertical projection onto a horizontal surface. Cf: traverse length. Aka: projected length.

MASTER TUBE. A dominant lava tube in a lava tube system. A master tube typically occupies the axis of a low, broad ridge built by subordinate tubes and overflow from the master tube itself, and is readily identified if the system is studied, e.g. topographic maps nearly always reveal a tell-tale series of collapse trenches. Locally, individual lava tube caves may be identified as segments of a master tube by certain characteristic features: size (relatively large, voluminous), vertically elongate cross section and multilevel development, modifications reflecting sustained activity (large benches, shelves, and multiple linings), indications of erosion (down-cutting by the lava stream into pre-flow strata), and presence of subordinate tubes and overflow complexity at various levels. (Un-segmented, inactive master tubes probably do not exist; none have been described.) Aka: apical ridge, axial feeder tube, axial tube, axial tube system, central drainage channel, central supply tunnel, central tube, central tunnel, dike-tube system, feeder conduit, feeder tube, feeding channel, large feeder tube, main axial feeder tube, main channel, main conduit, main feeder tube, main internal channel, main tube, main tube line, main tube system, major distributary, major drainage tube, major lava tube, parent lava tube, primary lava conduit, primary lava tube, primary passage, primary supply channel, primary tube, principal feeder, principal lava tube, rift, throughway tube, trunk channel, tube line.

MELT-OUT POCKET. A recess in the ceiling or wall seemingly created by remelting, usually found in clusters, sometimes in a perplexing association with fractures. Width and depth range widely, from a few centimeters to a meter or more. Related to lava tube boxwork. See also: remelt.

MICROGOUR. (a) A tiny rimstone dam (centimeter scale). (b) A small rimstone-like, or terrace-like deposit in lava tubes. They typically occur in stair step clusters on moderately sloping to vertical surfaces. Some are clearly compacted clastics; others appear to be mineral depositions. Though more common in lava tubes than rimstone dams, they are no better understood. Aka: gour, lava speleothem, lava wall gour, melt cup, rippled clastic flowstone.

MULTILEVEL TUBE. A lava tube having two or more levels, each longer than wide, separated by a lower level roof. Aka: compound tube, dike-tube, double decked, double tube, multiple levels, multistoried, multiple tube, primary tube, stacked, stacked drainage conduits, stacked passages, superimposed tube, tiered, two-storied, vertically stacked.

OPEN VERTICAL CONDUIT. An abandoned, essentially vertical passage through which lava rose to the surface. The mouth is usually, though not necessarily, at the top of some sort of vent structure such as a hornito, spatter cone, or spatter ridge. Aka: influx, influx tube, lava retreat, open vertical vent, spatter cone pit, vent, vent cave.

OVERFLOW CHAMBER. A cupola at the site of a lava tube overflow. Aka: distribution pool, former skylight [*sic*], overflow dome, rise chamber, roofed-over skylight [*sic*], upper balcony.

PAHOEHOE. A Hawaiian term for basaltic lava flows typified by a smooth, billowy, or ropy exterior and internally by lava tubes and nearly spherical vesicles. Pronounced PA-hoey-hoey. Literally "smooth" in Hawaiian. Cf: aa, cauli-

flower aa. Following are descriptions of various types of pahoehoe surfaces, as defined in Gary (1972).

Corded Pahoehoe. The typical kind of pahoehoe, having a surface resembling coils of rope. Syn: ropy pahoehoe.

Elephant Hide Pahoehoe. A type of pahoehoe having a wrinkled and draped surface.

Entrail[s] Pahoehoe. A type of pahoehoe that has a surface resembling an intertwined mass of entrails, formed on steep slopes as dribbles around and through cracks in the flow crust.

Filamented Pahoehoe. A type of pahoehoe, the surface of which displays thread-like strands formed by escaping gas bubbles, and that are recumbent and aligned with the direction of flow. It is a common type and often found superimposed on other forms.

Shark Skin Pahoehoe. A type of pahoehoe, the surface of which displays innumerable tiny spicules or spines produced by escaping gas bubbles.

Shelly Pahoehoe. A thin-shelled, glassy type of pahoehoe, the surface of which contains open tubes and blisters; its crust is 1 to 30 centimeters thick. Shelly pahoehoe is characteristic of near-vent regions where devolatilization can occur rapidly to form empty blisters.

Slab. A type of pahoehoe, the surface of which consists of a jumbled arrangement of plates or slabs of flow crust, presumably so arranged due to the draining away of the bubbles, and that are recumbent and aligned with the direction of flow. It is a common type and is often found superimposed on other forms.

Spiny. A type of lava which, on a broad scale, has the smooth, gently undulating billows and ropes of pahoehoe, but on a millimeter scale resembles aa, having a spiny and granulated surface.

PALEOSOL. A buried soil, weathering profile, or soil horizon developed during the geologic past. When exposed by lining collapse, such layers provide an opportunity to study the relation of the lava tube and its host flow to the pre-flow topography. Aka: fossil soil horizon, interbed, paratubal earth, pre-flow soil, pre-lava soil [*sic*], soil horizon.

PERENNIAL CAVE ICE. Cave ice that persists, year around, for a period of years, sometimes receding or accumulating a little each year in response to climatic trends. Perennial cave ice is usually recumbent, against the wall or floor, rarely pendant, more or less clouded, is smoothly contoured as a result of melting or sublimation, and usually displays a few prominent fractures. It is often layered, reflecting seasonal accumulation as well as impurities introduced during melting and refreezing, and crystallized due to refreezing or fracturing. Cf: seasonal ice. Aka: fossil ice, permanent ice, perpetual ice, prismatic ice, year-around ice.

PERCHED TUBE. A distributary or tributary tube connecting some distance above the floor of a main tube, left hanging above subsequent flows. Cf: cut-off branch. Aka: hanging tube, higher tube complex, ledge, overflow cave, subordinate tube, tributary tube, upper tube remnant.

PILLAR. A body of rock which divides a cave for a short distance. How big can a pillar be? The definition suggested in Chabert and Watson (1981) seems reasonable: it is a pillar if its largest dimension is less than the combined width of the two passages it separates. Cf: column. Aka: column, island, mitertite, rock partition. (Though seemingly solid, most pillars in lava tubes are built around pieces or accumulations of breakdown.

PIPE STEM STALACTITE. A partially deflated tubular lava stalactite having an oval or pinched transverse cross section, similar to the stem of a tobacco pipe.

PIT CRATER. A massive sink created by withdrawal of a large mass of lava. Not necessarily related to a lava tube.

PLUNGE POOL. A pool of lava at the base of a lava fall. Aka: lava fall pit.

PRESSURE PLATEAU. An uplifted area of a ponded lava flow, the uplift of which is due to injection of lava into a still-hot interior. Flows initially less than one meter thick which inflated to ten meters and more, have been described in Hawaii. Pressure plateaus are characteristic of tube-fed pahoehoe flows, created when the volume of lava delivered through a lava tube system exceeds the capacity of the flow front to expand.

PRESSURE RIDGE. An elongate buckling and uplift of the crust of a lava flow resulting from differential movement between the crust and underlying lava, that results in a ridge which is commonly cracked open at the top throughout its length, the cracks narrowing downward. An elongate tumulus. Cf: block rampart. Aka: fold, lava ridge, schollendom.

PRIMARY FEATURE. Conditions or features of a lava tube existing prior to cessation of lava flow and final cooling. (Note that collapse is as likely to be primary as secondary.) Cf: secondary. Aka: features of origin, intact, lava (as in "post-lava,"), original, pre-lava [*sic*], primary lava structures, synchronous, synflow, syngenetic.

PROFILE. An outline of a cave, along an arbitrary line, projected horizontally onto a vertical plane. Usually such a profile is a longitudinal section along the survey traverse, but in any event should be specified. Cf: cross section. Aka: cross section, longitudinal cross section, longitudinal section.

RAFTED BREAKDOWN. Single pieces or accumulations of solidified lava (usually pieces of breakdown) floated or entrained in a lava stream. Although solid basalt is slightly denser than the liquid, much breakdown floats because it contains vesicles. Cf: island. Aka: breakdown raft, lava-carried breakdown pile, raft, rafted, rafted blocks, synflow breakdown blocks.

RAISED-RIM CRATER. A surface depression created by collapse of a tumulus around which remnants of the tumulus remain as a raised rim or wall. Syn: block rampart. Aka: collapse blister, collapsed surface dome, collapsed tumulus, non-explosive craters with high outward-toppled rims.

RE-ENTRANT TUBE. A lava tube which, having branched from a main tube or some other point in a lava tube system, rejoins downstream. Aka: bypass, cut-around, loop passage, loop tube, meander loop, ox-bow, side passage.

REMELT. Re-mobilization of solidified or partially solidified lava by re-heating. Remelted lava is probably not totally representative of the original melt. Some researchers insist that radiant heat and convection alone won't remelt solidified lava – that remelt is evidence of combustion. Remelt may be implicated in formation of boxwork-like features which are separated by projections of fractures Cf: lava tube boxwork. Aka: refluxed, refusion.

RESIDUAL DEPRESSION. A pit-like depression characteristic of extremities of tube-fed pahoehoe lava flows, resulting from inflation of a lava flow surrounding a chilled area. Easily mistaken for a collapse sink.

RESIDUAL OPENING. A primary opening into a lava tube. Three common kinds of residual openings are hornitos, drainbacks, and unroofed sections of contiguous lava channel. See also: entrance, skylight. Aka: skylight.

RIB. A vertical, or near-vertical, drapery-like ribbon of lava flowstone that projects from overhanging inclined surfaces. The form is gradational from a lava stalactite to lava flowstone. Size is influenced primarily by the fluidity (and drip size) of the molten constituents and steepness of the host surface. Thickness ranges from 0.5 to 1.5 centimeters and up, horizontal width averages 2.5 centimeters, but length (measured parallel to the host surface) ranges widely, from the discernable up to several meters on favorable host surfaces. Aka: driblet ridge, flow ridge, lavacicles that bend and flow into normal lava dripstone, lava drip ridge, lava rib, lava ribbon, lava trickle, long dripstone lavacicle, projecting rib, ribbed lava, ribbed wall, ribbon-like roof pendant, ribbon of lava, rib-like flow ridge, rib wheel, ridge, rivulet, run, thin parallel ridge, thin projecting rib, thin raised line, wall flute.

RIFT TUBE. A lava tube formed in lava flowing inside and through a rift. Aka: dike-tube, fissure tube, hollow dike, rheogenetic fissure cave, rift cave.

RIMSTONE DAM. A relatively thin, dam-like deposit with a level top surrounding a pool of water, common in solution caves. Rarely, small examples ranging in length from centimeters to decimeters, occur in lava tubes where water is abundant. The latter are deposited in the manner of speleothems, others are clearly clastic in origin, but no detailed studies are known. Cf: gour. Aka: gour.

ROOF. The basalt strata overlying a lava tube, usually including the initial roof crust. See also: bridge, lower level roof. Aka: bridge, overburden.

ROOTLESS VENT. A source of lava that is not directly associated with a true vent or magma source, commonly an upwelling or overflow from a lava tube. See also: cupola, hornito, open vertical conduit, rise chamber.

ROPY LAVA. A lava flow with a corrugated surface resembling coils of rope. The corrugations are a broad scale distortion of various smoother surfaces, resulting from differential internal and external movement, e.g. cauliflower aa floors modified with "ropes" over a foot thick are not uncommon. The ropes are typically closely spaced, curved, and convex in the direction of underlying flow. Inside lava tubes and

channels, rope thickness ranges widely, from less than an inch up to a foot or more, but on the surface may be far thicker. Cf: festoon. Aka: clinkery pahoehoe ripple, corded pahoehoe, curved corrugations, drag fold, festooned ropy pahoehoe, flow ripple, flow wrinkle, frozen ripple, pahoehoe rope, pulled pattern, ripple, rippled lava, ripple marks, ropy pahoehoe, wrinkle.

RUNNER. Small, recumbent, roughly cylindrical, sausage-like rivulets of lava flowstone with a glazed skin, that are not fused with the surface on which they rest. Much like tubular lava stalactites, but usually of larger diameter. Cf: lava toe. Aka: lava dribble, lava trickle, rivulet, streamlet, worm, worm's nest.

SAND CASTLE. A column of clay, mud, sand, or similar clastic sediment left by preferential erosion of the surrounding material by dripping or flowing water. Aka: badlands, fairy castle, mud turret, sand castle stalagmite, sand stalagmite, silt pillar, tent rock. (The column is preserved either by a cap-stone, a relatively large piece of detritus which deflects the water drops, or a "dry" area in the pattern of dripping water.)

SCROLL. A unique form of lining failure that occurs when still-plastic lining rolls off the wall, creating a cylinder shaped like, but much larger than, a loosely or partially rolled parchment. Scrolls range in diameter from inches to several feet. Aka: "A" type lava ledge, banking up and curling back, bench of. . . curled lava crust, broken and curled lava crust, broken and curled slabs, cigar-like cylinder, curled detachment laminae, curl-up, curly bench, jelly roll (curl), laminae, lava roll, lava rope, lining scroll, low bench of curled-down lava crust, peeled lining, peeled off wall lining, peeling accretionary wall, peeling wall, peeling wall of lava plaster, peel-off, peel-off of dripstone plaster, peel-off of thin lava plaster, peel-off shell, plastic deformation, pull-off curb, pull-out, roll, shells of peeling lava plaster, snake-shaped pipe, wall lining, wall scroll.

SEASONAL CAVE ICE. Cave ice that forms in winter or early spring, and is gone by late fall. Seasonal ice may occur anywhere in a cave and in nearly all the well known speleothemic forms – crystals, flowstone, helictites, draperies, stalactites, and so on. Seasonal cave ice is usually optically clear unless formed of runoff water. Cf: perennial ice. See also: speleothem. Aka: annual ice speleothem, ephemeral ice, transient ice.

SECONDARY FEATURE. Modifications or additions to a lava tube following cessation of the host lava flow and cooling. (Note that collapse is as likely to be primary as secondary.) Cf: primary feature. See also: collapse, secondary. Aka: intact, intruding lava dripstone, post-activity (collapse), post flow, post-lava, post-volcanic, post-volcanic (roof) collapse, reactivated system, secondary basaltic ornamentation, secondary collapse, secondary flow features. (For example, collapse, invasion by subsequent lava flow, detrital deposits, mineral deposits (speleothems), and erosional modifications are secondary features.)

SEMITRENCH. A lava tube formed by roofing over of a lava channel having walls that are built up as levees.

SHARK TOOTH STALACTITE. A blade-like lava stalactite. Usually about as wide as long, they taper radically to a small drip-sized, spherical tip seldom exceeding one centimeter. in diameter. On horizontal ceilings they occur as individuals, are roughly symmetrical about a vertical axis, and resemble a large rose thorn. It is not unusual for two to be joined along a vertical centerline, forming a three-cornered base. If the host surface is inclined, the individual stalactites are skewed downhill en masse until ultimately, on near-vertical surfaces, they merge, forming drapery-like ribbons standing out from the wall. Shark tooth stalactites are typically smooth and thinly glazed externally, uniformly vesiculated internally, and do not reflect the restraint of a tough outer skin to the degree that tubular lava stalactites and runners do. Occasionally they are distorted en masse, parallel to the cave passage, as if deflected by gas or lava flow. Aka: drip pendant, lavacicle, homogenous stalactite, lava pendant, rose thorn pendant, shark's tooth projection, shark's teeth lava pendants, shark's teeth, tapered stalactite, triangular lava drip, wide triangular blade. (See rib).

SHELF. An elongate, overhanging crust, remnant of a crust, or accumulation of linings attached to a lava tube wall. Shelves are gradational to and from lower level roofs and, as a rule, follow the lava tube's grade. Cf: strandline. Aka: arched ledge, balcony, boundary ledge, bulge, cornice, cornice-like formation, cornice-like shelf, crust, curb, curb lining, flow crest line, former lava level, hanging ledge, high lava mark, high stand, lateral ledge, lateral ridge,

lava mark, ledge, overhanging flange, overhanging ledge, relict lava strandline, solidified edge, temporary surface level, tide mark, trench shelf, true balcony, wall ridge.

SINK. A general term for a depression in the land surface. Syn: sinkhole. See also: collapsed lava pond, collapse sink, residual depression. Cf: trench.

SKYLIGHT. (a) An opening in the roof of a cave that admits daylight. (b) An opening in the roof of a lava tube that admits daylight and is not considered to segment the lava tube. ("Skylight" is used interchangeably with "entrance," especially if it's the only or customary way in.) See also: entrance, drainback. Aka: breakdown, breakdown skylight, ceiling collapse, collapse hole, collapse pit, collapse to surface, residual skylight, skylight entrance, well, window.

SLIP BANK. The apron on the convex side of lava tube meander bend where occasionally cooler, slower moving lava accumulates. Cf: cutbank.

SLUMP BLOCK. A large lateral block of basalt that slumps, more or less as a unit, into a collapse trench as a result of being undermined by collapse of a lava tube. They range in size from one or two meters to tens of meters. Aka: lateral slump block, slumped-off column.

SODA STRAW STALACTITE. (Or simply "soda straw.") A predominantly straight tubular stalactite. Aka: lava soda straw stalactite, lava straw, lavatite, rod stalactite, soda straw, soda-straw cicle, soda straw-diameter stalactite, straw stalactite, straw tube, thin spindly lavacicle, tubular lavacicle, tubular soda straw-like stalactite.

SLUMPED LINING. Lining deformed by gravitational slumping and buckling while still plastic, literally sliding down the wall. See also: festoon. Aka: deformed glaze, drag fold, drapery, drapery of lava dripstone, plastic deformation, slump, slumped glaze, slump ripple, wall drapery, wrinkle, wrinkled flow ridges.

SPATTER. Small fragments or clots of ejected lava, commonly agglutinated upon coming to rest.

SPATTER CONE. A steep-sided cone of agglutinated spatter built up on a fissure or vent. Cf: hornito, open vertical conduit. Aka: agglutinate cone, blow hole, blowout, chimney, pneumatogenetic explosive cave, spatter vent, volcanello, vulcancito.

SPATTER RAMPART. A low wall of agglutinated spatter produced by fountains of very liquid lava erupted from fissures. Cf: spatter cone.

SPATTER STALACTITE. A lumpy, irregular, highly vesiculated, concentrically-layered lava stalactite accumulated from spatter. Common inside spatter cones. Cf: dip-layered stalactite. Aka: granular concentric stalactite, thick bodied lava stalactite.

SPLASH CONCENTRIC. Concentric ripples formed in a partially-hardened floor by a piece of falling breakdown. Occasionally found some distance down-tube from the site of the rockfall. Aka: concentric.

SPELEOTHEM. A mineral deposit formed in a cave. Coined in 1952 from the Greek "spelaion" (cave) + "thema" (deposit). A generally accepted, but frustrating term that differentiates an icicle formed in a cave from one formed under a highway bridge – and rests on the insecure definition of a cave. The most abundant mineral deposited in lava caves is ice. Next in order of abundance are silicates, sulphates, and carbonates – the latter usually co-deposited with silicates. Ice, mirabilite, and opal are more abundant in lava caves than solution caves. Common forms of minerals deposited in lava tubes are stalactites, films, coatings, coralloids, and crusts – less common are anthodites, crystals, flowstone, stalagmites, helictites, and heligmites. Aka: caliche, cave formation, cave ice, cave stalactite, coating, decoration, formation, glaze, ice candle, ice formation, lava blister, lava lace, ornamentation, post-volcanic speleothem, secondary, secondary deposit, secondary chemical deposit, secondary mineral, secondary mineralization, secondary speleothem, secondary stalactite.

