PROCEEDINGS
of the
THIRD
INTERNATIONAL SYMPOSIUM
on
VULCANOSPELEOLOGY

A Special Session of the 39th Annual Convention of the National Speleological Society Bend, Oregon, July 30 - August 1, 1982

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William R. Halliday
Chairman

With related biovulcanospeleological
papers also presented at the 39th annual meeting
of the
National Speleological Society

Cover illustration: View of Surtshellir, Iceland,
in an anonymous book entitled Natural Phenomenon,
published in London in 1849. Photo courtesy of Trevor Shaw.

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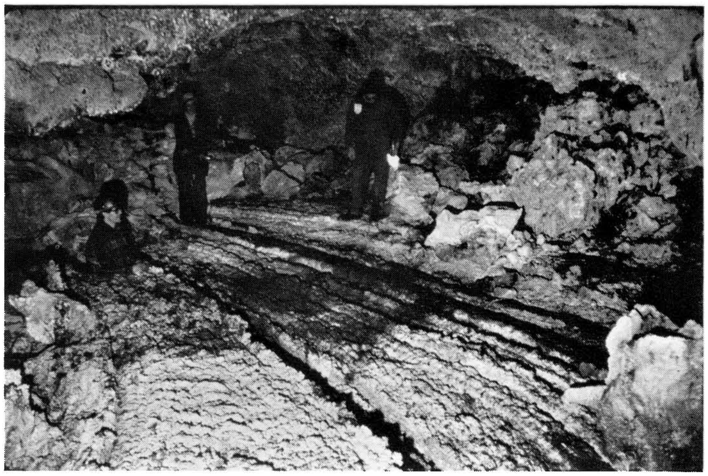
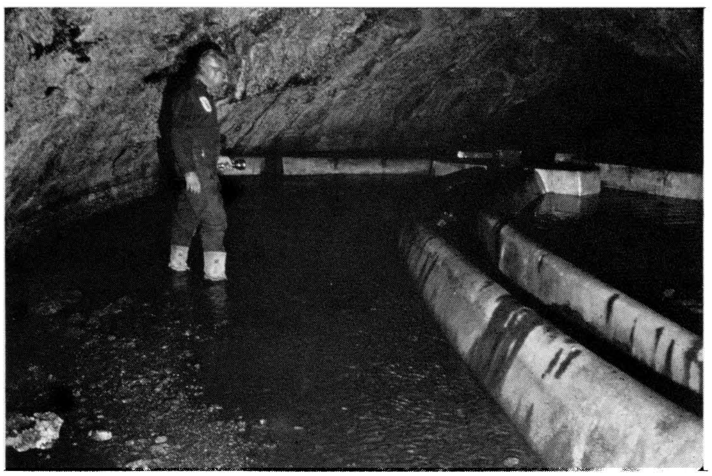
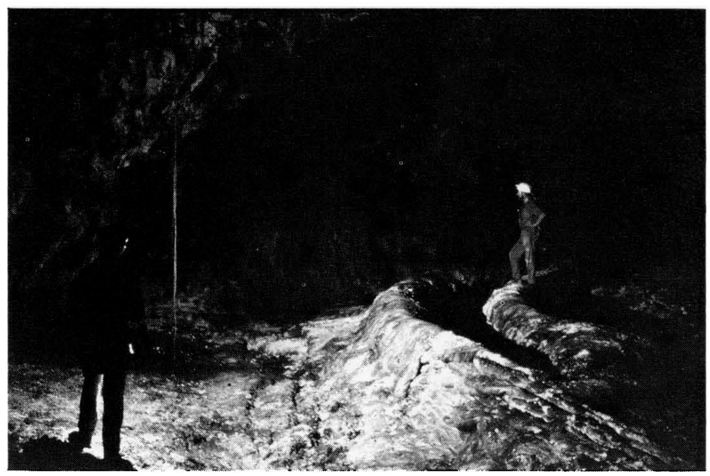


Gruto Dos Balcones, Azores. Entrance of tube-in-tube. Photo by W.R. Halliday.

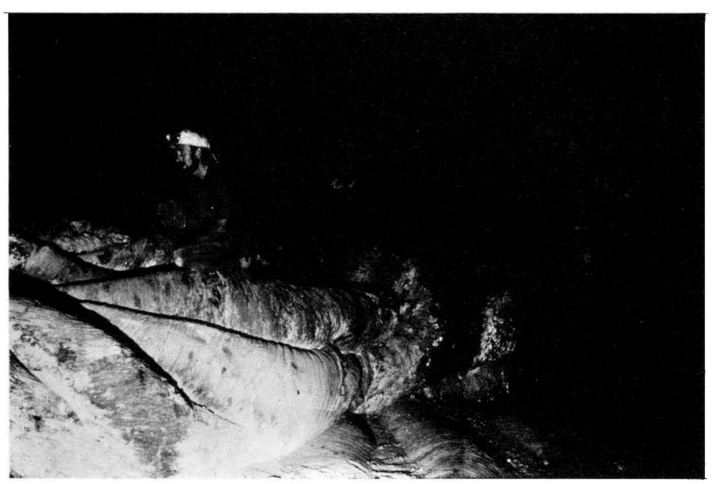
Mount Suswa system, Kenya. Blown microfilamentary lava speleothem. Photo by W.R. Halliday.



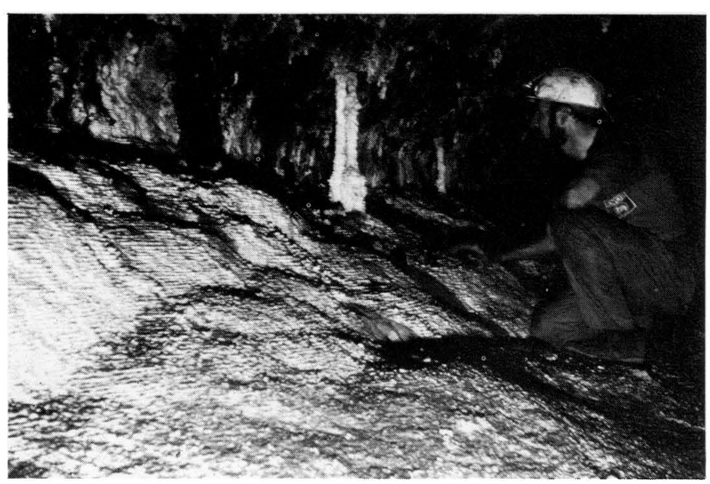
Furnas do Cabrito, Azores. Waterworks. Photo by W.R. Halliday.



Mount Suswa, Kenya. Lava channel and tube-in-tube. Photo by W.R. Halliday.



Mount Suswa system, Kenya. Hollow ropy lava. Photo by W.R. Halliday.



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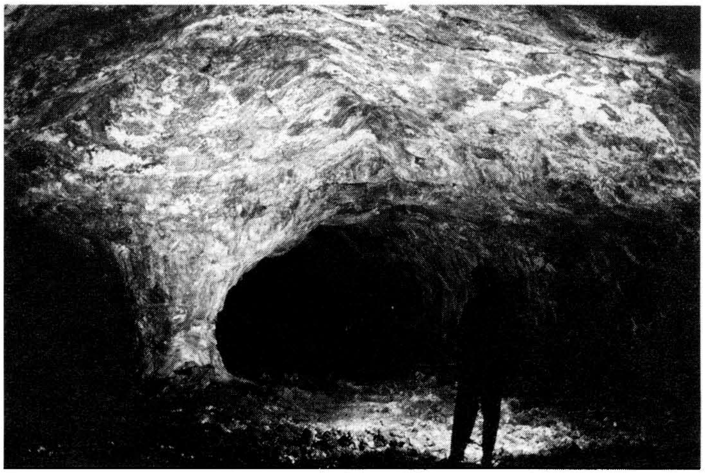
INTRODUCTION

The following Proceedings of the 3rd International Symposium of Vulcanospeleology has been published as the result of an anonymous contribution to the International Speleological Foundation (formerly the Western Speleological Foundation). Although belated in appearance, most of its contents remain as significant today as on the day of presentation. It joins the similar volumes of the first and second symposia (held respectively in White Salmon, Washington in 1972 and in Catania, Sicily, Italy in 1976), as the major published references to vulcanospeleology throughout the world. It is greatly to be hoped that the Proceedings of the fourth symposium (held in Catania in 1983) will join them soon.

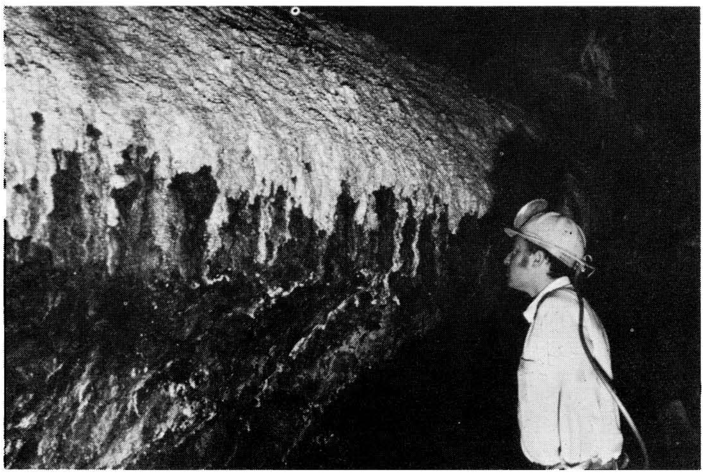
Omitted for reasons of cost are the Convocation and Chairman's Remarks, welcoming addresses by Robert R. Stitt (President of the National Speleological Society) and John Eliot Allen (Professor Emeritus of Geology of Portland State University, Portland, Oregon, USA, and Larry Chitwood, geologist of the Deschutes National Forest, Bend, Oregon, USA, as well as the text of audiovisual presentations on northwestern lava tube caves by Elizabeth Wolff and David R. and Janet McClurg. Some of the illustrations for these presentations are included in the text of the Proceedings. Also necessarily omitted are many photos and tables and some comparatively short sections of several papers which were somewhat outside the main thrust of the report. I sincerely hope that this has not seriously affected the message therein, and apologize in advance to any outraged authors, in the hopes that they are understanding and forgiving. Perhaps they will feel better to know that I did the same to my own papers.

I especially thanked--and again thank—the presenters of papers whose authors could not attend the meeting: Percy H. Dougherty, William B. White, Bette White, Ernst Kastning, Jack Hess. I also expressed great gratification over the progress in vulcanospeleology since the first symposium, which we announced with fear and trepidation, lest no one come. The contents of this volume surely document that progress. But there is so much yet to be done. I regret greatly the delay in publication of this major building block of the future of this exciting field. And I look forward excitedly to the 5th symposium, to the first on-site extra-terrestrial vulcanospeleological studies, and everything else that is to come. Let it not be long delayed.

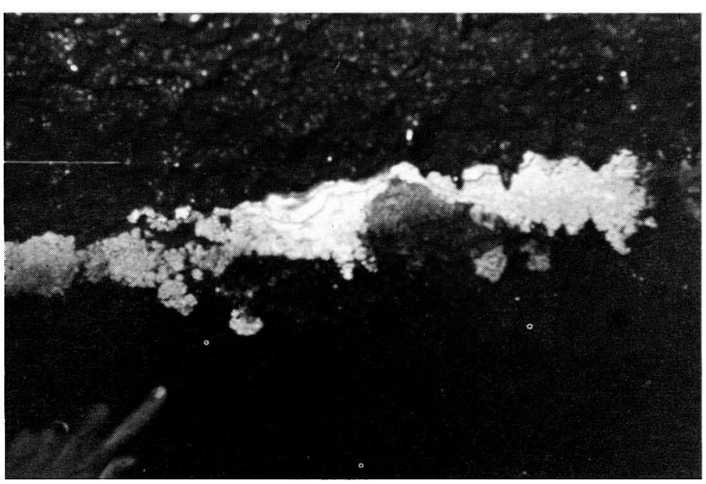
William R. Halliday, Chairman
Seattle, 1986



Pillar. Cueva de las Palomas. (Cueva de los Naturalistas.) Lanzarote, Canary Islands, Spain. Photo by W.R. Halliday.

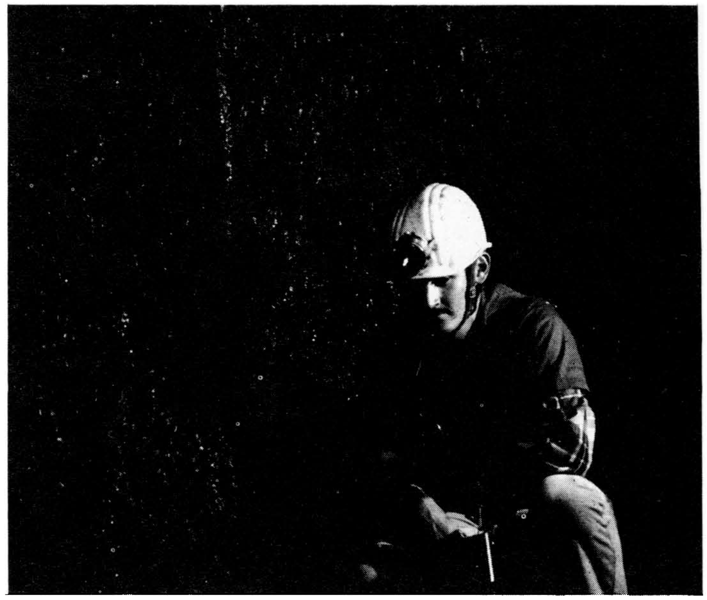


Siliceous flowstone and microgours. Cueva del Viento, Tenerife, Canary Islands, Spain. Photo by W.R. Halliday.

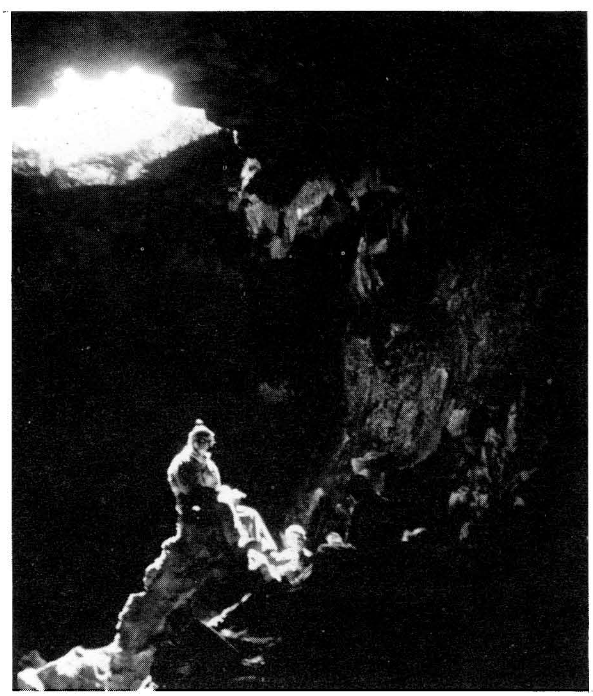


Siliceous coralloids, commonly called "popcorn" in northwestern lava tube cave. Photo by Wolff.

Cast of tree bark in northwestern lava tube cave. Photo by Wolff.



Lava speleothems in northwestern lava tube cave. Photo by Wolff.



Catwalk Cave, California, U.S.A. Overhanging pit entrance. Photo by Wolff.

OPEN VERTICAL VOLCANIC CONDUITS: A PRELIMINARY INVESTIGATION OF AN UNUSUAL VOLCANIC CAVE FORM WITH EXAMPLES FROM NEWBERRY VOLCANO AND THE CENTRAL HIGH CASCADES OF OREGON

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University of Oregon

1.0 INTRODUCTION

A wide variety of cavernous structures is found in rocks of volcanic origin. Of these, the best known and most thoroughly investigated has been the lava tube cave. Substantial studies of investigators such as Ollier and Brown (1965), Hatheway (1971), Greeley (1971), Halliday (1976) and Wood (1978) were carried out on lava tube and collapse depression systems in the 1960s and 1970s, stimulated in part by interest in analogous structures found on the Moon and later, on Mars.

There are, however, a number of minor and largely neglected forms of lava caves that are known to exist in extrusive volcanic rocks. One of the most unusual and interesting of these, the *open vertical conduit,* is the subject of this paper.

The open vertical conduit (hereafter referred to as the OVC) is an unusual structure found in recent volcanic rocks. The OVC is a nearly round or oval-shaped vertical tube ranging in depth from a few feet to at least 165 feet (50 m), though I will qualify this figure later. The diameter of the vertical tube, or conduit, varies from less than a foot to about 25 feet (8 m), though in the open conduits examined in this paper, the usual diameter was less than 10 feet (3 m). The interior lining of the OVC typically consists of remelted lavas that form a relatively smooth lining several cm in thickness that may be decorated with short lavacicles. The remelted lining of the conduit betrays the high temperature environment that once existed at the OVC, a vent for lavas and hot gases. In profile, many OVCs are bell-shaped (see Figure 2) when found in association with spatter cones and ramparts, though when found with hornitos, the conduit may open directly into a lava tube (also see Figure 2).

It also appears that an OVC can be found alone or that it may co-exist with other lava cave varieties such as spatter cone chambers, spatter-roofed fissure vents and lava tubes. The term *open vertical conduit cave* is probably best applied when the OVC is the dominant cave-forming feature and is not merely a minor adjunct structure found with another lava cave. When found in combination with other cave types, the combined depth of the conduit and the associated cave may extend beyond the length of the OVC alone. This was clearly the case at one of the caves examined, the Upper McKenzie Pits, and, no doubt, is true of other examples.

Specific landforms are found in association with all OVCs. Assorted sizes of spatter cones, spatter ramparts and hornitos invariably surround the OVC, again providing evidence of its function as a vent. OVCs are found in both pahoehoe and aa lavas, though most of the examples discussed in this paper occur in aa lavas.

OVCs are found at both primary and secondary (rootless) vents where they are representative of the final stages of volcanic activity.

I also want to clarify what an OVC *is not*, as it is possible to confuse them with at least three other, similar volcanic features of considerably different origin. The OVC is not a collapse feature such as a ceiling "skylight" entrance into a lava cave; the two can be easily distinguished by the lack of a remelted lining in the collapse feature.

More closely resembling the OVC are some vertical lava tree molds. It is not surprising that these upright molds could be confused as a vent structure, for they have a smooth interior lining combined with a round cross-section. The term *mortar* once had been applied to lava tree molds in the belief that they were small vents (Wentworth and MacDonald, 1953:55). OVCs can easily be distinguished from tree molds by the lack of accumulated spatter around the mold entrance, impressions of bark on the wall of the mold and the presence of nearby horizontal tree molds. [Editor's note: lava accretions are present around some tree casts or molds in the Cave Basalt, Mount St. Helens, Washington, and presumably elsewhere.]

Also possibly confused with an OVC is a structure created by the drainback of lava into a vent as the level of magma drops below the vent. This phenomenon is mentioned by Wood (1976a:130) and is documented by Swanson *et al.* (1979:31,32).

When found in association with spatter cones, most OVCs connect with a circular chamber, the floor of which extends below the outside ground level. A similar, beehive-shaped room can sometimes be found inside hornitos, though no OVC is also present, and the "beehive" is entered through collapsed or ruptured sections of the top or sides. These peculiar caves, not to be confused with OVC caves in spatter cones or hornitos, have been reported in New Mexico (Nichols, 1944:1062), in Idaho (Russell, 1902:101), at Jordan Craters in southeastern Oregon (Russell, 1903:52; Kittleman, 1962:107-108; Millhollen, 1965:22) and adjacent to the Devils Garden lava field in Central Oregon (Peterson and Groh, 1965:26). Several unreported examples are also found near Katati Butte not far south of Oregon's Newberry Volcano.

2.0 RESEARCH CONSIDERATIONS

The general aim of this paper is to describe the morphology, geographic distribution, possible modes of genesis, associated volcanic landforms and age and composition of the open vertical conduit (OVC). Another problem that I have been trying to clarify is whether the OVC qualifies as a specific cave

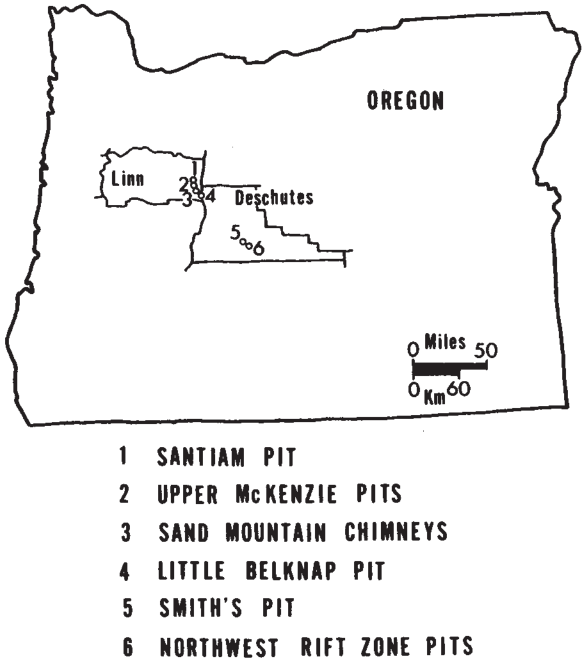

Figure 1. The location of the six open vertical conduits or groups of conduits examined in this paper.

type or whether it is merely found in association with other types. My answer, at this point, is that it may be either. Answers to these questions were gathered through the comparative investigation of several OVCs that are found in the central High Cascades of Oregon and along the northwest flanks of Newberry Volcano in central Oregon (Figure 1).

My investigation was largely qualitative. Once the conduits were located, they were mapped (if no prior map existed) and carefully examined. Analogies from observations of active volcanic activity were then sought in the literature in an attempt to reconstruct the eruptive history of each Oregon OVC. In addition, the literature was examined for other examples of open conduits. This search, while only moderately successful, led to the identification of several other definite cases, as well as several rather tentative ones, all of which are briefly mentioned in part 5 of this paper.

Regional geology, radiocarbon age determinations and the composition of lavas that were associated with the OVCs were available from several sources and all added substantially to the body of this preliminary investigation. X-ray fluorescence spectrometry supplemented by Atomic absorption analysis (for Na) was used to obtain some of the comparative data that appear in Table 2. This was carried out in the facilities of the X-ray fluorescence laboratory at the University of Oregon.

3.0 TERMINOLOGY

A number of terms are used quite specifically in this paper and to avoid confusion, I will define them at this point. All definitions are adapted from Wentworth and MacDonald (1953).

Primary Vent: An eruptive fissure or vent that is directly associated with the conduits that have brought magma from an underground reservoir to the surface.

Secondary (Rootless) Vent: A vent that is not directly associated with a primary vent. Several types or rootless vents are distinguished by Wentworth and MacDonald (1953:26-27) but the ones relevant to this discussion are those vents at hornitos that are fed (from a primary vent) through lava tubes.

Spatter Cone: These are small features (usually less than 50 feet in height), created at primary vents as molten and plastic clots of spatter adhere to form a cone of agglutinate.

Spatter Rampart: Similar to spatter cones, the spatter ramparts (sometimes called spatter ridges) are walls of welded spatter that are built by fountaining along a primary fissure vent. The accumulation of spatter creates a rampart ranging in height from a few inches to over 20 feet (6 m).

Hornito: These are mounds of spatter--usually small--that are built over rootless vents. Closely resembling spatter cones, hornitos are often confused with spatter cones, and spatter cones with hornitos.

The term open vertical conduit is adopted in this paper in order to describe the open vertical volcanic vents investigated. Other authors, however, have applied similar names to this variety of lava cave. Taylor (1965:126; 1967:9,12), when describing several OVCs in the High Cascades of Oregon, called them vertical conduits. I have simply added *open* to this term to eliminate any confusion between open conduits and filled conduits sometimes exposed in modified or eroded volcanoes. Nieland (1970:233), refers to some of the open conduits described by Taylor as "spatter cone pits." Russell (1902:81, 100-101; 1903:40), describing some examples in Idaho, labels them "chimneys" and Ollier (1964:68)

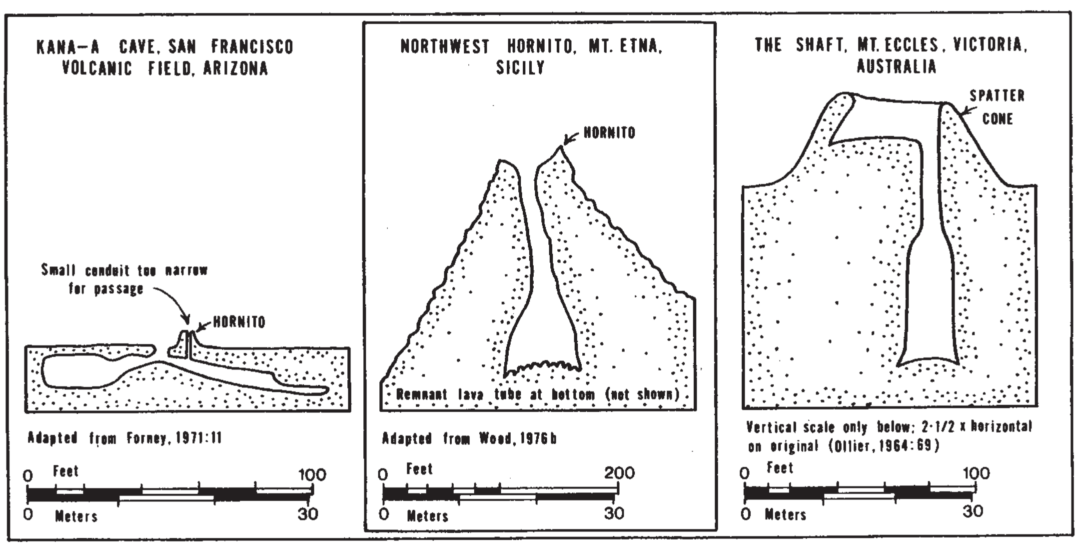

Figure 2. Three confirmed examples of open vertical conduits that are reported by other authors.

simply calls them open vents. [Editor's note: Russell's terminology is reflected in such names at Lava Beds National Monument, California, as Fleener Chimneys.]

4.0 PREVIOUS RESEARCH

Detailed descriptions of OVCs appear to be non-existent and only a few general references to this volcanic feature are found in the literature.

Wentworth and MacDonald (1953:53) state that hornitos commonly have an open pipe at the center, though they provide no details.

Wood (1976a:131) makes only a passing note of cavities beneath spatter cones, some of which are associated with OVCs.

MacDonald (1972:189) offers a brief description of OVCs found with spatter cones when he writes: "Welded spatter can stand in a bank that is essentially vertical . . . and the crater wall may be steep and irregular; and occasionally a pipe-like or fissure-like conduit may remain open to a depth of several tens of feet below the bottom of the crater."

In his early geologic study of the Snake River Plains of Idaho, Russell (1902:100-101) makes the earliest mention of OVCs: "There is still another variety of lava caverns due to the blowing out by escaping steam of still liquid or highly plastic lava through openings in a solid crust. The chimney-like openings in the parasitic cones . . . are examples of 'vertical caverns' . . . the cones . . . contain far more material than the vertical openings within them could have furnished. This is apparent when it is remembered that the vertical shafts are principally in the built up portions of the 'chimneys,' and hence the material must have been supplied in large part by the horizontal galleries to which the vertical shafts lead."

Other mentions of OVCs in the literature tend to be brief and purely descriptive and are considered in the next section of this paper. It was this noticeable void in information on OVCs that eventually impelled me to complete the investigation reported in this paper.

5.0 GEOGRAPHIC DESCRIPTION

Because OVCs are not a well-documented volcanic feature and the few examples are not described in detail, it was often difficult to ascertain whether a volcanic cave was, in actuality, an OVC or contained an OVC, or whether it was a structure that only resembled an OVC. Several probable examples, however, were located in a relatively extensive literature search, exclusive of the Oregon OVCs that are described below:

1. The Shaft, a spatter cone and OVC found on the slopes of Mt. Eccles in Australia (Ollier, 1964:68-69; see Figure 2).
2. The Due Pizza northwest hornito and OVC, a 165-foot (50 m) shaft on the slopes of Mt. Etna in Sicily. Located nearby and also known as Due Pizza is another hornito and OVC (Wood, 1976b:24-25; see Figure 2).
3. Kana-A Cave, a small hornito and lava tube in the San Francisco Volcanic Field of Arizona (Forney, 1971:10-11; see Figure 2).
4. The Ice Wells, an OVC or OVCs found in the Craters of the Moon National Monument of Idaho (Russell, 1902:101-102 and 1903:46; Stearns, 1928:19).
5. Spatter Cone Cave, Diamond Craters, Oregon, a small cone and OVC leading to a short lava tube (Benedict *et al.*, 1979).
6. The Bandera Crater Lava Tube, Bandera Lava Field, New Mexico; a hornito, possibly one of several, and OVC leading to a lava tube (Hatheway, 1971:216; Hatheway and Herring, 1970:325).

Several other caves were also located that might contain OVCs or be considered as OVC caves but whose description was not adequate to verify that fact. They were: the Algar de Funil on the island of Terceira in the Azores (Halliday, 1980:120); the Algar de Carvao, also located on the island of Terceira (Halliday and Others, 1978:28-29); the Caldeira of Graciosa chimney on the island of Graciosa, Azores (Pickering, 1908:347-49; Halliday and Others, 1978:30-31; and unknown open conduits and hornitos in the Hawaiian Islands (Wentworth and MacDonald 1953:52).

6.0 EXAMPLES OF OPEN VERTICAL CONDUITS FROM THE NORTHWEST RIFT ZONE OF NEWBERRY VOLCANO

The Northwest Rift Zone of Newberry Volcano is a narrow, 20-mile (32 km)-long belt of *en echelon* faulting and fissure eruptions on the northwest flank of Newberry Volcano, a massive composite volcano southeast of Bend. The rift zone stretches from the shores of East Lake in Newberry Caldera to Lava Butte near Bend (Figure 3). This zone of post-Mazama fissure activity has been dated at about 6,000 radiocarbon years in age. Activity along the rift zone was first described as a whole by Nichols and Stearns (1938) and anonymously (1939) and later, in more detail, by Peterson and Groh (1965:8-9; 1969).

A combination of quiet fissure eruptions and lava fountaining produced a wide variety of landforms along the fissure vents. These include several basaltic to basaltic-andesite aa flows, spatter cones, spatter ramparts, scores of lava tree molds and several OVCs.

These conduits, ranging in depth from only a few feet to over 30 feet (10 m) are found in two areas, one near the Lava Cast Forest and the others between the Lava Cascade and North Summit Flows.

6.1 UPPER NORTHWEST RIFT ZONE OPEN VERTICAL CONDUITS

In contrast to the several flows that originated from fissure vents along the middle and lower portions of the rift zone, the upper section is characterized by only small effusions of lava. Instead, most activity was restricted to a single small flow and several narrow zones of coalescent craters aligned along the eruptive fissure. Figure 4 illustrates one of these chains. In at least two locations along an area of the fissure known as "The Crack," OVCs have developed, rather than the simple spatter pits in Figure 4. One of the OVCs, though only penetrable

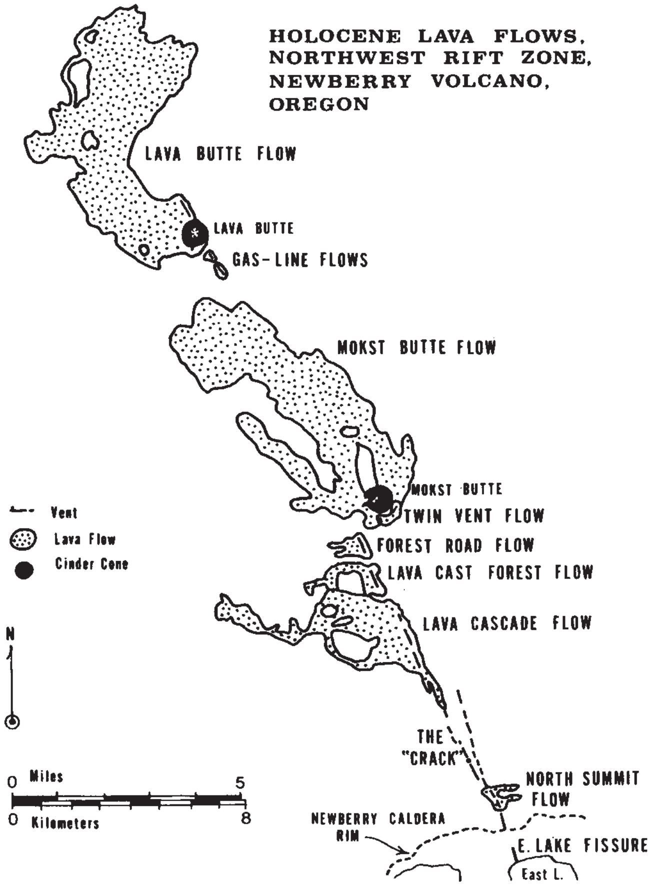

Figure 3. A post-Mazama (younger than about 7,000 radiocarbon years B.P.) flow of basalt and basaltic andesite along the Northwest Rift Zone of Newberry Volcano (base map is adapted from Peterson and Groh, 1965:8).

three feet (1 m) before a plug is encountered, clearly shows the typical circular vertical and lined structure of the OVC.