SQUEEZE-UP. An extrusion of lava emanating from a fracture or other opening in the solidified surface of a lava flow, e.g. from between the wall and floor crust in a lava tube. It may be bulbous or elongate, and may exhibit grooves. See also: grooved lava. Aka: lava boil, overflow squeeze-up, tumulus mound.

STALACTITE. A generally elongate, pointed or tapering, gravity-controlled, object of deposition that hangs from a ceiling or overhanging surface. A stalactite is not necessarily a speleothem. They form in all types of caves, as well as mines, vugs, veins, tunnels, hot springs, under bridges, and so forth. Coined in 1655 to describe many examples, some from caves,

which ". . . belong to the Icicle class. . . " (Worm, 1655). Stalactites composed of amberat, lava, minerals, mud, peat, pitch, sand, and sinter have been described. Virtually any material which is soluble, or can be carried as a colloid or in suspension, or which may melt under given conditions, can form a stalactite. Cf: helictite. See also: lava stalactite. Aka: cave stalactite, depositional stalactite.

STOPING. Upward migration of a chamber or passage due to ceiling collapse. There may be a corresponding accumulation of breakdown. See also: collapse. Aka: breakdown dome.

STRANDLINE. The congealed margin of a quiescent body of lava. Unlike a shelf that follows the hydrostatic grade, a strandline is horizontal. Cf: flow line. Aka: bathtub ring, high flood mark, high lava mark, high stand, shoreline, solidified edge, stand line, thin mini-ledge, tide mark.

STRETCHED LAVA. A body of partially hardened lava stretched between points or zones of attachment which moved apart. Distinctive stretch marks result, which generally reflect (among other things) viscosity, vesicularity, and always direction of tension. Stretched lava is common between patches of slumped lining which separated and between wall and subsiding floor. If tensile strength is exceeded, stretched lava projections result (see below). Aka: pulled pahoehoe, pull marks.

STRETCHED LAVA PROJECTION. Projections resulting when stretched lava is pulled apart. The torn shapes range from thread-like strands with needle-sharp points to wide, curtain-like, sharp-edged sheets. They are typically elongate and symmetrical in transverse section, with varying degrees of taper from base to point. Unlike stalactites, with which they are often confused, they need not be vertically oriented (often are not), and have sharp points or edges. Aka: blade stalactite, drooping "hands," needle-like lava stalactite, pulled stalactite, ribbon lavacicle, ribbon stalactite, shark's-tooth projection, shark tooth projection, shark teeth-slickenside, sharp lava stalactite, sharp pointed lavatite blade, stretched stalactite, tear-tite, treacly lava stalactite.

SURFACE TUBE. The hardened outer jacket of an elongate lava toe, or lobe, that drained. Typically, surface tubes have a uniform wall thickness and semi-circular cross section, flat side down against the surface on which they formed. Branching is common and broadly dendritic networks are not unusual. Widths range from a decimeter to several meters. Length depends primarily on an uninterrupted supply of lava and ranges widely. Surface tubes are far more numerous than is generally realized because most are subsequently buried. See also: lava tube. Aka: miniature lava brooklet, miniature tube, minor lava tube, surface lava tube, tertiary lava tube.

TEAT STALACTITE. A lava stalactite shaped like an inverted cone, having a generally circular transverse cross section and a drip-sized tip. Aka: conical ceiling stalactite, cow teat stalactite.

TERRACE. A wide bench.

TONGUE. An elongate, raised flow of lava. Tongues in lava tubes usually have a cauliflower aa surface. Aka: flow tongue, lava floor tongue, lava ridge, lava toe, narrow lobe.

TRAVERSE LENGTH. The length of the traverse on which a cave map is based. Roughly, the total distance one would travel if visiting all the cave's passages. Cf: map length. Aka: continuous linear development, linear development, slope length, sport length, total surveyed traverse, true slope length.

TRENCH. (a) A collapse trench. (b) An empty lava channel. Aka: lava trench. It can be difficult to discern the difference if relatively old and eroded.

TRIBUTARY TUBE. A lava tube that feeds into another. Aka: coalescent tube, confluent branch, confluent tube, convergent branch, feeder tube, ingressive branch, side tube. (True tributaries are rare; tubes which appear to be tributaries are usually re-entrant tubes.)

TRUE TRENCH TUBE. A lava tube formed by roofing over of a lava channel constituting a single flow unit.

TUBE-FED PAHOEHOE (lava flow). Tube-fed pahoehoe lava flows are characterized internally by lava tube systems and layered structure. Externally they are broad and thin, with a broadly dendritic plan, feathering out from low broad ridges overlying master lava tubes. Large collapses sinks and trenches, chains of hornitos, skylights, and small rootless lava flows (see rootless vent) are characteristic of the upper and mid parts of the flow. Various expressions of inflation, like tumuli, pressure plateaus, and residual depressions on decameter to kilometer scales are numerous at the extremities. Tube fed-lava reaches sites so far

removed from the vent only because lava tubes so efficiently carry lava with little loss of heat.

TUBE-IN-TUBE. A smaller tube resulting from medial closure of inward leaning levees, on the floor of a lava tube, and usually consisting of the last flow through the tube. The outer surface is typically cauliflower aa and the inner surface may be grooved. Complete tube-in-tubes are seldom long, but lengthy sequences of levees, roofed sections, and collapsed sections are common. Aka: coffin, encased tube, hollow tongue, internally developed tube, mummy's case, secondary lava tube, tube lining.

TUBULAR LAVA STALACTITE. A tubular stalactite composed of lava. Most are slightly and uniformly tapered. Their diameter, averages about 0.7 centimeter, and often decreases slightly toward the tip, but extremes from 0.4 to 1.0 centimeter have been noted. Lengths range from the perceptible to a meter and more. The tip may be hemispherical, or open for a considerable distance, but the interior is usually an entrainment of elongated vesicles and septa, The outer surface may be macrocrystalline and partially or completely marked with shallow annular grooves thought to be growth increments. They often serve as conduits for considerable quantities of fluid lava. Stalagmites of 100 times the volume of corresponding tubular stalactites are not uncommon. Frequently occurring in combination with lava helictites, they may be crooked, straight, branching, botryoidal, deflected, twisted, even deflated, or combinations of the above. See: pipe stem stalactite, soda straw stalactite. Cf: runner. Aka: bracken-like stalactite, conduit form, conduit speleothem, hollow dripstone tublet [*sic*], icicle-like pendant, icicle-like stalactite, icicle-like projection, irregular tubular lavacicle, lavacicle, lava formation, lava pipestem, lava straw, lavatite, rod stalactite, roof cicle, small stalactite, soda straw, soda-straw cicle, soda straw-diameter stalactite, straw stalactite, thin spindly lavacicle, tubular lavacicle, tubular soda straw stalactite, tubular soda straw-like stalactite, tubular stalactite, worm, worm stalactite.

TUBULAR STALACTITE. A hollow stalactite of nearly uniform diameter deposited from a hanging drop of liquid. Both mineral and non-mineral tubular stalactites have been described. See also: tubular lava stalactite.

TUMULUS. A doming or raising of the surface of a lava flow, typically elliptical in plan and lenticular in section, caused by hydrostatic pressure of underlying fluid lava (e.g. from a lava tube), or horizontal thrusting and buckling due to differential movement between the crust and underlying lava. They are a characteristic of the distal part of a well developed lava tube system. Tumuli are not usually hollow like blisters, although they may be as a result of lava draining out after their formation. A tumulus may be residual, i.e. surrounded by collapse resulting from differential draining away of underlying fluid lava. Gradational to pressure ridge. Cf: lava blister. Aka: agglutinate pile, hollow tumulus, lava bubble, lava dome, pressure dome, schollendom, stony rise, surface dome, trench.

UNITARY TUBE. An essentially unbranched lava tube. (Strictly speaking, only the smallest, most rudimentary lava tubes remain unbranched if flow is sustained, but segments of major tubes and systems without known branches of relative consequence are common.) Aka: simple (lava tube), unbranched, unitary conduit.

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The Rift Caves in Japan

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Abstract

In Japan many craters erupted from fissures can be seen on the volcanic line from Mt Fuji to Hachijou Island in the Pacific Ocean. But fissure eruptions have not always left rift caves. Recently I have investigated this area and recognized four rift caves at Mt Fuji, three on Miyake Island, and three on Hachijou Island. On Miyake Island, a long crack and outpouring of lava occurred at the time of the fissure eruption. It is possible to see rift caves only in the caldera.

In rift caves, thinly coated lava may be seen on the scoriaceous wall of the cavity and also sideways extensions by gas pressure on the surface of the earth. I have identified two types of rift caves:

- gas extends laterally and causes cavitation with subsequent blowout;
- gas formed the cavity with subsequent blowout.

Introduction

Rift caves are recognized at Mt Fuji, Hachijou Island, and Mt Oyama on Miyake Island, Japan. In the course of our research we found common characteristics as indicated below.

Mt Fuji

In this volcano are five lines of fissure eruption craters. Four rift caves are located in two of these lines.

1. Ice Fissure Crater Cave, Hyouketsu

This cave is located at an altitude of 1,440 meters, northeast of Mt Fuji. In this area (Figure 1) fissure eruption craters are located in a line about one kilometer long. Scoria was erupted from Yumiizuka volcano, and a thick layer was formed at Kooriike, Hakudairyuoo Volcano. From the crater of the latter, a small lava flow erupted (^{14}C 1,230 ±30 BP). The rift cave formed in this eruption (Figure 3) has a large cavity at its bottom. Lava crust attached to the scoria layer has peeled off from the ceiling and both sides of this rift cave. On the flow some scoria is incorporated in the layer.

2. Komitake Rift Caves No. 1, No. 2, and No. 3

Komitake-Fuketsu Lava Flow (Hyo), Kenmarubi Lava Flow (Ken). Oonagare-maruyama Lava Flow (Ona) erupted during the same period.

As shown in Figure 1, the Hyo lava flow is small but contains fissure eruption craters. Three rift caves are present at 2,063 to 1,980 meters above sea level. We were unable to enter Cave No. 1 because it is filled with solid ice from end to end. No. 2 and No. 3 Caves (Figure 5) are also ice-filled at their bottoms which thus cannot be investigated. In these caves (as in the others) the scoria wall layers are slightly coated by lava, some of which peels off. In the lower parts of the caves, a red scoria layer is present. This also occurs in other rift caves in Japan.

A thick scoria layer exists from here to the upper area. Snow melt has carried this layer to the lower area where the caves were created.

Hachijou Island

3. Eigou No. 1 Rift Cave

This rift cave is located at the northern foot of Mt Hachijoufuji (855.4 meters) on Hachijou Island. Rift caves here are found in fissure erup-

Figure 1—Geological map of the northwestern section of Mt Fuji showing the locations of Hyoketsu and Komitake rift cave areas.

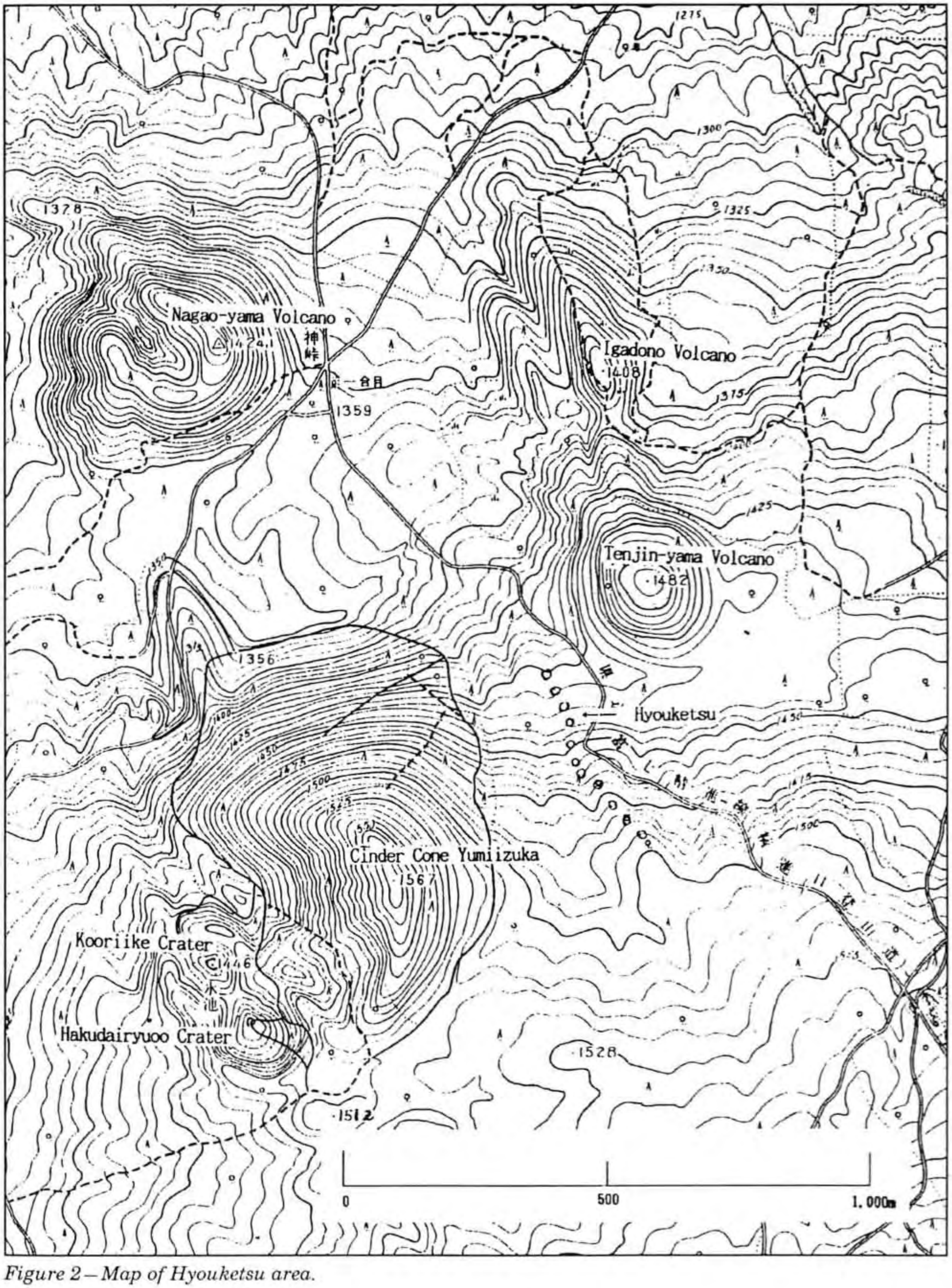

Figure 2 – Map of Hyouketsu area.

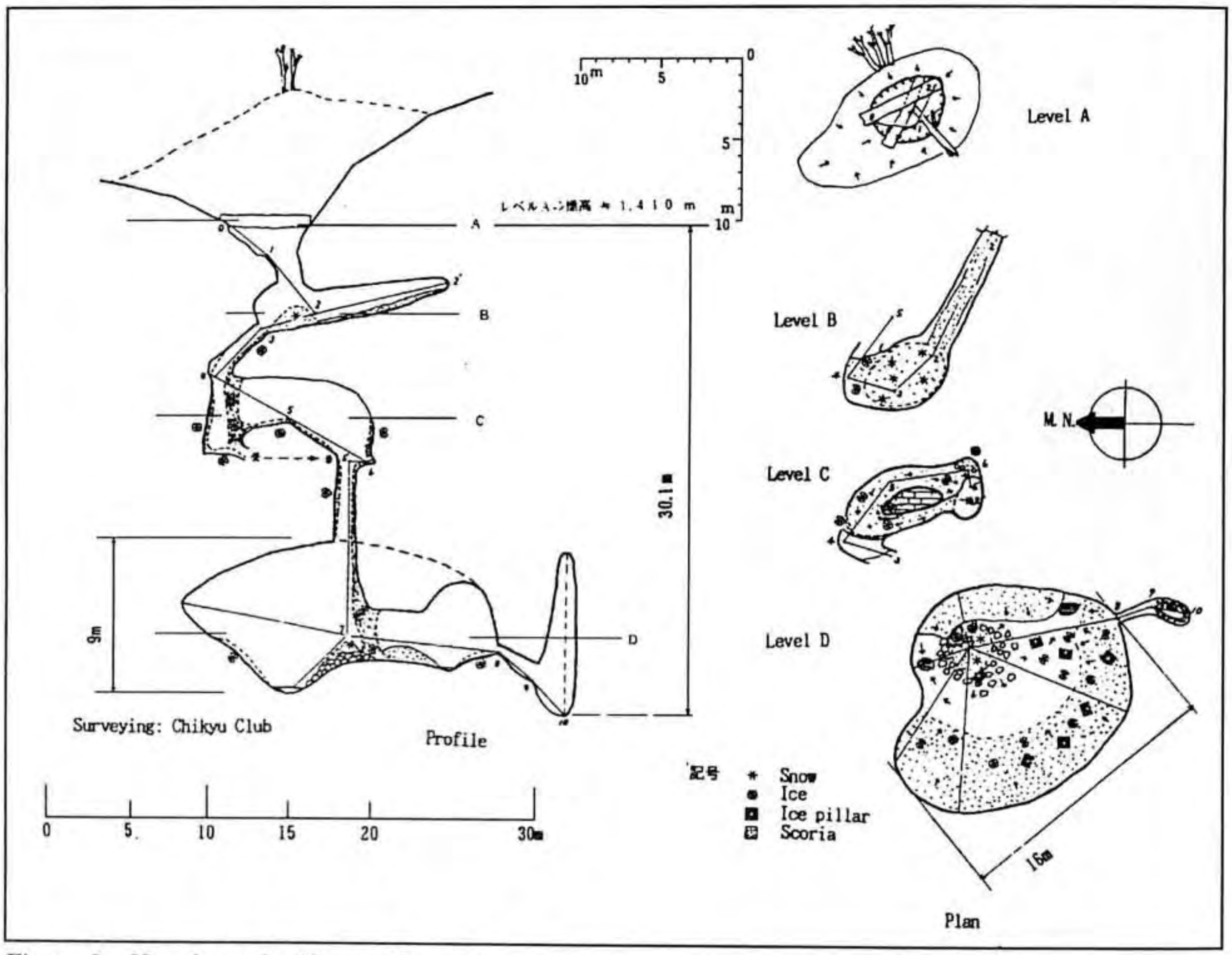

Figure 3 – Hyouketsu Ice Fissure Crater Cave.

tion craters formed near the beach (Figure 6). Among these, the rift cave at the lowest level has a deep shaft (Figure 7) and has the same internal appearance as other rift caves (Figure 5). This rift cave is one of the world's most complex examples because cavities extend vertically and are intertwined. Approach is difficult because of frequent peeling of the walls. However the original condition of the rift cave has been maintained.

4. Eigou No. 2 Rift Cave

The entrance of this small shaft is located just above the road which circles the island. It has not been investigated.

5. Eigou No. 3 Rift Cave

This is the uppermost rift cave in Hachijou Island (Figure 6).It extends in two directions. The horizontal part is narrow and the cavity extends vertically (Figure 8). This is similar to the No. 5 Rift Cave on Miyake Island (Figure 11). Because of some construction work, the overburden of this rift cave is exposed. Its thickness is over 20 meters. As we have seen at other rift caves, a very thick scoria layer is present.

Miyake Island

The 1940 fissure eruption on Mikake Island did not create rift caves. The 1983 fissure eruption, which extended more than 4.3 kilometers, created a rift cave only in its caldera. Cuevas Negras on Tenerife, Canary Islands, were formed through the same process by the 1949 eruption in Las Canadas caldera. Some condi-

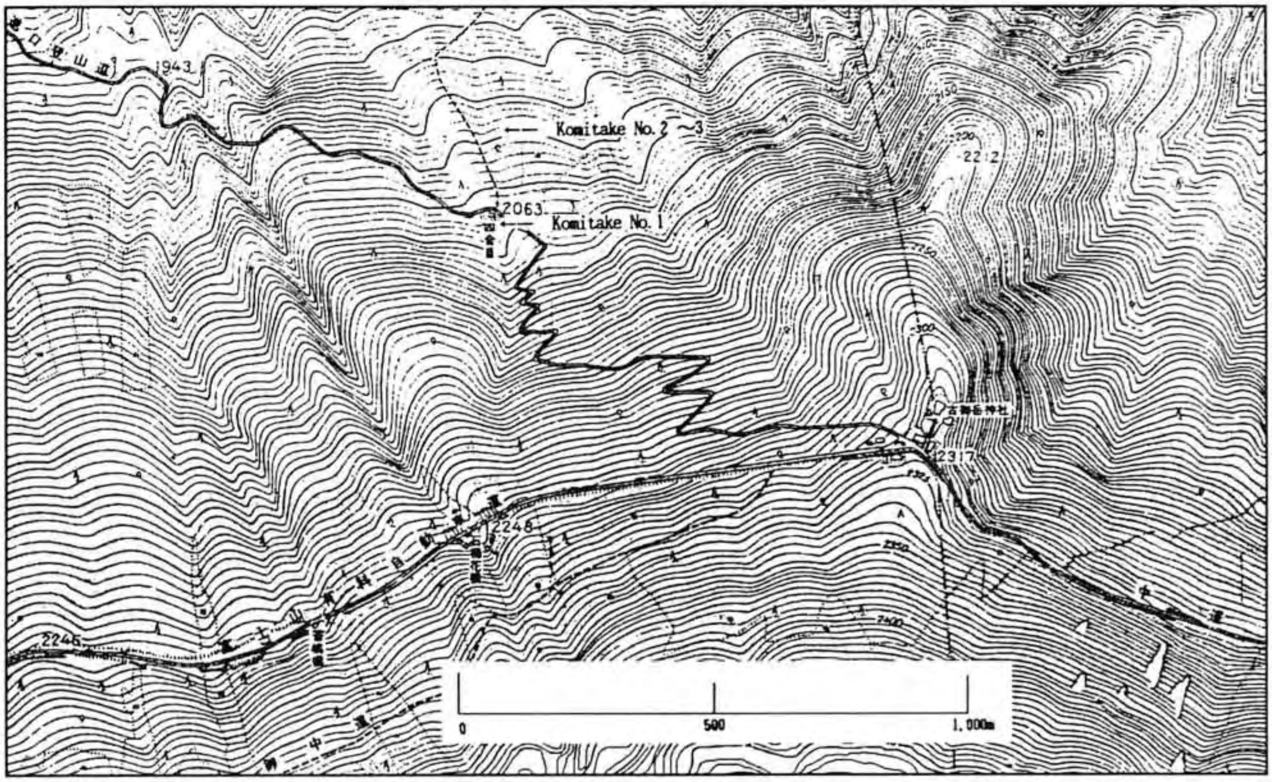

Figure 4—Map of Komitake Rift Caves area.

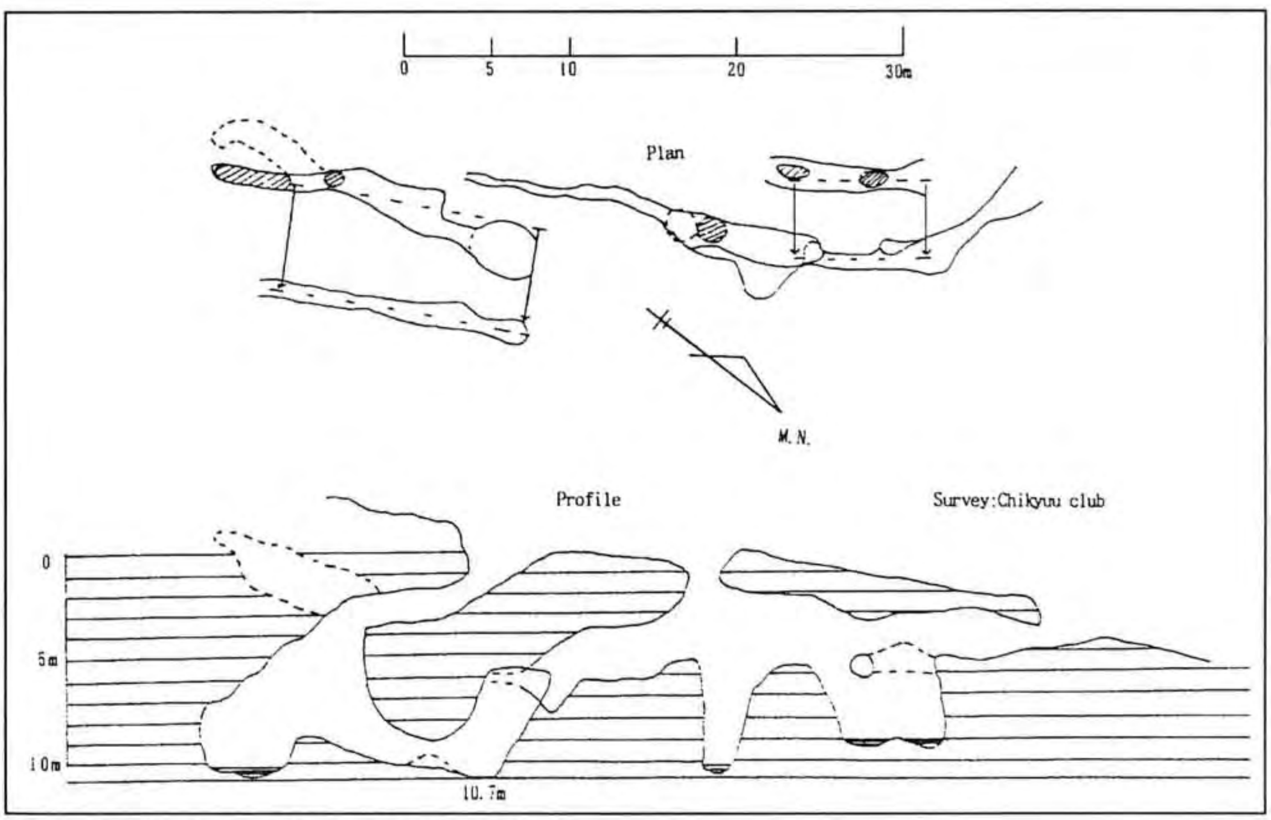

Figure 5—Komitake Rift Cave No. 2 and No. 3.

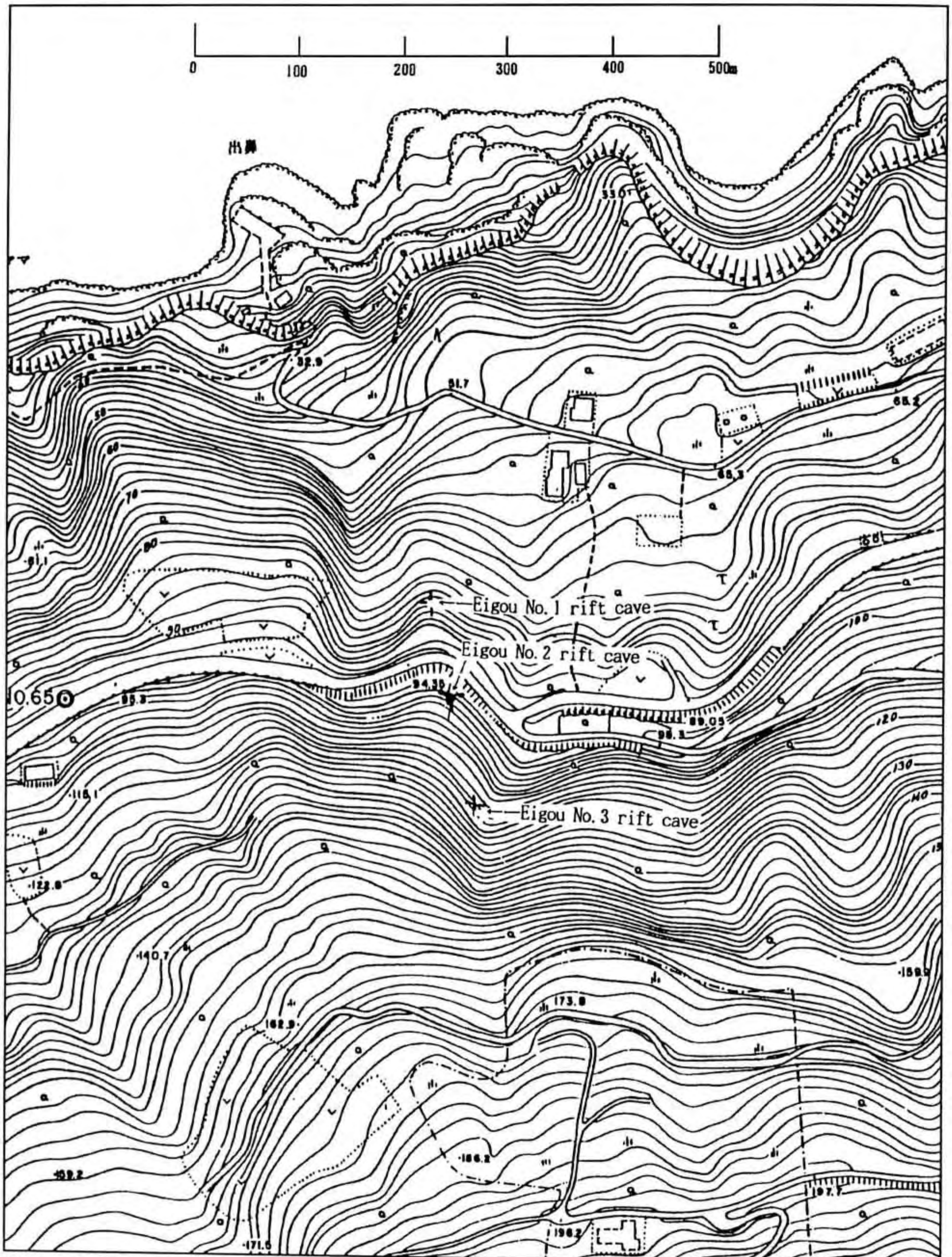

Figure 6 – Map of the rift caves area in Hachijou Island.

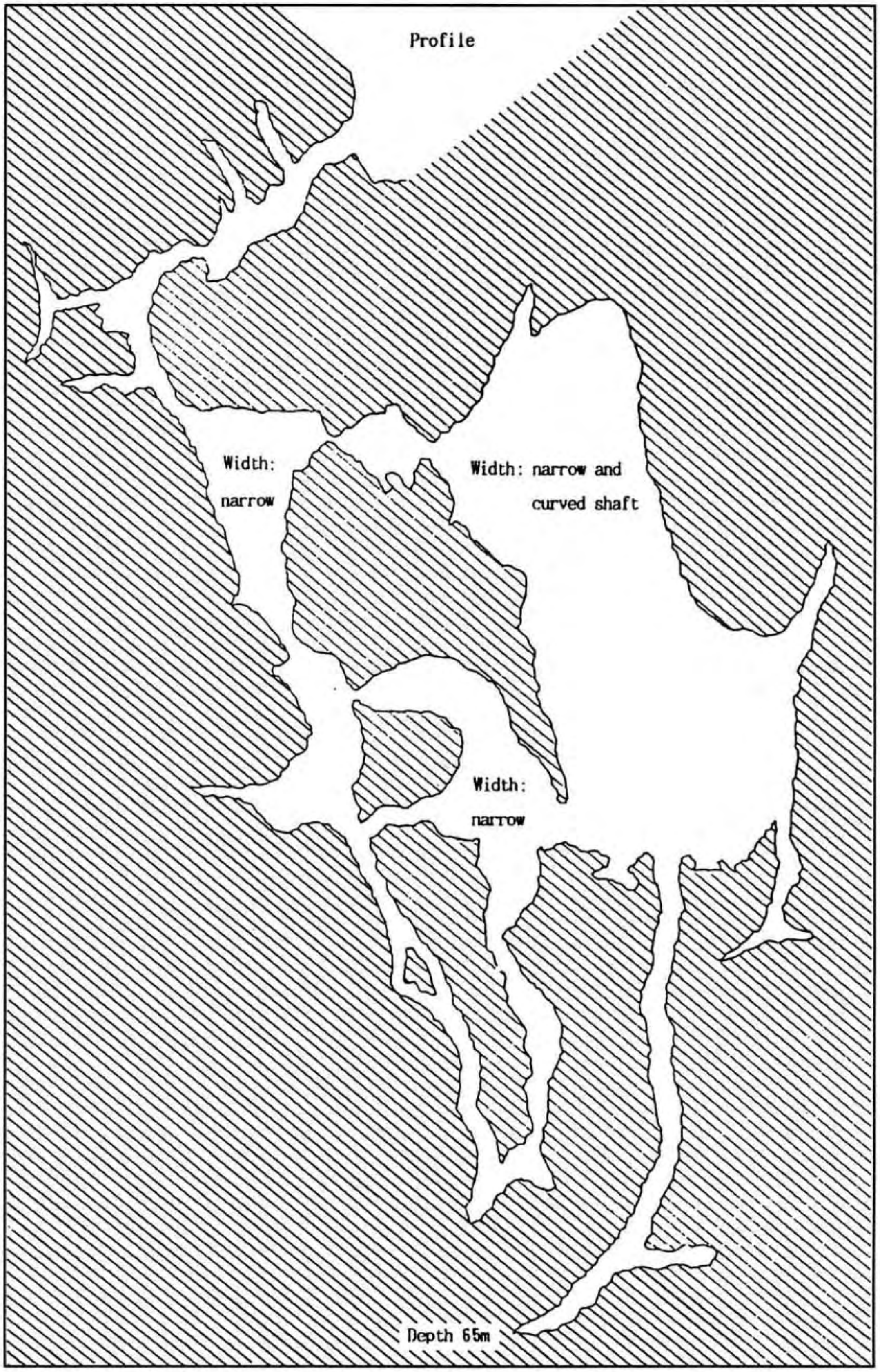

Figure 7—Eigou No. 1 Rift Cave.

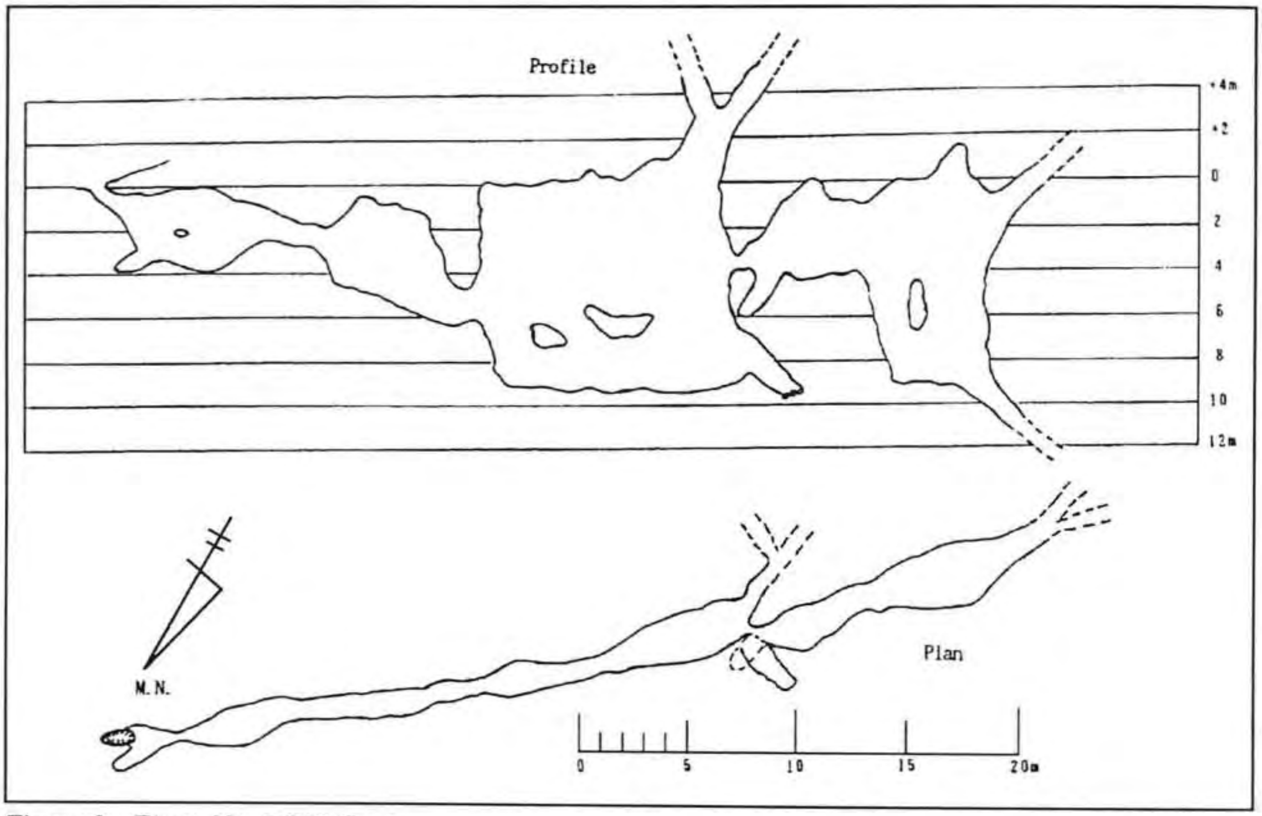

Figure 8—Eigou No. 3 Rift Cave.