Not far from this shallow conduit is the best example of an OVC along the upper section of the rift zone. This as-yet-unentered conduit is 8 feet (2.5 m) in diameter. As yet, it is unentered, but it can be seen to plunge at least 30 feet (10 m) and evinces the typical structure of the OVCs examined. The conduit lies directly over the main fissure vent and represents a localized focus of activity along a short segment of coalescent spatter pits.

6.2 SMITHS PIT

Lying nearly parallel to the main vents of the Lava Cast Forest Flow is an alignment of two spatter cones and two spatter-rimmed cinder cones. Found a half-mile (1 km) east of the Lava Cast Forests vents and possibly contemporaneous with the activity there, this group of cones is the site of another example of an OVC, Smith's Pit.

This pit (Figure 5), first described briefly by Larson (1973), consists of a 1.5 by 3 foot (.5 by 1 m) oval conduit entrance that quickly bells out into a small chamber. The floor of the chamber is about 10 feet (3 m) beneath the outside ground level. It lies 23 feet (7 m) below the entrance to the OVC. Seen on the chamber walls are numerous horizontal bench marks, remnants of different levels of magma stands inside the spatter cone. Its interior remelted lining is completely intact. Clearly this was a chimney-like vent during the final stages of activity. The structure is quite typical.

7.0 EXAMPLES OF OPEN VERTICAL CONDUITS FROM THE CENTRAL HIGH CASCADES

Situated between Three-Fingered Jack and the South Sister in Oregon's High Cascades is one of the largest displays of post-glacial volcanic activity in the Western United States. Here are over 85 square miles (200 km^2) of lava flows and dozens of cinder cones and vents. They prompted Howel Williams (1944:37) to write: ". . . for wealth of recent lavas . . . no part of this range surpasses the area embracing the Sisters and McKenzie Pass."

The Holocene lavas in this region are associated with an unusual number of excellent examples of OVCs. At vents on Little Belknap Crater and at several locations along the Sand Mountain Alignment (a linear chain of cones and vents) are a diverse collection of open conduits (Figure 6).

7.1 LITTLE BELKNAP CRATER CAVE SYSTEM

A spatter-roofed feeder conduit near the summit of Little Belknap Crater supplied a short cave system now composed of several small lava tubes. The most unusual system of this OVC is at the bottom of the conduit. Here is found another lava tube system that apparently acted as a drain, leaving open the conduit that led to the upper system (Figure 7). The presence of a two-level lava tube system and interconnecting OVC at a primary vent appears to be quite unusual.

This small but complex cave appeared in the literature as early as 1925 (Hodge, 1925:50-51) and several times since

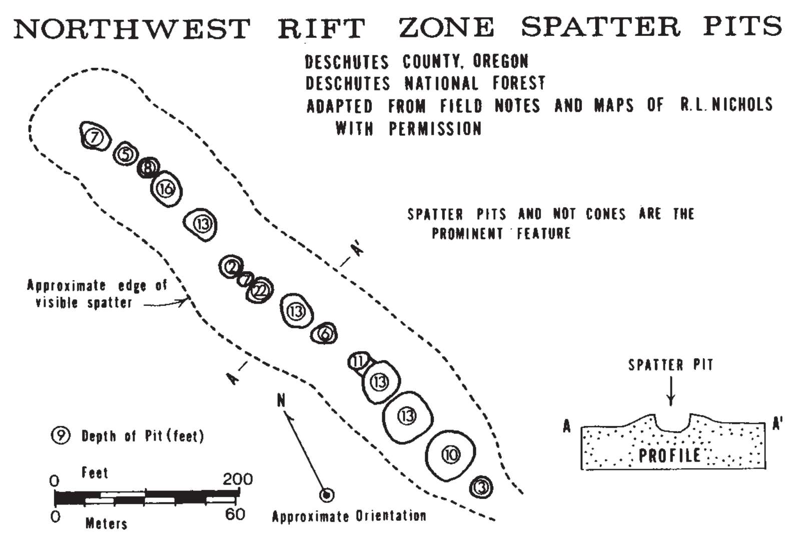

Figure 4. An alignment of spatter pits and low splatter ramparts along the upper segment of the Northwest Rift Zone of the Newberry Volcano. The exact orientation and location of this group are not known but aerial photograph interpretation suggests that it is found between the East Lake Fissure and the North Summit Flow. No open vertical conduits are found along this chain, though it is typical of others in which conduits are found.

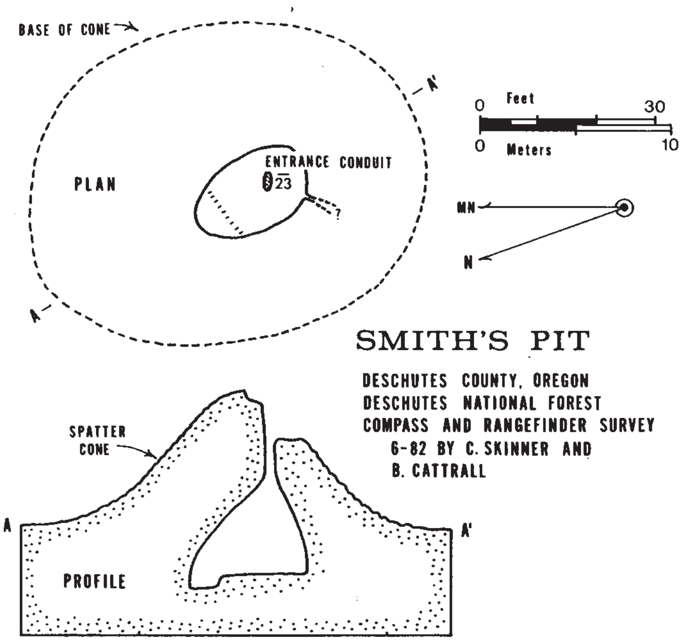

Figure 5. Smith's Pit, Northwest Rift Zone, Newberry Volcano.

(Williams, 1944:57; Peterson and Groh, 1965:29; Taylor, 1965:132 and 1967:20). It was described in some detail by Skinner (1979).

The OVC at this site is about 20 feet (6 m) in diameter and drops 24 feet (7 m) from the upper to the lower level cave system. Directly above the conduit (which merges smoothly with the upper level lava tube) is an open-topped spatter cone. In cross-section, the conduit is slightly oval-shaped with a remelted lining covered with short "lavacicle" stalactites.

7.2 SAND MOUNTAIN CHIMNEYS

Southwest of Sand Mountain, an east-west trending ridge of spatter rises above the surrounding forest. On top of this ridge are two OVCs: Century and Moss Pits (Figure 8).

Just west of the spatter ridge (which is the result of lava-fountaining along a fissure vent) is a crater 30 feet (9 m) in diameter, a former vent. The remnant of an OVC, identical in structure to the two intact ones, can be seen in the crater wall.

An entire complex of vents, including those at the Sand Mountain Chimneys, is located in a broad ridge at this site. It was the source of the Clear Lake lava flows. These are aa flows that moved west to form the east shore of Clear Lake.

Moss Pit is eight feet (2.5 m) in diameter at the entrance. It is 63 feet (19 m) deep. A small chamber at the bottom slopes downward another ten feet (3 m), for a total depth of 73 feet (22 m) (Nieland, 1970:233).

One-hundred fifty feet (46 m) east of Moss Pit and on the eastern edge of the spatter ridge is Century Pit. The entrance is three feet (1 m) in diameter. It is surrounded by a one to two-foot wall of spatter; the OVC drops vertically for 94 feet (29 m). In profile, the lower half of the OVC opens to a room measuring 10 by 25 feet (3 by 8 m) at the base of the shaft. At the western end of the bottom of the pit, an opening leads down an additional six feet before becoming blocked by breakdown (Nieland, 1970:235). These two OVCs were first mentioned by Taylor (1965:126; 1967:12) and were later mapped and described by Nieland (1970).

The entrances of both OVCs are typical: vertical circular pipes with relatively smooth remelted linings. I was not able to examine the lower sections of these two conduits. The elongate lower chambers that are shown in a revised version of Nieland's map (Figure 8) seem to be aligned along the axis of the eruptive fissure, suggesting that the structure of the lower segments of the shafts are controlled by the fissure or that the OVCs join an intact section of spatter-roofed open fissure vent.

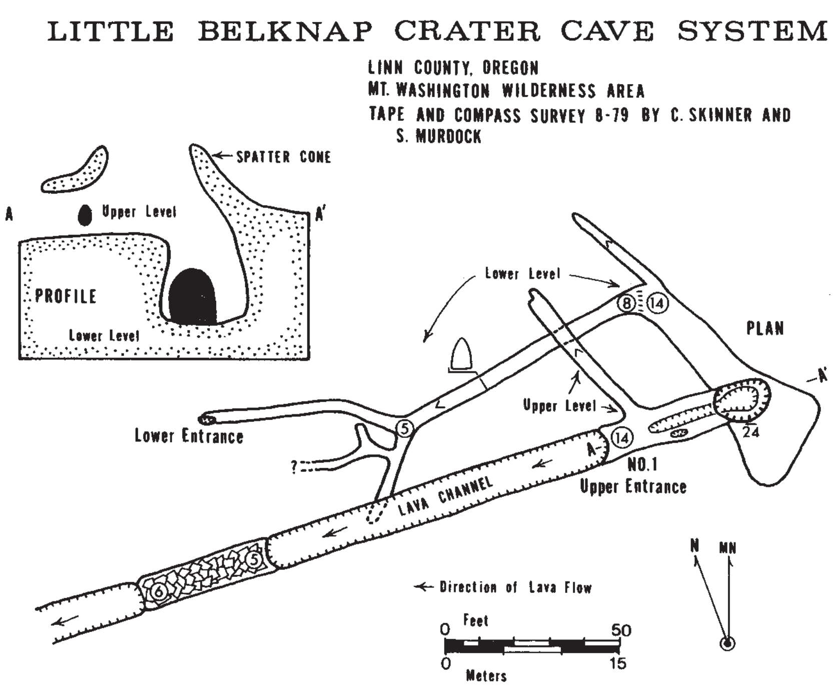

Figure 6. The Little Belknap Crater Cave System, McKenzie Pass area, High Cascades.

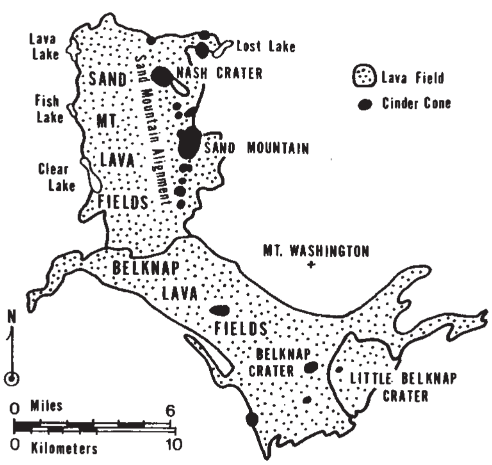

Figure 7. Holocene lava fields found associated with Little Belknap Crater and the Sand Mountain Alignment, High Cascades (base map adapted from Taylor, 1965:123).

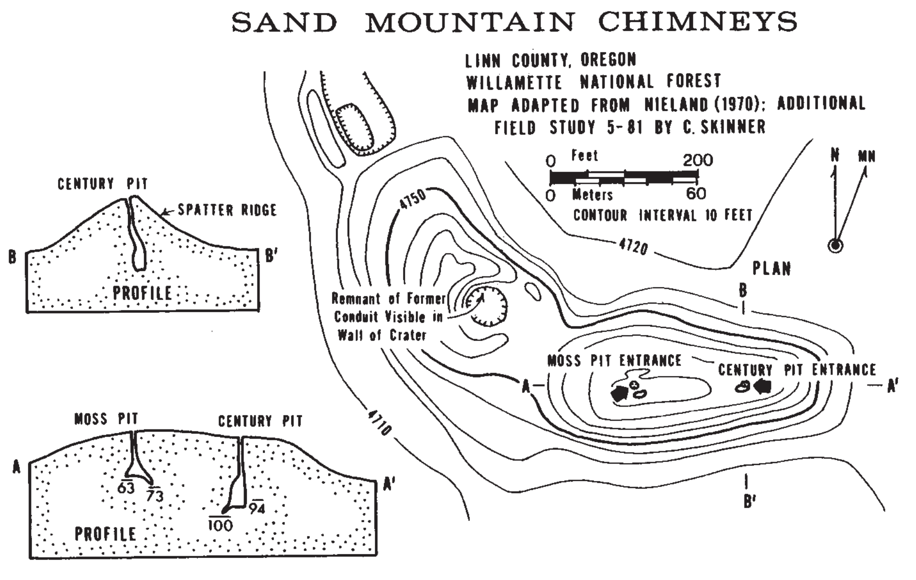

Figure 8. The Sand Mountain Chimneys (Century and Moss Pits), Sand Mountain Alignment High Cascades.

7.3 UPPER McKENZIE PITS

One of the most interesting of the OVC settings is an alignment of spatter cones, ramparts, OVCs and a roofed fissure vent (Figure 9). This vent complex, known as the Upper McKenzie Pits, houses the deepest volcanic pits reported in Oregon. Basaltic andesites from this fissure vent flowed west where they make up the eastern shore of Fish Lake.

The OVCs and roofed fissure cave at this site were the result of a fissure eruption that broke out on the flanks of Nash Crater, one of several major cones along the Sand Mountain Alignment. As the eruption proceeded, the fissure widened, presumably through a process such as dike injection (Jackson and Swanson, 1970). A roof of accreted spatter up to 30 feet (9 m) thick was eventually built over part of open fissure (this process is discussed by Swanson, *et al.*, 1979:17,35,37). Two open conduit vents penetrate the spatter roof (conduits 1 and 2 in Figure 9). In the last stages of the eruption, magma was drained from the roofed fissure, possibly by the lava channel found at the base of the large spatter cone. This left a large, spatter-encrusted chamber aligned with the fissure vent. Two OVCs are three feet (1 m) in diameter and three more entrances into the fissure were left as the result of post-eruptive ceiling collapse or incomplete fissure roofing. The fissure cave can be penetrated to a depth of 150 and 160 feet (45 to 50 m).

A large spatter cone was built down slope from the roofed fissure segment. An OVC 25 feet (8 m) in diameter--the largest of any investigated in this study--is accessible through a low spot in the cone wall. This OVC drops about 40 feet (12 m), narrows, then curves toward the prominent lava channel at the lower margin of the spatter cone. Finally, it is blocked by breakdown. This OVC, incidentally, is the *only* conduit described in the paper (with the obvious exception of the three-foot Newberry example) that is accessible without specialized vertical descending and ascending equipment.

The structure of the OVCs at the Upper McKenzie Pits is typical though the development of the lava lining of the large spatter cone conduit is noticeably less developed than the lining of the smaller diameter OVCs.

These pits were first recognized in the literature by Taylor (1965:126; 1967:9), who considerably underestimated their depth. They were later mapped by Skinner 1980.

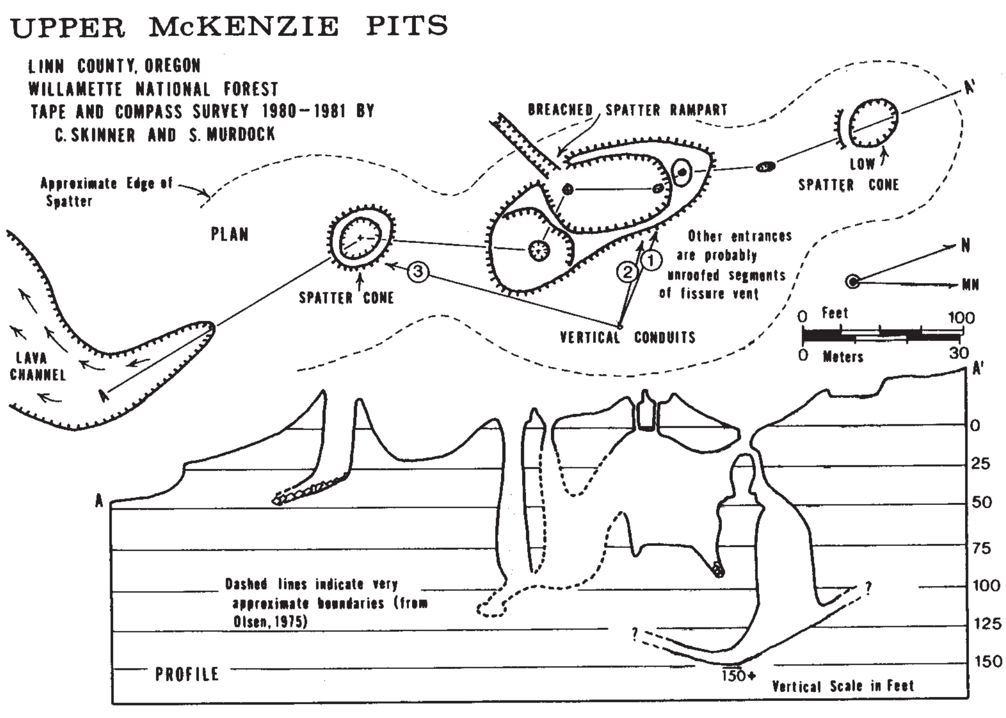

Figure 9. The Upper McKenzie Pits, Sand Mountain Alignment, High Cascades.

7.4 SANTIAM PIT

Near the northwest base of Nash Crater is another vent for two major flows that moved west to the shore of Fish Lake. The vent here is marked by a shallow cinder-and ash-filled depression ringed by a wall of spatter. Down slope from this vent is a small hornito that marks the entrance to Santiam Pit. In the center of this five-foot (1.5 m) high cone is a 30-foot (9 m) deep OVC three feet (1 m) in diameter. It joins a lava tube 50 feet (15 m) long, floored with sand. This lava tube is blocked by sand and debris at both ends.

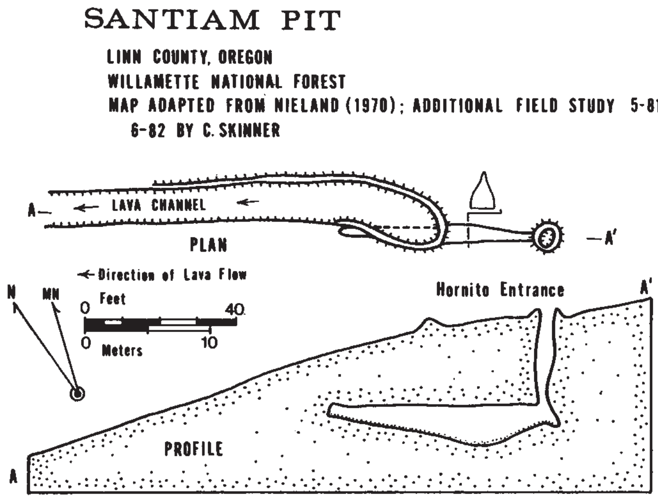

Figure 10. Santiam Pit, Sand Mountain Alignment, High Cascades.

Santiam Pit was first reported by Taylor (1965:126; 1967:9), though an early National Speleological Society list of Oregon caves is reported to have mentioned a Nash Crater Cave that may be Santiam Pit. The conduit was named and mapped by Nieland (1970:232-233).

This small hornito and conduit formed over a segment of lava tube that was fed by the nearby primary vent. This was the only OVC examined that was clearly associated with a rootless vent. The OVC displays the same circular form and remelted lining as those at primary vents. The presence of a lava tube in aa lavas is unusual, but not unknown (Warden, 1967; Wood, 1976b:22).

8.0 CLASSIFICATION AND SPELEOGENESIS

The open vertical vents examined in this study and those noted in the literature fall into two general categories: OVCs found at primary vents and OVCs found at rootless vents. These natural groupings provide the best criteria for the process-based classification of open conduits. Additionally, OVCs found at primary vents are generally associated with fissure eruptions, the conduit at Little Belknap Crater being a possible exception among those I examined. It is also possible that OVCs found at rootless vents could be fed by structures other than lava tubes, but no examples were noted either in Oregon or in the literature.

8.1 GENESIS OF OPEN VERTICAL CONDUITS AND ASSOCIATED LANDFORMS AT PRIMARY VENTS

Eruptive activity at primary fissure vents has been described by a number of authors. The hypothetical sequence of events pictured in Figure 11 is based on my interpretation of the observations of MacDonald (1959) and Swanson et al. (1979) of activity along the East Rift Zone of Kilauea and on summaries by Williams and McBirney (1979:71-73, 271).

Once activity has begun along an eruptive fissure vent, the tendency is, as the eruption continues, for fountaining or discharge of lavas to localize or focus along the vent. If, at the end of the eruptive activity, the magma level subsides or is diverted by the opening of another vent, the eruptive conduit may be left open. If it is well-developed, this will result in an OVC. This was seemingly the occurrence along the upper Northwest Rift Zone; activity there created numerous spatter pits, each a minor focus along the fissure vent. Depending on the length and volume of the eruption, spatter ejected from a vent builds various sizes of spatter cones or ramparts.

If the fissure vent is positively dilated, it may develop a roof of spatter through the accretion of crust and spatter to its upper walls. Spatter cones may develop, fed by conduits penetrating the roof, and holes may form through collapse, thus providing a vent for small lava flows and spatter (Swanson et al., 1979:37-38). Should the magma in the roofed section be withdrawn, an open chamber may remain. All of these events appear to be well documented at the Upper McKenzie Pits (Figure 9).

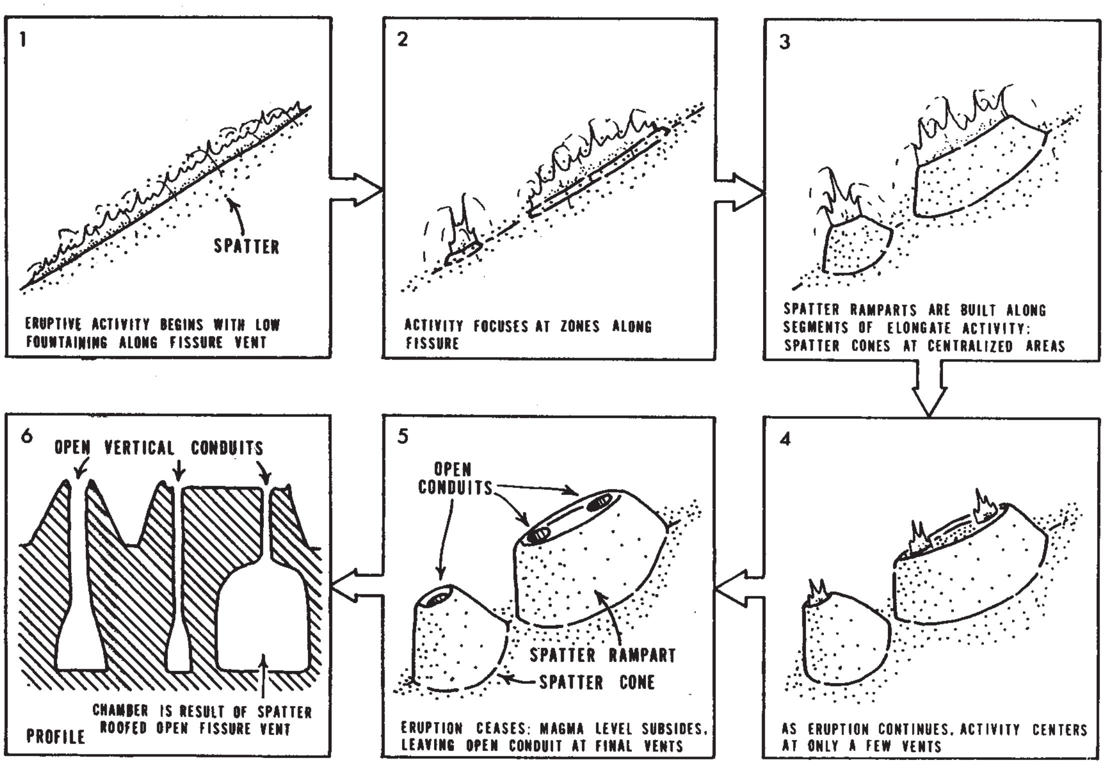

Figure 11. An eruptive sequence showing the formation of open vertical conduits and associated surface landforms at a primary vent.

8.2 GENESIS OF OPEN VERTICAL CONDUITS AND ASSOCIATED LANDFORMS AT SECONDARY VENTS

The processes that create hornitos and open conduits at rootless vents are considerably different than those operating at primary vents.

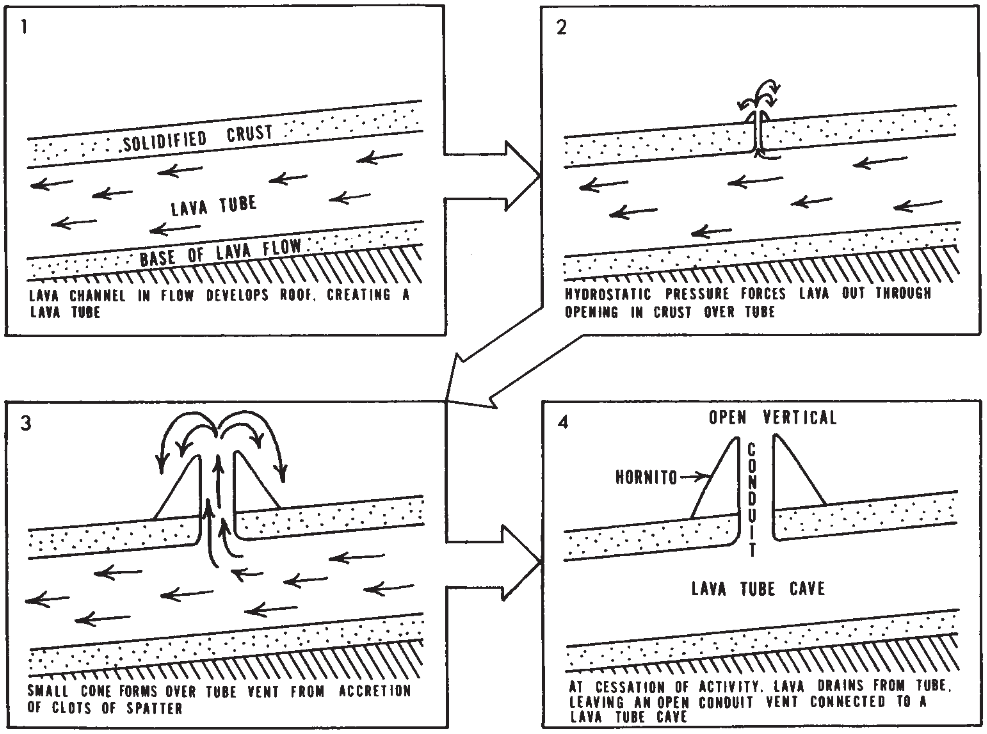

Figure 12. An eruptive sequence showing the formation of an open vertical conduit, hornito and lava tube at a rootless vent (box 3 is adapted from Fielder and Wilson, 1975:80).

As lava flows are extruded from a vent, distinct lava channels soon form, channeling lava to the front of the flow. As the eruption progresses, the channel tends to become covered by jammed pieces of crust or by the merging of levees developed on the channel margins (Wentworth and MacDonald, 1953:43).

Small vents may break out over the lava tubes, and gas-charged clots of spatter are thrown out, resulting in the construction of a hornito (Wentworth and MacDonald 1953:52). Several hornitos may sometimes be found aligned linearly or sinuously over a former tube.

At the cessation of activity at the vent, if the conduit remains unfilled, an open vent or OVC will result. When the feeder lava tube drains and remains uncollapsed, the OVC will join with the tube. This sequence of events is illustrated in Figure 12. Santiam Pit (Figure 10) illustrates this process as does the small hornito and lava tube combination shown in Figure 2.

9.0 COMPARATIVE RESULTS

As a result of the comparative investigation of the OVCs found in the six locations that I have described, generalization is possible about the associated landforms and cave types and about the age and composition of the

VERTICAL CONDUIT	ASSOCIATED AGE	REFERENCE
Santiam Pit	~600 dendrochronologic years B.P. 3850 ± 215 radiocarbon years B.P. maximum*	Roach, 1952:172 Taylor, 1967:41 Chatters, 1968:494
Upper McKenzie Pits	~600 dendrochronologic years B.P. 3850 ± 215 radiocarbon years B.P. maximum*	Roach, 1952:172 Taylor, 1967:41 Chatters, 1968:494
Sand Mountain Chimneys	~3000 radiocarbon years B.P. maximum**	Benson, 1965 Taylor, 1967:41
Little Belknap Crater Conduit	2883 ± 175 radiocarbon years B.P.	Taylor, 1967:42 Chatters, 1968:494
Smith's Pit	~6000 radiocarbon years B.P.?***	Peterson and Groh, 1969:76
Northwest Rift Zone Conduit	~6000 radiocarbon years B.P.****	Peterson and Groh, 1969:76 MacLeod *et al.*, 1981:85,89

* The flows from the Nash Crater vents overlie a radiocarbon dated unit, establishing that as the maximum age of the overlying flows.

** Overlies a lava flow that dammed the Upper McKenzie Valley, creating Clear Lake; drowned trees from the Clear Lake damming have associated radiocarbon dates of 3200 ± 220 years B.P. and 2705 ± 200 years B.P., establishing the maximum age of the lavas from the Sand Mountain Chimney vents at about 3000 years B.P.

*** Eruptive activity at Smith's Pit may be related to nearby fissure activity at Lava Cast Forest, an event dated at about 6000 radiocarbon years B.P.

**** These pits lie along a segment of the Northwest Rift Zone that has not been radiocarbon dated, but is bracketed by two dated and presumably contemporaneous lava flows, the Lava Cascade Flow and North Summit Flow. Radiocarbon dates associated with these two events are, respectively, 5800 ± 100 years B.P. and 6,090 years B.P.

Figure 13. The ages of lavas associated with the open vertical conduits examined in this paper.

	1	2	3	4	5	6	7	8	9	10
SiO_2	54.70	54.80	52.80	54.40	54.50	51.70	53.50	52.62	50.88	50.80
TiO_2	1.26	1.21	1.28	1.32	1.32	1.50	1.18	1.27	1.21	1.20
Al_2O_3	16.60	16.60	18.00	16.90	18.20	16.20	19.30	17.27	17.82	17.89
MgO	4.84	5.02	5.21	6.20	5.20	8.10	5.30	6.82	6.86	7.31
FeO	8.02	7.78	7.86	8.60	8.30	9.40	8.20	--	--	--
Fe_2O_3	--	--	--	--	--	--	--	9.32	9.32	9.17
MnO	0.16	0.16	0.15	--	--	--	--	0.14	0.14	0.14
CaO	8.43	8.37	9.18	8.80	8.40	9.10	8.60	8.28	8.28	9.40
Na_2O	3.80	3.84	3.79	--	--	--	--	3.59	3.59	3.19
K_2O	1.12	1.13	0.85	0.86	0.69	0.80	0.85	0.77	0.77	0.64
P_2O_4	0.26	0.25	0.23	--	--	--	--	0.25	0.25	0.30

Vertical Conduits

1. North Summit Flow, Northwest Rift Zone, Newberry Volcano (Beyer, 1973:15; sample NS-1).
2. Lava Cascade Flow, Northwest Rift Zone, Newberry Volcano (Beyer, 1973:15; sample LC-1).
3. Little Belknap Flow, Central High Cascades (Beyer, 1973:19; sample 17).
4. Clear Lake Flow originating from vent at Sand Mountain Chimneys, Central High Cascades (Anttonen, 1972:82; sample 47).
5. Fish Lake Flow originating from Nash Crater vent, Central High Cascades (Anttonen, 1972: sample 49).