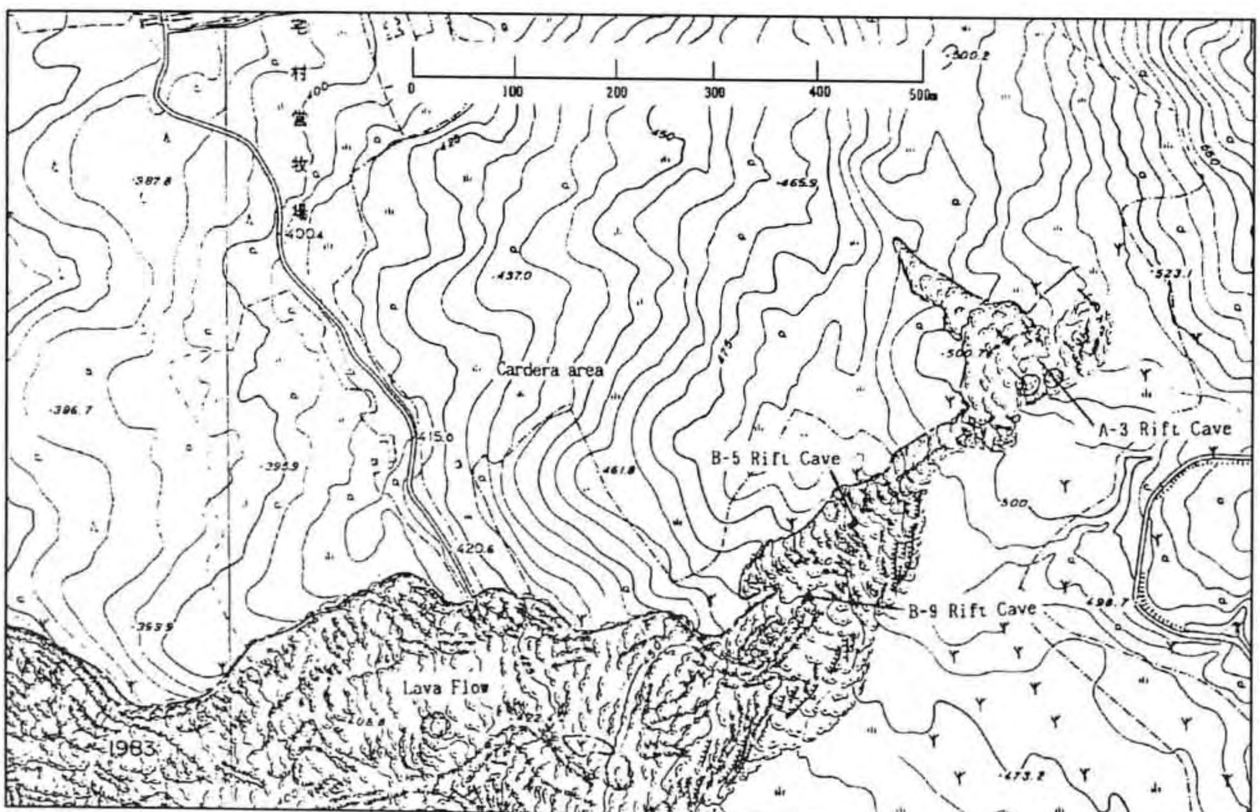

Figure 9—Position map of Rift Caves at Miyake Island.

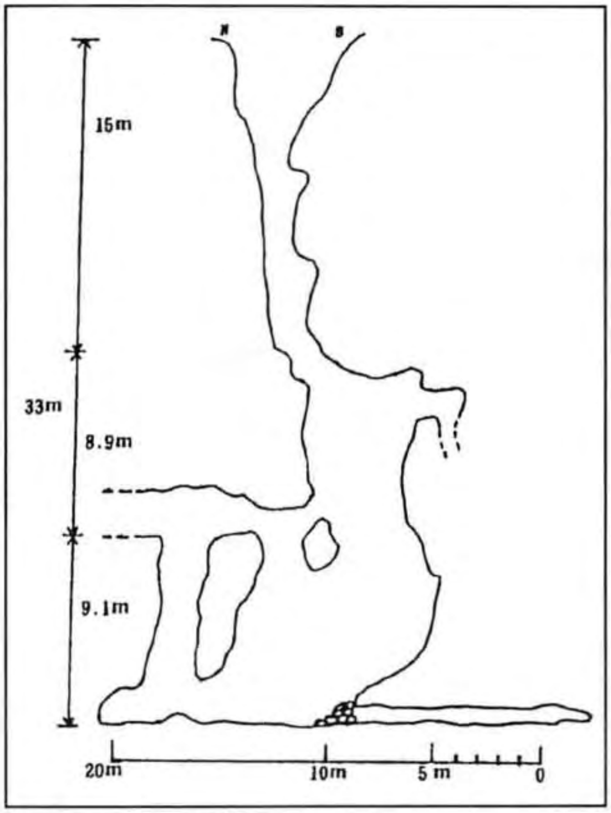

Figure 10 – A-3 Rift Cave Profile

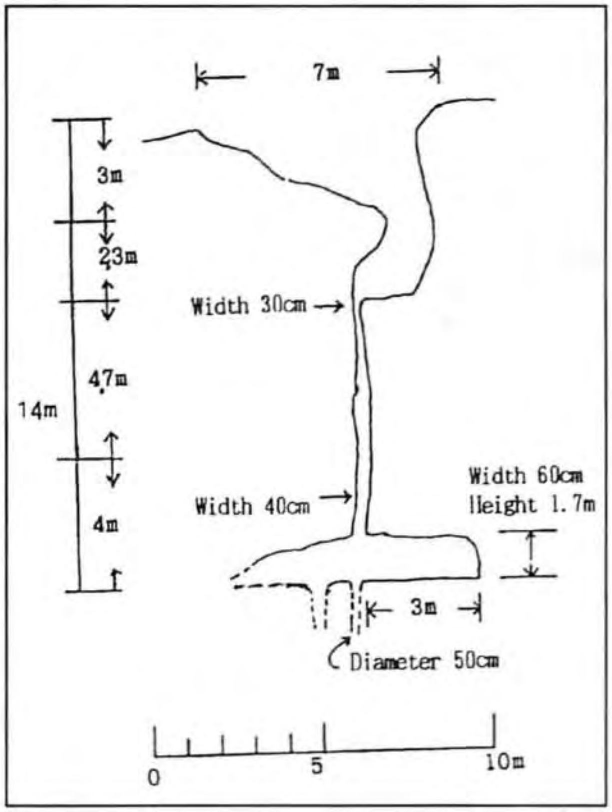

Figure 12 – B-9 Rift Cave Profile

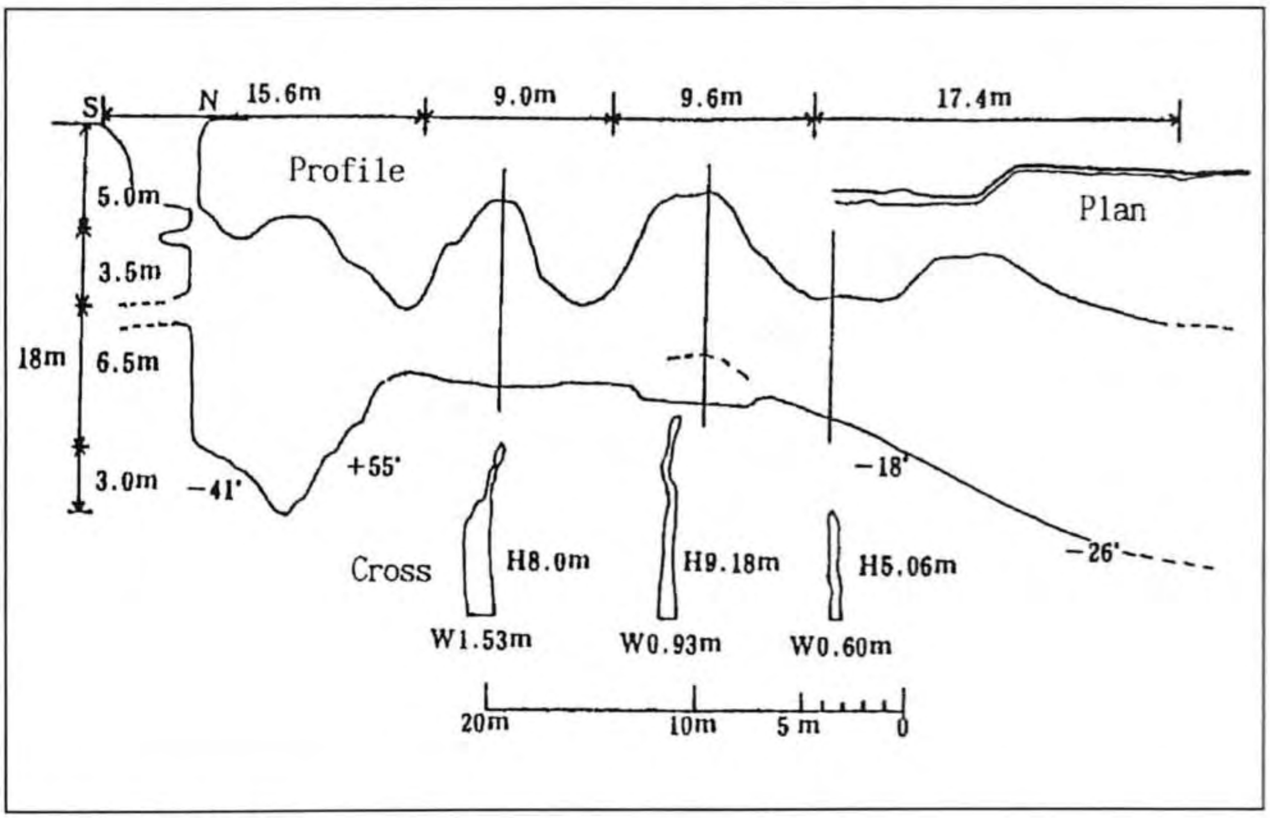

Figure 11 – B-5 Rift Cave.

tions of the caldera can be considered important factors in the creation of such rift caves.

6. A-3 Rift Cave

This rift cave (Figure 10) has a 33-meter shaft. Its lower part extends in two directions. This cave was formed by gas moving laterally at the time of eruption. Some of its terminal portion is narrow, with a width of 30 centimeters. The cavity is formed at the narrower part and extended horizontally.

7. B-5 Rift Cave

This rift cave (Figure 11) is similar to Cuevas Negras (Tenerife, Canary Islands), Komitake Rift Caves No. 3 and 4, and Eigou No. 3 rift cave. Its cavity extends only horizontally. In the nearer part of the entrance we can see the portion penetrated by gas like a hall. Because of the narrowness of its end, we can not enter it.

Fine ash has accumulated on the wall and floor as a result of its blowing up from the lower end of the cave. Factors common to all rift caves seen here are as follows:

- Lava was painted slightly on the surface of the scoria layer and formed a crust which can easily be peeled away.
- Scoria layers are exposed in many parts of the cave because of the peeling off of the crust.

8. B-9 Rift Cave

This rift cave is very narrow but the lower part is a little wider (60 centimeters) (Figure 12). At its far end are two pipe-like shafts, but it is not possible to enter.

Conclusion

Through these explorations we have found conditions common to rift caves in Japan. Rift caves are created only in thick scoria.

Scoria may hold more water than lava and this water becomes gaseous during an eruption. Just as in lava tube caves, lava painted on scoria creates a crust which easily peels off from the scoria side because of water vapor in the scoria. Also in welded tuff caves, gas collects behind the crust and makes small cavities like pockmarks.

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Floor Modifications in Small Lava Tubes

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Abstract

Molten lavas are thixitropic liquids: they have a lower viscosity while flowing than they have when stationary. This characteristic affects the passage shape and the floor structure of the resultant tube. The viscosity effect is also responsible for the existence of a relationship between the slope of the ground and the depth of the lava required to flow over it.

Numerous studies by Shaw *et al.* (1968, *et seq.*) on Hawaiian lavas have demonstrated that lava viscosity thins with increased motion. The highest viscosity is demonstrated by lavas that are not in motion. This assumes, of course, that other features of the flow such as temperature and dissolved gas content are held constant. A fluid with this quality of flow-related thinning is called a "thixitropic liquid." Other names applied to these liquids are "non-Newtonian fluids" and liquids that behave like Bingham bodies. The details of thixitropic fluids as applied to lava flows was investigated by Hulme (1974).

Another way of describing this peculiar behavior is to say that as lava moves faster, it becomes more fluid, which enables it to move faster, which makes it more fluid, which enables it... Of course there is a limit to all this. The effect is most pronounced in slow speed and stationary fluid.

Two interesting characteristics of this thixitropic behavior are exhibited in lava flows. One is that once stopped, the lava can remain molten without starting to flow again as long as it doesn't cool and crystallize. If a change comes, such as a surge of lava from up slope, the lava can remobilize and start flowing again. The other is that there is a critical depth-to-width-to-slope relationship that determines whether or not the lava will flow. Hulme derives ratios between flow width, flow depth, and levee width and relates them to the slope of the land and the physical characteristics of the lava flow.

One obvious relationship between the slope of the land and the lava flowing over it is that when the lava flows over a section of steep slope it will flow faster and become thinner. The thickness of the flow will become less and the cross section of the conduit necessary to transport a given rate of flow will also become less. The converse is also true. When the slope is flatter, the flow will be (must be) deeper in order to maintain motion. This is a more subtle point, but is borne out by field observations in Hawaii.

It was stated earlier that liquid lava can stop flowing and set up even though it has not crystallized into a solid. This is the phenomenon that gives rise to the original channel levee development. The flow moves over the land and to a lesser degree spreads laterally. As was mentioned before, there is a critical thickness required for a thixitropic fluid to flow down a slope. The flow thins in the direction of movement unless there is a replacement of lava from upstream. The lava at the sides of the flow will thus move until it becomes too thin for movement. Then it will pause and gel. The lava behind the levee will pile up until it is thick enough to move again. This required thickness will be least in the steepest down slope direction. The lateral levees will remain stationary as long as the lava volume doesn't increase and slowly crystallize. Surges or decreases in the quantity of lava being discharged that come after the levees have stabilized take the form of thin overflow layers that build up the levees or of lower ledge levees that form inside of the first-formed levees.

Small surface tubes often form near the front of the flow, branching and rejoining, a behavior that is called "anastomosing." This spreads lava out over the width of the flow front. These surface distribution tubes often have a flattened, half-ellipse cross section. They are comparatively small and shallow, and are often near the lower depth limits that permit lava flow. Their "distributiveness" results from the small quantity of lava that

produces them. The relatively short duration doesn't lead to depth, a significantly flow-modified shape, or the extensive lining and overflow features that are associated with major conduits.

The surface tube often has a smooth floor and is marked by solidified flow features along the floor and lower parts of the walls. As the lava supply dwindles, the level frequently fluctuates with minor surges and recessions. These fluctuations leave ridges of accretion (lava buildup) along the walls. When the flow falls below the critical thickness necessary for motion, the flowing slows and stops. This phenomenon is related to the thixitropic behavior of the lava and is not a primary response to the cooling and crystallization of the lava. The size of the lava conduit is related to the characteristics of the lava and the slope that it travels on. The depth of the liquid lava within the conduit when flow ceases is also a factor of the slope.

Lava flowing on a very flat slope must (according to Hulme's width-depth-slope interrelationship) be relatively thick in order to maintain motion. The roof layer of a surface tube formed in such a flow will often be about 30 centimeters thick. The flow through the conduit will be slow and the cross section of such a tube will often be significantly wider than high, with ratios of 3:1 to 4:1 occurring commonly. The appearance of the cross section is a little like the top half of an ellipse.

Such a slow-flowing surface tube often shows a strong tendency towards stream braiding. If the braids are short and close together, pillars form in the middle of the passage. Sometimes the only indication of a braid that didn't quite develop is a lowered ceiling in the middle of the passage.

Flow on a gentle slope requires a deep layer of lava. When the supply dwindles and the level of lava in one of these tubes starts to decrease, it can easily drop below the critical value needed to maintain flow and lowered viscosity. There will still be molten lava on the floor of the tube, possibly even to a depth of a few meters – it just won't be flowing. This phenomenon can be seen in the deep contraction cracks on the floors of some of these tubes (3 centimeters wide by 75 centimeters deep). Another indication is that a cross section through the tube looks like an ellipse that was partially filled from the bottom, often with acute angles between the floor and walls. In the Trout Lake cave area in Washington, Resurrection Cave and many of the small caves in the eastern end of the valley, such as Masseys Barn Cave, are very clear example of these cave-forming dynamics.

A situation that is often found in small anastomosing caves on steeper slopes is that some passages are much less sloped than others. The situation described above also applies here; small overflow tubes and side branches will often be partially filled with the remnant of their flows. Although connected to the main conduit, they fail to drain fully because the thixitropic nature of liquid lava means that the shallow overflows and side branches gel more easily.

The gradation between surface (distribution) tube and large main (primary) conduit is gradual and reflects the different function of each. At the flow front, lava tends to push out in all directions, feeding a fan-shaped lobe. The conduit tends to form a wide, shallow shape and the depth of the lava below the conduit is thin and close to the minimum necessary to enable flow. As the front of the flow passes downhill, the side branches of the lobe stop moving and eventually crystallize, while the interior shape of the tube becomes more regular as the thickness of the flow increases.

While the walls are largely gelled motionless, surges will easily remobilize portions of the walls making branching passages easier. Once the walls crystallize, surges will tend to coat the walls with linings and cover the cave roof with overflows. These activities lead to the formation of a more regular passage shape. All of the internal modification factors combined will result in a passage that is proportioned 1:1 or often even higher than it is wide.

A seal and plug in a lava conduit can form in several ways. After the cave-forming flow stops, extensive cooling of the ceiling occurs. The development of contraction cracks in the solidified basalt of the ceiling may cause a collapse which blocks the lava conduit. The connection between New Cave and Wildcat Cave, and between Jug Cave and Mikes Caves, are the result of such plugs. The last dregs of lava which move down the tube pond up behind this blockage. A little bit of lava may still flow through the dam, as can be seen in Lava Brook Cave at Lava Beds National Monument in California.

Another scenario is responsible for the formation of a true lava siphon. As the lava flows over a short level place, the channel conforms to the ground contours. After roof formation is completed, some portions of the roof thicken more than others and jut lower over the lava stream. A lowering in the flow level occurs during the late eruptive stages. If the depth-to-flow ratio passes the critical

depth for which motion takes place, the lava stops and gels. Very often the floor where this occurs in a lava tube will show the very deep, narrow contraction cracks characteristic of the massive cooling of a one-meter or more thickness of lava. New Cave, just down-slope from the middle entrance, shows a good floor which, if a little higher, would make a great siphon seal. The lower end of JaR Cave at Trout Lake is probably a true siphon, though no caver skinny enough has been found to verify this. If there is some movement of lava through the siphon before full solidification sets in, the result will be ripples of crystallized scum building up in the lake. They soon harden into a passage floor that completely blocks the cave. These features are sometimes referred to as "festoons" and can be seen at the lower ends of Cheese Cave and Davids Den at Trout Lake, Washington.

A rare feature resulting from the thixitropic nature of molten lava can be seen in Wildcat Cave at Trout Lake. This cave exhibits marked shelves along the walls. Wide, deep (3×50 centimeters) contraction cracks indicate that these shelves cooled from one homogeneous unit and are not composed of consecutively built up linings. The surface of the shelf is rough, with a texture that is easily distinguished from the adjacent upper walls. The space in the center of the passage, between the shelves, consists of a vertically sided trench up to three meters deep. The width of the shelves decreases down slope until they become indistinguishable. The tube itself also decreases in size down slope and ends in a lava plug.

The shelves formed when the flow in the tube was halted for a period of time near the end of the eruption, possibly by a temporary breakdown blockage at the cave's lower end. The lava level during the hiatus was not high enough to fill Wildcat Cave completely, hence the space between the top of the shelves and the ceiling of the tube. The thixitropic lava stiffened without solidifying completely. When the flow began again. The lava in the center mobilized first and cut a deep vertical channel in the mass that had gelled during the period of no flow. The concurrent seal that developed between Wildcat and New Caves held while the lava drained away; no new lava came from up cave to affect the final flow. The period of stagnation was long enough, and the slope shallow enough, that the shelves attained enough rigidity to retain structural identity when the passage center drained away. The emplacement of the shelves and lava seals mark the final motion of the lava in this portion of the lava flow.

The thixitropic nature of lava (that property that makes it more fluid while flowing and thicker while stationary) can thus be seen to be an important factor in the explanation of why surface distribution tubes have wide passages, low ceilings, and flat floors, and how such flow-thinning behavior explains some of the internal features encountered in lava tubes.

Formation Mechanism of Cave Systems Based on the Joining of Unit Caves

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Abstract

A formation mechanism of horizontally complex tunnel-shaped lava cave systems without traces of lava flows related to cave formation was proposed. The formation mechanism was discussed qualitatively in consideration of rheological properties of lava and morphology of lava caves (growth direction of unit caves, inside morphology of unit caves at a joining point, a state of collapse of unit caves at a joining point). The formation mechanism was discussed using the cave crust hypothesis because traditional theories cannot explain the lava cave systems. In order to establish the formation mechanism, only tunnel-shaped lava caves formed owing to cave crust were dealt with. Moreover, to simplify discussion of it, this paper studied the lava cave systems composed of two unit caves.

The formation mechanism is composed of coupling joining, penetration joining, buoyancy joining, and fracture joining. Furthermore, a T-shaped passage, an X-shaped passage, and a K-shaped passage can be explained by the four kinds of joining.

1. Introduction

The purpose of this paper is to propose a formation mechanism of horizontally complex tunnel-shaped lava cave systems.

The coalescing drainage model is responsible for some small three-dimensionally complex lava caves and some braided but not vertically complex lava caves (J.W. Harter, 1974). In this model, there are traces of lava flows inside lava caves because the caves are formed by lava flows. In Japan and South Korea, however, there are horizontally complex tunnel-shaped lava cave systems without traces of lava flows related to cave formation. Consequently, a new lava cave formation mechanism is necessary to explain the horizontally complex tunnel-shaped lava cave systems because the coalescing drainage model cannot explain them.

To establish the formation mechanism of the horizontally complex tunnel-shaped lava cave systems without traces of lava flows, the idea of a cave crust proposed by Ohsako (1982, 1986) is used as a precondition of discussion. Moreover, to simplify the discussion, this paper studies the formation mechanism of lava cave systems composed of two unit caves.

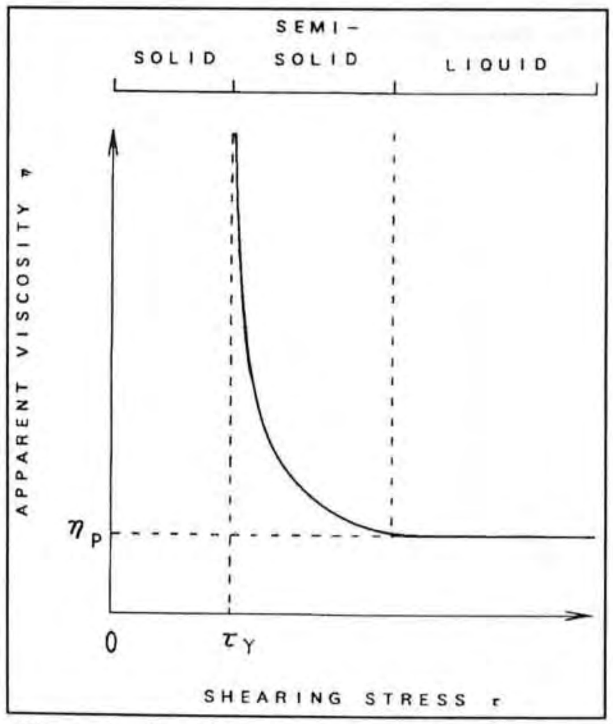

Figure 1—Ideal Behavior of a plasto-visco-elastic fluid.

2. Idea of a Cave Crust

The assumptions used in the idea of a cave crust will be described below.

(1) Lava flows have rheological properties such as viscosity, plasticity, and elasticity (Pinkerton and Sparks, 1978). That is, lava flows may be regarded as plasto-visco-elastic fluids.

As shown in Figure 1, a plasto-visco-elastic fluid behaves as a solid, a semi-solid, or liquid according to shearing stress (M. Reiner, 1969). Figure 1 shows that a solid lava crust (a cave crust) can be formed in a flowing lava region where the stress is below the yield value.

This assumption is the necessary condition to form a cave crust and a cave cap (a shell-shaped lava ball at the tip of a cave crust).

(2) A no-slip condition is satisfied on the boundary between a lava flow and a cave cap.

This assumption is the necessary condition to form a semi-solid lava layer around a cave cap. The advance of a cave cap transforms the semi-solid lava layer to a cave crust owing to degassing.

(3) There is local topography capable of forming a cave cap in a lava flow (K. Adachi and N. Yoshioka, 1973).

(4) Lava is moving during the formation of a tunnel-shaped lava cave (a unit cave).

This assumption is the necessary condition to advance a cave cap mainly on account of the visco-elasticity of a lava flow and thereby to grow a cave crust behind the cave cap.

As described above, the idea of a cave crust (the cave crust hypothesis) has a distinctive feature that does not require the solidification of lava based on cooling for the formation of tunnel-shaped caves.

3. Observations of Joining Morphology and Four Kinds of Joining

The joining morphology of unit caves was observed from the point of view of growth direction of unit caves, inside morphology of unit caves at a joining point, and a state of collapse of the unit caves at a joining point. Consequently, from observation, I see that the formation mechanism of the horizontally complex tunnel-shaped lava cave systems is composed of coupling joining, penetration joining, buoyancy joining, and fracture joining.

3.1 Coupling Joining

3.1.1 Growth direction of the unit caves.

- The lines of growth of the two unit caves lie on a curve.
- Two unit caves join in coupling. The unit cave on the upstream side joined at the starting point of growth of the unit cave on the downstream side.

3.1.2 Inside morphology of the unit caves at a joining point

(1) Morphology in a horizontal plane

- Some passages narrow at the joining point.
- Some passages widen on the upstream side of the joining point.
- The lines of growth of the unit caves sometimes break at the joining point.

(2) Morphology in a vertical plane

- There are some sharp drops in cave floor level and ceiling level.
- The remains of a cave cap are sometimes left on the floor of the unit cave on the downstream side.
- The lava of the unit cave on the upstream side sometimes flows into the part near the joining point of the unit cave on the downstream side.
- At the joining point, the unit cave has a low ceiling and/or a high floor when there are no sharp drops in cave floor level and ceiling level.

3.1.3 State of collapse of the unit caves at a joining point

- Collapse tends to be found when the two unit caves do not lie on a curve at the joining point.

3.2 Penetration Joining

3.2.1 Growth direction of the unit caves

- The two unit caves join in grade crossing.
- There is the joining point between a starting point and an ending point of the formation of the unit cave.

3.2.2 Inside morphology of the unit caves at a joining point.

(1) Morphology in a horizontal plane

- A T-shaped passage is formed when the cave cap of one unit cave approaches the other unit cave from about 90°.
- A K-shaped passage is formed when the cave cap of one unit cave approaches the other unit cave from about 0°.
- Figure 2 shows an instance of a K-shaped passage.

(2) Morphology in a vertical plane

- Sharp drops in cave floor level and ceiling level are formed when two unit caves with different passage widths join.
- Sharp drops in cave floor level or ceiling level are formed when the floor of one unit cave and the ceiling of the other unit cave join partially.

3.2.3 State of collapse of the unit caves at a joining point

- A cave cap tends to be found when collapse of the unit caves does not exist.

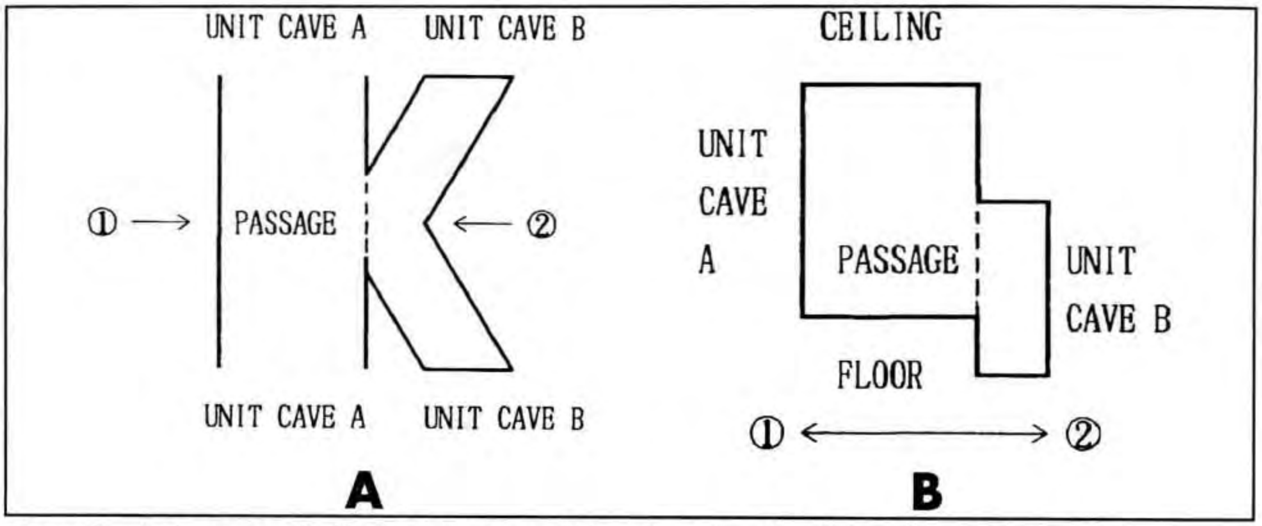

Figure 2—An instance of a K-shaped passage. (A) a schematic plan. (B) A schematic cross-section

3.3 Buoyancy Joining

3.3.1 Growth direction of the unit caves

- The two unit caves join in grade crossing.
- There is the joining point between a starting point and an ending point of the growth of the unit cave.

3.3.2 Inside morphology of the unit caves at a joining point

(1) Morphology in a horizontal plane

- A T-shaped passage is formed when one of the passages on the stretched side is separated.
- An X-shaped passage is formed when the passages on the stretched side are not separated.

3.3.3 State of collapse of the unit caves at a joining point.

3.4 Fracture Joining

- In the above three joinings the joinings with collapse are defined as fracture joinings.
- Items 3.1.3, 3.2.3, and 3.3.3 show that the deformation rate of the cave crusts is larger than the relaxation rate of the cave crusts. That is, a plastic flow of the joining part changes into ductile fracture under this condition (M. Reiner, 1969).

4. Joining Mechanisms of Unit Caves

I will propose four kinds of joining mechanisms of unit caves in consideration of the observations described in Section 3.

4.1 Mechanism of Coupling Joining

Figure 3 shows the mechanism of coupling joining.

(1) A unit cave A is formed in a lava flow on the basis of the cave crust hypothesis described in Section 2.

(2) Another unit cave B develops in a lava flow located on the upstream side of unit cave A.

(3) The local topography is eroded by the semi-solid region of unit cave B and the thickness of the topography is reduced gradually as a result.

(4) The cave cap of unit cave B collides against the local topography. We assume here that deformation rates of the cave cap and the local topography are slower than their relaxation rates.

(5) A shearing stress is thereby set up in the collision area. We assume here that the shearing stress is beyond the yield stresses of the local topography and the cave cap.

(6) The plastic flow part of the cave cap extends to the upstream side as the cave cap of unit cave B advances downstream. On the other hand, the plastic flow part of the local topography extends from the upstream side to the downstream side.

(7) The cave cap goes through the local topography with the length of the cap shortened by the above process.

(8) Unit cave B will join unit cave A when the cave cap can wholly go through the local topography.

4.2 Mechanism of Penetration Joining

Figure 4 shows the mechanism of penetration joining.

(1) There is a unit cave A in lava.

(2) A unit cave B approaches unit cave A.

(3) The cave cap of unit cave B collides against a cave crust (a side wall, a ceiling, or a floor) of unit cave

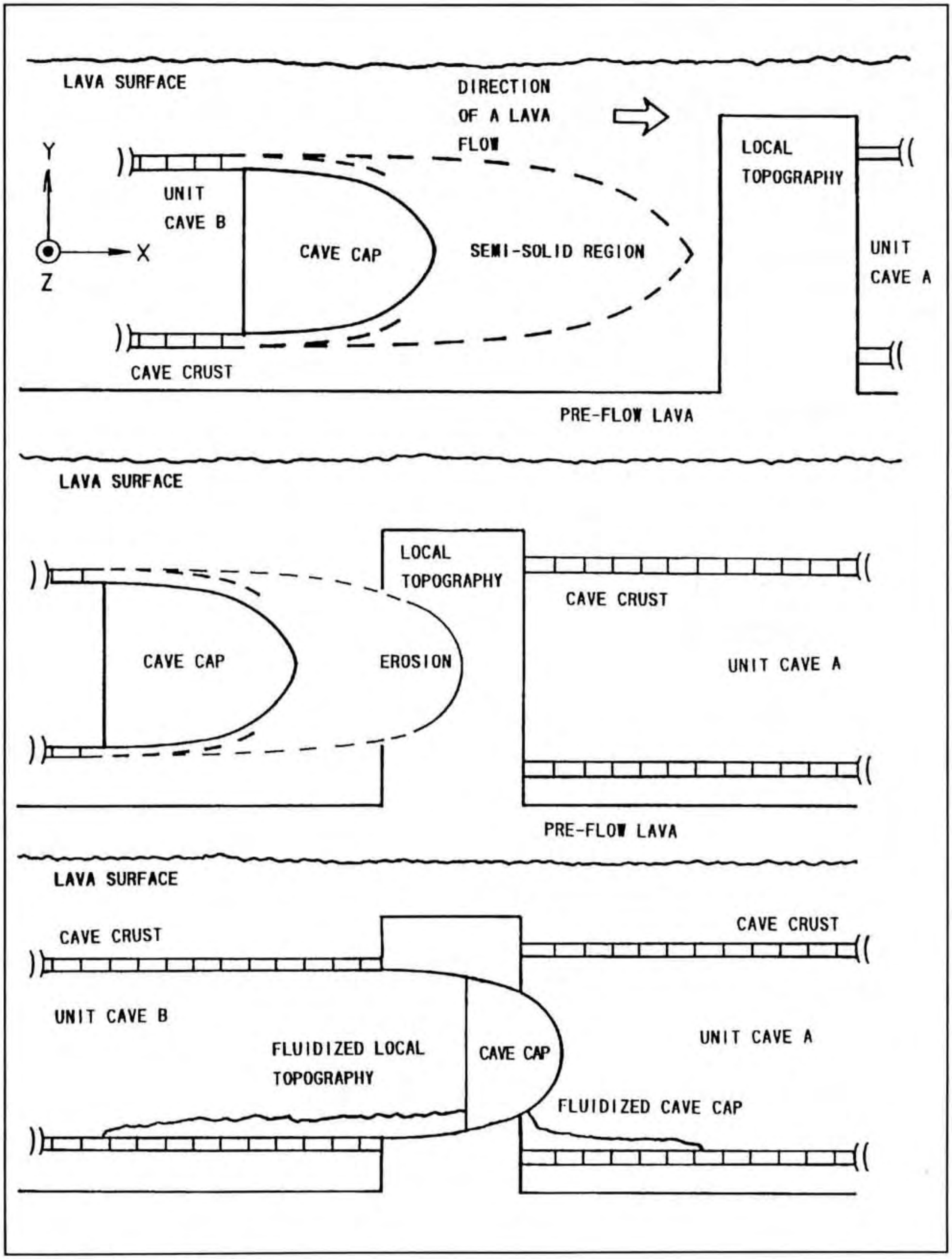

Figure 3 — Coupling joining

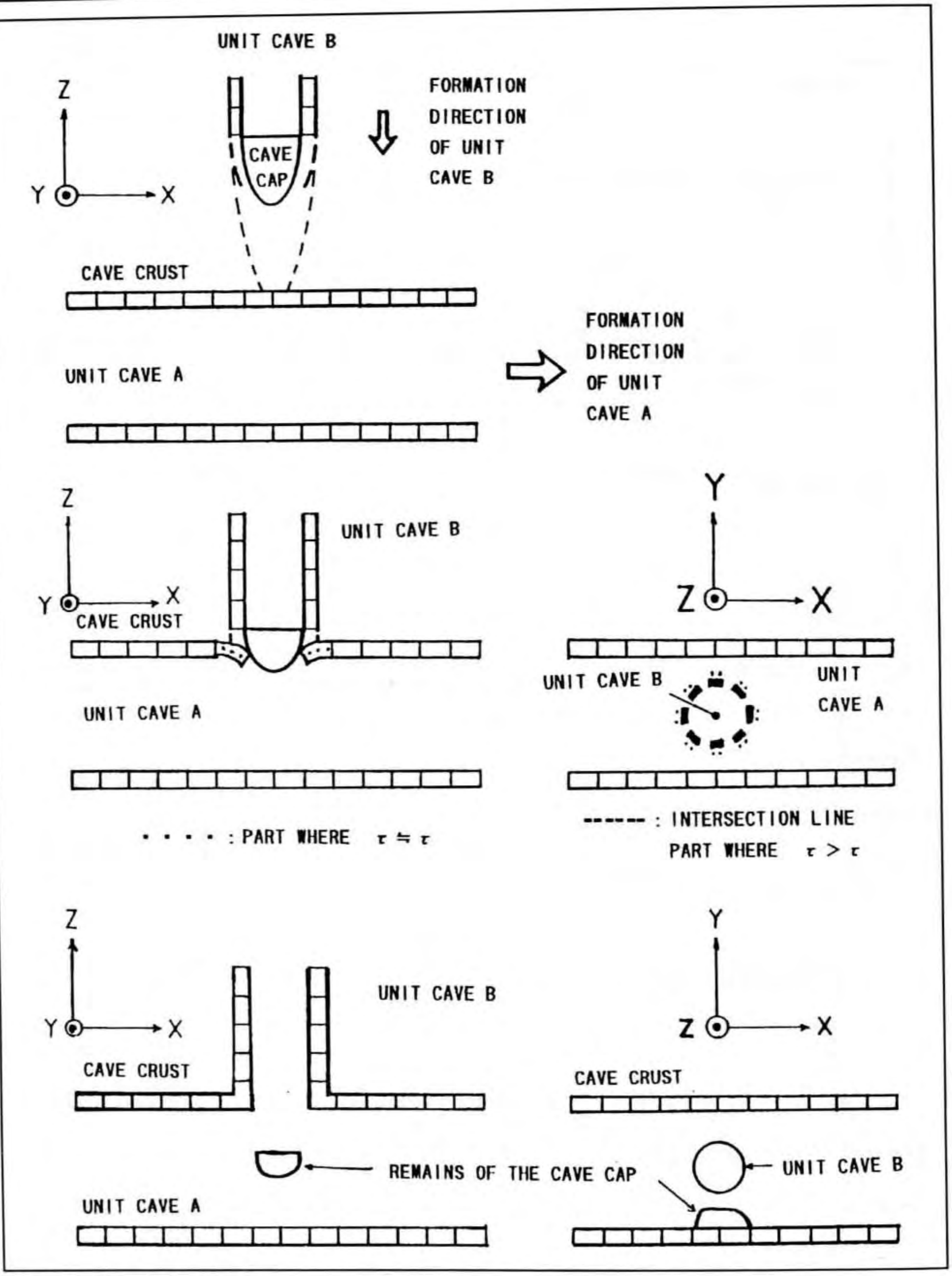

Figure 4—Penetration joining

A with deformation rates of the cave cap and the cave crust being slower than their relaxation rates.