Lava Tubes

6. Sawyer's Cave Flow, Central High Cascades (Anttonen, 1972:82; sample 13).
7. Sixmile Butte Flow, Central High Cascades (collected at Skylight Cave; Anttonen, 1972:80; sample 37).
8. Sims Butte Flow, Central High Cascades (collected at Ectomorph Ice Cave; X-ray fluorescence analysis by the author).
9. Lava Top Butte Southeast Vent Flow, Newberry Volcano (collected at Tie Cave; X-ray fluorescence analysis by the author).
10. Lava Top Butte Northwest Vent Flow (collected at entrance to small tube that drained lava pond; X-ray fluorescence analysis by the author).

Figure 14. *The composition of lavas (weight percent oxides) associated with the open vertical conduits examined in this paper. The composition of nearby lava tubes is shown for comparison.*

vertical conduits. The results of this comparative study are significant for at least two reasons:

1. OVCs could function as a "signature" for a particular type of volcanic system. Predictions of age and composition, for instance, might be made on the basis of the presence of an OVC.
2. The existence of OVCs might be predicted by the presence of certain known volcanic environments. It seems, for example, that a Holocene fissure vent that was the source of basaltic andesite lavas would be a likely place to look for an OVC.

9.1 ASSOCIATED LANDFORMS

All of the OVCs examined, both in the literature and in the field, were found associated with predictable varieties of surface landforms. OVCs at primary vent areas were found with either spatter cones or ramparts, while OVCs at rootless vents were found with hornitos. While aa lavas predominated, pahoehoe lavas were also present.

9.2 ASSOCIATED CAVE TYPES

The association of certain cave types with OVCs was less predictable than with the surface landforms. In general, OVCs at primary vents were found in conjunction with either spatter cone chambers or with roofed fissure vents. OVCs at rootless vents were generally found with lava tubes, though little might remain intact. On only one occasion was a lava tube found with a primary vent OVC (at Little Belknap Crater) and it seems to have played a quite different role than the tubes found at rootless vents.

9.3 AGE

The ages of the lava flows associated with the conduits investigated here are well known and are shown in Table 1. The exception to this is the tenuous relationship of Smiths Pit with the well-dated activity at the Lava Cast Forest Flow. The presence of Mazama ash provides a convenient time datum in this area, but the porous nature of the spatter cone containing the conduit makes it unclear whether its origin was pre- or post-Mazama. The freshness of the lavas indicate that a very late Pleistocene to Holocene age can be appropriately assigned to the cone and OVC.

My initial conclusion is that OVCs are geologically very transient features, quickly filling through collapse and accumulation of debris, and that they are probably confined to lavas of a Holocene or late Pleistocene age.

9.4 CHEMICAL COMPOSITION

The composition of some of the lavas associated with the Oregon OVCs is also available and is reported in Table 2. Analyses 1 through 5 are from samples collected at flows that are linked with the OVCs. Analyses 6 through 10 are from samples that were gathered at lava tubes that were found in the same general area as the investigated vertical conduits.

As can be seen in Table 2, the OVCs are found primarily in basaltic andesite or lava of similar composition (53-58 weight percent SiO_2). The silica composition of the units with lava tubes, on the other hand, shows a tendency to fall into the basaltic range (48-53 weight percent SiO_2).

There is some overlap between the two groups and the error inherent in the interlaboratory comparisons could nullify any differences, but there does appear to be a trend for OVCs to be found in lavas that are slightly more siliceous than flows in which lava tubes develop. Perhaps the higher viscosity of the more SiO_2-rich lavas (as shown by the predominance of aa lavas at OVC sites) is a factor in the formation of open vertical vents.

10.0 CONCLUSIONS

Open vertical volcanic conduits are an unusual and little described type of cavernous lava structure found in areas of Holocene and late Pleistocene basalts and basaltic andesites throughout the world. They are vertical pipes, coated with a remelted lava lining, that have remained unfilled by the final eruptive activity at a vent.

These open conduits appear in aa and pahoehoe lavas. They may occur singly or in alignments along fissure vents and as an adjunct structure to some other forms of lava caves. Open vertical conduits are present at both primary and secondary (rootless) vents and are invariably found in conjunction, respectively, with spatter cones and ramparts or hornitos. When found in association with a rootless vent, they may be connected to the still intact lava tube for which they originally acted as a vent. Conduits found at primary vents are often found associated with other cave types, including spatter cone chambers, spatter-roofed open fissure vents and, occasionally, with a lava tube that drained the magma from the conduit, leaving it open.

The surface diameter of most open vertical conduits is less than 25 feet (8 m) and more commonly is between ten and three (3 and 1 m). The depth of reported and observed open vertical conduits or of associated caves for which the conduits are a major component varies from a few feet to at least 165 feet (50 m).

It is likely that other OVCs exist in many other areas of extensive volcanic activity in the world. The presence of several conduits in Oregon suggest that open vertical conduits are an obscure, rather than rare volcanic feature.

ACKNOWLEDGMENTS

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SPELEOLIFEROUS LAVA FLOWS ASSOCIATED WITH THE BROTHERS AND SUBSIDIARY FAULT ZONES OF CENTRAL AND SOUTHEASTERN OREGON

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ABSTRACT

The Pacific Northwest at the western edge of the North American Plate is impacted by the interactions of three types of plate boundaries. As the Pacific Plate slips northward toward subduction in the Gulf of Alaska, it is dragging western Oregon northward. During the last 10 to 12 million years, the terrain south of the Brothers Fault Zone has been extended an estimated 50 miles over a distance of 200 miles. The Brothers Fault Zone, along which magma has upwelled repeatedly, is the "pivot" between the older highly folded rocks of the Blue Mountain Province and the younger highly faulted rocks of the Basin and Ranger Province. The basaltic lava fields along the Brothers and subsidiary parallel fault zones include: the Horse, Arnold, Potholes, Matz, Lava Pass, Devils Garden, Squaw Ridge, Green Mountain, Four Craters, Diamond Craters, Voltage, Saddle Butte, Jordan Craters and Cow Lakes. Caves have been discovered in most of these lava fields; their basalts vary in age. A second group of cave flows are associated with the stratovolcanoes which result from magma produced by the subduction of the Juan de Fuca Plate. The highly plastic, small and thin, warm and youthful Juan de Fuca Plate, originating from a spreading center located about 270 miles offshore from the Oregon-Washington line, is subducting at an oblique angle under the more buoyant North American Plate. Examples of the stratovolcanoes with speleoliferous basaltic flows are Mt. St. Helens and Mt. Adams in southern Washington, Newberry Volcano in central Oregon, and Medicine Lake Volcano in northern California.

(No paper received for publication)

CAVES OF MOUNT ST. HELENS AND THE IMPACTS OF THE 1980 ERUPTIONS

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Cascade Grotto of the National Speleological Society

The Cave Basalt is the only known speleoliferous lava flow of Mount St. Helens. It dates to about 1950 years B.P. Some of its caves underwent extensive aggradation about 450 years ago, by two post-eruptive flash floods and/or mudflows. These deposits underwent extensive erosion and reworking prior to the 1980 eruptions. Two and possibly more of the 1980 eruptions caused significant vertical airfall of tephra in the cave area. An unusual sequence of mudflows and flashflood landforms developed, both above and below ground. Some caves and other subsurface spaces acted as conduits and/or sediment traps. Two caves and parts of others have been filled by 1980 and reworked pre-1980 deposits. In comparison with the recent events elsewhere on Mount St. Helens, however, the impact of the 1980 eruptions and post-eruption events has been spotty and comparatively minor. Some of the greatest impacts to date correlate with pre-1980 human activity.

INTRODUCTION

Prior to 1980, some geological, speleological and popular reports mentioned modification of certain pre-existing lava tube caves by later eruptive episodes, and a few discussed them on a deductive basis. For the first time, however, the 1980 and subsequent eruptions of Mount St. Helens have permitted sequential observation and measurement of spelean effects of a variety of peri-eruptional phenomena in an area of exceptional interest, significance and accessibility.

Under St. Helens Research Committee Permit #9, and successor permits, field parties of the Western Speleological Survey were permitted to begin studies of these effects on June 22, 1980. Several subsequent reports have been published as Bulletins of the Washington Speleological Survey, in *Geo^2*, in the Proceedings of the 8th International Congress of Speleology, and elsewhere. Despite ongoing bureaucratic obstruction of research discussed elsewhere (Halliday, 1981), studies are continuing here and in other types of pseudokarst on and around the volcano.

Significance of the area

The national and international significance of the Mount St. Helens cave area has been recognized for more than 20 years. Mention of Ole's Cave (as Spencer's Cave) appears in the international speleological literature as early as 1900 (Martel, 1900). For several years after its initial mapping in 1958, Ape Cave was considered to be the world's longest lava tube cave. Even today, it is the longest known on either American continent. Although almost entirely undeveloped, it is a very popular year-round public attraction. Several other caves in the area qualify as world-class according to the criteria of the International Union of Speleology, and numerous smaller caves here have major biological, geological, historical, recreational, wilderness, and other values (U.S. Senate, 1982; U.S. House of Representatives, 1982). In 1962, I urged creation of a Lava Caves National Monument here (Halliday, 1962). Subsequently, Pryde (1968) listed it as one of the three essential parts of a Mount St. Helens National Monument, a proposal currently well-received by Congress. (A bill creating a Mount St. Helens National Volcanic Monument was enacted by Congress, and signed into law by President Ronald Reagan in August 1982.)

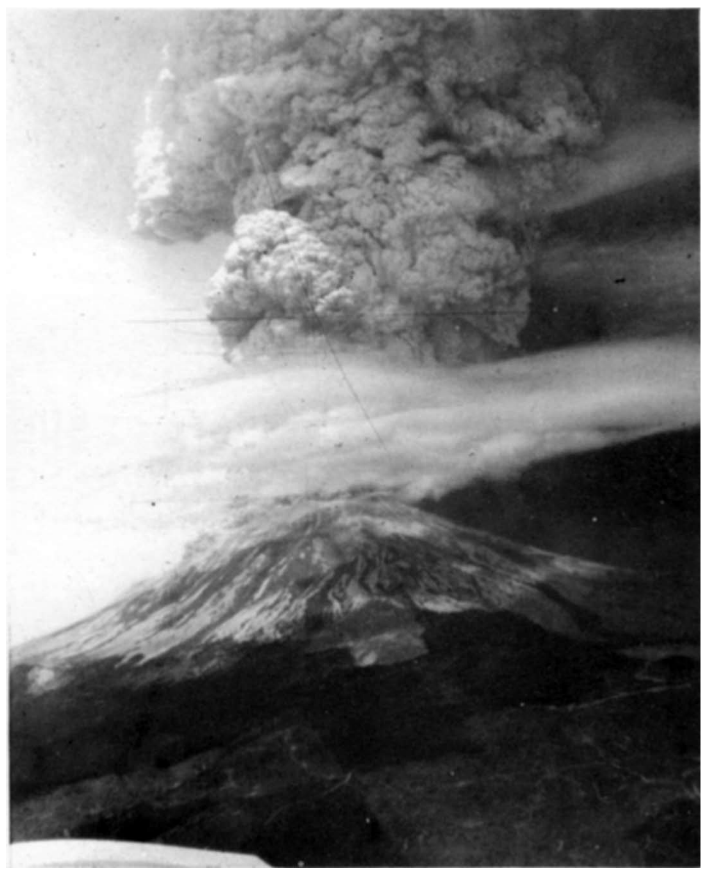
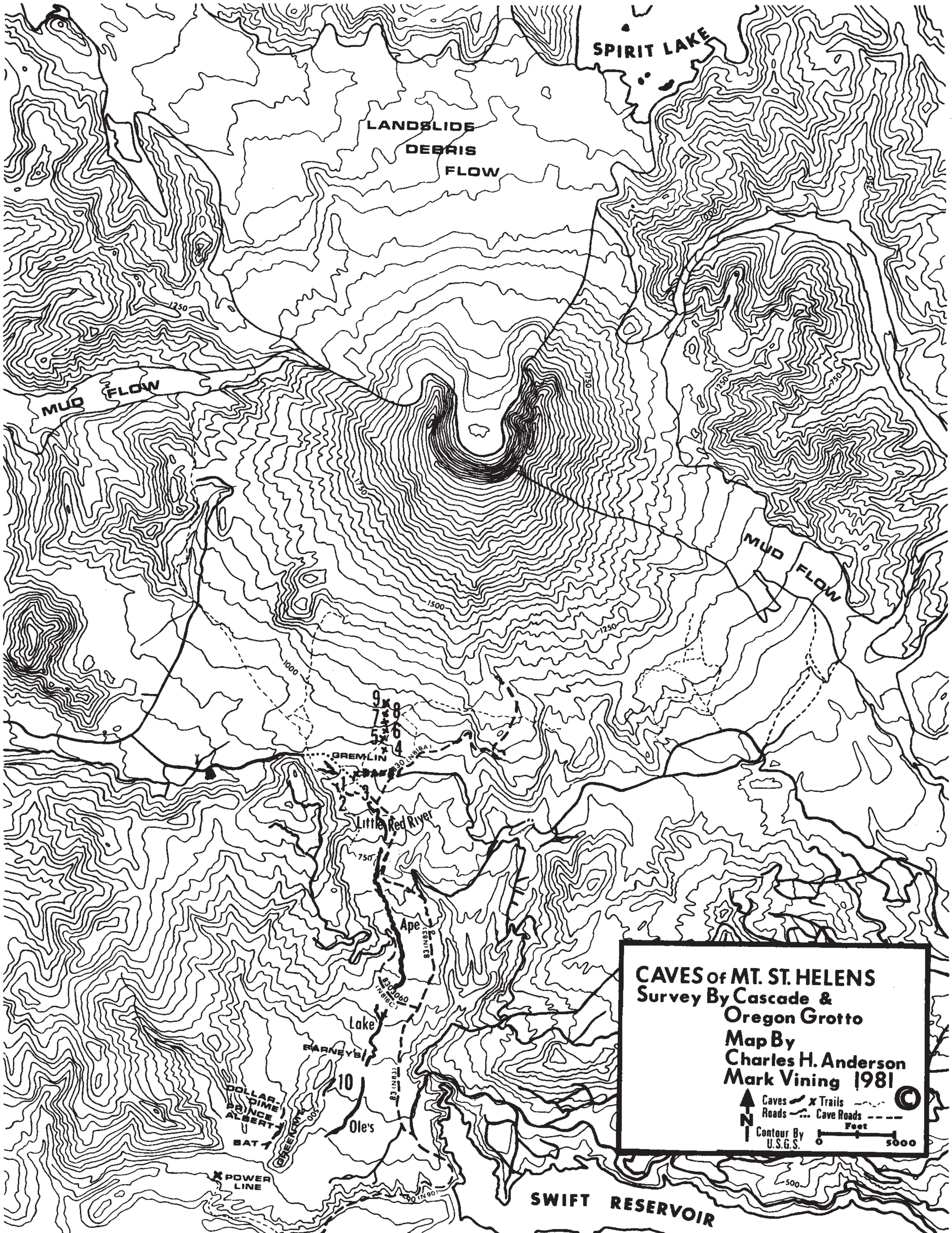


Figure 1. Commercial photo on May 18, 1980 shows that cave area was free of tephra fall during that eruption. Uppermost identifiable part of the Cave Basalt Flow is in the triangular clearcut in the lower left of that photo. Photo Vernon McCall.

Basic Geology of the Mount St. Helens Cave Area

The cave area of Mount St. Helens is on the gently-sloping lower slopes of the south-southwest quadrant of the volcano, at a distance of about five to twenty km from the rim of the 1980 crater. It is almost 180° away from the axis of the lateral blast of May 1980 and the pyroclastic flows which followed it. The

Figure 2. *Mount St. Helens area, August 6, 1981. Aerial photo courtesy of U. S. Geological Survey.*



1 Spider — 2 Flow — 3 Little People — 4 Breakdown — 5 Moss — 6 Railroad Track
7 Surprise — 8 Arch — 9 Lava Spring — 10 Beaver C

Figure 3. *The Mount St. Helens cave area is almost exactly 180 degrees away from the axis of the lateral blast of May 18, 1980. Map by U.S. Geological Survey.*

study area discussed here consists of the south lobe of the Cave Basalt Lava Flow, a Quaternary structure about 1,900 years old (Greeley and Hyde, 1972). It is the only known speleoliferous lava flow on Mount St. Helens and consists primarily of pahoehoe lava with a little aa. Its upper and lateral portions are largely covered by later lava, tephra, other aggradational deposits and by various types of forest and other plant cover, especially above road 81. The lava is best visualized in the caves. A total of about 10 km of caves has been mapped in this flow. The flow can be traced from an elevation of about 1,500 m to the north fork of the Lewis River, at an elevation of about 200 m. Contrary to some earlier opinions, its vent probably was at or near the pre-1980 summit. The flow contains several subunits which have not been adequately defined or described. These are especially prominent in the Utterstroms Caves area where all the caves except Breakdown Cave appear to be in a superficial subunit which may be significantly later than the bulk of the flow. In the mid-portion of the flow, Barneys Cave is in another subunit distinct from that containing the main throughway passage of nearby Lake Cave.

The section of Ape Cave downslope from its main entrance has two mudflow deposits about 450 years old. Each is at least 1.5 m thick. Other pre-1980 mudflow or flash flood deposits are present in Lake Cave and Little Red River Cave.

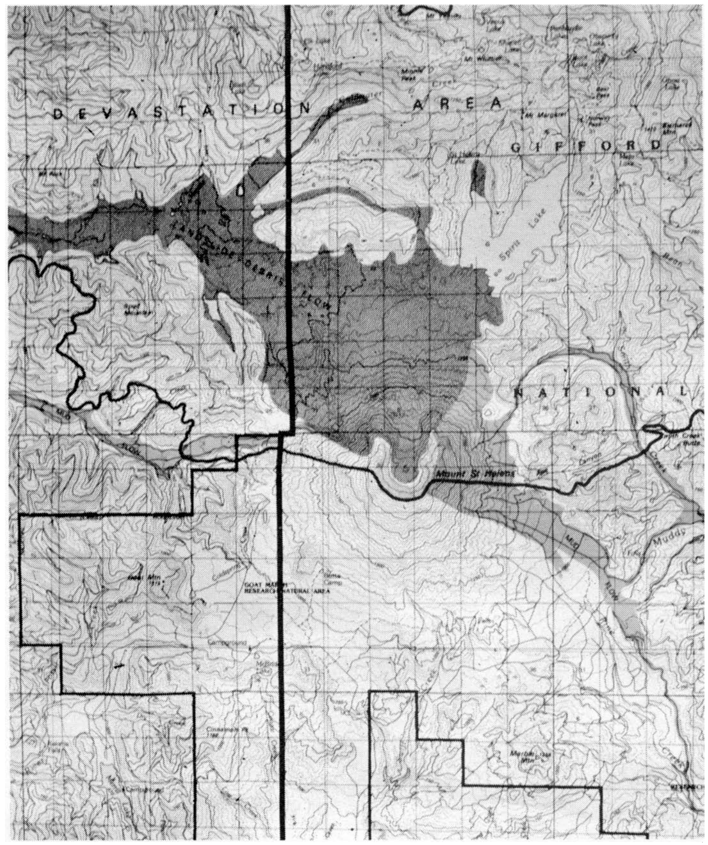


Figure 5. The Mount St. Helens cave area is almost exactly 180 degrees away from the axis of the lateral blast of May 18, 1980. Map by U. S. Geological Survey.

Airfalls of Tephra

Although the Western Speleological Survey research permit predated the famous May 18, 1980 eruption, we were not permitted to use it until June 22, 1980 and thus have no data on earlier post-eruption findings in this study area. Some aerial photographs taken in the first few minutes of the May 18, 1980 eruption suggests that collapsing columns of airborne tephra should have deposited airfall here. However, an interview with Mr. Ron Fields, a U.S. Forest Service employee who was at the northwestern corner of the cave area at the time of the eruption, indicates that the column collapse did not reach the ground here, and this is confirmed by photographs taken later on May 18, 1980 showing no tephra on the snowpack upslope from the cave area. Small amounts of airfall may have occurred here during the minor eruptions in March and April 1980, but if so, it was minimal and all traces thereof were obliterated by larger, later airfalls.

Figure 4. Other caves at Mount St. Helens are of national and international significance because of their size and features. This is a notable trench and tube-in-tube in Prince Albert Cave Photo by W.R. Halliday.

Presumably, on May 25 and June 12, 1980, however, the entire cave area underwent two episodes of airfall before our June 22 studies. Two accumulations of almost identical depth were found throughout the area. Oral communications from U.S. Geological Survey staff persons indicate that a third airfall occurred in the study area in September or October 1980, but use

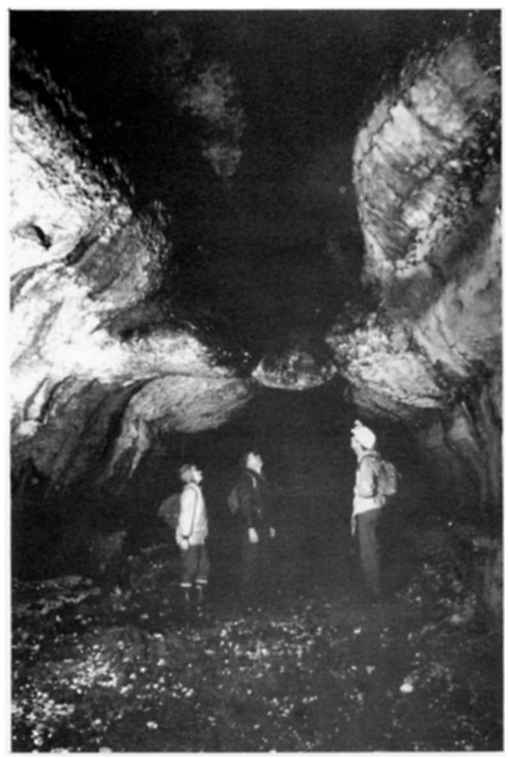


Figure 6. For several years after its initial mapping in 1958, Ape Cave was considered the world's longest lava tube cave. It is still the longest lava tube cave on either American continent. Photo by W.R. Halliday.

Figure 7. This is an unusually long lava "straw" stalactite in a Mount St. Helens Cave. Photo by W.R. Halliday.

Figure 8. Before this photo, at the main entrance of Ape Cave in June, 1980, two tephrafalls had deposited about 1 cm here. By November, 1980, heavy rains had washed almost all of it off the trees, which looked almost normal again. Photo by W.R.H.

Figure 9. Tephrafall at Moss Cave, about 6 km from the 1980 crater, was about twice as much as at the main entrance of Ape Cave. Photo by W.R. Halliday.

Figure 10. Eroded remnants of two pre-1980 mudflows in Ape Cave. Excavation has shown that the lower flow is at least 1.5 m thick. Photo by W.R. Halliday.

of our research permit was especially obstructed at that time and all evidence of this third airfall was obliterated by heavy rainfall in early November 1980.

Throughout the study area, the May and June 1980 airfalls were vertical. In the Utterstroms Caves area (about 5 km from the new crater), it measured up to 5.5 cm thick in compressed form. At the main entrance of the Ape Cave, its maximum thickness was 2.4 cm. Two distinct layers were present. At Ape Cave, the tephra had a powdery, fine-grained texture but washing revealed coarser elements. Closer to the crater, the tephra was increasingly coarse-textured and granular in appearance, but still contained a large percentage of powdery components. A few isolated fragments of light, airborne pumice were found in the cave area in June 1980. These were randomly distributed. The largest measured 3.8 x 2.5 x 2.5 cm; it was on the trail from the Ape Cave road to the main entrance of the cave. In March, 1982, showers of newly ejected pumice fragments were found atop the snow on and north of Road 81 north of Little Red River Cave. The largest of these was about twice as large as those found at Ape Cave in June 1980.

In comparison with mudflow events discussed later, only very small amounts of tephra entered caves as a result of gravity transport, with or without the effects of rainfall in the cave entrance. With the exception of some loss of moss and other low vegetation, the parts of the study area impacted only by airfall now look much as they did before the eruptions and provide a control area for parts of the Cave Basalt Lava Flow impacted by subsequent mudflows and other parts of the Mount St. Helens area as a whole.

Impact of Mudflows in the Cave Area

Post-eruption mudflows of two or three types caused large-scale physical changes above and below ground in some parts of the cave area. A clear sequence involving both post-eruption aggradation and down-slope delivery was observed, both above and below ground, related to:

1. the nature of the tephra,
2. the local surface and subsurface topography, and
3. surface and subsurface runoff.

Endogenous Mudflows

Except under unusual circumstances, the first aggradation in the study area was separation of a light tan mud from the remainder of the tephra. Its consistency was clay-like. Some clung to vegetation for many months, despite winter storms.

Yet, most of it separated quickly from larger tephra particles with light rain, long before seasonal rains seemingly washed the area clean in early November 1980. It hydrated and dehydrated quickly, and flowed and halted with seemingly minimal changes in hydration. By June 22, 1980, after light summer rains, it had accumulated locally to depths of many cm in the center of the study area. In the shallow sink of Hopeless Cave, it formed a quicksand which half-filled the low entrance. Two months later, after additional light summer rains, some of these local accumulations were several times as thick as in June. Locally, some had coalesced to form mudflow tongues. Some of these tongues had flowed into pseudokarstic swallets smaller than the entrance of Hopeless Cave. Although the color still was light tan, the mud was siltier and a small amount of gravel and pumice had begun to appear on its surface. By this time, the entire entrance sink of Hopeless Cave had been filled, with only a small swallet revealing its site. Subsequently, this entire area was buried by an accumulation of more than two meters of mixed streamwash, resembling the detritus of a desert wash. This location is about 150 meters up-slope from the main entrance of Ape Cave and the Hopeless Cave mudflow extended diagonally across the course of the cave. As of mid-1982, small new accumulations of this tan endogenous mud still can be observed after each rainfall in the general area of Ape Cave, especially at the downhill ends of mudflow tongues where the extremely fine-grained particles seem to separate disproportionately with low velocity waterflow.

Figure 11. Local runoff leading into Hopeless Cave after local aggradation in August, 1980. Photo by J. Nieland.

In limited underground reconnaissance in June 1980, we found no aggradation of 1980 tephra. In August 1980, we found thin deposits of tan 1980 mud in parts of Ape Cave. We were allowed to visit at the time, both upslope and downslope from the main entrance. It was entering through small local spatter points and through paratubal orifices unrelated to any discernable surface feature. Subsequently, reworking caused the tan mud to disappear in the part of Ape Cave downslope from the main entrance. Beneath the Hopeless Cave mudflow, this tan mud remains, up to eight cm thick. Present drip in this part of the cave, however, no longer contains mud. Therefore, it appears that the tan clay-like particles form a layer impervious to larger particles which has sealed minute orifices originally permitting its passage.

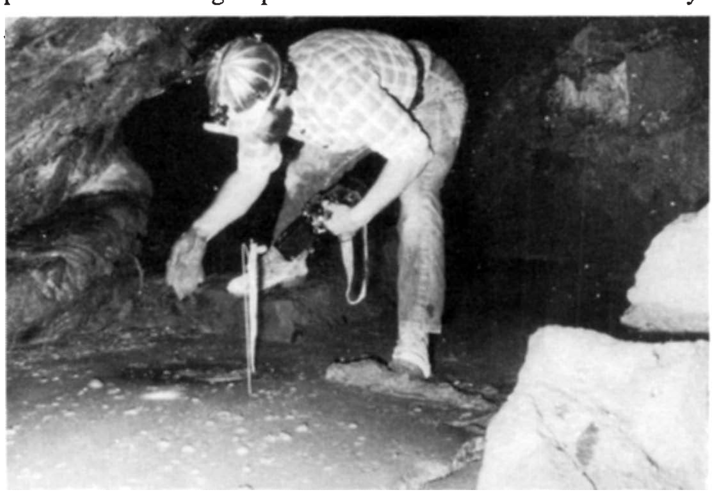


Figure 12. Tan mud rivulet in Ape Cave, August, 1980. Reworking soon destroyed all trace of this phase in this part of the cave. Photo by W.R. Halliday.

Exogenous and/or Mixed Mudflows

On June 22, 1980, we found another form of post-eruption aggradation in a small area east and south of the Utterstroms Caves, near the north end of the study area. This locality is about 5 km south of the new crater. Some local endogenous tan-colored mudflows were present here also, but in addition, the light summer rains had deepened one small gully arising high on the volcanic cone and a small amount of exogenous material had accumulated at various points along its course and spillover points. Also, we found unexpected headward erosion in a gully which had destroyed half the width of the Breakdown Cave access road, with obvious downslope transport of eroded material. Along the edges of this gully, large perched boulders indicated at least one recent period of torrential flow seemingly disproportionate to the light rains of the season.

About 1/2 km farther downslope, changes were more dramatic. Considerable pre-1980 streamwash had been redistributed from the bed and walls of the gully into and through an old "borrow pit" located in a clearcut. The upslope walls of the borrow pit had undergone marked headward erosion, exposing stumps and other features deeply buried by pre-1900 mudflows. These mixed materials contributed to a

Figure 13. Site of Hopeless Cave after Hopeless Cave Mudflow of about November 1, 1980. This view is looking past the site of the cave entrance to the road; formerly there was a bank about 1.5 m high at the edge of the road. Photo by W. R. Halliday.

new downslope aggradational plain composed variously of tan clay-like tephra, silty tan tephra and grey-brown tephra adulterated with pre-1980 materials, largely sorted by particle size. In the main axis of a braided downslope delivery system, streamwash had slightly gullied and aggraded a width of several hundred meters of Road 81 (then N818). The plain extended a few dozen meters downslope on the lava flow, from Road 81, close to several important caves. We named this complex the Road N818 Mudflow (later changed to Road 81 Mudflow when the enumeration of the road changed).

On August 24, 1980, we found one major gully in the Utterstroms Caves area temporarily lined with what appeared to be welded tuff, resulting from an exogenous mudflow associated with the August 7, 1980 (or July 22, 1980) eruption. A small tongue of this material extended as far south as Road 81. This soon disappeared as a result of reworking, however.

During the next six months, these gullies underwent rapid, extensive erosion, with repeated reworking and downslope enlargement of the Road 81 Mudflow. All traces of the "borrow pit" were destroyed by January 1981, and by November 1980, Road 81 was so deeply gullied as to constitute a geological exhibit rather than a road. This process is continuing, with broad sections of dying forest now standing in what looks much like a desert alluvial fan. Debarking of trees, and wedging of large boulders between trees several meters above gully floors, demonstrates the effect of heavy seasonal rainstorms.

A little low-load floodwater has spilled into Little Red River Cave, located close to the largest gully associated with the downhill extension of this mudflow and the site of at least one major pre-1980 subterranean mudflow. Another tongue of this mudflow, however, has deposited several cm of mixed streamwash in the main passage of Little Peoples Cave. A small subterranean tongue of the Road 81 Mudflow also resurged about 30 m north of Flow Cave and has deposited a small quantity of fairly fine-grained material in the entrance section of the cave.

Figure 14. Photo taken around 1965 of the road materials "borrow pit" on Road 81. After tephrafalls of mid-1980, headward erosion of this borrow pit resulted in extensive aggradation downslope and contributed to Hopeless Cave Mudflow. W.R.H. photo.

Different tongues of the Road 81 Mudflow are not simultaneous in advance and enlargement. The westernmost tongue was comparatively slow to advance. It did not reach the road until the summer of 1981. However, in approximately February 1981, it began to spill laterally into the lower entrance of Sand Cave. By October 1981, that entire pit entrance had been filled and a small tongue of mud also had entered the upper entrance. Only about 5% of the original volume of this cave is unfilled at present.

Figure 15. Road 81 just below the borrow pit in August, 1980. Subsequently, this area became so deeply gullied that it was difficult to see that a road had ever existed here. Photo by W.R. Halliday.

At the northwestern corner of the study area, the easternmost tongue of the Kalama Springs Mudflow (which we termed the Gremlin Cave Mudflow) entered the cave area at an undetermined time prior to August 22, 1980. At that time, we found it to be a largely silty mudflow just beginning to spill laterally into the lower entrance of Gremlin Cave after passing diagonally across most of its length. At this time, the mudflow was being enlarged by glacial meltwater carrying a heavy sediment load. It was aggrading Road 81, which it crossed at a 90° angle, thence following logging roads downslope as it spread out in the Gremlin Cave clearcut. Some of this meltwater also was running along a drainage ditch which then existed along the north edge of Road 81.

Subsequently, it became apparent that Gremlin Cave already had become part of a significant underground downslope delivery system. It continues to serve as an active intermittent

Figure 16. Figure 16. Possible welded tuff lining a shallow gully near the Utterstroms Caves group (August 1980). Photo by W.R. Halliday.

conduit for floodwaters and meltwater which intermittently carry heavy sediment, with sequential erosion and deposition of

Figure 17. Same location [as Figure 14] in January, 1981, after seasonal rains caused severe gullying. This process has continued to enlarge this and other nearby gullies. Photo by W. R. Halliday.

Figure 18. Aggradational plain and gullies downslope from Road 81, in the area of the Road 81 Mudflow. Photo by W.R. Halliday.

Figure 19. Lower (pit) entrance of Sand Cave in May, 1981, when a western lobe of the Road 81 Mudflow recently had begun to invade this entrance. Within a few months this entrance was too deeply buried for its site to be found. Photo by W.R.H.

sandy material and vegetable debris along the spelean streamcourse which begins near the lower entrance. Headward erosion of the aforementioned trench along Road 81, with redirection of the main downslope delivery axis to the southeast, however, had reduced the burden of the stream in this cave. At present, erosion of subterranean post-1980 deposits is proceeding near this entrance, with continuing deposition primarily in the rarely-visited lower end of the cave.

On the surface here, some headward feeders of the flow still remain despite the redirection of most of the aggradation southeastward, down the remains of Road 81. These have enlarged and lengthened the western lobe of this mudflow. There has been some increasingly coarse aggradation, and some rechannelization of the eastern lobe into the cave, although much more slowly and on a much smaller scale than originally feared.

In January 1981, we found the sites of two resurgences of silty mud about 100 meters downslope from the farthest point of advance of this mudflow. They were in line between Gremlin Cave and Spider Cave, which is the next cave downslope. Their sources could have been any of several small, closed depressions invaded by tan, silty tongues of this mudflow, as well as Gremlin Cave itself.

The various exogenous and mixed mudflow tongues and post-eruptive gullies coalesced in a confluent zone west of Little Red River Cave and the upper part of Ape Cave. Thence, intermittent flow of high and low-load floodwaters has followed an old intermittent stream channel along the west edge of the lava flow to a point about 150 m upslope from the main entrance of Ape Cave. At this point, the stream course was blocked around 1960 by construction of a length of U.S. Forest Service road along the bed of the stream channel. This obstruction of the natural drainage appears to have been at least partially responsible for the diversion of floodwaters which in November 1980, caused the burial of Hopeless Cave. Subsequently, this was aggravated by the construction of a dam about 1/4 mile long here, consisting of bulldozed mudflow and quarry run rock, designed to keep the road open above Ape Cave. More than 1.5 m of mudflow debris has accumulated behind this dam to date, and it may already have been overtopped by low-load floodwaters. The result has been

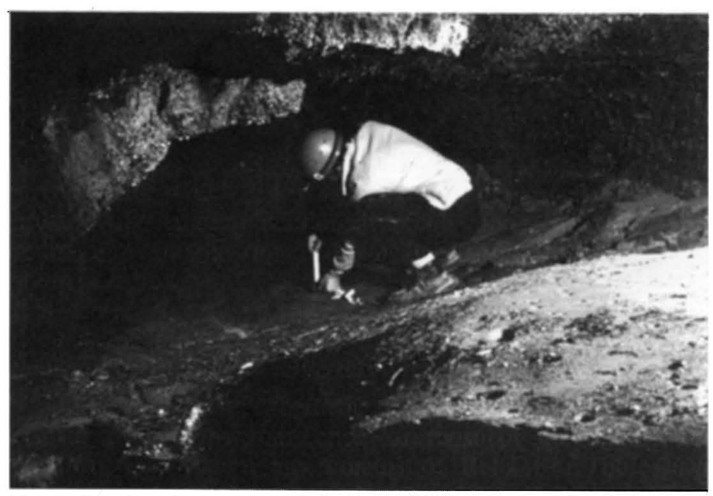


Figure 20. Another tongue of the Road 81 Mudflow invaded the upper entrance to Sand Cave by October, 1981. Formerly this was walking passage. Photo by C. A. Anderson, Jr.

Figure 21. The Gremlin Cave Mudflow in August, 1980. The upper entrance of the cave is near the left edge of the photo; the lower entrance is just out of the photo at the right lower corner. Photo by J. Nieland.

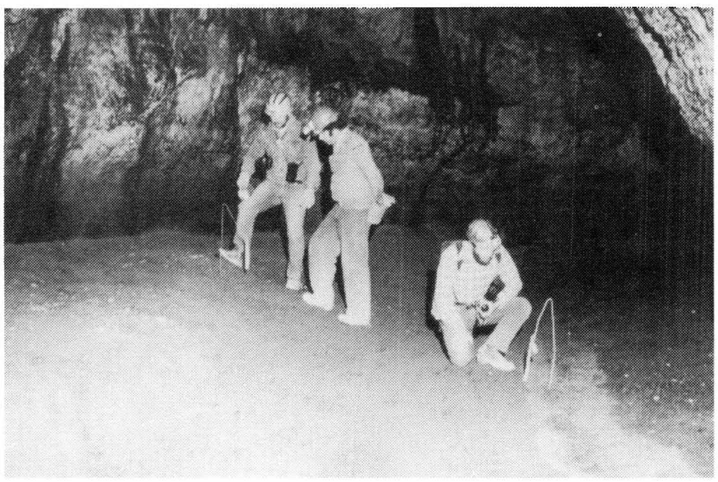


Figure 22. Initially, the reworked tephra passing through Gremlin Cave was watery and fine-grained. Photo by W.R. Halliday.

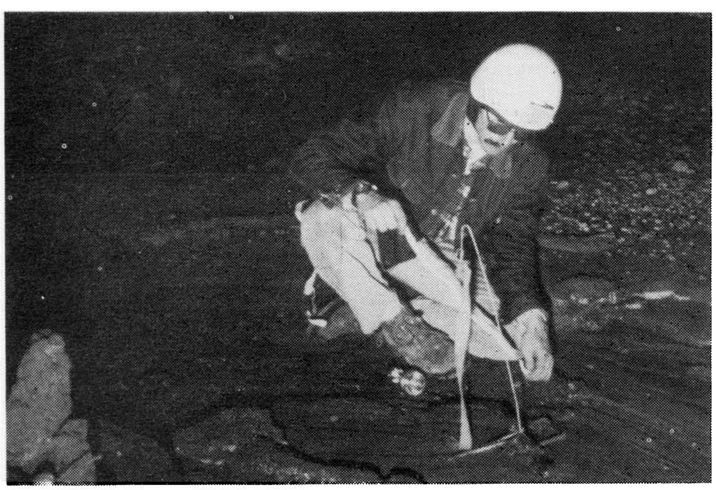


Figure 23. Subsequently reworked material passing through Gremlin Cave became grainier and packed firmly. Organic debris on the station marker indicates recent high-velocity flow. Photo by W.R. Halliday.

Figure 24. For about one year, reworked tephra in Ape Cave could be distinguished from pre-1980 materials by its lesser consolidation. Photo by W.R. Halliday.

Figure 25. This mudflow resurgence upslope from Flow Cave is at the apex of a barely perceptible lava dome. Photo by W.R. Halliday.

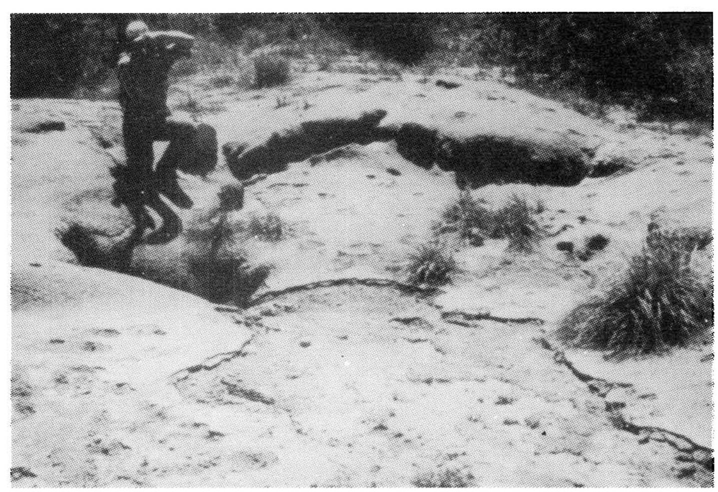


Figure 26. A small amount of mud from this resurgence entered Flow Cave. Photo by W.R. Halliday.

production of an alluvial plain at, and around the site of Hopeless Cave, reworked with each significant rain. Downslope, where the slope is steeper, braided tongues of this Hopeless Cave Mudflow extended southward, hundreds of meters past the main entrance of Ape Cave. Farther downslope, where the gradient was less, their coalesced bulk formed a small mudflat along the north side of the Ape Cave Road near the Lava Cast Picnic Area. Still farther south, where the gradient again is steeper, additional narrow tongues of similar material have been carried downslope in narrow gullies on both sides of the flow near Lake Cave. Lake Cave itself, the lava tree casts, and the downslope part of the lava flow apparently have not been impacted by this process.

To date, Ape Cave appears much as it did before the eruptions began. Only small quantities of low-load floodwaters have entered its main entrance, and their most significant effect was the destruction of the tan mud tongue seen in August 1980. Some 1980-'81 grey inwash can be distinguished from pre-1980 aggradation by its lesser degree of consolidation, and small quantities of sand have accumulated in the lower terminal crawlway. If the two-meter dam close to the main entrance should be breached by overtopping, with subsequent headward erosion in the mudflow debris accumulated behind the dam, however, invasion of Ape Cave by a mudflow tongue comparable to those of about 450 years B.P. may occur with little or no warning.

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VULCANOSPELEOLOGY OF THE LOWER SNAKE RIVER BASIN, IDAHO

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The Snake River plain is a broad, arc-shaped downwarp trending across Idaho from west to east. This basin has been filled with plateau basalts interbedded with loess and river sediments. The plain can be divided into a lower, older section, and the easterly younger or upper section. This paper will look at origins of the Snake River Plain and how vulcanospeleologic landforms have played a part in formation of today's structures.

SNAKE RIVER PLAINS: REGIONAL SETTING

Volcanism has greatly influenced development of the western North American continent. This volcanism is due to the collision and subsequent interaction of the North American Plate with the Pacific Plate. Volcanism, periodic oceanic submergence, continuing metamorphism and orogeny have produced the complex history of western North America. Action continues today, as witnessed by the recent eruption of Mount St. Helens, continuing seismic activity throughout the Northwest, and the relatively recent eruptive sequences of Craters of the Moon National Monument.

GEOMORPHIC DEVELOPMENT

Historically, geology texts have oversimplified by classifying the Snake River Plain in the same geomorphic class as the Columbia River Basalts and other plateau basalts like the Deccan Basalts of India. Others have attempted to class volcanoes as Hawaiian or effusive and Strombolian or explosive, again an over-simplification. Recent studies by Ronald Greeley and others have shown that the Snake River Plain is indeed a separate morphological class of volcanism. Greeley terms the volcanism of the Snake River Plain as Basaltic Plains volcanism and places it intermediate between basaltic flood eruptions and Hawaiian, sharing characteristics of both.

Idaho has had its share of the complex development of western North America, ranging from the Precambrian Belt Series of metasediments and Jurassic batholithic intrusions to the recent Columbia River Basalts and Snake River Basalts. The Snake River Plain crosses southern Idaho from the Island Park Caldera in the east, 500 km westward to the Oregon border, in the shape of a gentle arc. It ranges from 500 km wide in the east to 80 km wide in the western portion. The youngest rocks are found in the central and eastern portions of the plain. The lavas are principally olivine tholeiites with low SiO_2 and alkalis with high Fe content.

SUBPROVINCES AND SPELEOLOGY

The Snake River Plain is divided into two separate subprovinces, approximately at the Great Rift area: the Eastern Snake River Plain and the Western Snake River Plain. Gravity anomalies, well core data, and other field research suggest that the Eastern Snake River Plain is a broad downwarp, while the Western Snake River Plain is a graben filled with interbedded sediments and basalt flows to depths of at least 1,000 m.

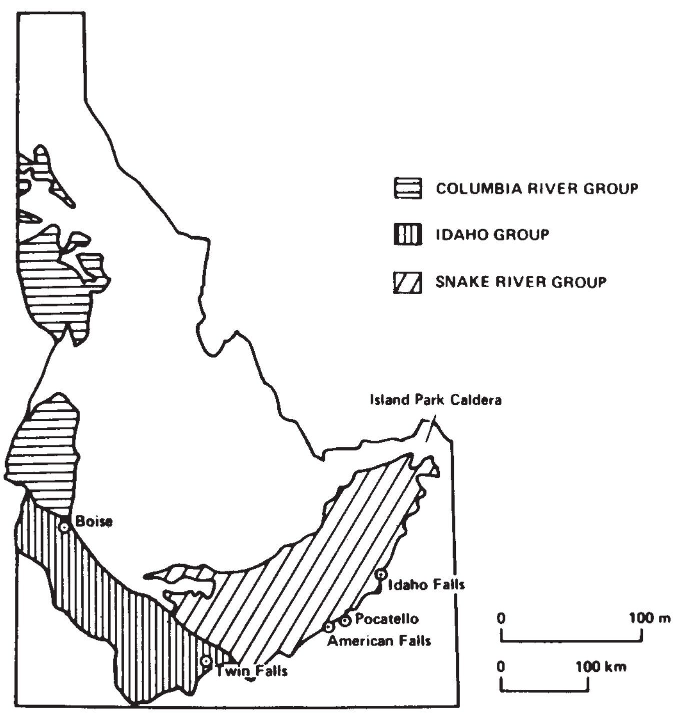

Figure 1. Distribution of Snake River groups and other Cenozoic lavas in Idaho (from Greeley).

Subsidence in the Western Snake River Plain has taken place along a series of northwest-trending faults. The northern edge of the plain is a sharp escarpment which is estimated by Malde to have an aggregate throw of at least 3 km. Malde suggests that the Western Snake River Plain may be structurally controlled by a major break in the earth's crust. Extensive fissure flows fill the western graben while vents or short fissures produce a series of complex overlapping flows filling troughs and valleys of the undulating subsurface floor of the Eastern Snake River downwarp.

In both, features are typical of lava flows, such as: pahoehoe, flow margins, pressure ridges, columnar basalts, pillow basalts, subsidence troughs, calderas or craters, and (of course) lava tubes. These features are similar to those found in Hawaiian and Columbia River Basalts, but differences exist. Columbia River Basalts have vaguely defined fissure-controlled vents and a low profile, while Hawaiian-type vents are

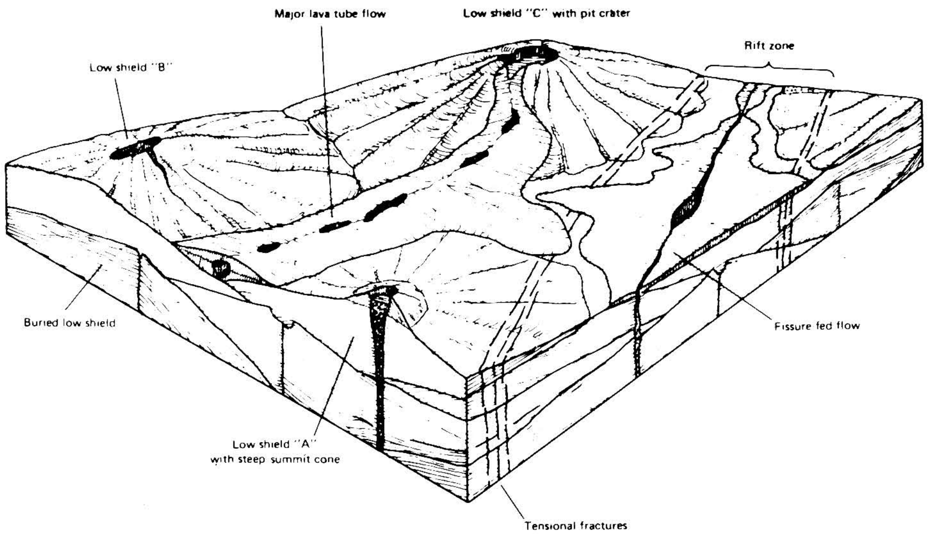

Figure 2. Block diagram (from Greeley) showing the relationship of low shields, major lava tube flows and fissure flows.

well-defined with a higher profile. Greeley notes these differences and distinguishes the Snake River Plain vents, calling them low shields. This difference is easily observed in viewing the vents from a distance. The low slopes and spreading flows have produced lava tubes of short length, usually found near the vent where slope is sufficient to allow tube drainage and thus final formation of a cave. In a few cases, such as Bear Trap Cave, Bear Den Butte, and Black Ridge Crater, a flow of large size was emplaced. In these larger flows, trenches formed, but apparently the slope did not allow extensive drainage, producing only sporadic, minimal-length lava tube caves.

In a few cases, such as the Tee-Maze System and Gypsum Cave, flow was confined by low local topography and slope was sufficient to produce open tubes of substantial length. Pot O'Gold Cave in the

Figure 3. Typical lava tube opening in the study area (Boneyard Cave).

Figure 5. An unusual lava blister cave in the Shoshone area (Abo Dome).

Figure 4. Gypsum Cave is 2 km long. Here, the flowing lava was confined by topography, producing lava tube caves of unusual length.

Figure 6. Bifurcation in T-Maze Cave.

Figure 8. Parts of Pot O'Gold Cave are unusually spacious.

Figure 9. Ledge detail in Pot O'Gold Cave.

Tee-Maze System has a length of 2.5 km, while Gypsum Cave is 2 km long, but these are exceptional for the area.

CONCLUSIONS

Volcanic vents and lava flow played a large part in the development of the Snake River Plain. Unfortunately, environments suitable for formation of extensive lava tubes were rarely present, resulting in the prevalence of short-length tubes found today. The lavas probably formed additional tubes which were not drained due to the low slope gradient.

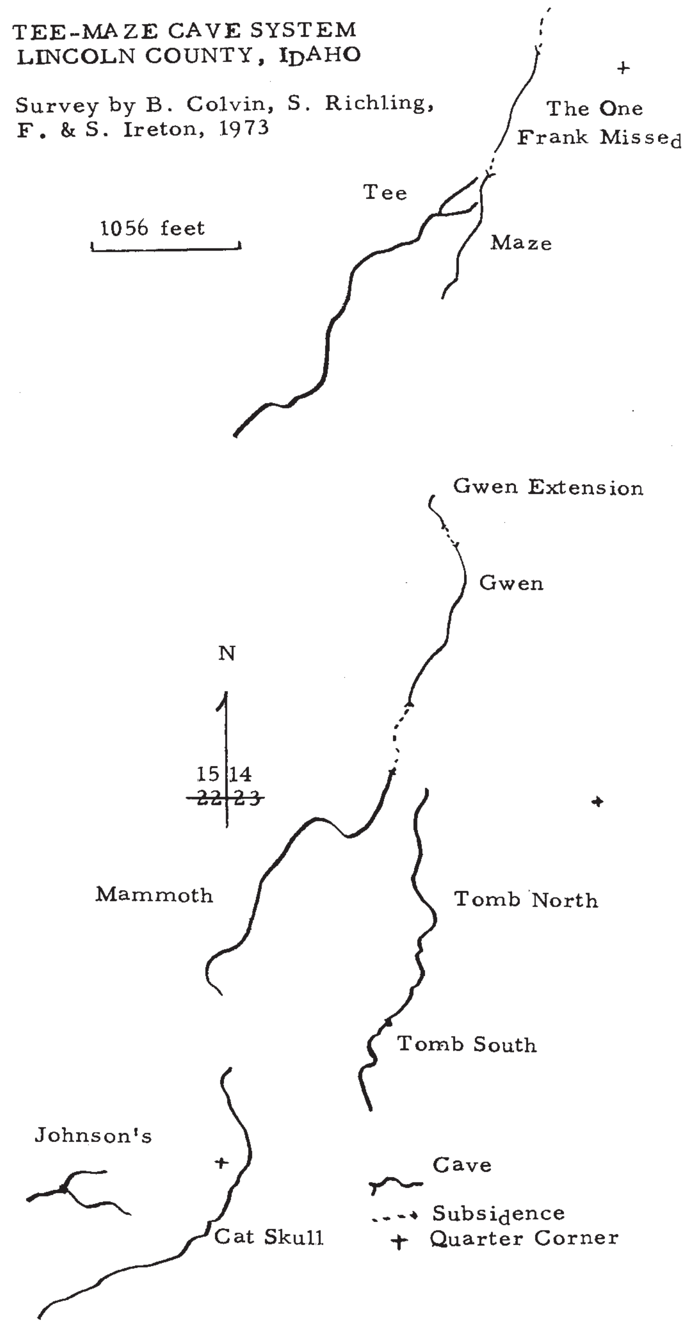

Figure 7. Tee-Maze Cave System, Lincoln County, Idaho.

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THE CATLIN GABEL LAVA TUBES OF WEST PORTLAND, OREGON
Remnants of a Plio-Pleistocene Cave System

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During mapping of the Portland Hills, the author and his students found evidence of lava tubes. Their existence was first noted during a foundation study of the St. Vincent Hospital, but their origin and extent was not apparent until our field investigation in May 1974. They occur among a cluster of cinder cones and associated lava flows of Pliocene to late (?) Pleistocene age that occupy an area of approximately 25 square miles on the west side of the Portland Hills (probably they are the westernmost of this age in Oregon), and the fragmentary remains of their lava tubes present a very unusual opportunity to study the effects of the passage of time on such cave systems.

During detailed mapping of the Portland Hills for the Portland Environmental Geology project, the author and his students found evidence of lava tubes near Catlin Gabel School on the western slope of the Portland Hills. While only fragmentary remnants remain, they are the oldest known in Oregon and present a very unusual opportunity to study the effects of the passage of time on such cave systems.

Existence of the tubes was first noted by R. J. Deacon (Shannon and Wilson, Inc. 1968) during a foundation study at the St. Vincent Hospital site just west of the Catlin Gabel School and was later discussed by Squier (1970). But the origin and extent of these interesting volcanic features were unknown until our field investigation in May 1974.

The Catlin Gabel lava tubes occur among a cluster of cinder cones and associated lava flows of Pliocene to late (?) Pleistocene age (between 5 and 1 million years old) that occupy an area of approximately 25 square miles on the west side of the Portland Hills (Figure 1). Lava tubes have not previously been described in Oregon lava flows older than Holocene (last 10,000 years).

Mount Sylvania is the largest of the Pliocene-Pleistocene volcanoes in the map area, but at least four and possibly as many as eight other volcanic vents and associated lava flows lie to the northwest as far as Germantown Road, 12 miles north of Mount Sylvania, and one other lies to the southeast. These volcanoes are probably the westernmost of this age in Oregon.

The area covered by lava flows and vents was first mapped by Trimble (1963), who assigned these rocks to the Boring Lava, a geologic unit first named by Treasher (1942) after a cluster of volcanoes around the town of Boring about 10 miles southeast of Portland.

The source of the lava containing the tubes is a small volcanic vent situated between two others near the southern end of the northern area of volcanoes (Figure 1). Its elevation is 974 feet above sea level. From the base of this vent, the lava extends south and then west for about 2-1/2 miles. It is about 500 feet wide and slopes approximately 150 feet per mile, or 3 percent (Figure 2). Near its center, the total thickness of lava is 235 feet, as shown by a drill hole located 1,000 feet south of the central depression (Schlicker and Deacon, 1967, pl. 2, C-C').

The lava overlies 434 feet of silt of the Troutdale Formation, which in turn lies upon Columbia River Basalt. The surface of the Columbia River Basalt rises very steeply to the northeast and crops out only 2,000 feet east of the vent (Figure 3).

During foundation excavation for the St. Vincent Hospital, Shannon and Wilson (1968) found that the upper lava unit containing the tubes was about 90 feet thick and the overlay was very compact silt.

Recent erosion has modified the original surface expression of the lava, and a mantle of Portland Hills Silt as much as 30 feet thick has further masked the surface. It is perhaps surprising, in view of the age of the flow, that its outlines can still be mapped with a reasonable degree of confidence (Figure 2).

A southern lobe of lava, which extends almost a mile south of Sunset Highway (Fig. 2), is interpreted to be an older flow unit, possibly from the same vent, that filled most of a pre-Boring valley.

Multiple eruptions from the source vent produced several flow units which apparently followed down a pre-existing valley on the west slope of the Portland Hills. The lava tubes developed in the uppermost flow when the surface

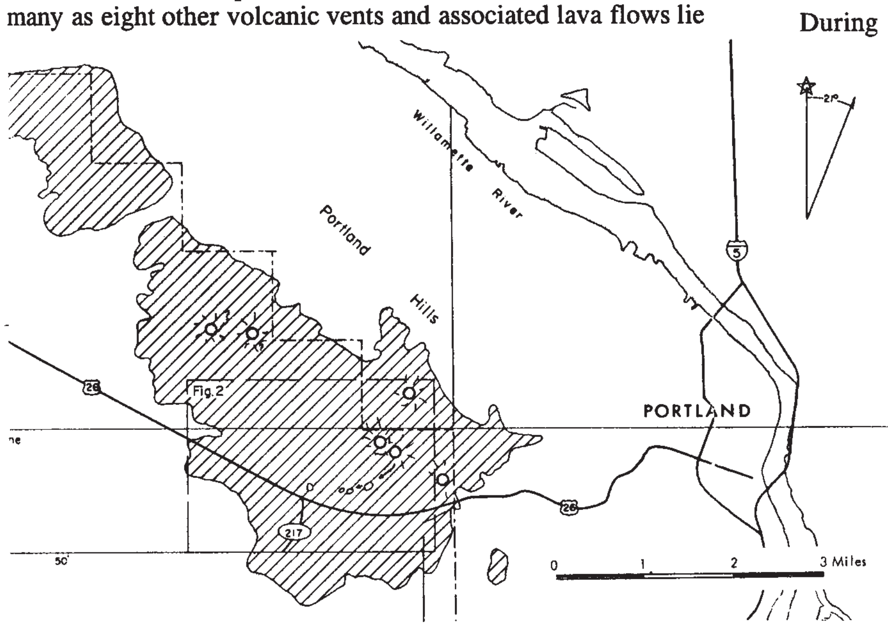

Figure 1. *Location of Catlin Gabel Lava Tube and nearby vents. Shaded areas are Boring lava of Plio-Pleistocene age.*

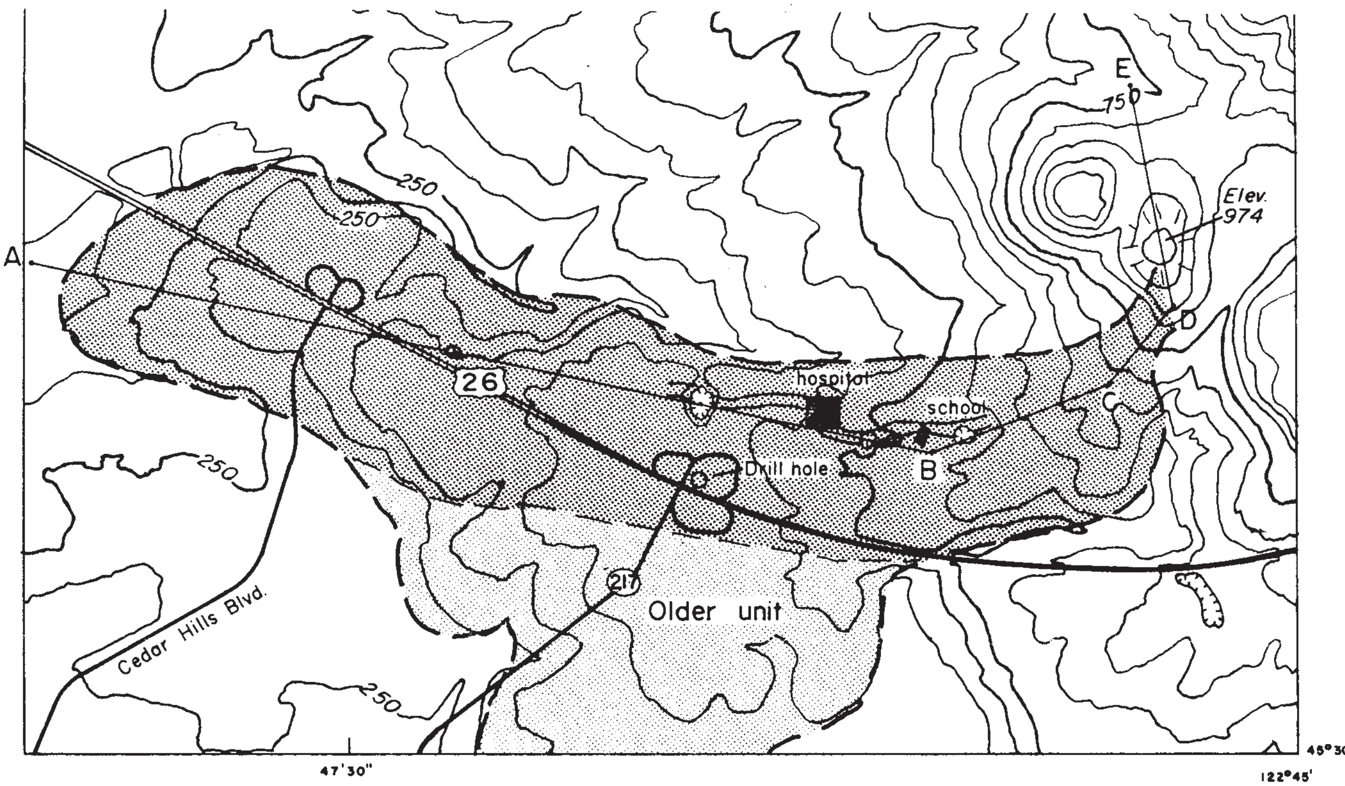

Figure 2. Catlin Gable lava flow and lava tube depressions.

of the lava congealed and the interior continued to advance until drained.

Tne lava of the latest flow extends south from the vent and then west in an arc which lies just north of and nearly parallel to Barnes Road (Figure 2). Along the center of the arc, within a distance of 6,000 feet, are five closed depressions.

From east to west, the five depressions are as follows: The first (55 feet deep and 500 feet across) lies just east of Catlin Gabel School; the next two depressions (35 and 45 feet deep, 100 and 200 feet across) lie just west of the school; the fourth (30 feet deep and 400 feet across) is north of the interchange of Highway 217 with Sunset Highway; and the fifth depression (50 feet deep, 150 feet across) lies just north of Sunset Highway and 1,000 feet east of the Cedar Hills Boulevard interchange. (See USGS Linnton 7-1/2 minute topographic quadrangle).

Since there are no visible openings to uncollapsed segments of the tube system, little is known of its characteristics. Apparently, at least part of its course was made up of branching or tributary lava tubes. At the St. Vincent Hospital site, excavation revealed two northwest-trending collapsed tubes that joined to the northwest. The two rubble-filled channels were up to 40 feet wide and 60 feet deep and required special engineering design for the foundation of the 15-story building (Squier 1970).

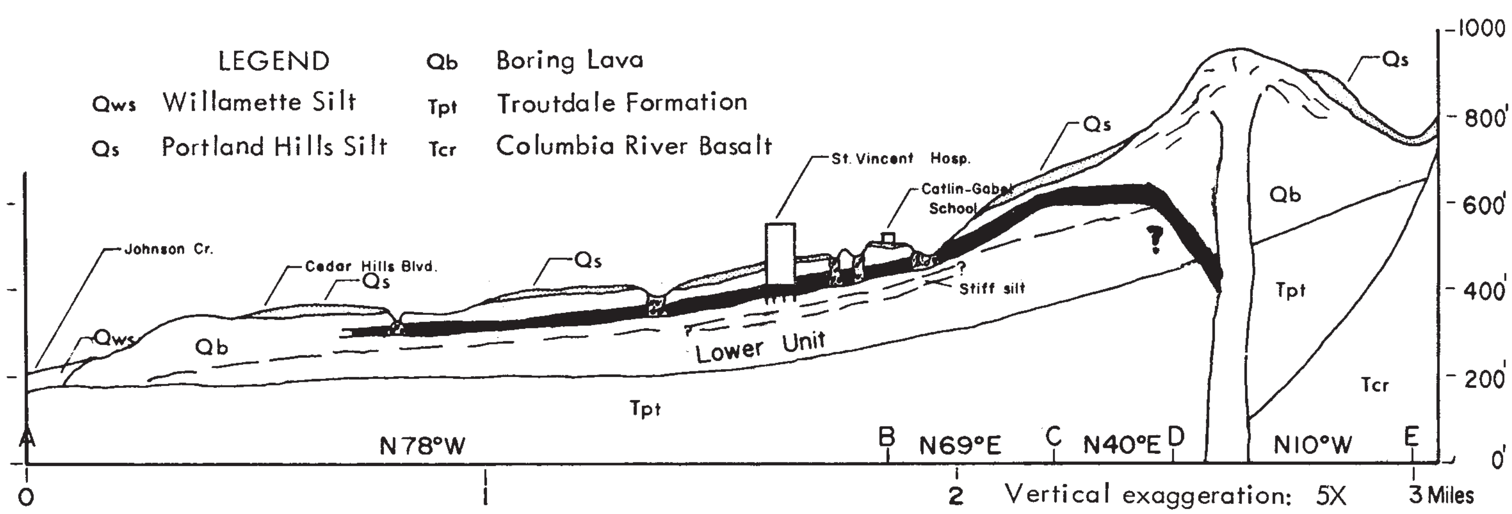

Figure 3. Generalized longitudinal section of the Catlin Gable lava flows showing relative positions of tube and latest collapse depressions. Plan of cross section A through E shown in Figure 2.