(4) A shearing stress is thereby set up in the collision area. We assume here that the shearing stress is beyond the yield stresses of the cave can and the cave crust.

(5) Slip-lines penetrate the cave crust because the cave crust is thin compared to the local topography, and, as a result, plastic flow occurs more easily in the cave crust than in the case of coupling joining.

(6) The collision parts undergo plastic flow, so that the cave cap makes a hole in the cave crust of unit cave A.

(7) Part of the crust where the shearing stress is equal to nearly the yield stresses is bent inward at the same time. This bend is due to the visco-elastic properties of the cave crust.

(8) This bent part prevents molten lava from flowing into the unit caves by a bandlike constriction around the cave cap.

(9) This bent part acts as an adhesive agent in joining the two unit caves.

(10) This bent part solidifies again after the cave cap has penetrated because the shearing stress is below the yield stresses.

(11) Unit cave B will join unit cave A in this way.

(12) The cave cap of unit cave B cannot make a second hole in the other cave crust (side wall) of unit cave A because the passage increases rapidly in volume through the joining, so that degassing will not occur.

4.3 Mechanism of Buoyancy Joining

4.3.1 Formation of an X-shaped passage

Figures 5(a) 5(b) and 5(c) show the formation of an X-shaped passage.

(1) A crust of solidified lava flow is formed on the surface of a stationary lava flow.

(2) A unit cave A can rise in the stationary lava (by buoyancy) to come in touch with the surface crust if the buoyancy force is superior to the power of resistance due to the apparent viscosity of the stationary lava.

(3) We assume here that the deformation rates of the cave crusts (ceiling, side wall, floor) are slower than their relaxation rates.

(4) A plastic flow does not occur between the cave crust and the surface crust because the touch is not in the condition of point contact but in the condition of line contact, hence the shearing stress is not large enough to generate plastic flow.

(5) The buoyancy is generated when a tensile force due to the advance force of the cave cap decreases.

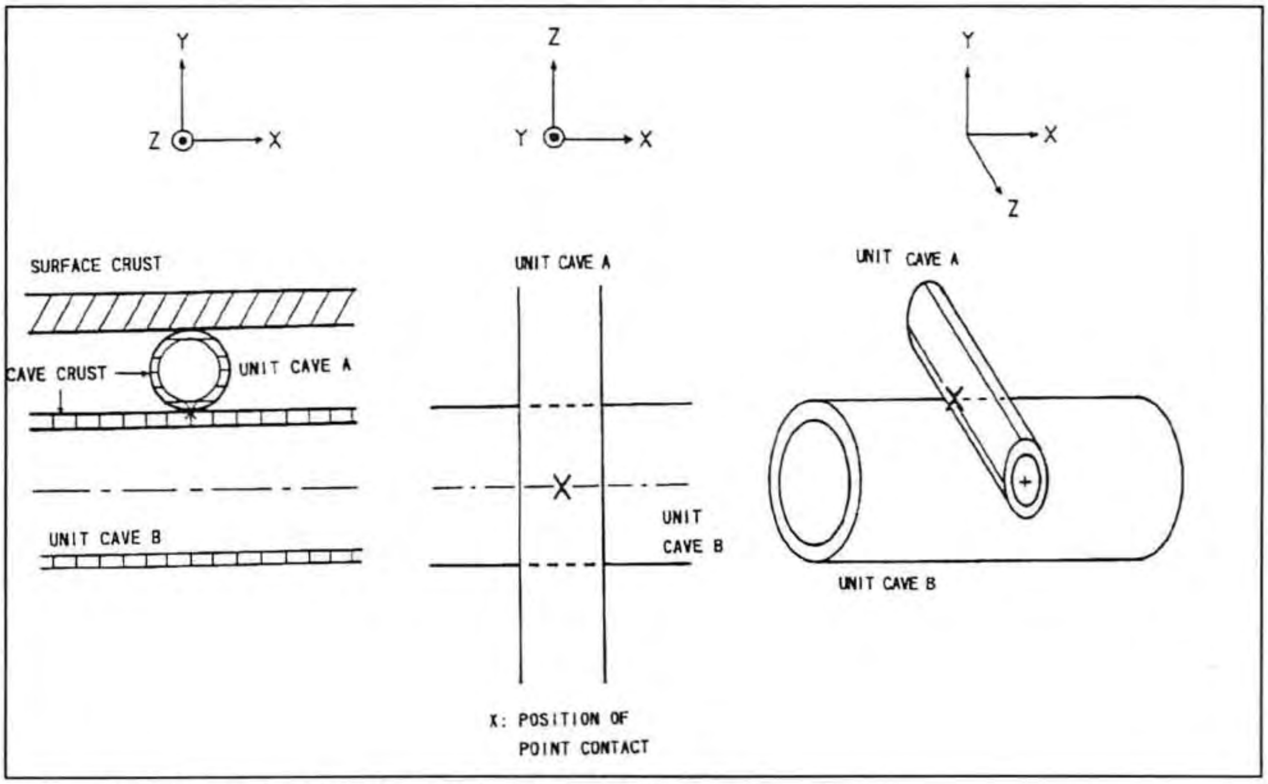

Figure 5(a) – Formation of an X-shaped passage – Initial stage

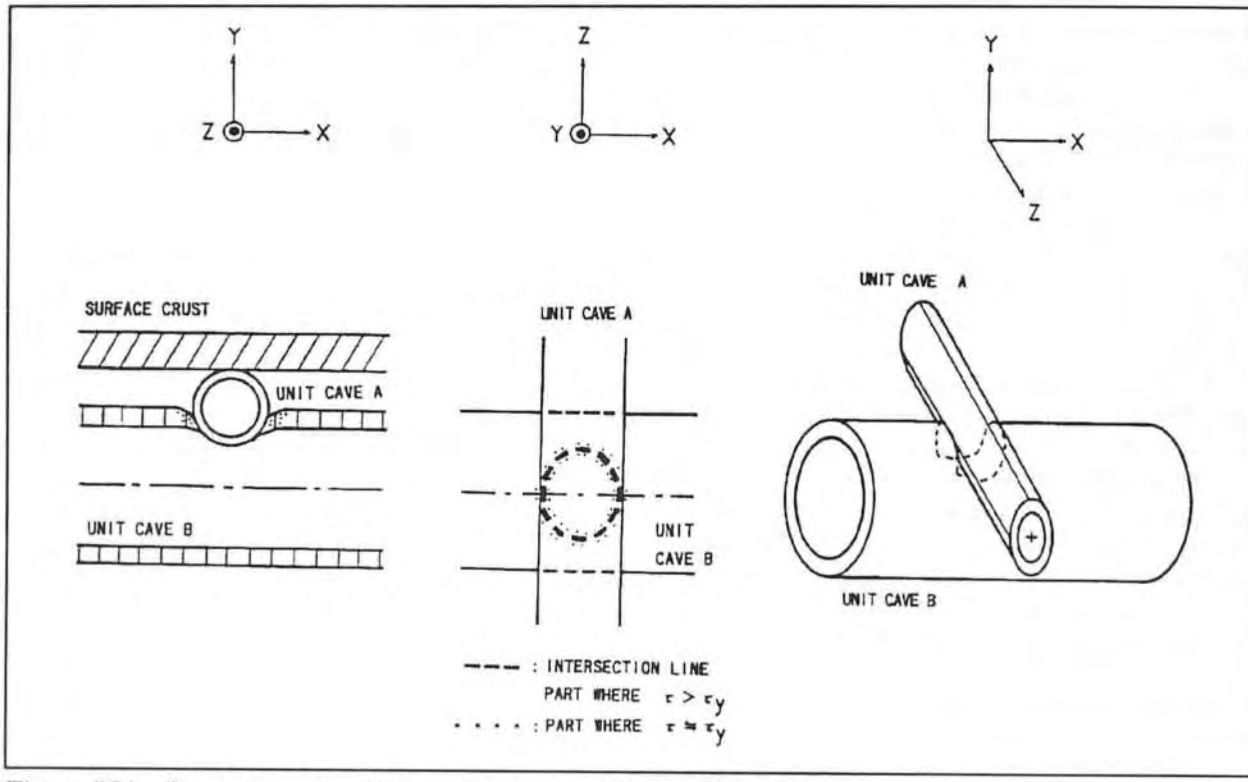

Figure 5(b) – Formation of an X-shaped passage – Intermediate stage

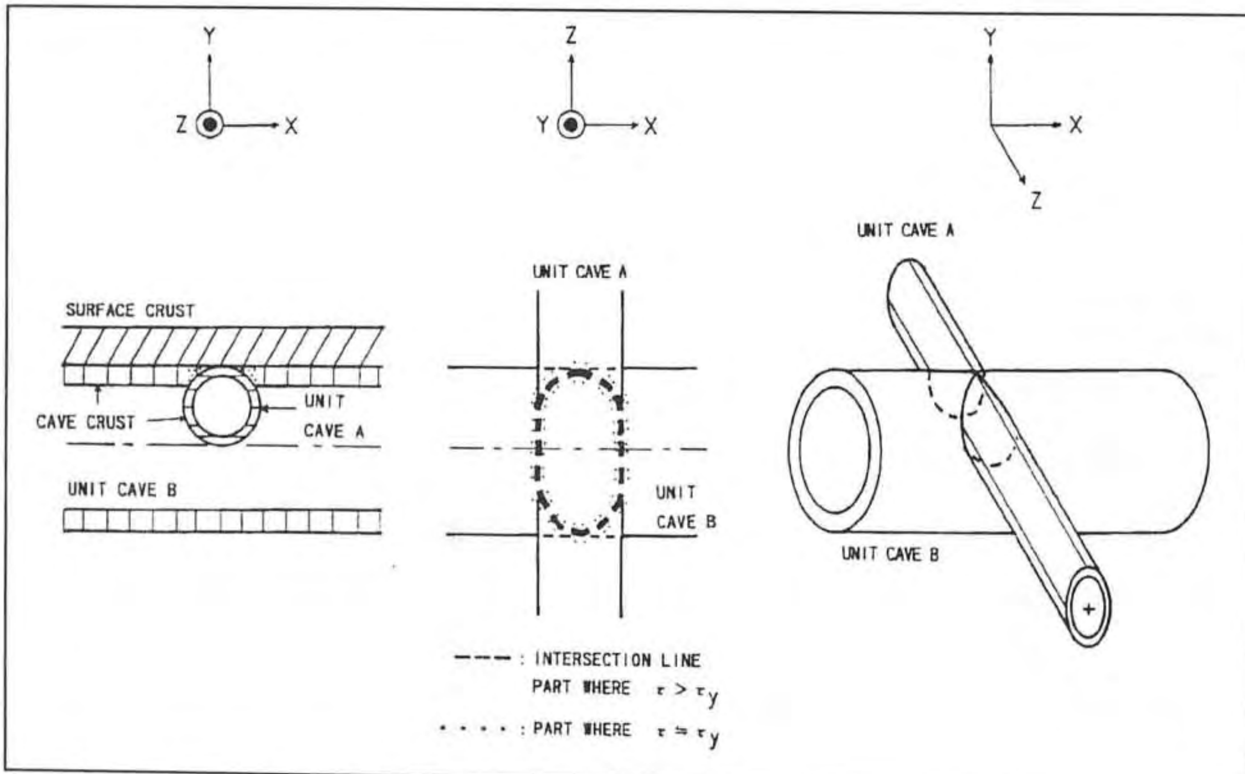

Figure 5(c) – Formation of an X-shaped passage – Final stage

(6) Unit cave A and unit cave B will overlap each other crosswise.

(7) Unit cave B rises because of buoyancy and collides against unit cave A.

(8) We assume here that shear force acts on the collision parts of the crusts (the floor of unit cave A and the ceiling of unit cave B), so that the shearing stress is beyond the yield stresses of the crusts of the two unit caves.

(9) Plastic flow occurs on the intersection line.

(10) The intersection line obtained by the crossing of the two unit caves develops with forming a closed curve.

(11) The part where the shearing stress is nearly equal to the yield stress is bent downward by the rise of unit cave B. This bend is due to visco-elastic properties of the cave crust.

(12) The bent crust of unit cave B returns to its original shape. That is the elastic recoil of the cave crust due to the visco-elastic property.

(13) This bent part acts as an adhesive agent in joining the two unit caves.

(14) The bent crust solidifies again after the unit cave has penetrated because the shearing stress is below the yield stresses.

(15) Furthermore this bent part prevents molten lava from flowing into the unit caves.

(16) Unit cave B comes in touch with the surface crust so that the buoyancy joining is finished.

4.3.2 Formation of a T-shaped passage.

Figure 6 shows the formation of a T-shaped passage.

(1) We assume here that unit cave A is stretched in the direction of the X-axis and unit cave B is not stretched in the direction of the Z-axis. Unit cave A may be regarded as a tube with one end fixed and the other end free.

(2) There is a fixed end of unit cave A in the negative range of X values. Let the origin (o) be a joining point of unit cave A and unit cave B.

(3) Items (1) through (9) in Section 4.3.1 occur.

(4) Unit Cave A is sandwiched between a surface crust and unit cave B, so that the cave crust in the positive range of X values is stretched, while the cave crust in the negative range of X values does not come to be stretched.

(5) In the positive range of X values, a higher shearing stress is set up in the cave crust of unit cave A compared to the shearing stress in the cave crust of unit cave B because the compression stress lies in the cave crust of unit cave A while the tensile stress is applied perpendicular to the compression stress (S.P. Timoshenko, 1952).

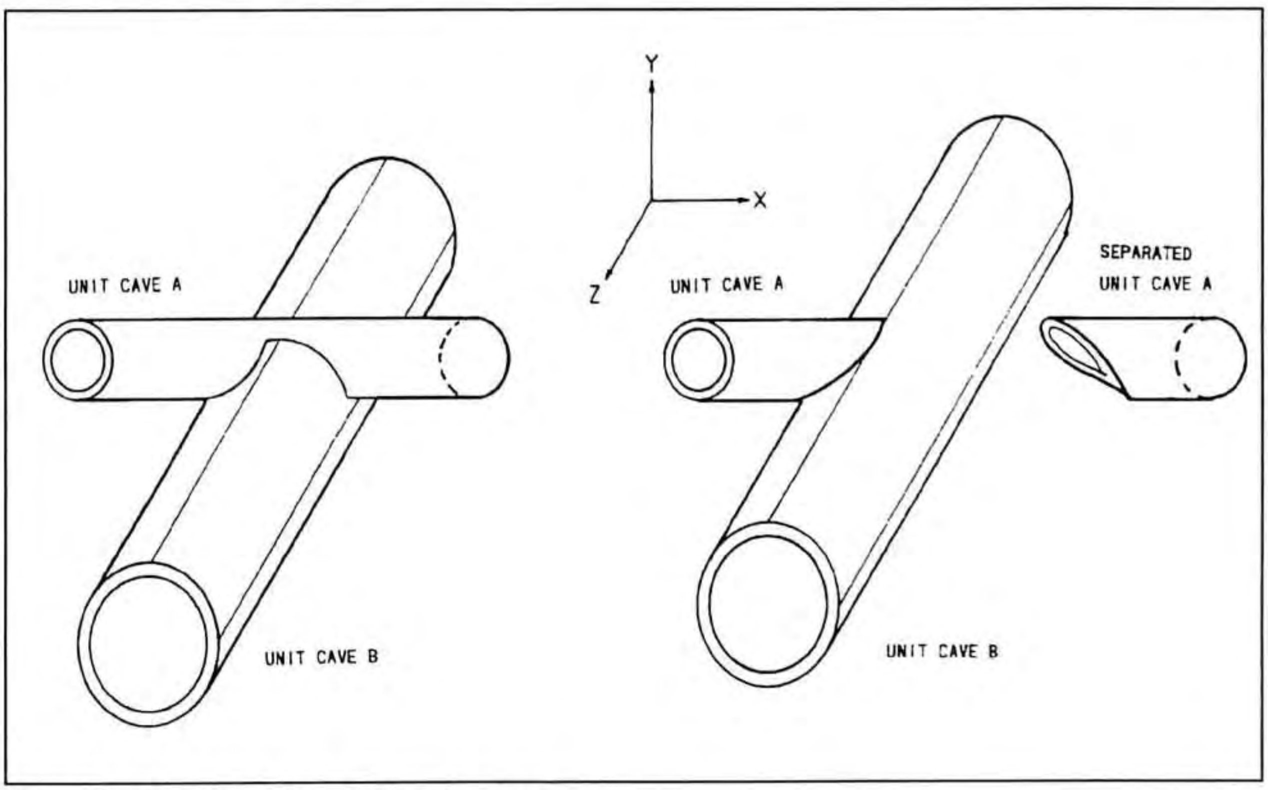

Figure 6—Formation of an T-shaped passage

(6) In the negative range of X values, the shearing stress in the cave crust of cave A is equal to one in the cave crust of cave B.

(7) In the positive range of X values, an apparent viscosity η_A of unit cave A decreases with increasing shearing stress as is evident from Figure 1. On the other hand, there is no change in an apparent viscosity η_B of unit cave B. Consequently, η_B will be bigger than η_A.

(8) Unit cave A in the positive range of X values is separated from unit cave B, while unit caves A and B in the negative range of X values join in the same way as the formation of an X-shaped passage.

4.4 Mechanism of Fracture Joining

4.4.1 Fracture joining in coupling joining

When the local topography is stressed rapidly by a cave cap and thereby deformation rates of the local topography and the cave cap exceed their relaxation rates, elastic energy cannot be used up in such a short time through a plastic flow and hence ductile fracture occurs in the joining part (M. Reiner, 1969).

4.4.2 Fracture Joining in Penetration Joining

When a cave crust is stressed rapidly by a cave cap, ductile fracture occurs in the joining part in the same way as stated above.

4.4.3 Fracture Joining in Buoyancy Joining

When a cave crust is stressed rapidly by another cave crust, ductile fracture occurs in the joining part in the same way as stated above. When the shearing stress is beyond the yield stress, the unit caves are destroyed by the buoyancy force acting on the cave crusts because ductile fracture cannot form the joining so that lava around the caves cam not flow into the unit caves. Accordingly, it is necessary for the shearing stress to be nearly equal to the yield stress.