Although the cross section (Figure 3) shows segments of the tube still intact, an alternate possibility exists — the entire tube system may have collapsed. In that event, the tubes would consist of channels filled with the debris of the collapsed roofs. According to R. J. Deacon (Shannon and Wilson 1968), the "rubble-filled channels" beneath the hospital site were masked by undisturbed layers of ash and silt. This indicates that the roof of the two tubes at that location may have fallen in before the ash and silt were deposited. If this alternative is valid, it has important engineering implications: those structures such as Catlin Gabel School, that directly overlie the projected course of the tubes, would be in less danger of collapse.

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PROCESSES OF DEVELOPMENT OF LAVA TUBES AT MAUNA ULU, KILAUEA VOLCANO, HAWAII

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ABSTRACT

During the prolonged eruption of basaltic lava at Mauna Ulu from 1969 to 1974, many lava tubes developed. Conditions frequently allowed close and systematic observations, which greatly improved understanding of the processes involved.

A basic requirement for a lava tube to form is a prolonged flow at a steady rate, during which the flow becomes confined to a discrete channel. Chilling of the upper surface of the flow results in the development of thin, scum-like crust on the molten surface. Such crusts commonly adhere to the margins of the channel, and during extended flow, the crust grows outward from the margin across the flow surface. If the level of the surface remains constant, the crusts growing from opposite sides of the channel merge in the center. This initial roof is thin and weak, and either a rise or fall of the lava surface will cause it to break. But if the flow rate remains constant, continued cooling allows the crust to become thicker and stronger, and

Figure 1. Lava stream emerging from an earlier-formed tube and flowing toward the camera. A thin crust is accreting to both lateral margins of the stream and growing across the surface of the flowing lava. A few days later the crust had grown completely across the stream, forming a roof and creating a new lava tube. August, 1970.

Figure 2. Lava stream flowing from right to left, emerging from beneath a newly formed crust. On the right, the crust has been growing completely across the surface, and it is accreting downstream toward the left. Slender, flexible fingers of crust extend from the downstream edge; they gradually thicken and merge laterally and new fingers then develop along the advancing edge of the crust. The downstream growth rate may reach as much as several meters an hour. February 13, 1971.

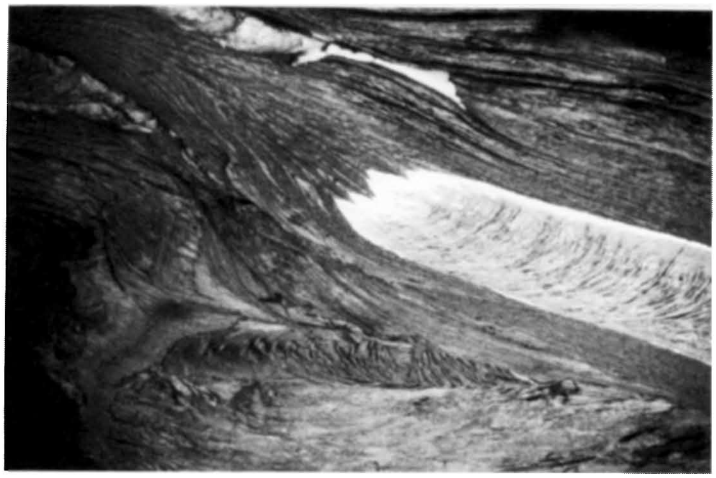

Figure 3. Aerial view of a crust forming across a stream flowing from upper left to lower right. Crust is growing both laterally across the surface from the banks and downstream from the bridged crust. Open stream is about 4 meters wide. When rate of flow remains constant, the crust continues to thicken as solidifying lava accretes to the underside of the roof. The crust is soon strong enough to support itself if the stream drops to a lower level. It also thickens if new lava flows over its surface, as seen in the upper part of this view. If the rate of flow declines abruptly before the crust has strengthened, the roof collapses and the embryonic tube is destroyed. September 26, 1972.

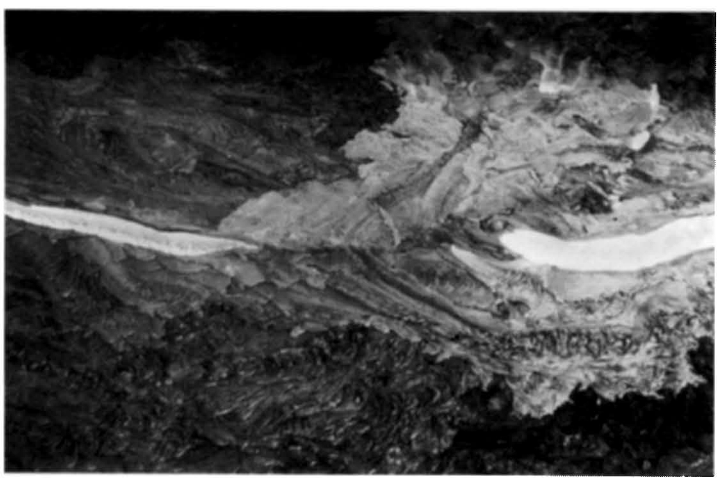

Figure 4. Aerial view of a lava stream. flowing from left to right, bridged over by a roof in the center of the view to form a lava tube about 30 meters long. A "seam" marks the line along which the crusts form each bank joined together. Downstream from the tube, the stream divides into several branches, each of which is being crusted over where it emerges from beneath the roof. Upstream from the tube, a thin crust has developed and is floating along the central part of the stream as flexible "rafts." The open stream on the right is about 5 meters wide. R. I. Tilling, December 28, 1972.

Figure 5. A second process of roof development is illustrated here. Stream, moving from the left, has rafts of floating crust that have piled up against a constriction where the stream enters a roofed-over section. By this process, the roof is extended upstream. November 7, 1973.

Figure 6. A third process of lava tube development is shown here. A channelized stream may undergo occasional brief surges, and lava overtops the banks, quickly solidifying when the stream subsides. Each overflow leaves the bank slightly higher. In this view, successive small overflows have built inward-tapering levees about a meter in height; such levees may ultimately meet at the top to form a lava tube elevated above the adjacent land surface. March 5, 1974.

Figure 7. With sustained flow, the stream within a lava tube may erode its bed to a lower level, leaving the roof unsupported. Thin or weak spots may collapse, forming skylights, which allow observations of the still-flowing lava stream. Here the surface of the active stream has dropped about 4 meters, and the thin edge of the remaining crust is about 15 cm thick. January 9, 1973.

***Figure 9.** The roof at this skylight is nearly 2 meters thick. Cooling of the molten lava as it passes by the skylight causes development of an incipient, floating crust, shown by slightly darker surface in the center of the stream. At the lower right, a crust is growing outward from the bank across the stream; it may ultimately form a complete roof across the stream beneath the skylight, forming a multi-level tube. R. L. Christianson, May 2, 1973.*

eventually it becomes strong enough to support itself. Many variations to this basic process may operate, such as bridging when floating crustal fragments are constricted. Partial collapse of roofs results in skylights, which permit observation of the flowing lava in the tube, further verifying the processes.

The roof serves as a heat insulation, and once the channel has been enclosed, the lava beneath retains its fluidity, allowing it to flow for long distances. The strong tendency for tubes to develop is a significant factor causing the gentle slopes of shield volcanoes.

***Figure 8.** View into skylight showing terraces on the wall marking levels of the surface of the stream as it dropped successively lower. Lava stalactites hang from the ceiling, formed when the incandescent coating of the tube interior achieved enough fluidity to flow. Tube diameter about 3 meters. September 11, 1972.*

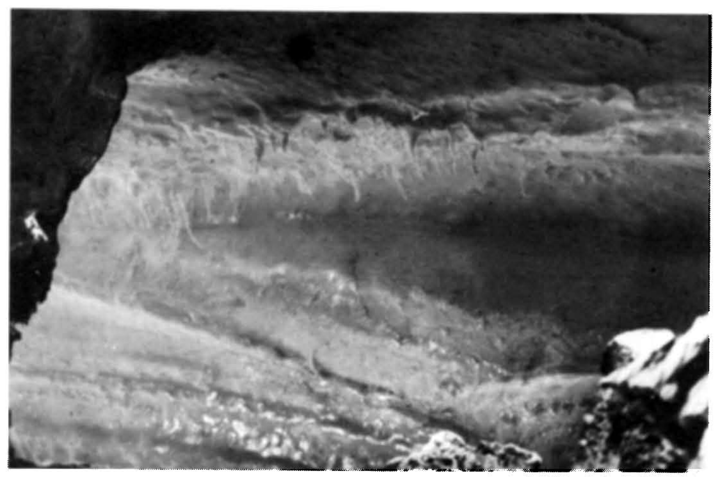

***Figure 10.** Lateral view through skylight into a tube with a sloping roof (see Fig. 6). Successive terrace levels are seen on the incandescent walls. Growth of stalactites was arrested because of cooler temperatures that resulted when the skylight formed, but some are bent toward the opening, evidently the result of hot air surging out of the opening while the stalactites were still pasty. Tube diameter about 2 meters. September 19, 1972.*

Photos by the author unless otherwise noted. (No paper received for publication)

SOME OBSERVATIONS OF HAWAIIAN PIT CRATERS AND RELATIONS WITH LAVA TUBES

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Societe Speleogique de Suisse

During a two-month expedition in Hawaii in November and December, 1981, it was possible to collect information during descents into pit craters in Hawaii Volcanoes National Park. Although the main aim of the expedition was a 16 mm movie film about speleology in lava, we had some free time to explore new lava tubes and pit craters in the Kau Desert, with the help of geologists of the volcanological observatory. In this paper, we describe the morphology of some pit craters in relation to their genesis and terminology (crater, pit crater, cone crater) and we consider whether there are relationships between known lava tubes near the surface and lava tubes or "pseudo lava tubes" inside magmatic chambers developed under or near "pit craters" along fault zones or dikes. In comparison, a standard lava tube (John Martin's lava tube) of 6.4 km, partly explored and surveyed during the expedition, also is described.

INTRODUCTION

The well-known Hawaiian Islands are situated in the northern Pacific Ocean. This area provides good examples of lava tubes because of the existence of large, low-angle shield volcanoes such as Mauna Loa and Kilauea. Our investigations took place on the island of Hawaii near Kilauea Caldera in the Puna District and in the Kau Desert.

During November and December 1981, five members of the Speleological Society of Geneva (Switzerland) stayed on the "Big Island" of Hawaii for speleological explorations and the production of a 16 mm documentary film about lava tubes and pit craters. On this occasion, it also was possible to collect information and make observations in relation to the pit craters' genesis and evolution. During the expedition, almost 8 km of new galleries were explored and mapped. Pit craters were explored to a depth of 90 meters. Our interest was not limited to the extent of the lava tubes or pit craters, but included the relations of the genesis, the morphology, the evolution and the mineralogy of these structures.

First, we shall describe some discoveries of lava tubes and pit craters during our trip and relate some observations in relation with these subjects.

LAVA TUBES

Our main work was to explore and map 6,263 meters of John Martin's Lava Tube. Previously, members of the Cascade Grotto of the National Speleological Society had explored 2,200 meters of this cave (Wood 1980). This is a very interesting lava tube, with many different features. From observations in this cave and on the surface, we have tried to develop an outline of the formation of lava tubes.

During an eruption, the lava effusion can move among dikes or fissures without necessarily coming to the surface. On the other hand, when it emerges as lava fountains or flows, fluid lava quickly begins to descend along sloping channels and a current begins, following the steepest gradient, and forming a river which is the quickest path to the fore of the flow. There it finds an outlet.

Fed incessantly by the river upstream, this lava torrent gradually "erodes" the former underlying flows, and bit-by-bit, creates an ever-deepening channel. As proof of this, we observed at Apua Cave how a small tube, which had formed before the last flow, was crossed by the new lava tube (on the left bank). We take this to be proof of a major flow with wide-scale lava emission, because in more minor flows, tubes can only develop in the subsequent flow without affecting earlier deposits. Active trenches between 3 to 20 meters wide can reach a depth of 5 to 10 meters.

As the most active current tends to flow along the bottom and center of the canal, the speed of flow tends to lessen at the surface, and when it comes in contact with the air, a crust forms on top. This solidification also occurs in the case of overhangs which tend to form on upper levels of the trench. And so the "lava tube" comes into being, with the surface crust hardening in contact with the air. With new flows from the same eruption, new layers build up on the outside, which may be unable to use the original tube with limitation of the rate of flow, and overflow in successive layers. Thus, several meters of lava may separate the tube from the surface at the end of the eruption, as is the case of Apua Cave.

The rate of flow in the tube can vary in the course of an eruption and thus internal flow can be "phreatic" or "vadose." Massive basalt banks form bulges or shelves. Taking into

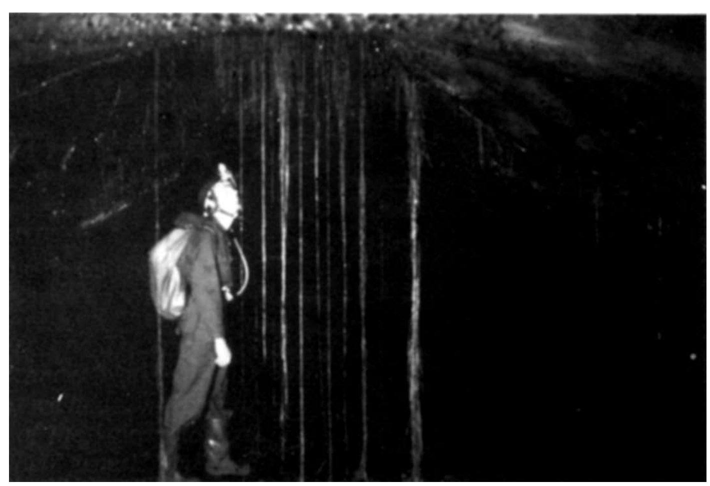
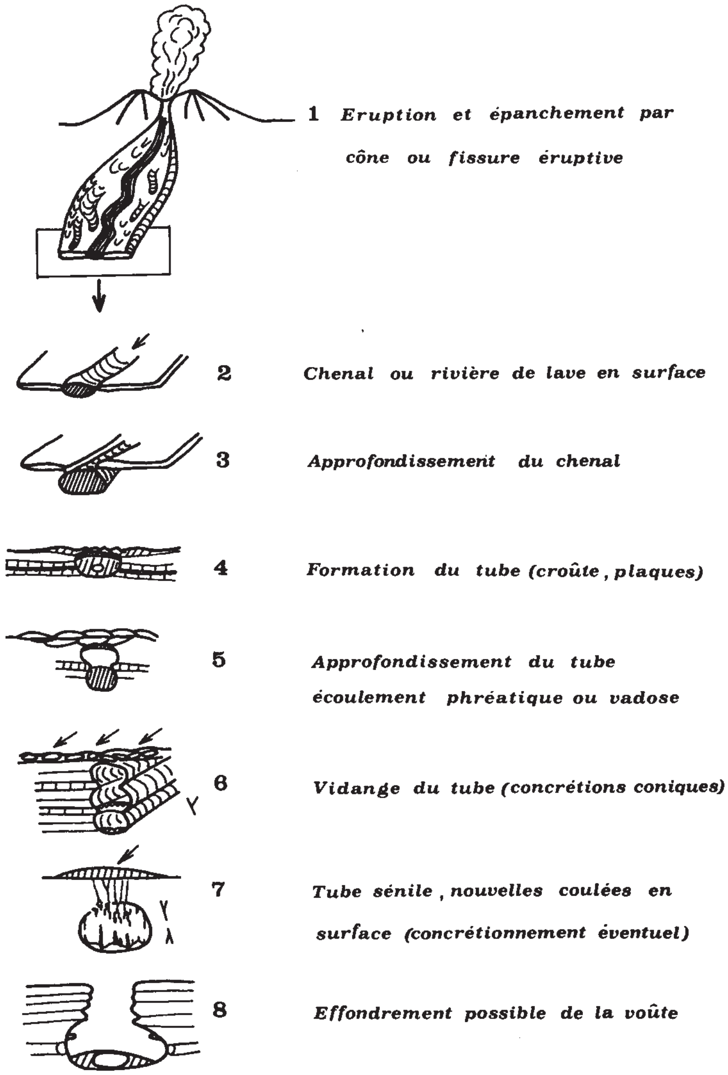


Photo 1. *Roots penetrating the roof of John Martins Cave, Puna, Hawaii.*



account the fluidity of the lava, these findings are quite feasible with hydraulics, and our observations coincide with theory.

In the course of its movements underground, the lava loses only a little of its thermal energy and when it appears several meters down slope ahead of the flow, the lava often appears as a radial or deltaic system, from ramifications of the main tube. During variations of the rate of flow (either during the initial outpouring or later), the lava stream flows freely in the tube. In certain cases, lava tubes form, and in others, small residual streams congeal later. In still other cases, rough lava streams ("aa") use tubes formed in "pahoehoe." When flow slackens, lava sumps hinder its progression.

At the end of an eruption, lava in a tube fan drains off down slope because basalt retains its mobile characteristics in the tube being sealed off from surface air. Once it has drained, the tube may undergo a process of concretion, forming lava stalactites and stalagmites by lava coming from new flows, filtering through fractures and dripping into the tube, like drops of melted wax. Then, in the old-age period of the tube in which the roof may collapse, being thin or broken, if "skylights" or longer unroofed segments do not exist, the tube may be protected from subsequent filling by later flows.

In the case of fluid lavas, the lava tunnels or tubes thus act as transporting stages for the formation of lava streams which in certain cases (Australia) can be as long as 100 km. Effusions of such scale by purely surface flow, quickly cooled by atmospheric air, are difficult to imagine. This observation shows the essential role played by these tubes, and is important in the understanding of the emplacement of lava fields and of the geomorphology of the Hawaiian volcanoes. Flattened cones would not appear without these volcanic channels and lava tubes, thus emphasizing the importance of listing, exploring and classifying lava tubes, as well as observing their morphology. It is clear that numerous types of lava tube formations exist. From a speleological standpoint, Hawaiian lava tubes represent underground networks with a long horizontal extension.

PIT CRATERS

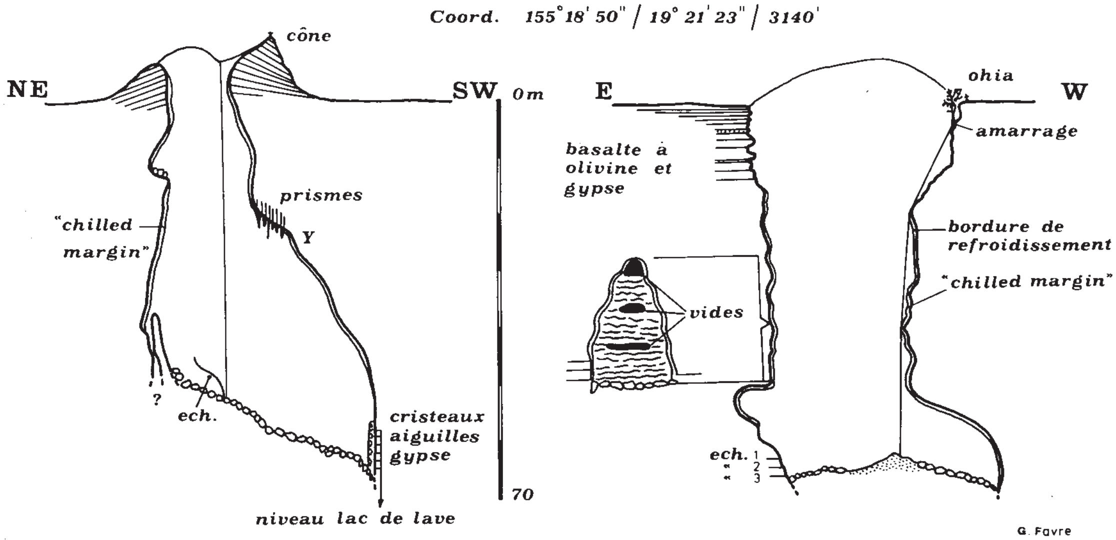
Pit craters are holes in the volcanic base which have developed by stoping of underlying magmatic chambers. These "volcanic gulfs" have no direct relation with the type of lava tubes just mentioned. Their existence is linked to major masses of molten lava which have built up underground and erupt through fissures or **cone craters**, which are volcanic cones 10 to 50 meters high. When such lava has erupted and its depth has decreased, significant gaps develop about ten meters below the surface. These appear soon, as the roof collapses. The cross section of the cavity therefore is similar to collapse features in limestone, often on a grand scale. In Hawaii Volcanoes National Park beside the highway, Puhimau Pit Crater measures no less than 200 meters in diameter and is 150 meters deep. One hundred meters of rope is needed to reach the talus slope at the bottom. No entrance exists for entry into subterranean magma chambers here. Along the walls, gas emissions hamper ascents and descents, but this is an excellent natural cut for stratigraphic studies.

PIT CRATERS AND CONE CRATERS

With geologists from the Hawaiian Volcano Observatory, we went to the center of the Kau Desert to explore several pit craters and to attempt to explain the relationship between these collapses and lava tubes. Here, three aligned orifices approximately 30 meters in diameter appear punched into the basalt plain. Only the easternmost emitted lava; it is surrounded

Photo 2. *Pit craters, Kau Desert, Hawaii.*

Cône et Pit Craters (KAU DESERT)



by a volcanic cone 10 meters high. This is a cone crater; the other two are pit craters. The westernmost already had been explored by Norman Banks, an American geologist. He descended as far as minus 60 meters. The central crater (#2) has an opening about 30 meters in diameter. Because of the danger of falling rocks, only one of our group reached the bottom, at minus 70 meters. At minus 15 meters was the solidified margin of the magma chamber (its roof). After 40 meters descent, we emerged into an enlarged chamber which continued on into the depths. There, also because of numerous collapsed rocks, we did not continue further back. We collected three samples of the rock surface.

At the cone crater, we found difficulties in anchoring, because of the lack of rocks or trees nearby. With the aid of a 40 meter ladder, we encircled a large rock and made a descent. The view was very aesthetic for 50 meters. We landed on a rock cluster at the bottom of a chamber, the sides of which were covered with small gypsum needles.

These three cavities do not open out into a vast underground system. Nevertheless, they form a very interesting trio, significant to our understanding of related phenomena. Very near the surface, magma can be stored for a time in lateral spindle chambers which interconnect along the axis of the break. Since the two pit craters on the western side are the result of stoping of a thin overburden and the cone crater served as an outlet for lava from the system, it may be inferred that other caverns linked with the surface must exist nearby, as seen in the following example.

WOOD VALLEY PIT CRATER

Located on the western edge of the Kau Desert, not far from the main road, this pit crater opens as a circular shaft 30 meters deep and 30 to 40 meters in diameter. Massive surficial basalt forms on overhang to a depth of 10 meters. After a vertical drop past a mass of large fallen rocks (which are the home of wild bees), we reached the first ledge at minus 40 meters. Edging further downward another 10 meters, between stratified lava and breakdown, we reached an underground magma chamber, the floor of which was cluttered with rocks. Only the arch and surface lining of stratified lava are covered by a congealed basalt margin typical of these lava reservoirs.

At the far end of this cavern, we again crawled through scattered rocks and at minus 90 meters, we came out at a totally glazed lava tube which, after 80 meters, led into an underground magma chamber which is entirely intact with no breakdown. The room towers 40 meters and various stalactites hang from the stratum. It is 40 meters long and 10 meters wide. At the far end is a narrower tunnel from which an air current was emerging. After crawling or ducking for about 100 meters in a passage 8 x 5 meters, is a lava sump.

Photo 3. *Cone crater and wall of pit crater, Kau Desert, Hawaii.*

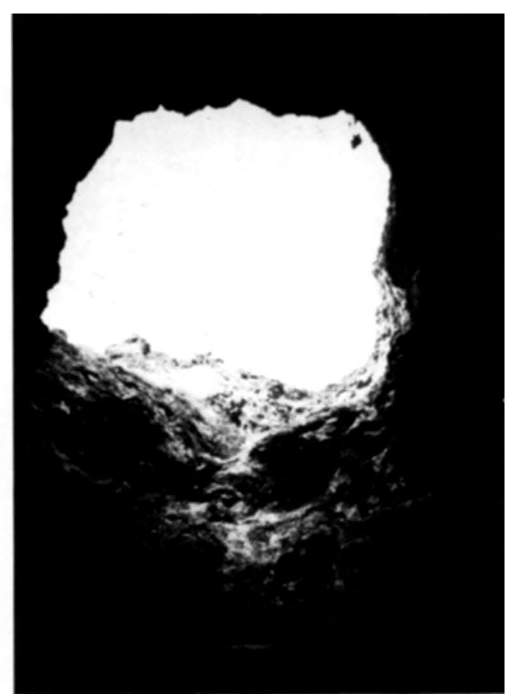


Photo 4.*Looking upward in cone crater, Kau Desert, Hawaii.*

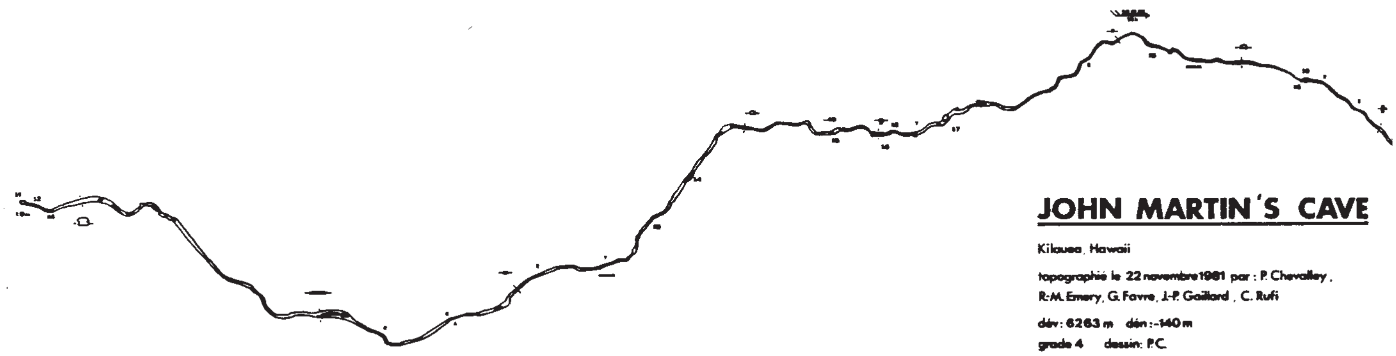


Photo 5. *Mauna Ulu, Hawaii.*

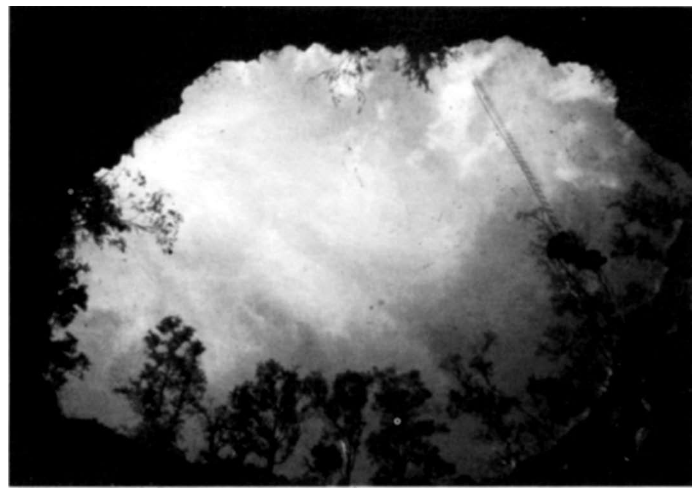
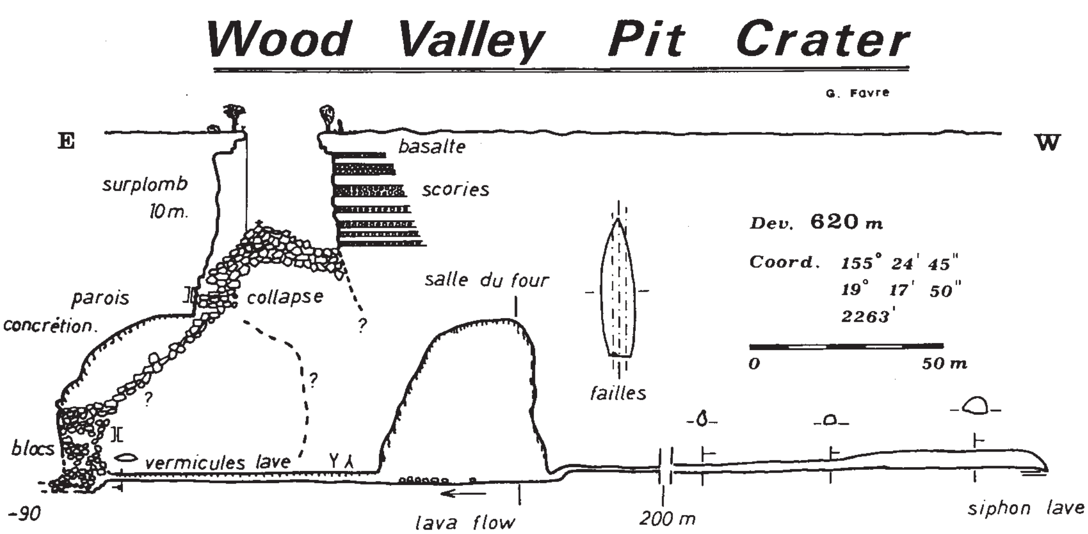
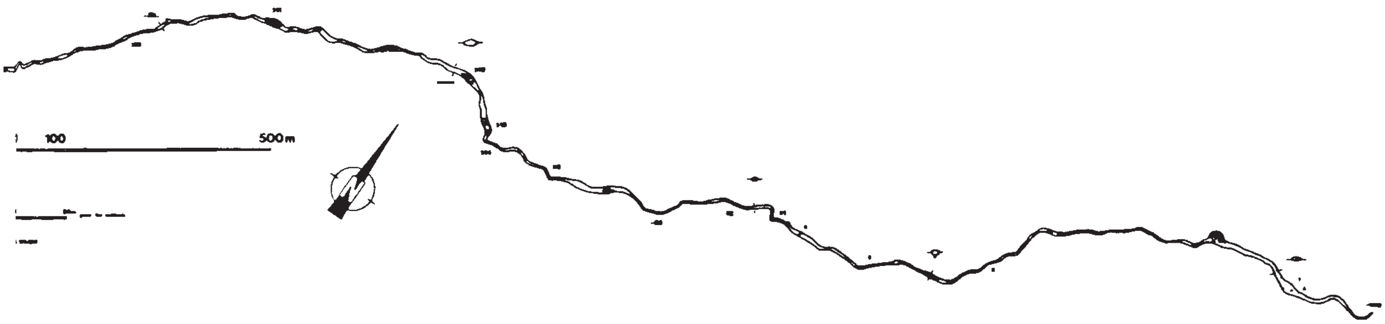


Photo 6. *Looking upward in Wood Valley Pit Crater, Hawaii.*

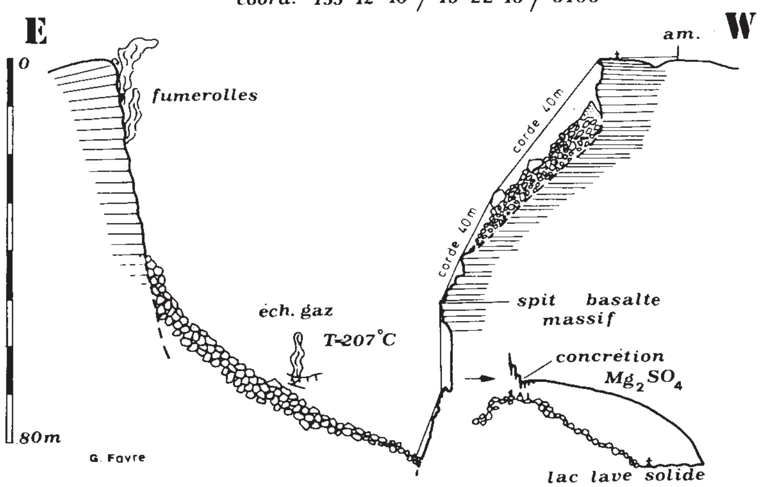
This unusual discovery raises an interesting question of the relation between pit craters and lava tubes. The final section of this tunnel resembles an ordinary lava tube at surface level. Yet it is clearly a lava tube of different origin, or "pseudo lava tube." It seems very unlikely that an old lava tube would have developed precisely aligned with the vertical fractures which we observed in the chamber. Taking into account the changes in the course of the lateral section, we believe that this is a vertical pipe of tectonic origin with its lava derived from a dike. At magma chambers of the form we observed and in certain other fractured sites, bedrock somehow can be consumed by magma moving along the axes of fracture. Along this tube, a lava stream traveled from west to east. At the base of the mass of fallen rocks, in the continued axis of the system's development, other holes may exist.





Mauna Ulu Crater

coord. 155° 12' 10"/ 19° 22' 10"/ 3100'



MAUNA ULU CRATER

Mauna Ulu is one of the most recent volcanic structures, having been active from 1972 to 1976. Its major flows extended south 12 km to the ocean. Some gas emissions still continue at the edges and in the depths of the crater.

At the head of this crater is an oval "mouth" about 125 by 100 meters in a unsymmetrical cone. Scree-covered slopes on its southwest side cover alternating strata of scoria and basalt. On the opposite wall, thick and thin basalt layers are seen. Some gas-emitting fissures exist on the upper side. At the foot of the southeastern side, their temperature reaches 207° C, but on the southwestern side, they reach only 55° C.

Ten meters above the highest point between the rock mass and the wall is a former magma chamber, recognizable by the congealed layer which lines the walls and covers the original strata. Its lenticular orifice is 15 meters long and 2 meters high. It is wholly covered by an extraordinary forest of peculiar concretionary forms of magnesium sulfate, lemon-yellow, orange, pale green or creamy white in color. The existence of such formations was previously unknown in Hawaii. Some loose samples were recovered for analysis.

The blocky incline falls away sharply and we came to the surface of a lake of solidified lava. Its temperature proved that molten lava was not very far.

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Editor's note: The April, 1980 issue of *Cascade Caver* (19:4) contains several accounts of explorations and studies on the island of Hawaii in November and December, 1980, including John Martin Cave, Kazamura and nearby caves; Kaumana, Makalei, Apua, Blair caves; Cave of Refuge, Joel Cave, and the first descent of Western Cone Crater by Phil Whitfield, Dave Jones and Norman Banks. It also contains vulcanospeleological abstracts and reprints of earlier reports, and accounts of a few caves on Oahu and Maui.

Photo 7. *Spelean chamber, Mauna Ulu Crater, Hawaii.*

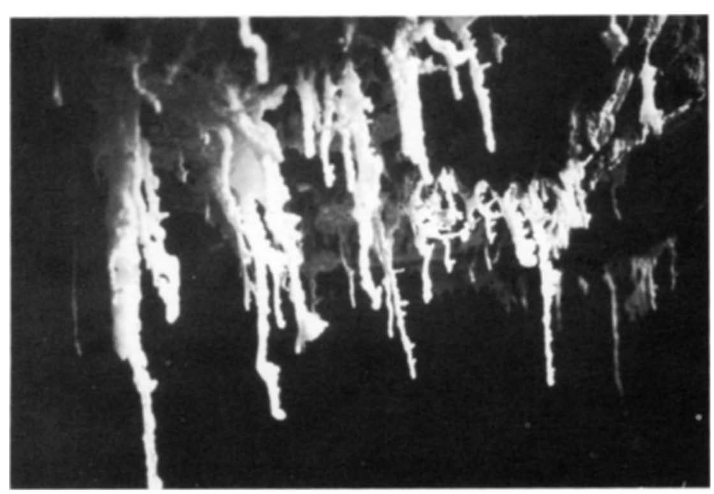

Photo 8. *Magnesium sulphate stalactites and helictites, spelean chamber of Mauna Ulu.*

THE UNITED KINGDOM SPELEOLOGICAL EXPEDITIONS TO THE HAWAIIAN VOLCANOES

C. Wood
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In 1979, a team of British cavers explored nearly 30 km of cave passage on Kilauea and Mauna Loa volcanoes, Hawaii Island. Detailed investigations of the lava flows produced during the 1969-74 Mauna Ulu flank eruption of Kilauea proved the existence of some respectable caves, one of which was an outstanding stalactite cave. The speleological work added significantly to the knowledge of the Mauna Ulu tube system, the formation and operation of which was previously observed by scientists from the Hawaiian Volcano Observatory. Exceedingly long lava tube caves were discovered to be very abundant elsewhere on Kilauea, particularly on the northeast flank. Here, Kazumura Cave was mapped to a length of 11.713 km, while Ainahou Ranch Cave on the south side of Kilauea was mapped to a length of 7.11 km. The expedition was left with the overwhelming impression that there is an enormous potential for very long caves on the Hawaiian volcanoes, and that these caves are full of geological, biological and archaeological interest. It is for this reason that a second expedition is being mounted from the UK to investigate more caves on Kilauea and Mauna Loa in 1982.

INTRODUCTION

Few cavers appreciate the speleological significance of the island of Hawaii. Entirely volcanic, and geologically very young, this island is likely to yield some of the world's longest and deepest caves. Its lava tube caves were little investigated until a party of UK cavers undertook a program of systematic exploration and mapping in 1979. In five weeks, the party explored 30 km of cave passage, of which 24 km were mapped. Important geological observations were made relating to the morphology and operation of lava tube systems. So successful was the 1979 UK expedition, and so abundant were the Hawaiian caves, that a second expedition to Hawaii Island is planned for 1982. This paper reports on this first comprehensive study of the Hawaiian caves, and outlines the proposals for the impending 1982 expedition.

BACKGROUND GEOLOGY

The Hawaiian Archipelago represents the southeastern end of a submarine mountain range, known as the Hawaiian Ridge. The ridge has been constructed above a melting zone in the earth's interior. It consists of a row of enormous volcanoes, some rising to as much as 9 km above the ocean floor. Volcanism has now ceased throughout most of the length of the ridge, except on the island of Hawaii at the extreme southeast. This island apparently lies closest to the modern melting zone. It is renowned world-wide for its active volcanoes; Mauna Loa and Kilauea.

The island of Hawaii may have been built from seven or eight volcanic edifices, though only five are apparent today. Listed in the order of oldest to youngest, with heights above sea level, these are Kohala (1,670 m), Mauna Kea (4,206 m), Hualalai (2,521 m), Mauna Loa (4,170 m), and Kilauea (1,228 m). Mauna Loa and Kilauea have been repeatedly active throughout the last century, with Mauna Loa erupting on *average* every 3.8 years, and Kilauea displaying some form of activity perhaps every 2-3 months.

The Hawaiian volcanoes are immense lava cones, each composed of many thousand thin basaltic (tholeiitic) lava flows. Mauna Loa is the archetypal "shield volcano;" its immense smooth, low-angled profile is indicative of a shield under development. The older Hawaiian volcanoes are capped with more alkaline and silica-rich lavas, ashes and cinder cones, making their profiles steeper and more irregular.

Kilauea is smaller than Mauna Loa, but it is nonetheless truly shield-like. Like its neighbor, it possesses such characteristic features as a large summit caldera, pit craters, and radiating eruptive fractures known as rift zones.

REASONS FOR THE 1979 EXPEDITION

What was the attraction that drew eight cavers half-way around the world to look for caves on the world's most active volcanoes?

A. **Reports in the Caving Literature:** The caving literature contains many indications that Hawaii could be fruitful speleologically. Halliday was making such comments as far back as 1955 (Halliday, 1955), while recently Mills (1979) listed 158 references to Hawaiian caves. Howarth (1972) described the 10 km-long Kazumura Cave, while Greeley's *Hawaiian Planetology Conference Guidebook* (Greeley, 1974) contains abundant evidence of a wealth of caves on Hawaii Island. Most recently, visits to Hawaii Island by the cavers Stephen Kempe (Kempe, 1978) and Jim and Libby Nieland (Nieland and Nieland, 1978) have shown that exciting caving can be done on the island with only limited resources.

B. **Scientific Reasoning:** In a thesis on lava tube systems completed in 1978 (Wood, 1978), this author proposed that equilibrium lava flow through lava tubes may account for the apparent anomaly of exceedingly long lava flows emplaced down very low-angled slopes. The proposal is far reaching, for

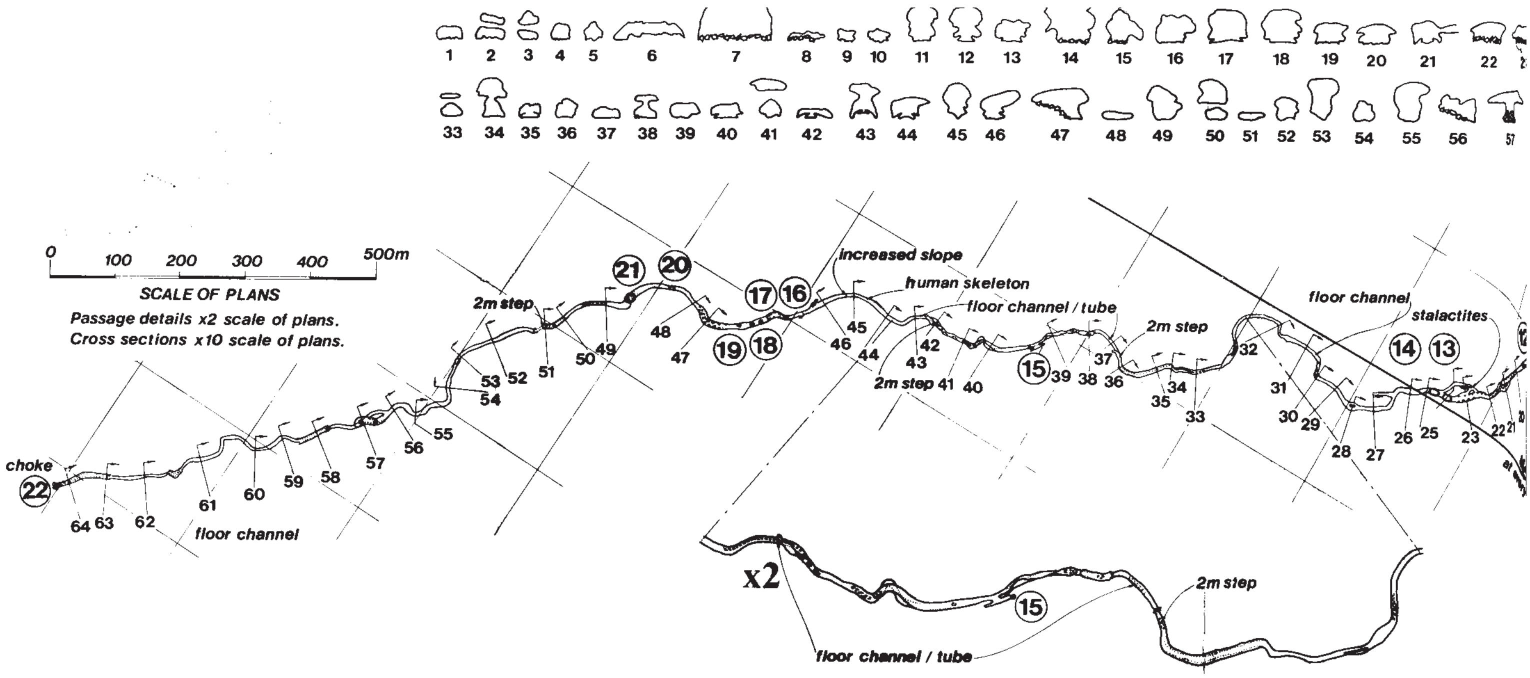
Figure 1. *Apua Cave is a principal feeder below major palis, and probably conveyed much of the lava that constructed a coastal delta.*

Figure 4. *Secondary mineralizations also are present in Apua Cave.*

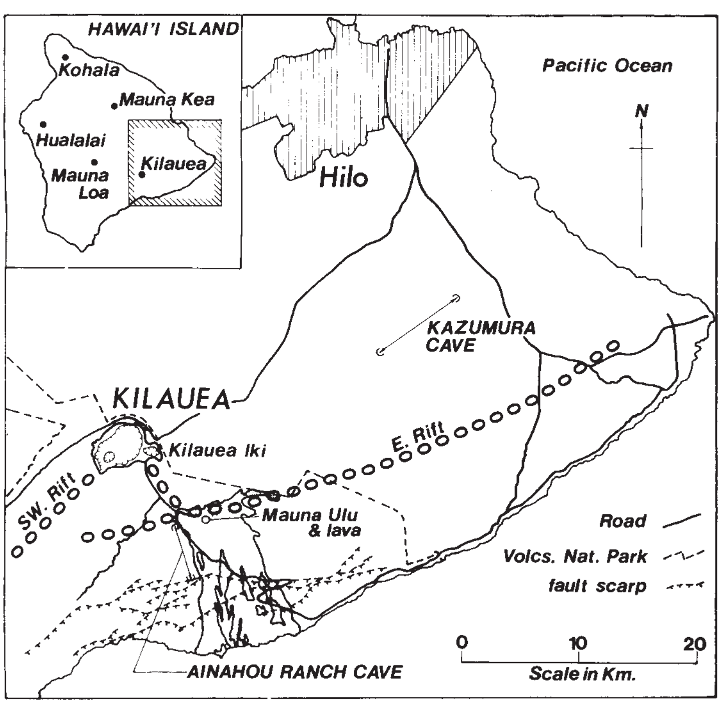
Figure 6. *Away from the axial feeder tubes, toe extension appears to have been the major method of advance of the flow. Where the Chain of Craters Road has sliced through the Mauna Ulu lava, cross sections of many small lava tongues are visible and several have a small cave at their core.*

Figure 7. *Caves a considerable distance downflow from the vent have a wall structure composed of horizontal units ranging up to 2 or 3 m thick. Such a structure does not reflect tube construction from channel closure, and may result from evolution by tube enlargement and extension behind a steadily advancing flow front, with the axial feeder tube elongating across earlier delta zones and capturing dispersed flow. Photo by B. Weaver.*

Figure 5. *In the Mauna Ulu flows, each major tongue-shaped unit contained a large axial feeder tube; the walls of the axial tubes were composed of many thin, superimposed sheet flow units which represent layered overflow from the channels from which the tubes evolved.*



Location map



Long Caves of Kilauea

ACKNOWLEDGEMENTS:

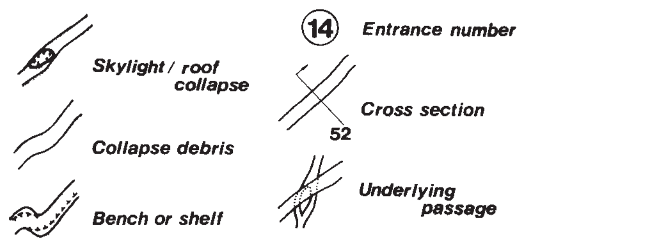
Mapped - Aug. 1979 by UK Speleological Expedition to Hawai'i.

Calculation of co-ordinates - Dec. 1979 & May 1980 by Ivan Young.

Plotted - Ainahou Ranch Cave, Feb. 1980 by M.T. Mills. Kazumura Cave, June 1980 by C. Wood.

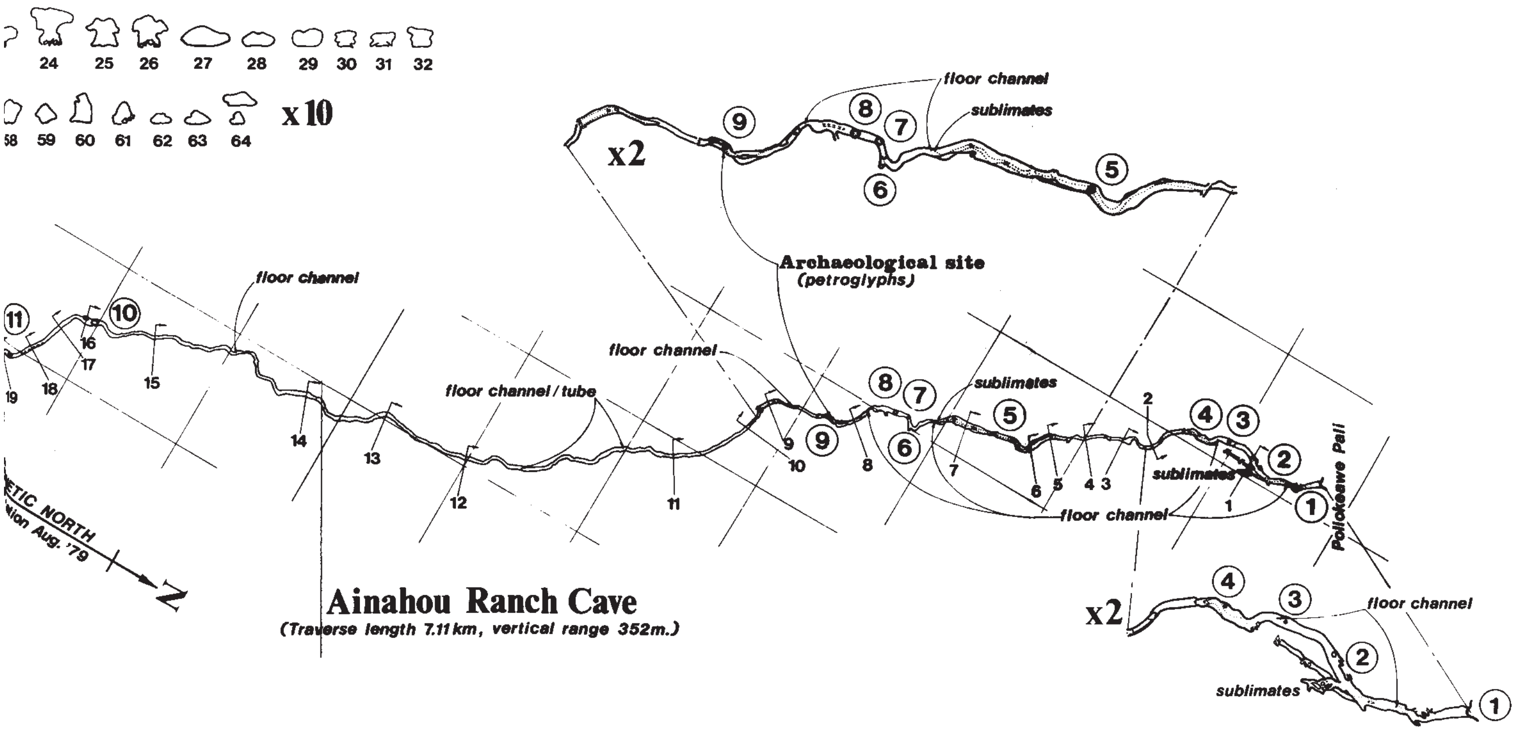
This map compiled and drawn July 1980 by C. Wood.

KEY:



in theory accumulations of tube-fed flows would form a shallow lava shield if they were erupted from a single vent, or form an expansive lava plain if erupted from multiple vents. To some extent, this was borne out by a photogeological study of the summit area of Mauna Loa by Greeley, Wilbur and Storm (1976), when it was estimated that 82% of the surface lava flows in the study area were either tube-fed or channel-fed. Clearly, a speleological expedition to the Hawaiian volcanoes would test this proposal further.

C. **The 1969-74 Mauna Ulu Flank Eruption of Kilauea:** Observations of the Mauna Ulu flank eruption of Kilauea confirmed much about the operation and construction of lava tube systems, and drew the attention of geologists to the important role played by lava tubes in the development of Hawaiian-type shield volcanoes (Greeley, 1971 and 1972; Cruikshank and Wood, 1972; Swanson and Tilling, 1974). Yet, because of the subsurface nature of functions of lava tubes, many important observations could not be made during the



olcano, Hawai'i Island.

Figure 9. Apua Cave is notable for its content of lava stalactites and stalagmites. Photos by A. C. Waltham.

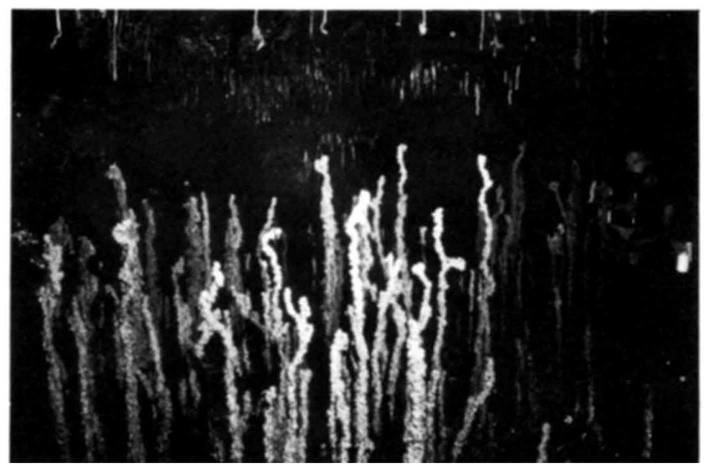


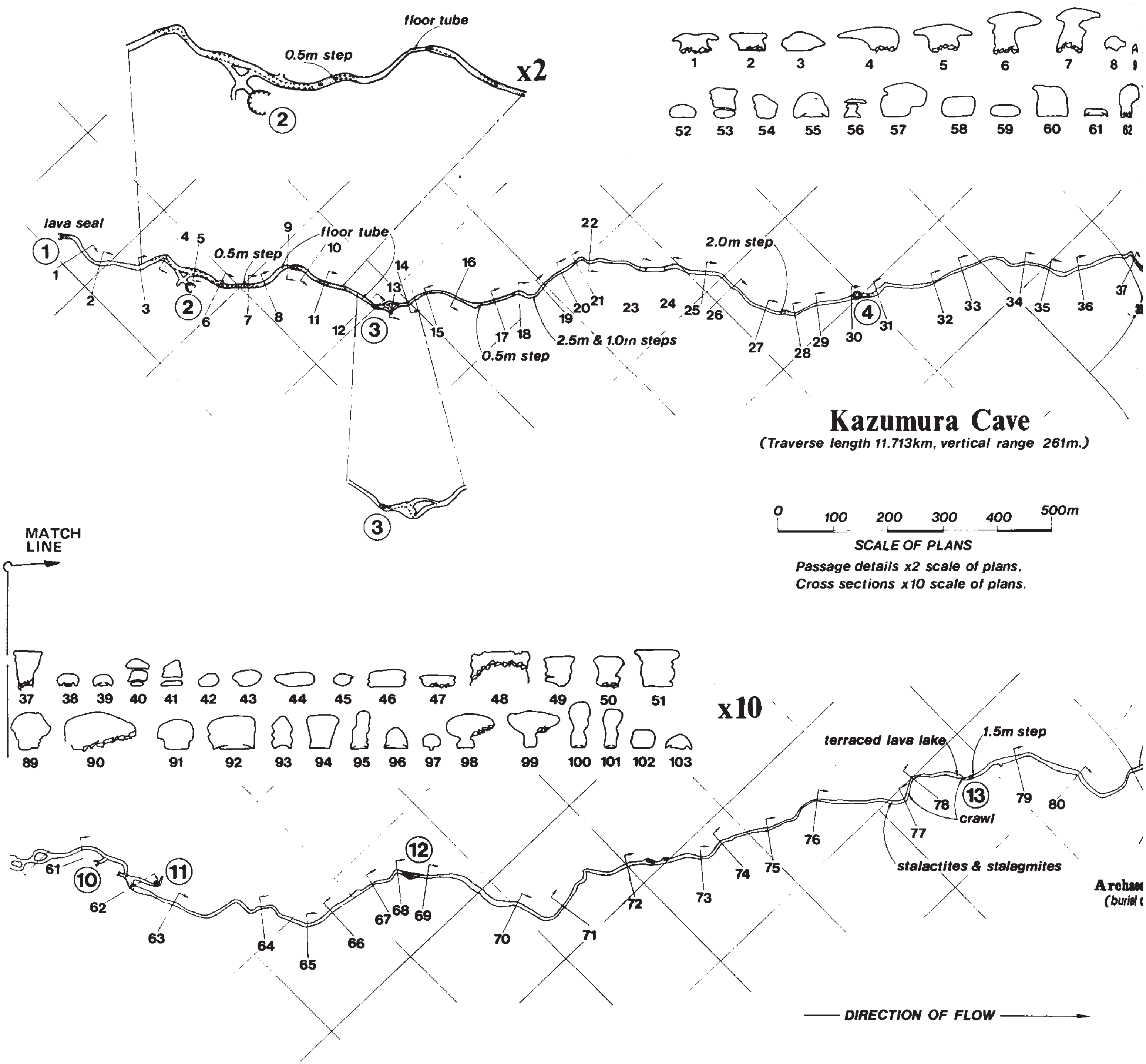
Figure 10. Apua Cave is notable for its content of lava stalactites and stalagmites. Photos by A. C. Waltham.

activity. If the Mauna Ulu tubes had drained and cooled, however, the resulting caves could be entered and mapped. The results, together with the previous observation of the liquid flow through these tubes, would provide a basis for an interpretation of the morphology of the tube system, and a partial understanding of the mechanics of the lava river it transported.

Here on Hawaii, then, was an unrivaled opportunity to undertake exploration in caves of probable world stature, and in so doing, to advance our knowledge of tube-fed lava flows and the formation of major basaltic landforms, such as shields and plains.

CAVE DESCRIPTIONS AND GEOLOGICAL OBSERVATIONS

Particularly important in an understanding of the development of the Hawaiian volcanoes, was the spectacular eruption from the upper east rift zone of Kilauea between 1969 and 1974. A new parasitic lava shield, eventually called Mauna Ulu, 120 m high and 2 km across, was constructed astride the rift. Lava flows, fed mainly by a complex system of lava tubes, tumbled down immense fault scarps (palis), before they entered the ocean 15 km distant from the vent. These flows ultimately covered 4,050 hectares of bush and forest within the Hawaii

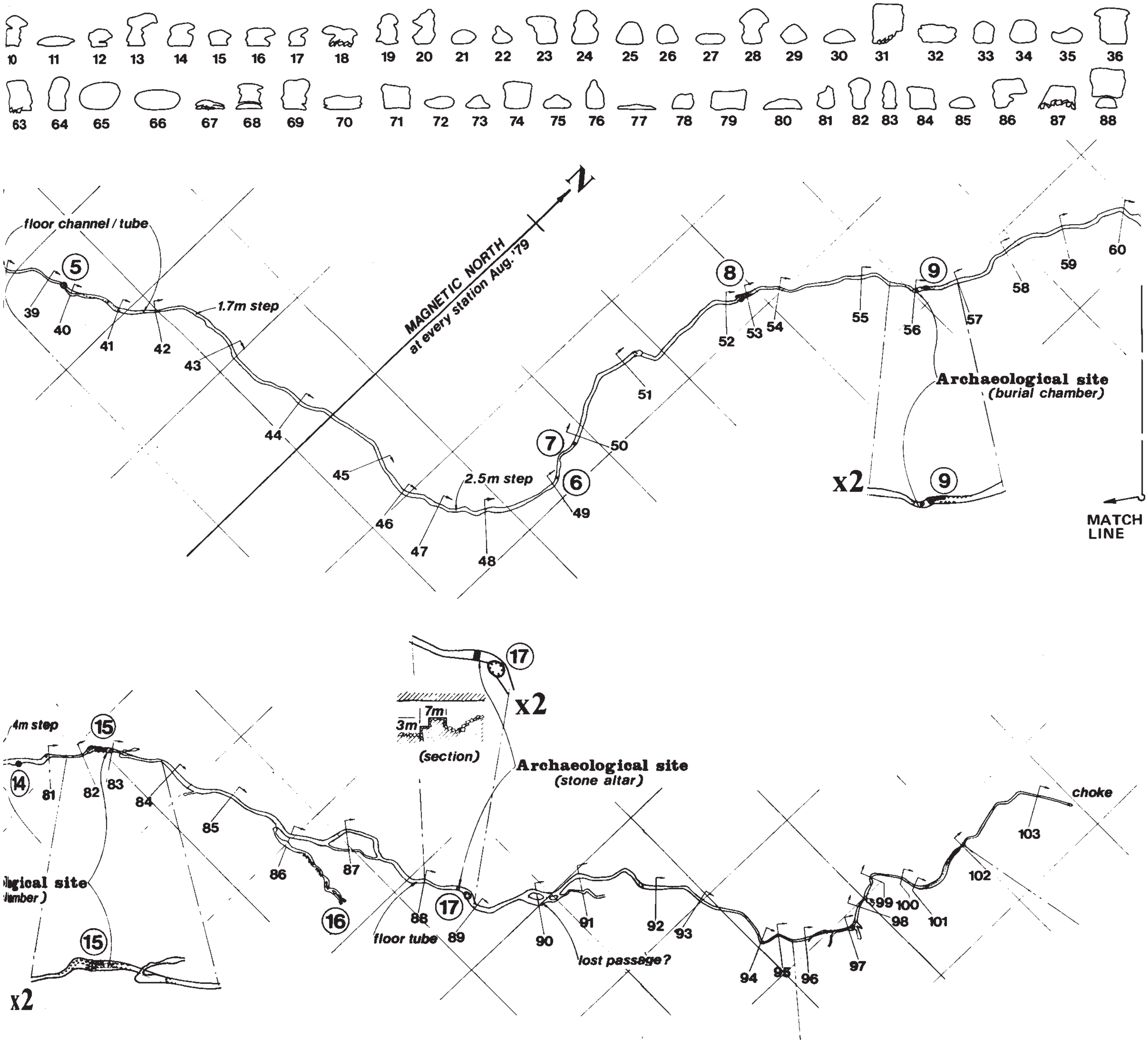


Volcanoes National Park, and added 80 hectares of new land at the coast.

During the activity, geologists were able to establish the routes of principal lava tubes from the lines of fume clouds emitted from skylights (roof collapses over an active tube). This information enabled Robin Holcomb to plot the position of the main tube-lines with some accuracy when constructing his map of the cooled flows (Holcomb, 1976). Holcomb's map, plus published observations of the eruption, formed the basis for cave hunting in 1979. The system we adopted each day was to follow a single tube-line from vent to coast, investigating each of the many skylights and post-activity collapses in the hopes of entering a significant cave.

The beautiful, glassy, contorted patterns of the surface of the Mauna Ulu lava must be seen to be believed. Vast seas of pahoehoe billow in the flows, at times overlain by aa clinker. Open and closed channels abound, and it was plain how the contorted patterns of the flow surface recorded the style of the emplacement of the lava. Yet, these beautiful expanses of glassy toes held danger, for reflected sunlight caused bad sunburn, and bodies became quickly dehydrated.

The party must have examined several hundred likely



looking holes in the surface of the flow. Many were very interesting, and one tube line in particular possessed over 30 spectacular skylights and post-activity collapses, overlying 2 km of segmented cave.

Nearly 3 km of cave passage was discovered in the Mauna Ulu lava by the expedition. Most of the parent lava tubes had drained off very little of their liquid flow, and many caves contained long crawls. Several were quite well decorated, although some of the caves are within 100 m of the Chain of Craters Road and future vandalism is expected.

Particularly outstanding was the largest cave we discovered in the Mauna Ulu lava. Apua Cave, as we called it, has a mapped length of 1.34 km, and two large collapse entrances are situated in its middle part. Its great dimensions indicate that the tube was a principal feeder, probably conveying much of the lava that constructed the coastal delta near Apua Point. What makes the cave so outstanding, however, is its notable display of lava stalactites and stalagmites.

What did our investigations of the Mauna Ulu tube system tell us about the geology of the lava flow? Firstly, cave explorations confirmed that each major tongue-shaped flow unit (the "arms" of the flow) contained a large, axial feeder tube, which divided into a mass of smaller tubes in the manner of a delta at the flow front.

Secondly, the walls of the axial tubes were composed of many thin, superimposed sheet flow units which obviously represented layered overflows of the walls of the channel from which the tube evolved. Sheets and lobes produced by overflows are easily identified on the fresh surface of the flow, bordering open lava channels or surrounding skylights. In my opinion, such evidence confirms the inappropriateness of exotic theories to explain layered wall structures in lava tube caves.