5. Discussion

I discuss qualitatively the formation mechanism of horizontally complex tunnel-shaped lava cave systems without traces of lava flows related to the cave formation in consideration of the rheological properties of lava. Consequently, four kinds of joining (coupling joining, penetration joining, buoyancy joining, and fracture joining) can be interpreted as the factors in the present formation mechanism from three points of view (growth direction of caves, inside morphology of unit caves at a joining point, and a state of collapse of unit caves at a joining point) as shown in Table 1. That is, two unit caves join without collapse when a plastic flow occurs at the joining point. On the other hand, two unit caves join with collapse when ductile fracture

Table 1 Conditions of four kinds of joining

DIRECTIONS OF 2 UNIT CAVES	SHEARING STRESS τ	DEFORMATION-RATE VERSUS RELAXATION-RATE	FLOW / FRACTURE	KINDS OF JOINING
PARALLEL	$\tau > \tau_Y$	D < R	PLASTIC	COUPLING JOINING
		D > R	DUCTILE	FRACTURE JOINING
GRADE CROSSING	$\tau > \tau_Y$	D < R	PLASTIC	PENETRATION JOIN
		D > R	DUCTILE	FRACTURE JOINING
TWO LEVEL CROSSING ⇩ GRADE CROSSING	$\tau > \tau_Y$	D < R	PLASTIC	BUOYANCY JOINING
	$\tau \fallingdotseq \tau_Y$	D > R	DUCTILE	FRACTURE JOINING

occurs at the joining point. Furthermore, I interpret that the general formation mechanism of the horizontally complex tunnel-shaped lava cave systems without traces of lava flows is formed by repetition of the same factor and/or different factors in the present formation mechanism.

Up to now we do not know how to interpret collapse in a passage within the range of traditional theories of lava cave formation. Collapse in a passage can be partially interpreted by the present formation mechanism. Furthermore, we can now explain a K-shaped passage, a T-shaped passage, and an X-shaped passage, while only a Y-shaped passage has been explained by traditional theories.

6. Conclusion

In the present paper, I discuss only tunnel-shaped lava cave systems formed on the basis of the cave crust hypothesis. Furthermore, I deal with lava cave systems composed of two unit caves to simplify the discussion. Under these conditions, I propose that the formation mechanism of the horizontally complex tunnel-shaped lava cave systems without traces of lava flows related to the cave formation is composed of coupling joining, penetration joining, buoyancy joining, and fracture joining. The present formation mechanism will be a great help in explaining structures of other horizontally complex tunnel-shaped lava cave systems. The next stage is to determine whether the cave crust hypothesis is applicable to an L-shaped passage.

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Lava Tube Formation: A Cave Diver's Perspective

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Abstract

Volcanic geomorphologists have studied and written about lava tubes that are relatively dry and above sea level. There are, throughout the world, many lava tubes that were formed when sea level was as much as 100 meters lower than present. They were subsequently flooded as sea level rose at the end of the ace age.

Exploration of the submerged section of Jamos del Agua in Lanzarote, Canary Islands, has added over three kilometers of cave to the seven kilometers of historically significant dry passage. Diveable passage terminates in a lava sump at a depth of 70 meters below sea level. Hawaiians named the small circular pond on the south point of Hawaii Lua o Palahemo. Exploration has shown that this pond is the flooded skylight of a lava tube that extends southward beneath the shore line of Hawaii and continues under the Pacific Ocean for several hundred meters. Passage heights range from one meter to over 25 meters. Diveable passage terminates in a white calcareous sand choke. These two examples illustrate that cave diving researchers have the ability to gather data on submerged lava tubes. The additional 40% of tube length available for study in the Canary Islands and the discovery of a large tube at the southern extent of the southwest rift zone of Mauna Loa have the potential to contribute toward a better understanding of the genesis and morphology of lava tubes.

The literature on lava tube formation is compared with field observations from several submerged tubes with emphasis on the Lua o Palahemo tube.

Inventory, Evaluation, and Management of Publicly Owned Caves in the Western United States and the Impact of the Federal Cave Resources Protection Act

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Abstract

Over the past decades many inroads have been made in the management of publicly owned caves in the western United States. Not the least of these is the Federal Cave Resources Protection Act of 1988. This act, for the first time, clearly mandates federal agencies to manage caves. A variety of management strategies and techniques have been formulated, some of which are described in this paper. Agencies are overcoming a lack of funding and a lack of qualified cave management specialists through training and use of knowledgeable volunteers. This paper, in a general sense, applies to management of all western caves but special emphasis is placed on management of lava tube caves.

Publicly Owned Caves

The concept of managing caves is nothing new, but the principles of management have changed over the years. Caves in the West were first managed for commercial or recreational purposes. In some cases improvements were added such as stairs, trails, railings, lights, and a guide was provided to entertain visitors and perhaps even share a bit of natural history. Tourist caves were the norm and the improvements provided were intended to enhance that use. The incentive was two fold: first, provide a recreation experience for visitors; second, generate income to help fund the endeavor.

Not all caves had guides, many were developed as dispersed recreation sites where the public was encouraged to come and explore on their own. The caves would be advertised on maps and in brochures and generally attracted a fair amount of use. The problem is that use was uncontrolled. Due to the remote locations in which the caves are found, vandalism was a problem. Vandalism in some cases was intentional, but frequently was unintentional. The trampling of floor features, leaving of litter, use of smoky torches or flares, taking a rock souvenir home, all contributed to a general degrading of cave resources. Many of these caves remain today open to the public as they have been for over fifty years.

Starting in the late 1960s, emphasis began to be placed on caves as an outgrowth of public concern. The Bureau of Land Management, the Forest Service, and the National Park Service in the Guadalupe Mountains of New Mexico developed joint management agreements. They agreed to a cave inventory and classification system that would be used by all. This system, with minor refinements, is still in use today. It was developed for and is well suited for the delicate and often dangerous caves of the area.

In 1986 the Forest Service and Bureau of Land Management developed directives for managing cave resources. Field units were directed and given guidance in dealing with caves. In November of 1988, President Reagan signed into law the Federal Cave Resources Protection Act which made it the policy of the United States to manage cave resources.

Federal Cave Resources Protection Act

The concept of cave management has only recently emerged as a discipline of land management. The catalyst in this emergence was the signing into law of the Federal Cave Resources Protection Act of 1988. This law makes it "the policy of the Untied States that Federal Lands be managed in a manner that protects and maintains,

to the extent practical, significant caves." Before this time there was concern, in certain circles, that cave resources were being impacted but any coordinated effort to address the situation was frustrated by the lack of a clear mandate. The Federal Cave Resources Protection Act of 1988 settled the question: now it's law.

It would seem that all problems are now solved, but that's just not so. The real work is yet to begin. When the act was drafted there was concern that "protection and maintenance" of every cave might be too burdensome and that it would be better if only "significant" caves fell under protection of the Act. In some cases, promoters of the act felt that this compromise was better than having no caves protected at all and were willing to agree to the last minute amendment.

This amendment was advanced largely as a cost-savings measure by agencies, but will probably prove to be more costly. As the Act stands, agencies will be required (in a practical sense) to evaluate caves to determine if they meet significance criteria. To impact caves before this evaluation and determination is made could place agencies into non-compliance with the purpose of the act. It is expected that projects in cave or karst areas will require investigation and evaluation prior to the start of the projects.

How will determinations of significance be made? The Departments of Interior and Agriculture are jointly developing regulations that will describe the methods to be used in making determinations. The exact methods are still under development and will require a period of public review and comment before being completed.

It is generally understood that an evaluation of cave resources will be the basis for decisions. Resources to be evaluated will include, but not necessarily be limited to: biological; geological, mineralogical, or paleontological; educational or scientific; hydrological, cultural or historical; or recreational values. Special consideration may be given to areas designated as national parks or monuments, areas of critical environmental concern, special interest areas, research natural areas, and so on when those designations were made in whole or part because of the presence of cave resources.

Cave Inventory Projects

While implementation regulations are in preparation, many offices are gathering cave data using the above criteria. They expect that the regulations will be flexible enough to take into account local differences in cave values. Since the gathering of basic data for future evaluation can proceed without the implementation regulations, many areas have decided to actively pursue cave inventories.

Inventories are being performed mostly by volunteers. Members of the National Speleological Society are particularly active, as well as the Cave Research Foundation, the Indiana Karst Conservancy, the Northwest Cave Institute, Prince of Wales Island Expeditions, and many others. Agencies generally lack, or have chosen not to allocate, funding for cave resource management. If it were not for so many willing volunteers, very little would be happening. Perhaps in no other resource area is there greater involvement of volunteers, or agencies more dependent upon their support, than cave management.

A danger for government officials not familiar with cave management is assuming that volunteers have all the answers. It is critical that managers exercise their responsibility to manage the resources they are charged with managing and not try to shift that responsibility to volunteers. Volunteers are an excellent source of assistance and can help generate a wealth of good ideas that can be implemented. The official must always keep in mind laws, policies, and directives and make decisions based on all factors, not just local public opinion. The manager's responsibility is to manage.

Cave Specialists

A difficulty in managing caves on public lands is a lack of qualified cave specialists. To be qualified one needs to be a generalist with knowledge of cave resources, followed by an understanding of surface management. Additionally, one needs an understanding of pertinent laws and regulations under which their agency works, and have the personal attributes needed to work with individuals of divergent interests. To be successful, an individual needs technical skill, but equally important is skill in interpersonal relationships.

Most cave specialists working for agencies are individuals who have come up through the ranks. They have generally developed an interest in caves outside of work, many times through sport caving. The interest in caves is often pursued through specialized technical training in geology, biology, or other sciences. In some cases individuals with

technical training have developed an interest in caves as an outgrowth of their specialty.

One can anticipate a steadily increasing demand for qualified individuals to work in cave management. Over the past two decades agencies have gone from no cave management specialists to the creation of positions at most important caves or cave areas. To implement the Federal Cave Resources Protection Act it will be necessary for a great many more positions to be created. This is good news for people wanting to make cave management their career. Agencies are starting to consider appropriate grade levels for differing levels of responsibility.

A variety of laws and regulations exist or will soon exist for the management of cave resources. The important point to remember is that cave management is dynamic and ever changing. As new ideas are brought forward and tried, ideas and concepts change with them. Cave management is an emerging field of natural resource management and will take its place along side traditional fields such as forestry, range, wildlife, and recreation management. Traditional management has focused entirely on surface resources, cave management focuses on those resources beneath the soil/air interface. The surface and the underground are linked and dependent upon each other in ways we are just now starting to understand.

Inventory and Evaluation of Lava Caves

When a cave inventory and evaluation process is developed it is usually developed for local use. Various authors have proposed unified systems for use across a wide range of cave types and geographical areas. Managers have found that it is better to customize the system to meet local needs. They have found that the concerns for managing lava tubes are quite different from those of limestone caves. As a result, changes are needed in the way evaluations are conducted.

Lava tubes tend to be gently sloping linear systems without the complexity normally found in solution caves. Vertical drops tend to be short, less than 100 feet, and are found only at entrances and in some mature tubes subject to erosional or depositional modification. Formations are less common in lava tubes than solution caves and are usually the result of melting or extrusion while the tube was forming. Secondary speleothems are rare due to the young age of lava tubes.

Lava tubes have generally been thought of as lacking in interest and as robust caves that can withstand great human impact. Exactly the opposite is true. Undisturbed lava tubes have been found to contain delicate coralloids near their entrances, and sometimes at other places where evaporation is accelerated. These form most readily on floors and lower wall surfaces. In arid areas gypsum flowers, crusts, and selenite needles are not uncommon. Lava stalactites and stalagmites are common in certain caves and because of their small cross sections are highly vulnerable to breakage. In some caves the floor will be encrusted by small sphericals of lava drip which can be crushed by careless explorers. Deposits of drip-eroded volcanic ash or clay often cover lava tube floors and are as important to the beauty and interest of the cave as secondary formations are to solution caves.

Tree roots are often found emerging from ceiling cracks and extending to the cave floor. These provide one of the few nutrient sources for cave adapted invertebrates and are easily damaged by either careless explorers or removal of trees from the surface. Cave biota is usually more scarce in lava tubes due to the lower levels of nutrient input but are highly evolved. Some researchers feel that only a small part of the populations are found in the humanly passable openings and that large parts of the population inhabit contraction cracks in the lava flows. In desert areas lava tubes have been found to provide refuge to plants, animals, and insects that inhabited the surface when climates were wetter and colder than they are today. The microenvironment found in cave entrances often provides the only remaining habitat for species which have otherwise become extinct on the surface.

Pack rat middens and dried pack rat urine called amberat is an important source of information concerning past climates and vegetative types. Rat middens in dry caves hold samples of thousands of years of vegetative history as does pollen embedded in amberat.

Ice deposits during the Pleistocene epoch provided a water source for native Americans. Around the entrances can be found evidence of extensive village sites and in the caves are found great quantities of charcoal from fires built to melt the ice. The cold-trapping nature of lava tubes has made them nearly exclusive in this past human applica-

tion. In other areas, such as Hawaii, where surface water is nonexistent due to the porous nature of the lava fields, early humans collected dripping water. Because lava caves were a focus of prehistoric use, they are among the best preserved and important sites for deciphering human history.

A Lava Tube Evaluation Method

The common practice is to evaluate lava tubes using resource categories from the Federal Cave Resources Protection Act. The following system is used at Mount St Helens National Monument to create a cave evaluation and classification matrix. Values are compiled using the resource rating guide. The matrix is a convenient method of displaying the relative importance of cave resources and is helpful when making classification determinations.

The value of developing resource value ratings is that they can be done with relatively little field work. At Mount St Helens a group of local cave experts was asked to rank caves according to their values. Following an extensive inventory project, there was no appreciable change in ranking. This shows that initial classification is possible prior to doing an extensive inventory. The quality of the product will, however, depend upon the use of knowledgeable experts and the existence of some prior work.

Resource Rating Guide

The following rating guide provides, in a simplified narrative form, brief statements that can be used to assign a value to respective resources. When viewed in a larger matrix it is possible to compare relative values between

Sample Cave Evaluation and Classification Matrix
Mount St Helens National Volcanic Monument

Cave Name	Biological	Hydrological	Historic	Recreational	Geological Paleontological, etc	Educational, Scientific	Cave Classification
Ape Cave	2	1	3	3	3	4	2
Barneys Cave	2	0	1	2	2	2	3
Beaver Cave	4	0	1	3	3	3	1
Beaver Bay Cave	3	0	1	2	2	3	3
Bat Cave	5	0	1	3	4	5	1
Breakdown Cave	2	0	1	1	1	1	3
Blue Ribbon Cave	2	0	1	3	4	3	1
Christmas Canyon Cave	2	0	1	2	4	4	3
Column Cave	3	0	1	1	3	1	3
Dollar-And-A-Dime Cave	3	0	1	4	3	4	3
Dogwood Cave	1	0	1	2	2	1	3
Duckwalk Cave	2	0	1	1	1	1	3
Flow Cave	3	0	1	3	3	3	3

Table 1 – An evaluation and classification matrix is useful for displaying the relative importance of various resource values.

caves. The relative values can be used as an indication for certain management needs such as gating, restricted access, special surface management, and so on. One should use this approach with great caution and not rely solely on the ratings for management direction. Good judgment and careful analysis of individual caves should never be overlooked.

Biological Resources

Value	Explanation of Value
0	Biological components lacking.
1	Biological components exist but of low apparent significance.
2	Biological components present and numerous, sensitivity low.
3	Biological components present, numerous, and of moderate sensitivity.
4	Biological components numerous and sensitive to disturbance.
5	Biological components very numerous and highly sensitive to disturbance. Habitat is critical to species survival. The cave contains unique species, or ones found on state or federal sensitive, threatened, or endangered species lists.

Hydrological Resources

Value	Explanation of Value
0	Hydrologic components lacking.
1	Hydrologic components present but of low importance.
2	Hydrologic components present but of low sensitivity.
3	Hydrologic components present and of moderate sensitivity.
4	Hydrologic components important and very sensitive.
5	Hydrologic components complex and highly sensitive.

Cultural or Historic Resources

Value	Explanation of Value
0	Cultural resources lacking.
1	Potential for cultural resources low.
2	Potential for cultural resources moderate.
3	Cultural resources present or implicated by historic records. Site may be eligible for the National Register of Historic Places.
4	Cultural resources present and sensitive to disturbance. Site eligible for the National Register of Historic Places.
5	Cultural resources present and highly sensitive to disturbance. Site eligible for the National Register of Historic Places.

Recreational Value	
Value	Explanation of Value
0	Cave lacks recreational value.
1	Recreational value low. Little or no scenic appeal.
2	Recreational value low but receiving some use. Scenic values low.
3	Recreational values, scenic values, and use moderate.
4	Recreational values, scenic values, and use high.
5	Recreational values, scenic values, and use very high. A major cave of regional or national significance.

Geological, Mineralogical, or Paleontological Value	
Value	Explanation of Value
0	Features of significance lacking.
1	Some interesting features present.
2	Features present and resistant to disturbance.
3	Features present and of moderate sensitivity to disturbance.
4	Features numerous and of high value. Features sensitive to disturbance.
5	Features rare, valuable, numerous and/or of great sensitivity to disturbance.

Educational or Scientific Value	
Value	Explanation of Value
0	Cave lacking educational or scientific value.
1	Cave with low educational or scientific value.
2	Cave with features that can be used for educational or scientific study but are otherwise considered common to the area.
3	Cave which provides opportunity for educational or scientific use.
4	Cave providing *unusual* opportunity for educational or scientific use.
5	Cave with *unique* opportunity for interpretation and public education or scientific study.

Cave Classification

At Mount St Helens caves are placed into one of three classifications depending upon the resource value.

Many different cave classifications are possible depending upon the type of resources, resource sensitivity, and expected impacts. No classification system has been widely employed but all have certain similarities. It is more important that systems

Cave Classification	
Class	Explanation of Classification
Class 1	**Sensitive Caves.** Caves considered unsuitable for exploration by the general public either because of their pristine condition, unique resources, or extreme safety hazards. They may contain resources that would be impacted by low levels of visitation. These caves are not shown on maps or discussed in publications intended for general public use such as guides, brochures, and magazines.
Class 2	**Directed Access Caves.** Caves with directed public access and developed for public use. These caves are shown on maps or have signs directing visitor access. Frequently have guided tours and artificial lighting. Regardless of the level of development, public visitation is encouraged. The caves may have sensitive resources that are protected.
Class 3	**Undeveloped Caves.** Caves that are undeveloped or contain unmaintained or minimal developments that are suitable for exploration by persons who are properly prepared. In general, these caves contain resources that resist degradation by recreational use. However, public use will not be directed toward them.

Table 3—At Mount St Helens caves are placed into one of three classifications. Each classification carries specific management direction.

be adjusted to fit local conditions than to try for uniformity. Over time, as various systems are employed, refinements will no doubt occur, making future systems better than those used today.

Standards and Guidelines

A common method of describing management actions is through use of standards and guidelines. This allows a manager to develop a list of standard actions that will be applied whenever cave resources are encountered. The following is a listing of standards and guidelines common in the Northwest.