Figure 13. In the Mauna Ulu flows, lava which was fed by a complex system of lava tubes tumbled down immense fault scarps (palis) before they entered the ocean 15 km distant from the vent. These flows added 80 hectares of new land at the coast.

Away from the axial feeder tubes, toe extension appears to have been the major method of the flow. When the Chain of Craters Road has sliced through the Mauna Ulu lava, ellipsoidal cross sections of many small lava tongues are visible, many possessing a small cave at their core. Such internally developed tubes may also be observed in overflow units on the surface of the lava flow.

Yet, one very big problem concerning tube construction and operation remains that is not adequately explained by the structural evidence. Caves a considerable distance downflow from the vent (Apua Cave in the Mauna Ulu lava, and also other similar large remote cave segments in other lava flows) have a wall structure composed of horizontal units ranging up to 2 or 3 m thick. Such a structure does not reflect tube construction from channel closure, and thus I suspect that these caves evolved by means of a process of tube enlargement and extension behind a steadily advancing flow front. That is, as the lava front advances, the axial feeder tube elongates across earlier formed frontal deltaic zones, capturing the dispersed flow and developing an axial form that enables a more efficient transfer of heat and mechanical energy downflow.

Work on the Mauna Ulu lava lasted about two weeks, after which time the exploration net was cast wider and other caves were investigated. The potential for caving on the Hawaiian volcanoes is enormous. For example, some of the numerous pit craters on Kilauea may provide access to quite large caves. These spectacular pits in the Kau Desert, for example, are the subject of another paper in this symposium.

Also in the Kau Desert is an older parasitic lava shield of the Mauna Ulu type, known as Mauna Iki. The main outflow from this shield was fed by a large lava tube. Unfortunately, on a cursory visit to this site, we could find no entrance to the undoubted cave beneath the many great collapses.

Rifts and cracks on the volcanoes also make for exciting caving. They must be very deep. In 1973, National Park Service officers descended the SW Rift of Kilauea to a depth of about 100 m in order to rescue a man who fell by accident.

In 1978, Jim and Libby Nieland published an excellent account of their short, but productive caving jaunt to Hawaii Island. Especially interesting was their account of Ainahou Ranch Cave, situated on the southern slope of Kilauea. The Nielands explored abut two kilometers of the cave, and came to no termination upflow or downflow. We thought that we would undertake a full exploration of the cave. We discovered and mapped 7 km of the remarkable cave; this distance being broken in the center by an impenetrable collapse. Ainahou Ranch Cave extended from the Chain of Craters Road to a window high on the Poliokeawe Pali, but lines of collapses indicate that the cave continued from the base of the pali to the top of the lower Holei Pali, and even perhaps as far as the ocean. Geologically, the cave was unusually interesting. It was awesome in form, being truly conduit-like in many places. Frequently, it was unusually sinuous. Commonly, the passage would be divided into two or three tiers, with windows in the false floors connecting one tier with another. There were no significant side passages; the cave had the pattern of just one long snake, winding wildly down the gentle gradient to the pali top. Of great significance, bright orange clinker had invaded the cave were the walls had collapsed. Examination of the wall

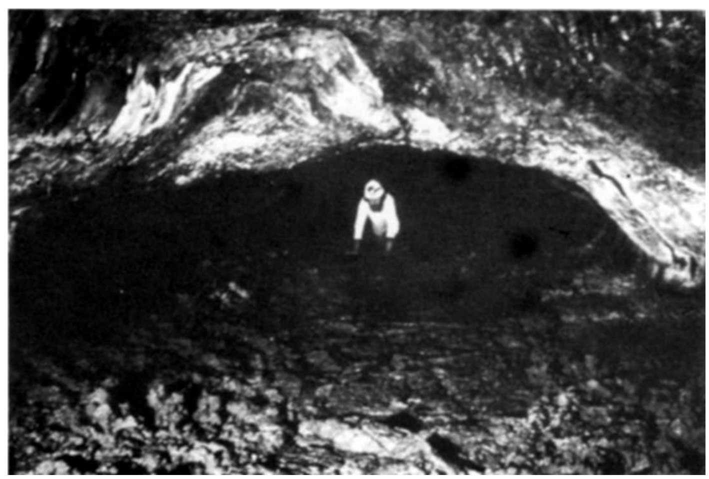


Figure 14. Although nearly 3 km of cave passage was found in the Mauna Ulu flows, most of the parent lava tubes had drained off very little of their liquid flow and many caves contained long crawls.

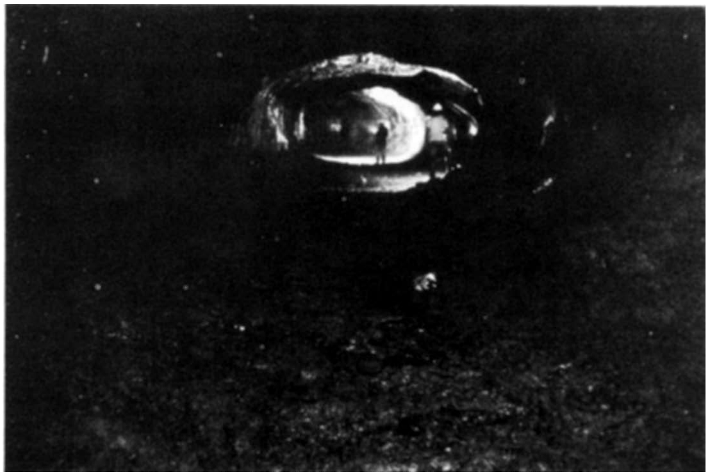


Figure 15. Ainahou Ranch Cave is conduit-like in many places.

itself showed that it was mainly very thin, sometimes as little as 3-5 cm thick! The clinker occupied about one-half of the vertical space behind the wall, and this was overlain by a thin layer of ash, which in turn was overlain in the upper half of the vertical space by typical, grey, stratified basalt, such as that found in all other lava tube caves. Clearly, the clinker was anomalous, and there was evidence to suggest that it was part of an aa flow that was older than the flow containing the cave, and into which the lava tube had been incised.

Ainahou Ranch Cave possessed some remains of ancient Hawaiian culture, including a skeleton, artifacts, and some outstanding petroglyphs (wall carvings).

The most important area for giant caves is the northeast flank. Robin Holcomb of the USGS, was on the island of Hawaii during the period of the expedition, completing his mapping of the surficial flows of Kilauea (Holcomb, 1980). His work has pointed to an important historic eruption site over the position of Thurston Lava Tube. His map of the lava flows emanating from this source postulates immensely long lava tubes, extending all the way down to the coast, south of Hilo. The lengths of some of these tube-fed flows must be 50 km or more, and the meandering tubes within them must have been much longer. Holcomb identified the tube lines from aligned collapse depressions seen on aerial photographs of the flows. I can vouch for the accuracy of this mapping; when investigated on the ground, these flows invariably yielded big caves. For example, caves such as Blair Cave, Kazumura Cave and John Martins Cave are members of this group.

Figure 1. In addition to steeply inclined "cascades" of lava, Kazamura Cave has several vertical lava falls.

Kazumura Cave had previously been explored by Frank Howarth, Hawaii's leading resident caver. He had estimated a total traverse length of 10 km. Our own survey, undertaken with Frank's assistance, resulted in a length of 11.713 km -- at the time making it longer than any other lava tube cave known. It has 17 skylight or collapse entrances, only three or four of which are enterable without tackle, and all of which are extremely difficult to locate in the boggy forest on this side of Kilauea.

Figure 16. Some sections of Kazamura Cave are impressive in diameter.

The cave is a single, at times enormous, sinuous passage. There are side passages, but mostly these are insignificant crawls. This long cave has many interesting features, including a location where the lava pooled to form a lake. Withdrawal of the liquid lava from this lake left a surrounding terrace. At other times, the lava cascaded down steep inclines or plunged over steps in the floor as lava falls. Conical ceiling stalactites abound, possibly indicating dripping off the roof as the tube emptied from a full-bore state. Lowering of the roof, and development of false floors is common in Kazumura Cave, and mainly indicates the position of former skylights. In the downflow part of the cave are some large loop passages.

Above all, Kazumura Cave is an illustration of the immensity and awesome form of the great lava conduits to be found on Kilauea's northeast flank. I have no doubt that the cave extends downflow for a considerable distance beyond the present terminal choke (which probably resulted from road building above this point), and if the choke is passed the length of Kazumura Cave, may possibly be extended to 15 km or more. And Kazumura is just one of the tens of parallel caves in the area, none of which

Figure 17. Conical stalactites possibly indicate dripping as the tube emptied.

have been adequately investigated.

The investigation of these caves is of fundamental importance to an understanding of the role played by lava tubes in the building of the Hawaiian shields. Probably nowhere else in the world is there such a collection of large lava tube caves, readily accessible to serious exploration and mapping. Robin Holcomb has demonstrated the quantity of tubes in the area, and it is now imperative for systematic cavers to map the cavernous portions of these tubes, in order to gain a comprehensive picture of the magnitude and geology of the tube-fed eruption style in this classical area. The task is big, but the accomplishments of the 1979 UK expedition illustrate what

Figure 18. Large loop passage in Kazamura Cave.

can be done during one short field season.

One particular proposal for the use of map data is to attempt to calculate the volume of liquid movement through individual tubes. For example, conduit-like parts of the main passage of Kazumura Cave, with conical ceiling stalactites, strongly suggests to me that this part of Kazumura Cave transported a full-bore flow. I am intrigued by the apparent concentric banding on the walls, which, because of the low lighting, I never noticed whilst I was in the cave. Are these bands helical striations, caused by corkscrew motion of the passing fluid?

If, in fact, this part of the cave did carry full-bore flow, its dimensions could form a basis for the calculation of discharge of the former tube. With a larger sample of this passage type from one cave, these calculations of discharge could become

Figure 19. Are these helical striations? Kazamura Cave photo by C. Wood and A. C. Waltham.

more meaningful. Such knowledge of tube discharge, together with an estimate of the volume of the parent lave flow, would permit calculation of a figure for the duration of the vent effusion. Robin Holcomb has dated many of the lava flows on Kilauea's northeast flank, and if these calculations were done for many tubes, a comprehensive picture of the development of this part of Kilauea would be developed.

This is just one example of the benefits to be gained from a close study of the caves on Kilauea's northeast flank. The UK

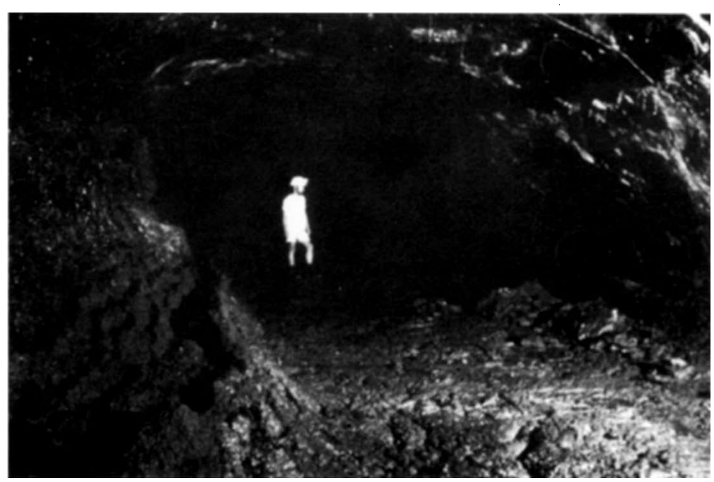


Figure 20. Multiple lateral crusts, Kazamura Cave.

team plans to contribute further to this work by returning to Hawaii Island in December, 1982. The plan is to seek out other long caves on Kilauea and Mauna Loa. Ten experienced cavers are currently reviewing aerial photographs, identifying long flows with lines of collapses. The idea is to compose a "hit list" of potentially rich cave sites, so that little time is wasted once we are on Hawaii. We are particularly excited about potential sites on Mauna Loa, and are preparing for the difficult problem of maintaining caving parties in remote areas of this mountain for long periods of time. Scientifically, we are very interested in understanding more about the morphology of long axial feeder tubes, and this is one reason for seeking caves longer than those currently known. For example, it would be interesting to know what form the feeder tube of the 1880-81 flow from Mauna Loa took and how the flow was maintained after a journey of 50-60 km down an average slope of less than 3-1/2°. This expedition will also be well equipped to record the biology of the caves visited, and parties are expected to discover further archaeological and geological features of note.

* * *

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KALUAIKI AND THURSTON LAVA TUBE: AN UNRECOGNIZED JAMEO SYSTEM?

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Western Speleological Foundation
Cascade Grotto of the National Speleological

Thurston Lava Tube is a famous but relatively featureless cave near the crater of Kilauea Volcano on the island of Hawaii. Its native name is Keanakakina. The cave extends downslope about 450 meters from the downslope end of a sizeable closed depression called Kaluaiki, located close to the crater of Kilauea Iki.

Traditionally, Kaluaiki has been considered to be a pit crater which was the source of a flow unit containing Thurston Lava Tube. Recent speleological reconnaissance suggests a different interpretation, namely, that Thurston Lava Tube is merely a small overflow or "squeeze-up" structure related to an unknown, larger lava tube extending down-slope from Kilauea Iki, at greater depth. According to this interpretation, Kaluaiki is a jameo-type sink, probably originating entirely through stopping and collapse. These features are compared with similar features in the Cueva de Los Verdes system of Lanzarote, Canary Islands. Methods of further field investigation are suggested.

Traditional interpretations of many geologic concepts of the island of Hawaii are necessarily undergoing extensive reconsideration, and vulcanospeleological observations and concepts increasingly are seen as providing important clues for deciphering the histories and hazards of basaltic volcanoes (Holcomb, 1980, 1981). In this context, a re-evaluation of Thurston Lava Tube and Kaluaiki — an adjoining so-called pit crater — is especially timely.

Thurston Lava Tube is partially developed as a major tourist attraction and interpretive site of Hawaii Volcanoes National Park. Thus, it is one of the world's most widely known lava tube caves. Also, it is one of the world's most featureless lava tube caves. In this, it contrasts strikingly with other shallow lying lava tube caves farther down the Puna lava flows which have a wealth of prominent speleogenetic features. Downslope from the 300-foot tourist section, Thurston Lava Tube is not so sparse of features. The distal part of ,the cave contains well-developed flow shelves, a drained bubble chamber, lava speleothems, and other speleogenetic features. It ends at a lava seal in a second bubble chamber, clearly undrained. Yet in general, it has the characteristic appearance of a relatively featureless overflow tube rather than a major throughway conduit.

The main entrance of the cave is near the top of the side wall of a closed depression. Its location is close to the margin of the Kilauea Iki section of the present-day Kilauea caldera-crater complex. This closed depression has the Hawaiian name Kaluaiki. It is at or near the apex of a broad lava dome about 40 m high, virtually on the west rim of Kilauea Iki. In this dome are several other smaller closed depressions.

In the past, Kaluaiki and all the other closed depressions (except the obvious small collapse sink forming the tourist exit from Thurston Lava Tube) generally have been considered to be pit craters, presumably independent of the various vents in

Figure 1. *Thurston Lava Tube is a well-known tourist attraction.*

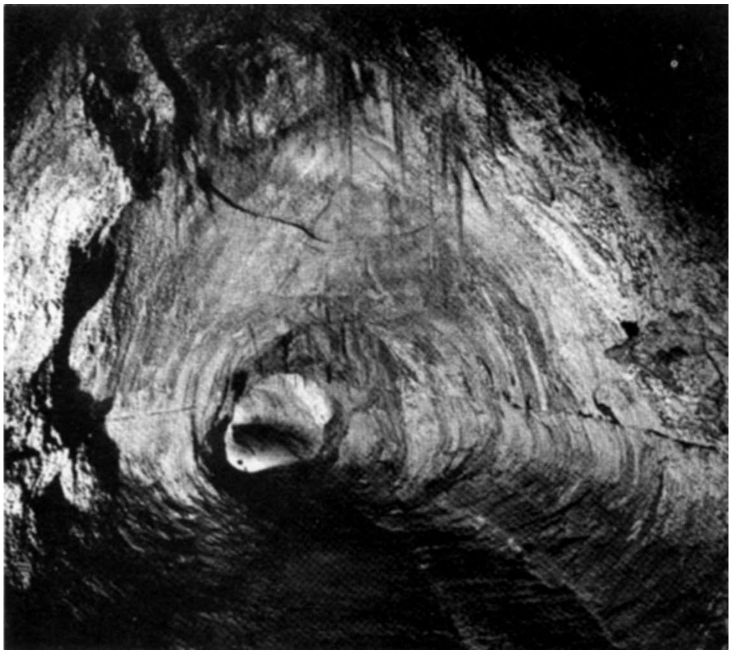

Figure 2. Numerous commercial postcards show the relatively featureless nature of the developed section of Thurston Lava Tube.

Kilauea Iki and the main caldera of Kilauea even though virtually on its rim.

To date, no one seems to have given much consideration to this lava dome despite its prominence on the topographic map. I am unaware that it has received any name. Tentatively, I will refer to it as the Kakina Dome, from the original name of Thurston Lava Tube, Keana Kakina (Powers 1920). The presence of this dome may be additional evidence that one or more pit craters actually does exist here, but at least one other alternative explanation exists. In any event, it must be considered in any speleogenetic analysis of Thurston Lava Tube.

Presently, this dome is classified by Holcomb (1980) as "5Dps" — part of a large lava shield 350-500 years old, with a predominance of tube-fed pahoehoe and minor proportions of surface-fed pahoehoe and aa, but morphologically surface-fed pahoehoe. In addition, he inferred a buried crater at the approximate location of Kaluaiki — structures about 750 years old. But these structures were overtopped about 350 years ago by a major flow sequence from Kilauea which formed extensive flows in Puna with a lesser southward extension. This was followed by extensive subsidence in the caldera and a complex subsequent history including the

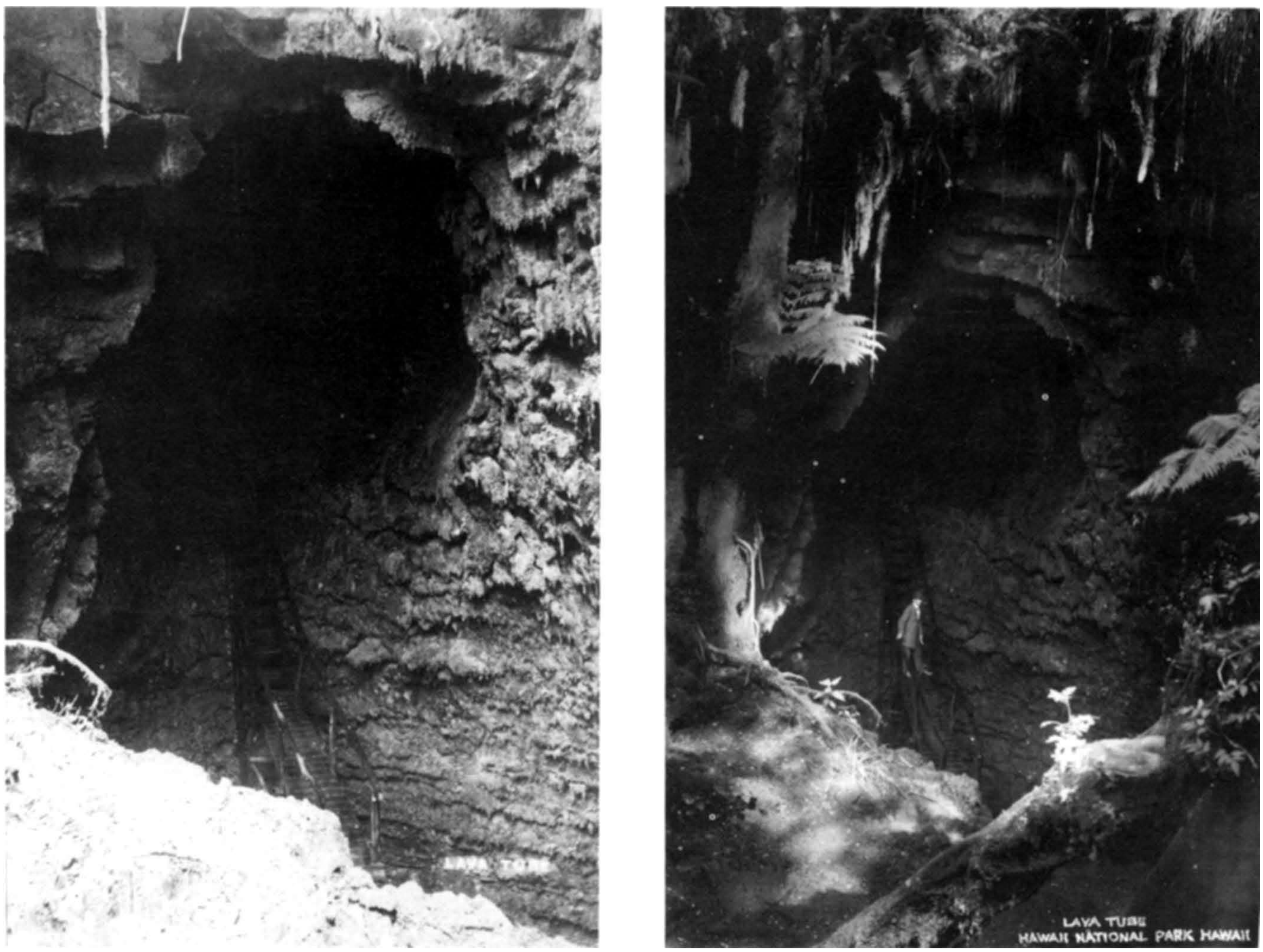

Figure 3. The date of the photographs used on these photo postcards is not known. They were taken before vegetation became lush in the entrance sink and before high-technology trail and footbridge development further obscured the relationship of the cave entrance to the sink.

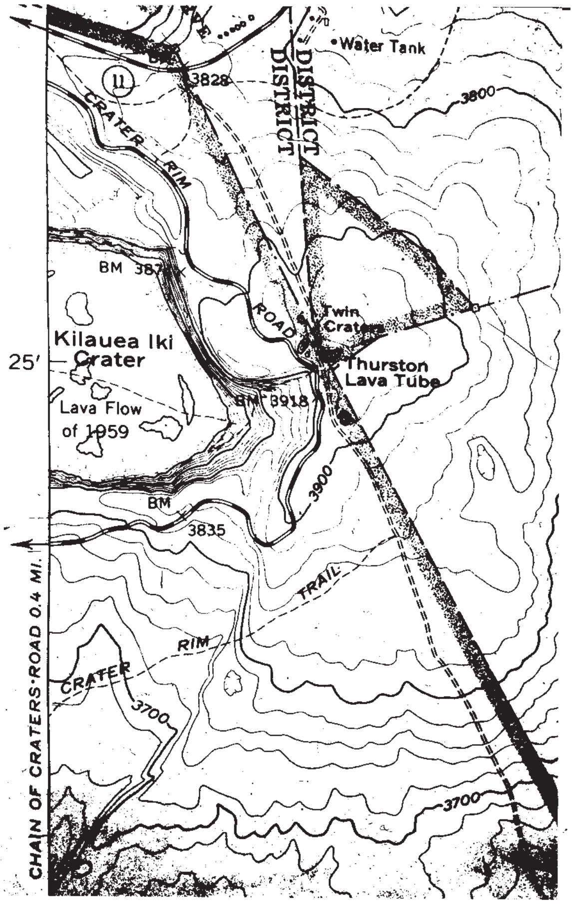

Figure 4. Topography of the vicinity of Thurston Lava Tube. Map by U. S. Geological Survey.

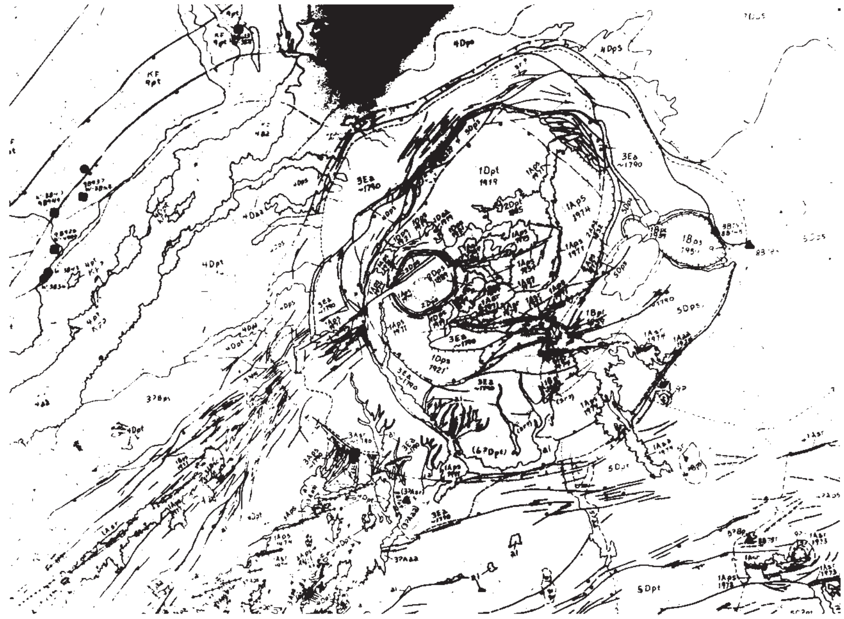

Figure 5. Holcomb's map of Kilauea volcano and vicinity. The location of Thurston Lava Tube is easily determined by its position just east of Kilauea Iki near right

development of Kilauea Iki about 100 years later.

The original map of Thurston Lava Tube (Powers 1920) depicts Kaluaiki as almost perfectly circular, as in the case of such nearby pit craters as Devil's Throat. Actually, Kaluaiki is elongate and slightly sinuous. Its walls are nearly vertical. The floor consists of irregular piles of rubble, covered with dense vegetation which obscures many details.

At both ends of this short, trench-like depression, the rubbly floor slopes downward, not upward as is characteristic of pit craters. At the end of the trench beneath the entrance of Thurston Lava Tube, the rubble slopes down to the rock wall of the depression. At the other end, observation is hindered by vegetation, but I found that it slopes into a cavity of some sort, or at least into an overhanging space. The slope is unstable and at the time of my only opportunity for observation, I had no gear nor any backup crew. However, it appears that this alcove or cave leads back toward Kilauea, and that it is below a partial breach in the rim of the depression — a low point used by the tourist trail.

This low point in the rim of the trench continues westward a few dozen meters before becoming lost in the slopes of Kilauea Iki. It appeared to me to be approximately at the level one would expect if Thurston Lava Tube were to be collapsed. The lower grotto or cave is several meters lower. I did not get close enough to determine whether it has any features of an intact or a stopped lava tube. It appears, however, that studies could easily determine whether Kaluaiki is a trench segment of a lava tube system with at least two levels of unroofing. The uppermost level would be a shallow, almost imperceptible trench just mentioned. The lower level (or possibly an intermediate level, with one or more additional levels still lower) would be represented at the west end of the trench by the grotto or cave several meters lower than the present low point in the rim. At the other end of the trench, it would be represented by an undiscovered cavernous passage, probably stacked beneath Thurston Lava Tube.

Multi-level lava tube trenches and caves are fairly common in the United States. Perhaps the most dramatic example of multi-level trench segments is the Big Trench Cave System in Washington State (Halliday 1963). Here, abrupt change in the level of the floor of the trench clearly demonstrate collapse of various segments of a stacked multi-level lava tube cave system, of which only small portions now can be entered. In the same area of Washington State, a shallow inconspicuous trench much like that at the west end of Kaluaiki extends upslope from the entrance of Dynamited Cave, representing an unroofed segment of another stacked multi-level lava tube cave system.

Outside the United States, an especially notable stacked lava tube cave system is located on the island of Lanzarote in the Canary Islands — the Cueva de Los Verdes System. Deep, steep-walled collapse sinks along the course of this system are known as jameos. As in the case of the Big Trench Cave System, some of these jameos vary abruptly in depth. Much more of this system's caves can be entered and studied, however. Its levels occur at depths of approximately 5 to 30 meters. The lower levels are throughway passages; the upper levels are smaller and probably never were fully integrated longitudinally (Halliday 1972).

Those jameos which extend all the way down to the levels of the large, deep-lying throughway passages characteristically have steep walls and a central rubble accumulation which slopes downward at each end, as in Kaluaiki. In some cases, the cavernous passage can be entered by descending this rubble slope. In other places, the rubble blocks the cave and it must be entered at another jameo.

Although on a much smaller scale than in some of the jameos of the Cueva de Los Verdes System, the Kaluaiki-Thurston Lava Tube complex has many of the characteristics of a jameo system. If a Jameo-type system in fact does exist here, Thurston Lava Tube is a minor disconnected upper level of a larger throughway lava tube passage or passages, quite possibly stacked precisely beneath Thurston Lava Tube.

Such stacking does occur in Hawaiian lavas. Several km downslope from Thurston Lava Tube, Dock Ballou's Cave is a disconnected upper level, stacked above Kazumura Cave.

Other so-called pit craters nearby also may be jameos or other types of collapse sinks, and the topography suggests the possibility of access to undiscovered feeder tubes fanning out approximately 180° from the Kakina Dome.

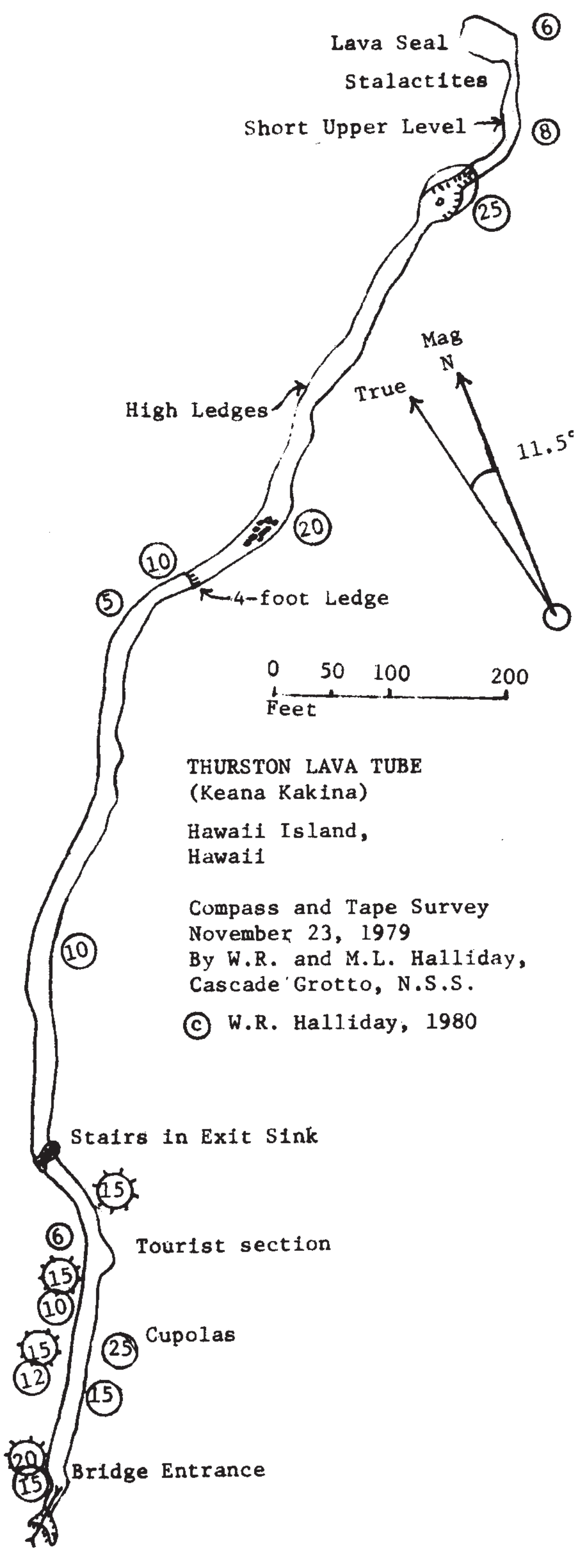

Figure 7. View of Jameo de la Gente, Cueva de Los Verdes System, Lanzarote, Canary Islands. This jameo is a compound collapse sink in a unitary system with stacked levels as described in Halliday (1976).

If such a system or systems exist here, undiscovered, the entire Kakina Dome may have developed through hydrostatic overflow when one or more of the distal throughway conduits became obstructed during the major Puna flows about 350 years ago. In that case, unfortunately, a principal conduit would not necessarily be stacked beneath Thurston Lava Tube and discovery and access would be considerably more difficult.