- Logging, road construction, and other uses of heavy equipment above or in the vicinity of a cave with a thin roof, or over the course of such a cave, should be restricted if there is potential for damage.
- Vegetation in the vicinity of a cave entrance or over a cave's course should be retained if required to protect the cave's microenvironment.
- Cave entrances should not be altered or used as disposal sites for slash, spoils, or other refuse.
- Management activities should not be permitted within any area draining into a cave if they may affect the cave ecosystem with sedimentation, soil sterilization, the addition of nutrients or other chemicals, or will change the cave's natural hydrology.
- Surface drainage shall not be diverted into caves.
- Public access should be limited if required to prevent damage to the cave ecosystem, artifacts, or other features.
- The location of caves will be kept confidential when needed to protect archaeological sites, habitat for endangered wildlife, sensitive cave biota, and unique geological features.
- Communication and cooperation between the agency, caving organizations, and recreationists will be fostered. Exchanged information will not be made public if it could lead to the degradation of sensitive caves.
- Caves with high resource value, high hazard, or high public use will be subject to a written cave management plan. The plan will describe specific management measures, methods of implementation, and a monitoring plan to determine effectiveness of the management measures.

Depending upon the local conditions and the expected impacts, many other standards have been written. Here again, it is important to tailor management strategy to local needs and expected impacts and not limit one's thinking to actions which have been taken elsewhere.

Accurate Survey of a Hawaii Island Lava Tube for the Purpose of Conservation and Management

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The Hawaii Cave Conservation Task Force of the N.S.S

Abstract

A major project of the Hawaii Cave Conservation Task Force is the preservation of Pahoa Cave, a major lava tube in the Puna District of the island of Hawaii. In 1987 the Hawaii State Departments of Land and Natural Resources and Agriculture requested that we accurately survey the portion of this cave underlying agricultural lots leased by the State to private growers. The problem of cave roof collapse due to heavy equipment had caused the lessees to return the land to the State. In order to determine which survey method would meet the required accuracy, we compared three non-electronic survey methods: theodolite, plane-table, and tripod-mounted compasses. We initially believed that the compass method would not be accurate because of the problem of paleomagnetism in the lava rock. We did not use triangulation due to time factors and occasional narrow passages. The theodolite, while giving the highest precision for individual readings, had the greatest closure error: 18.7 meters. The plane-table also had an unacceptable closure error: 11.4 meters. In spite of paleomagnetism, the tripod-mounted compasses gave the least closure error: 1.3 meters in 906 meters total distance. Since the theodolite and plane-table errors are cumulative, we decided that closure reduction by statistical methods was not acceptable, so we re-shot several stations. During the survey, we also determined that Pahoa Cave contained significant archaeological, biological, and geological features worthy of protection. The Hawaii Cave Conservation Task Force has been instrumental in developing a proposal in which the State has agreed in principle to lease 25 acres of land, including two miles of Pahoa Cave, to the University of Hawaii as a Cave Preserve.

Diplura of Lava Tube Caves

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Abstract

The examination of campodeid diplurans collected from 21 lava tube caves in Washington, Oregon, Idaho, and northern California has revealed seven or eight species belonging to the genus *Haplocampa*. One species may belong to the endogean species *H. rugglesi*, originally described from Mount Rainier. The others are new undescribed species. A morphological study of the cave species was done in an attempt to learn their phylogenetic relationship to each other and to the known endogean and cavernicolous (in limestone caves) species of *Haplocampa*. Lavacicle Cave in Oregon is unusual in that it contains two species of diplurans; in the United States only two other caves (limestone) are known to do so at present. However, this distinction may vanish following the study of some extensive collections of diplurans from lava tube caves in Washington state. Considering their wide occurrence in the lava tube caves of the northwestern United States, it is somewhat surprising that diplurans are so poorly represented in the fauna of volcanic caves elsewhere in the world.

Introduction

Diplurans are small, white, eyeless, wingless hexapods that live under stones, in the soil, and in caves. There are seven taxonomic families recognized for the Order Diplura (Ferguson, 1990), but most of the cave species belong to the family Campodeidae and are characterized by having two long multisegmented cerci (tails) which macroscopically somewhat resemble the antennae (Figure 1). Over 40 species, belonging to 10 genera, of campodeid diplurans are known from caves in the United States (Ferguson, 1981). The species known so far from lava tube caves belong to a single genus, *Haplocampa*.

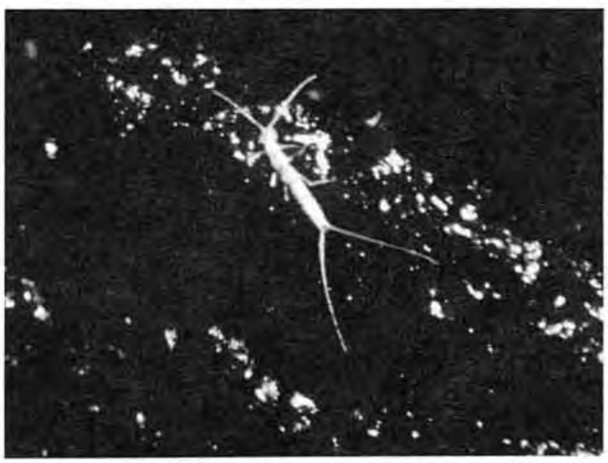

*Figure 1 – Campodeid dipluran (*Haplocampa *sp.) on wet rock, Upper Falls Creek Cave, Washington. (Photo: F.G. Howarth)*

This genus is found in the central and western United States, particularly the northwest, and into Canada. It is represented by endogean (soil-dwelling) forms in northern California, Oregon, Washington, Montana, and Alberta; by cavernicoles in limestone caves in Illinois, Missouri, Utah, Arizona, and Washington; by cavernicoles in lava tubes in Idaho, Washington, Oregon, and California; and by a species from a mine in north central California.

Distribution in the Continental United States

The first dipluran from a lava cave that I was able to examine was collected by Stewart and Jarmila Peck in 1969 at Boy Scout Cave, Craters of the Moon National Monument, Idaho, while Stewart was studying a cave beetle found in the lava tubes there (Peck, 1974). Since then, collections by Frank Howarth, John Holsinger, Rod Crawford, Clyde Senger, and me, aided by Libby Nieland and others, have revealed seven or eight

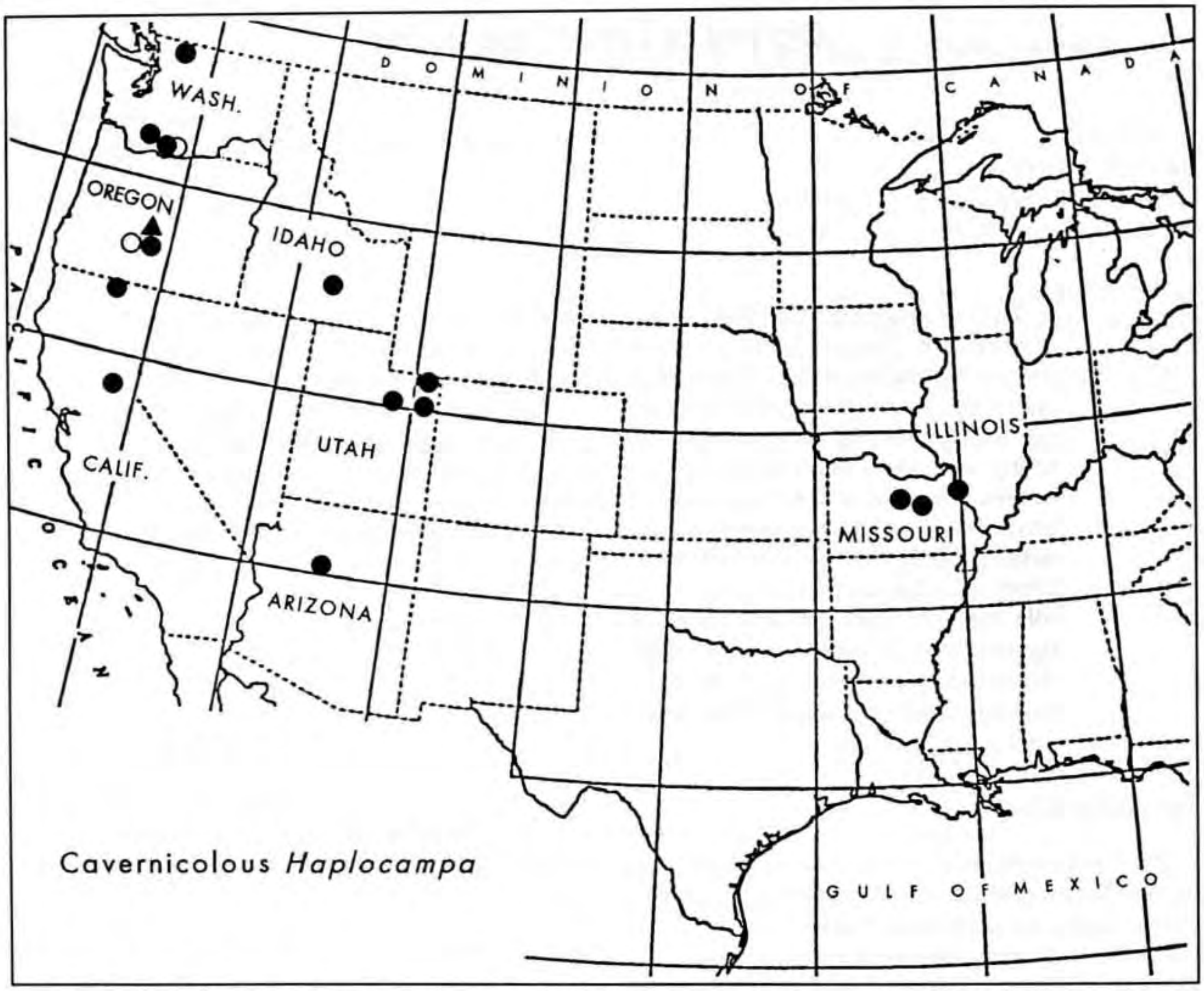

Figure 2—Distribution of cavernicolous campodeid diplurans in the western United States. See text for explanation.

species of campodeid diplurans from 21 lava caves in the states of Idaho, Washington, Oregon, and northern California.

The distribution of species is as follows (see Fig. 2). In Idaho the only collection is the one specimen from Craters of the Moon National Monument mentioned above. Additional attempts to collect more specimens myself in 1972 were unsuccessful. The Idaho form represents a new (undescribed) species of *Haplocampa*.

In the state of Washington, the northernmost solid circle on the map in Figure 2 represents Windy Creek Cave in Skagit County. This is a limestone cave. The species found here is probably *H. chapmani*, an endogean known from nearby Mount Baker. In southern Washington the more westerly solid circle represents a new species found in Ape Cave and others (Dollar and Dime Cave, Little Red River Cave, and Lake Cave) in Skamania County associated with the Mount St Helens lava flows. The easterly solid circle represents another new species from Cheese Cave, Thanks Cave, and Jug Cave in Klickitat County and Dead Horse Cave, New Cave, Big Cave, Dynamited Cave, Ice Rink Cave, Dry Creek Cave, Lower Falls Creek Cave System, and Upper Falls Creek Cave System in Skamania County associated with Mount Adams.

The open circle in southern Washington stands for Snowpatch Cave in Klickitat County. The species found here also appears to inhabit Lava River Cave in south central Oregon, also represented by an open circle symbol. These collected specimens may belong to the endogean species *H. rugglesi*, originally described from Mount Rainier.

The solid circle in northern California indicates the location of Lava Beds National Monument, Siskiyou County, where I found another new species in Merrill Ice Cave in 1982. (More recently, in 1989, Rod Crawford has collected campodeid diplurans there in Catacombs Cave, Fern Cave, Lost Pinnacle Cave, and Merrill Ice Cave as well.) The solid circle in north central California represents Sunnyside Mine in Plumas County, the site of another new species of *Haplocampa*.

The solid circle to the east in Oregon stands for a new species found only in South Ice Cave in Lake County. And the solid triangle indicates Lavacicle Cave, Deschutes County, which is unique in that the cave contains two species of *Haplocampa*. In fact, only two other caves (both in limestone) in the United States are currently known to have two species of campodeids in them. One is Steeles Cave, Monroe County, West Virginia, the other is Panther Creek Cave, Hancock County, Tennessee. Elsewhere in the world this condition of syntopy for cave diplurans is rare also.

The unique situation for Lavacicle Cave may soon change however. Due to intensive sampling of many lava tubes in Washington by Rod Crawford and Clyde Senger (1988) using baited pit fall traps, a large number of specimens (707!) are now available to study. Since then Crawford has collected many more diplurans in California and Washington lava tube caves (personal communication). Now that we know that two (or more ?) species can exist in a single cave, every specimen of these large collections needs to be intensely studied to make species identifications, and not just a representative sample as has been done in the past.

Phylogeny

Referring again to the map in Figure 2, the other solid circles on the map represent limestone caves and possibly four additional species. Just considering the phylogeny of the species known from lava tube caves, based on the morphology of the specimens, the two species found in Ape Cave *et al*. and Cheese Cave *et al*. are very closely related and probably had a common ancestor.

In fact, all of the lava tube diplurans in the northwestern United States show a close affinity to one another and to the surface or endogean species found there. They represent a fairly homogeneous group. In contrast, the *Haplocampa* species in Arizona, Utah, Missouri, and Illinois are distinctly different from one another and from the northwestern forms.

The identification and phylogeny of campodeid diplurans is based largely on the number and distribution of certain large bristles and hairs. Little can be said about the adaptation to living in caves, i.e., becoming a troglobite, by using such features. However, some characteristics which presumably troglobitic diplurans display are: (1) An increase in overall size. *Haplocampa* species, however, are all relatively large bodied forms, even the ones only known as endogeans. (2) Claws with large tergal (dorsal) crests. All known *Haplocampa* species have such claws already. Indeed this is one of the characteristics of the genus. Interestingly, the species from Sunnyside Mine in California has the largest feet of all! (3) Apical segment of the antennae with a cup-like depression at the tip containing five or more complex sensilla (sensory devices). All of the species known only from lava tubes seem to meet this criterion. Therefore, perhaps they are true cavernicoles or troglobites.

To summarize the findings for lava tube caves in the continental United States, seven or eight species of the campodeid genus *Haplocampa* have been identified from 21 lava tube caves, and specimens have been collected from at least 11 more caves in the same region. Also several of the collections consist of large numbers of specimens. Therefore, campodeid diplurans seem to be fairly numerous and common in lava tubes in the continental United States. What about other areas of the world in which lava tubes are found?

Elsewhere

In 1986, when I visited Surtshellir Cave in Iceland, about 100 kilometers northeast of Reykjavík, I found several invertebrates including a couple of species of flies and a rhagidiid mite, but no diplurans. One might suppose that in Iceland it is too cold for such organisms to occur regularly, so what about in the tropics, like in Hawaii? Many lava tube caves are known from the islands, and a fair number of troglobitic arthropods have been found to inhabit the caves there (Howarth, 1983). There is even an endogean campodeid on the island of Oahu, *Litocampa (Cocytocampa) perkinsi* (Silvestri, 1934; Bareth and Condé, 1972); however, none have ever been found in a cave. The somewhat similar primitive thysanuran *Nicoletia* has been found in caves there.

Other volcanic islands in the tropics with lava tubes include the Galapagos Islands, where Peck and Kukalova-Peck (1986) and others (Hernández *et al.*, 1992a) have found *Lepidocampa zeteki* Folsom in caves there. This species is a hardy endogean, not a troglobite, whose setae are modified into scales which probably make it more resistant to desiccation, and therefore, more capable of dispersal than other moisture-loving soil dwellers. It is known from many localities in Central and South America.

Other islands with lava tubes which are being biologically investigated are the Canaries (Hernández *et al.*, 1992b) and the Azores (Borges *et al.*, 1992). They do not specifically mention the presence of campodeid diplurans; however, other cave invertebrates have been found. One could suppose that the geographic isolation of volcanic islands and the resulting chance immigration (sweepstake route of dispersal) of plants and animals, and the relatively young geologic age of many volcanic islands, all reduce the chances of ancestral campodeids reaching the islands and then populating the caves. Yet it has happened in the Galapagos Islands and elsewhere by similar arthropods (but not campodeids).

As for continental areas, such as the Auvergne region of south central France, from my brief look at the area with all of its cinder cones, basaltic lava flows, and long line of volcanos, it would certainly seem that there would be lava tubes associated with this area; yet I am unaware of any cavernicolous diplurans having been identified from there. (The meticulous French zoologists and biospeleologists certainly would have discovered them if they were there.) Therefore, in light of the common occurrence of campodeid diplurans in the northwestern continental United States, and the widespread occurrence of these primitive arthropods in caves in general, it is somewhat surprising that they are not more widely known from lava tube caves elsewhere in the world.

Acknowledgements

I would like to thank the collectors mentioned above and others – past, present, and future, without whose labor we would know even less about the biota of lava tube caves.

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Behavioral Divergence in Populations of the Cave-Adapted Planthopper Species *Oliarus Polyphemus* on the Island of Hawaii (Homoptera Fulgoroidea Cixiidae)

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Abstract

With 80 described endemic species, the cixiid genus *Oliarus* is known to have undergone extensive adaptive radiation on the Hawaiian Islands. In *Oliarus*, however, adaptive radiation is not restricted to surface habitats. Several evolutionary lines have invaded caves on the islands of Molokai (one species), Maui (three species), and Hawaii Island (two species). They have acquired typical troglomorphies such as reduction of eyes, wings, and pigment. Populations of one of the cave invasions on Hawaii Island, the completely blind, flightless and pigmentless *Oliarus polyphemus* have been found in numerous lava tubes within all major volcanic systems. This apparently wide distribution of a species which is restricted to the cave environment was thought to be the result of underground dispersal through the mesocavernous rock system.

Recent investigations on the mating behavior, especially the analysis of the courtship signals of seven *O. polyphemus* populations, however, have revealed a high degree of divergence: the signals of all seven populations studied differ significantly even between populations from caves within the same volcanic system, and only a couple of miles apart. Since the communication signals serve mate recognition, they are sexually selected and species-specific, thus the seven *O. polyphemus* populations tested are regarded as reproductively isolated entities, i.e., separate biological species.

Hypotheses to explain this high degree of divergence among *O. polyphemus* populations are discussed. Future research will concentrate on the quantification of the observed divergence on the molecular level using mitochondrial DNA sequence data, and on the correlation of divergence events with evolutionary time.

Anchialine Lava Tubes and Their Biota

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Abstract

The word "anchialine" was proposed by Professor Lipke B. Holthuis (1973) as a term for land-locked coastal saltwater pools with subterranean connections to the sea. The term has been broadened and is now commonly used to describe costal caves that contain tidal phreatic water. There are many anchialine lava tubes throughout the world that have provided a window to the underwater crevicular habitat of volcanic islands. Access by cave explorers using SCUBA to the submerged sections of these lava tubes has resulted in biological collections of interest to taxonomy and biogeography. Two lava caves, Jameo del Agua, Lanzarote, Canary Islands and Lua o Palahemo, Hawaii Island, have produced cavernicolous invertebrates of great phylogentic age that were previously known only from collections made in the Bahamas, Bermuda, and Ascension Island.