In any event, however, detailed study of Kaluaiki plus well-planned excavation and/or drilling around the so-called pit craters of the Kakina Dome seem likely to yield important clues in the deciphering of the history of Kilauea and the dynamics of its basaltic lava flows.

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ON LAVA CAVES IN JAPAN AND VICINITY

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Association of Japanese Cavers

INTRODUCTION

Among approximately 830 active volcanoes in the world, 67 are in Japan. Most of them have had phreatic explosions. The volcanoes around Japan exist along the Japan trench which is formed between the Pacific Plate and the Philippine Plate.

Nearly all of these volcanoes are of andesite, similar to that in the Cascade Mountains in America, and in New Zealand.

But the volcanoes on the islands in the inner Pacific Ocean are chiefly of basalt, which is similar to that of eastern Africa and the Mediterranean volcanoes, and contain much K_2O. The boundary line between the volcano area, whose main component is andesite, and the area of basalt, is called the Andesite Line. It bisects Hokkaido and Northern Honshu, running south into the sea just west of Tokyo Bay; on the Pacific side of this line, volcanoes contain no olivine, but a small amount of tholeiitic basalt or calcalkali basalt. The Izu Islands, Miyake Island and Hachijo Island are among these.

On the continental side of the Andesite Line are alkali basalt volcanoes, which contain much Na_2O and K_2O, without any pyroxene or olivine, but with a small amount of SiO_2. The volcanoes in the western part of Japan — Daikon Island and Fukue Island —and Cheju Island in Korea, and Chin Puo in China belong in this category.

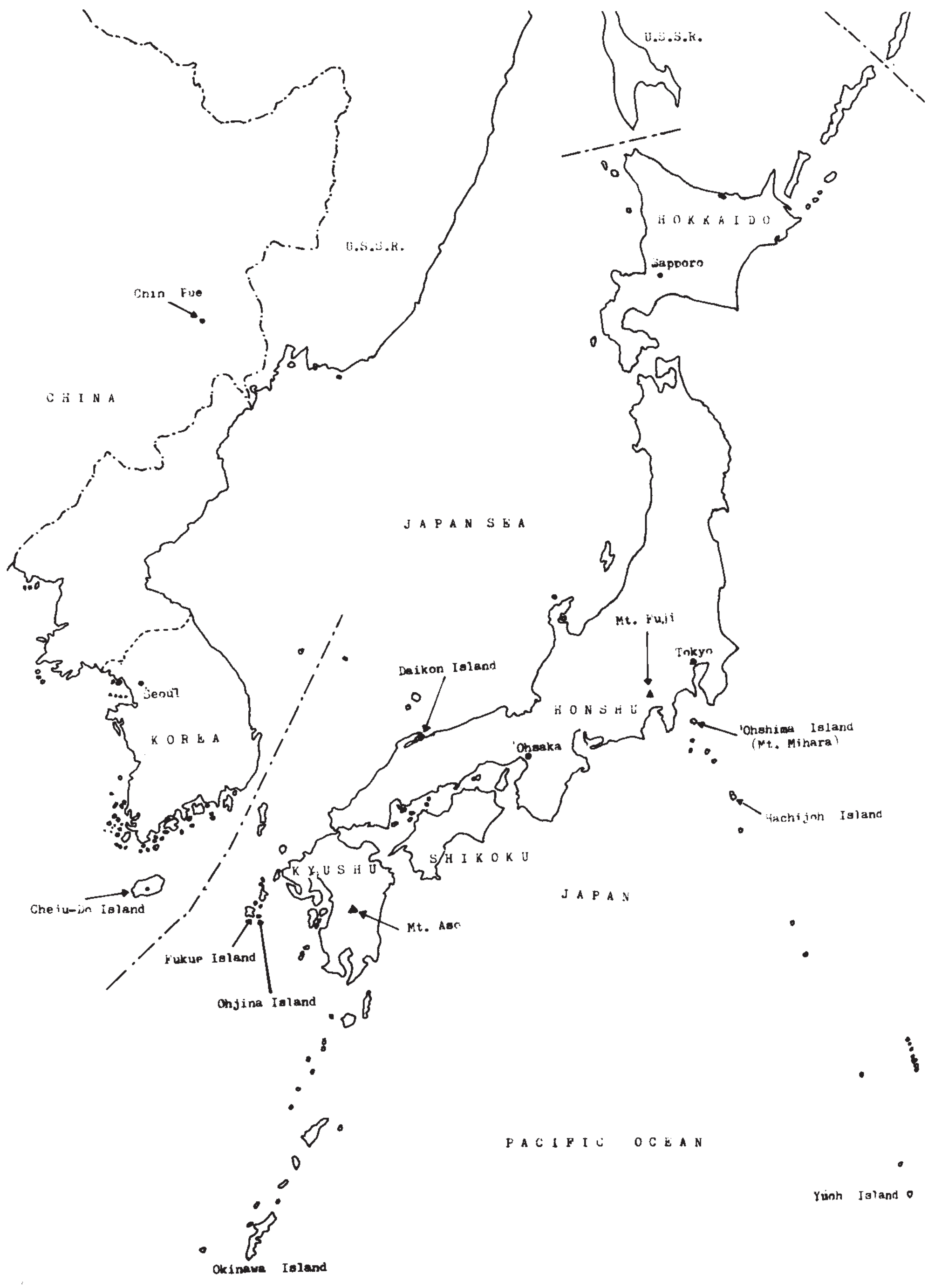
Between these is an intermediate type which contains much Al_2O, and high-alumina basalt volcanoes. In Japan, Mt. Fuji and Mt. Aso are this type.

JAPANESE LAVA CAVES, ESPECIALLY THOSE OF MT. FUJI

There are over 150 lava flows on Mt. Fuji, but only ten have lava caves; unless the lava flow is thick enough, there are no caves. At present, 95 caves are known which are over 30 meters in length, and two or three more are discovered every year. The longest is Mitsuike Ana, which is 2,139.75 meters long. Eight caves are more than 500 meters long.

The caves formed on level ground and have a complicated plan and profile. Those formed on slopes are mostly of tube-type and are of simple construction.

Mt. Fuji is a stratovolcano consisting of lava flows which contain only basalt and volcanic ash. It began to erupt 13,000

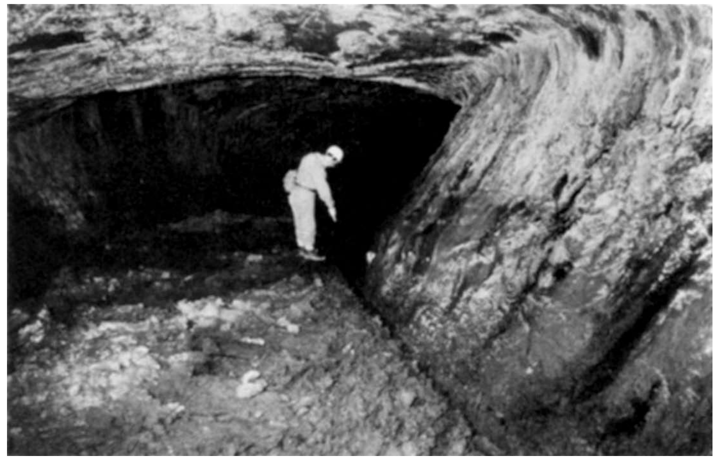


Location of lava caves in Japan, Korea and China.

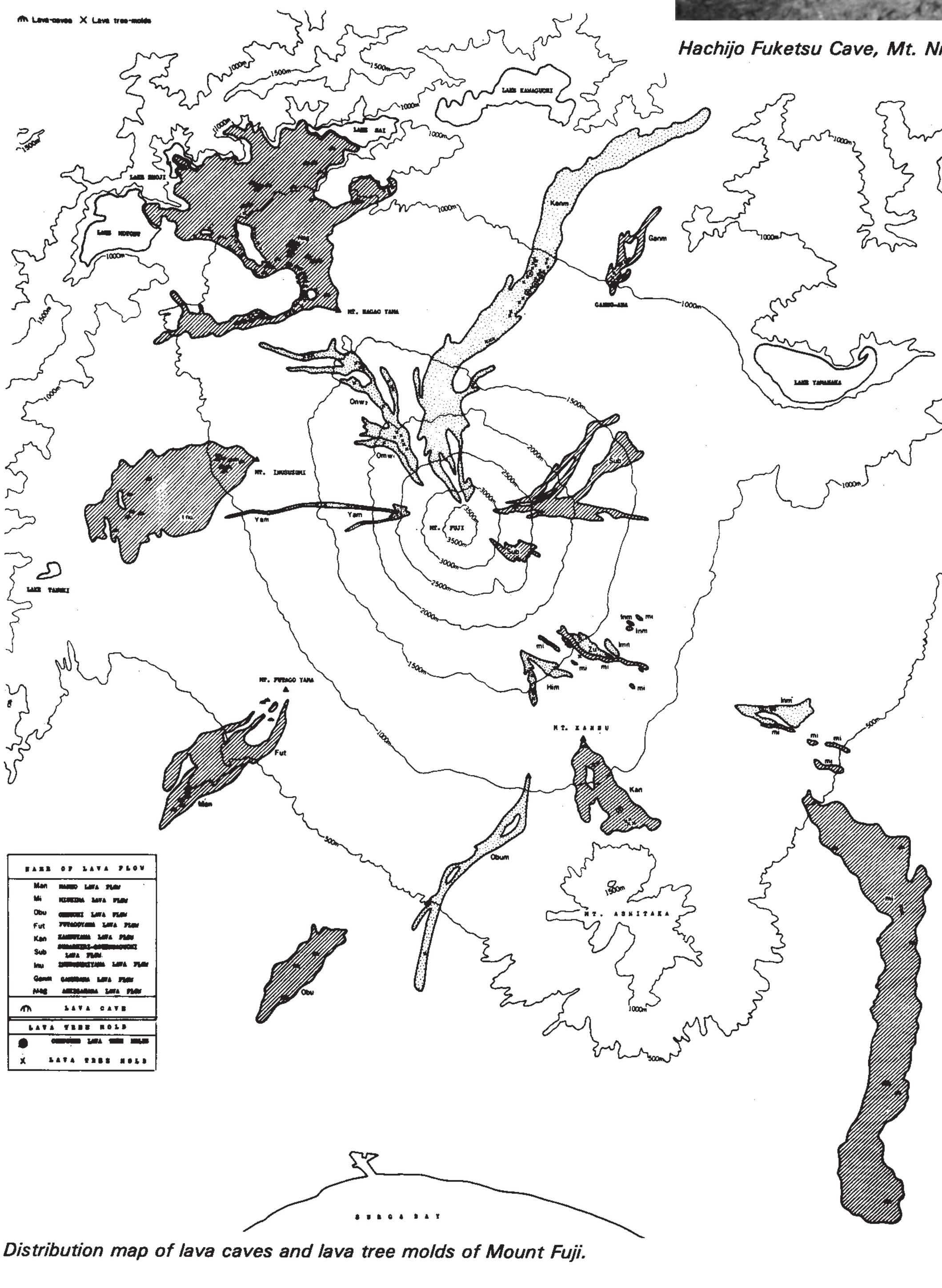
years ago. Its last eruption was in 1707 A.D.

Among the lava flows which contain lava caves, those whose date is clear are the Mishima lava flow and the Manno lava flow (13,000 B.C.), the Inusuzumi-yama lava flow (approximately 2650, more or less, 30 B.P.), the Kansu-yama lava flow (1250, more or less, 20 B.P.), and the Aokigahara lava flow (864 A.D.).

Besides Mt. Fuji, there are caves in lava belonging to the Fuji Volcanic Zone such as Mt. Mihara of Izu Oshima Island (in a flow formed by the eruption in 1962 A.D.), and a flow associated with Mt. Nishi of Hachijo Island which appeared after the eruption in 1606 A.D.



Hachijo Fuketsu Cave, Mt. Nishi, Hachijo Island, Japan.



Distribution map of lava caves and lava tree molds of Mount Fuji.

The cave of Mt. Mihara is small and was formed at the volcanic edge. A lava ledge of A-type can be seen there. Mt. Nishi has six lava caves, the longest one being the Hachijo Fuketsu lava cave, its length being 1,403.8 meters.

JAPANESE CAVES OUTSIDE THE MT. FUJI AREA

Outside the Mt. Fuji area, there are 23 lava caves in Japan, although some are smaller than 30 meters in length.

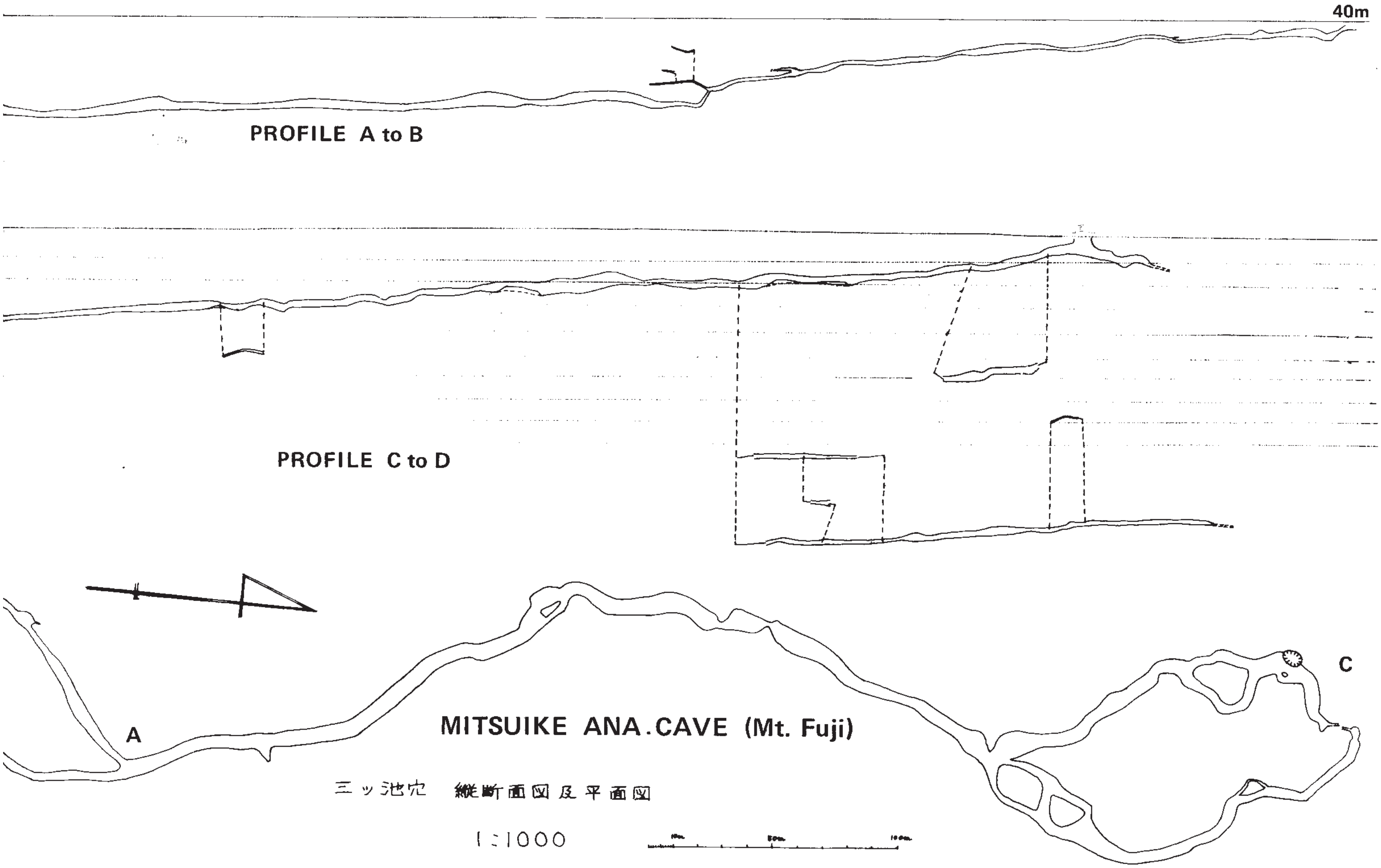
Daikon Island in the western part of Japan has two lava caves over 30 meters in length, but they do not have any noteworthy features. In Yukido Cave, the B-type lava ledge can be found. There is some water inside these two caves. The eruption date is considered to be the oldest of all the lava caves in Japan.

On Fukue Island, in the westernmost part of Japan, are two caves over 30 meters long and 11 of lesser length.

At Mt. Aso are nine lava caves, but only three are more than 30 meters long. This lava flow is, among the Japanese lava flows, the closest in quality to andesite, and most of these caves are featureless.

LAVA CAVES IN JAPAN

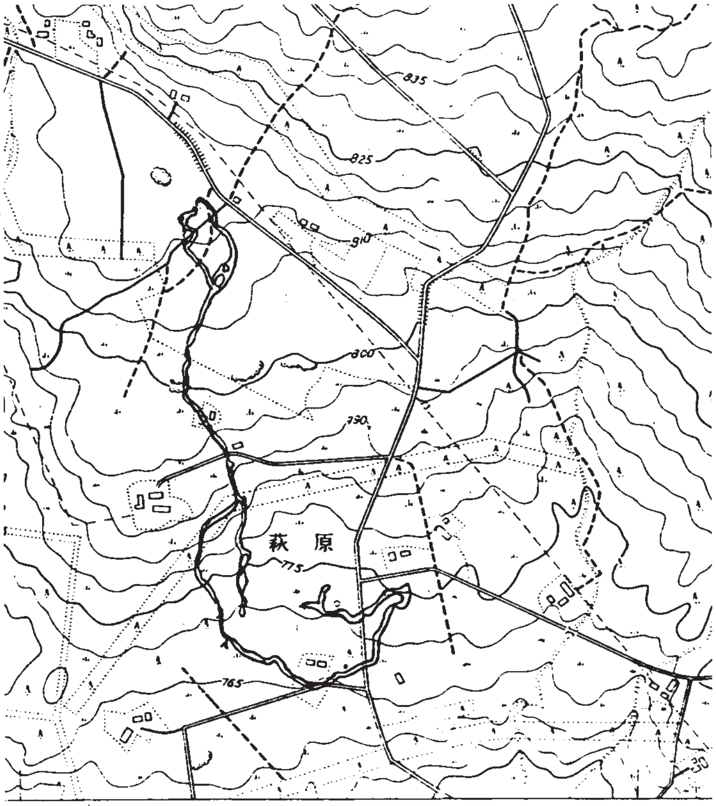
	Lava flow and cave name	Length (m)	Elev. (m)	Place
	*** Mishima lava flows**			
1	Ohno Fuketsu No.1 (Buried)	/	480	Mt. Fuji
2	Ohno Fuketsu No.2	375	480	" "
3	Komakado Fuketsu	625	355	" "
4	Iwanami Fuketsu	220	260	" "
5	Susono Fuketsu No.1	116	115	" "
6	Susono Fuketsu No.2	121	125	" "
7	Mishima Fuketsu	*250	45	" "
	*** Ohbuchi lava flows, Mount Fuji**			
8	Fudo Ana	124	200	" "
9	Hachiman Ana	187	150	" "
10	Atsuhara Fuketsu	89	110	" "
	*** Futagoyama lava flows, Mount Fuji**			
11	Banba Ana	621	675	" "
12	Futagoyama Komori Ana No.1	*60	695	" "
13	Futagoyama Komori Ana No.2	127	690	" "
	*** Manno lava flows, Mount Fuji**			
14	Yashiki Ana	239	310	" "
15	Kobo Ana	*40	270	" "
16	Mado Ana	510	265	" "
17	Dainichi Ana	908	250	" "
18	Ginga Fuketsu	* 40	250	" "
19	Chikusho Ana (Buried)	/	230	" "
	*** Inusuzumiyama lava flows, Mount Fuji**			
20	Inusuzumiyama Fuketsu No.1	192	1140	" "
21	Muzina Ana	118	1095	" "
22	Inusuzumiyama Fuketsu No.2	*130	1060	" "
23	Inusuzumiyama Fuketsu No.3	*50	1015	" "
24	Inusuzumiyama Fuketsu No.4	*120	1000	" "
25	Inusuzumiyama Fuketsu No.5	*800	975	" "
26	Inusuzumiyama Fuketsu No.6	*250	975	" "
27	Inusuzumiyama Fuketsu No.7	95	980	" "
28	Inusuzumiyama Fuketsu No.8	76	985	" "
29	Inusuzumiyama Fuketsu No.9	49	990	" "
30	Inusuzumiyama Fuketsu No.10	/	1200	" "
31	Teppo Ana	/	1020	" "
32	Mitsuike Ana	2140	820	" "
33	Ubu Ana	123	760	" "
34	Uzura Ana	820	735	" "
35	Shin Ana	150	720	" "
36	Hito Ana	83	690	" "
37	Mamashita Ana (Buried)	/	820	" "
	*** Kansuyama lava flows**			
38	Kaminari Ana	35	1210	" "
	*** Zunazawa lava flows**			
39	Suyama Tainai	40	1490	" "
	*** Subashiri-Gotemba lava flows**			
40	Subashiri Tainai	*20	263	" "
	*** Aokigahara lava flows**			
41	Karumizu Fuketsu	433	1265	" "
42	Zinza Fuketsu & Kamaboko	443	1260	" "
43	Zinza Fuketsu No.2	51	1255	" "
44	Zinza Fuketsu No.3	170	1190	" "
45	Zinza Fuketsu No.4	*100	1220	" "
46	Zinza Fuketsu No.5	*100	1230	" "
47	Zinza Fuketsu No.6	*85	1240	" "
48	Megane Ana	154	1220	" "
49	Ohmuro Fuketsu No.1 (Buried)	95	1165	" "
50	Ohmuro Fuketsu No.2	40	1150	" "
51	Shyoiko Fuketsu No.1	230	1150	" "
52	Shyoiko Fuketsu No.2	56	1140	" "
53	Shyoiko Fuketsu No.3	35	1135	" "
54	Shyoiko Fuketsu No.4	32	1130	" "
55	Motosu Fuketsu No.1	494	1155	" "
56	Motosu Fuketsu No.2	238	1165	" "
57	Motosu Fuketsu No.3	61	1145	" "
58	Motosu Fuketsu No.4	32	1140	" "
59	Motosu Fuketsu No.5	*40	1150	" "
60	Motosu Hyoketsu	68	1150	" "
61	Fuji Fuketsu No.1	511	1110	" "
62	Fuji Fuketsu No.2	57	1120	" "
63	Fuji Fuketsu No.3	52	1120	" "



64	Fuji Fuketsu No.4	118	1120	" "
65	Fuji Fuketsu No.5	143	1120	" "
66	Fuji Fuketsu No.6	60	1120	" "
67	Fuji Fuketsu No.7	130	1120	" "
68	Katabuta Ana	*30	1190	" "
69	Gyoja Ana	93	1190	" "
70	Kazuhito Ana No.1	254	1180	" "
71	Kazuhito Ana No.2	44	1180	" "
72	Kazuhito Ana No.3	*30	1175	" "
73	Kazuhito Ana No.4	102	1170	" "
74	Kazuhito Ana No.5	*60	1160	" "
	*** Aokigahara lava flows**			
75	Shyoji Oana, Nichi Do	161	985	" "
76	Shyoji Oana, Gats Do	247	980	" "
77	Shyoji Fuketsu No.1	*40	970	" "
78	Shyoji Fuketsu No.2	*50	970	" "
79	Shyoji Fuketsu No.3	*30	970	" "
80	Shyoji Fuketsu No.4	130	960	" "
81	Shyoji Fuketsu No.5	32	960	" "
82	Shyonin Ana	77	970	" "
83	Aokigahara Fuketsu	*40	1060	" "
84	Narusawa Hyoketsu	156	1025	" "
85	Fugaku Fuketsu	258	1005	" "
86	Ryugu	96	955	" "
87	Saiko Komori Ana	386	920	" "
88	Saiko Fuketsu No.1	72	950	" "
89	Saiko Fuketsu No.2	317	945	" "
90	Saiko Fuketsu No.3	41	945	" "
91	Narusawa Komori Ana No.1	69	1005	" "
92	Narusawa Komori Ana No.2	71	1005	" "
93	Narusawa Komori Ana No.3	40	1005	" "
94	Narusawa Komori Ana No.4	48	1005	" "

*** Gannoana lava flows**

95	Kusure Ana	*130	1020	" "
96	Mihara Fuketsu	*20	673	Mt. Mihara
97	Hachijo Fuketsu No.1	1404	165	Mt. Nishi
98	Hachijo Fuketsu No.2	*100	140	" "
99	Gokuraku Ana	*200	10	" "
100	Shin Gokuraku Ana	*300	10	" "
101	No.20 Boku Fuketsu	*35	513	" "
102	No.21 Boku Fuketsu	*45	528	" "
103	Yuki Do	*200	5	Daikon Is.
104	Ryusei Do	*80	16	" "
105	Komezuka Fuketsu	*20	870	Mt. Aso
106	Ohgawara Fuketsu	/	645	" "
107	Nagaobane Fuketsu No.1	44	75	" "
108	Nagaobane Fuketsu No.2	*20	750	" "
109	Mizonokuchiue Fuketsu	*25	600	" "
110	Mizonokuchiue Komori Ana	*15	600	" "
111	Inuotoshi Fuketsu	*40	640	" "
112	Gannome Fuketsu	/	635	" "
113	Jao Fuketsu	/	522	" "
114	Unishiura Fuketsu	32	800	" "
115	Yurunkuchino Ana	41	26	Mt. Taoakari
116	Sakishirazunoi Ana	965	30	" "
117	Iyano Ana	*15		" "
118	Furutsutsumino Ana	*5		" "
119	Iankawano Ana	*15		" "
120	Kuroseno Ana	*20		" "
121	Kichiga Ana	/		" "
122	Ohjima Ana	/		Ohjima

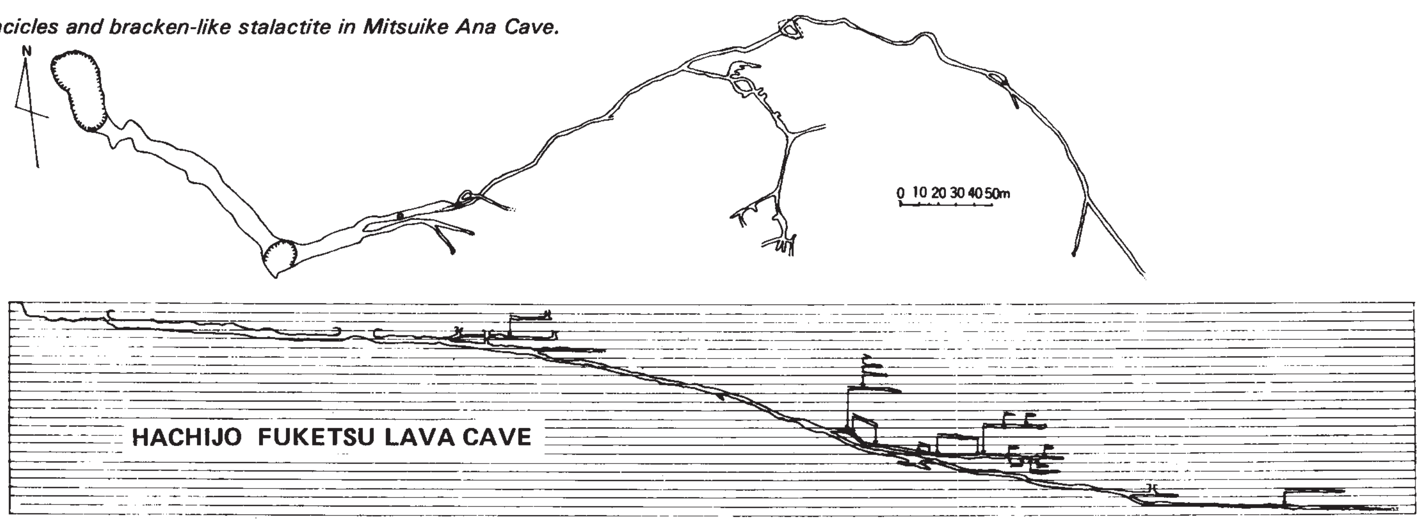


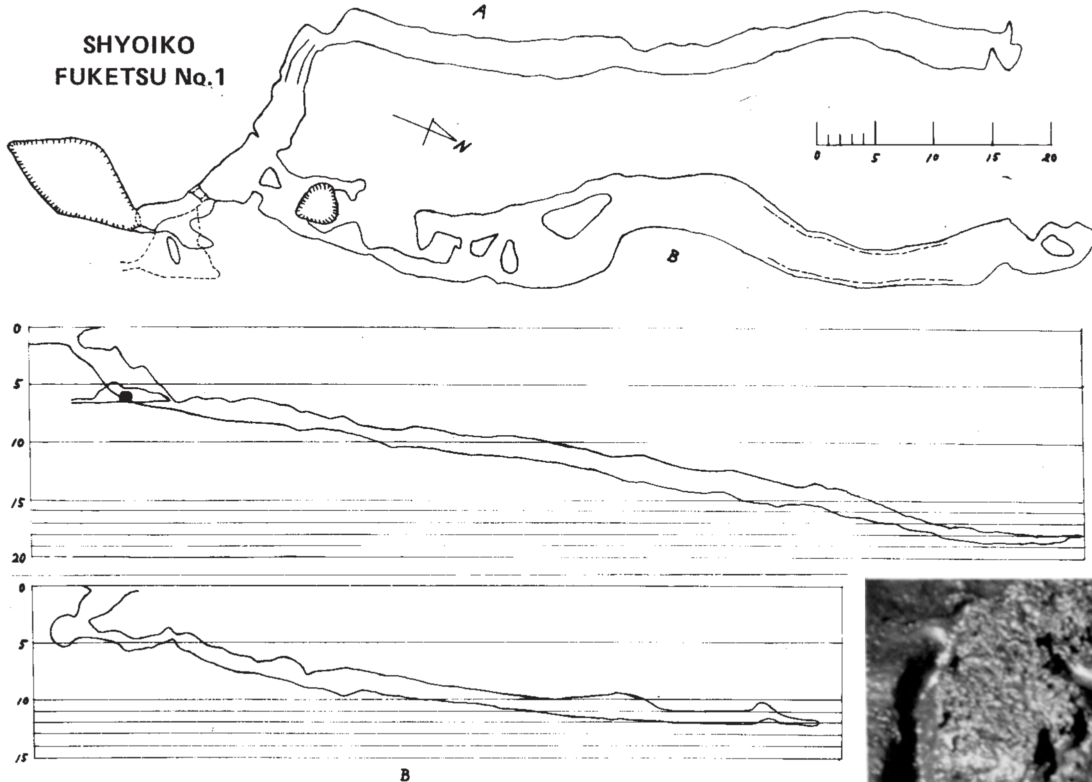
MITSUIKE ANA, Mt. Fuji 500m 1000m

Laminae of the side wall in Mitsuike Ana Cave, Mount Fuji, Japan.

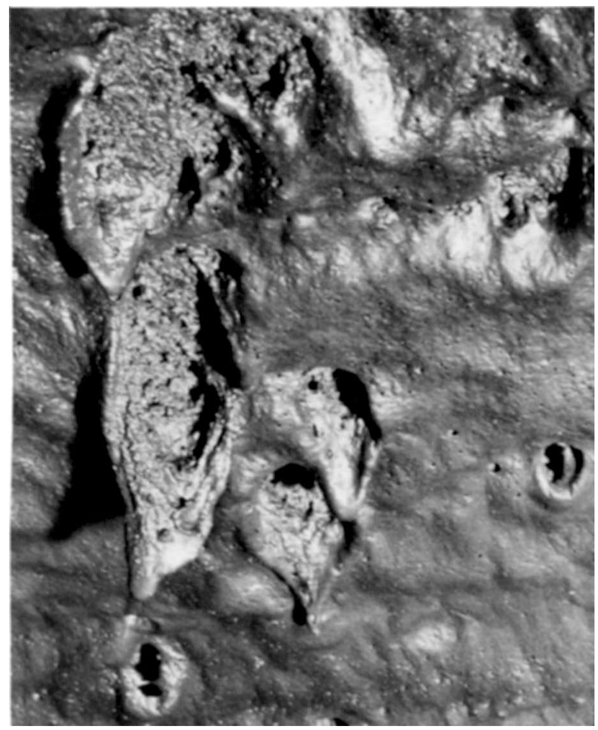
The outer crust of the cavity, Mitsuike Ana Cave, Mount Fuji.

Lavacicles and bracken-like stalactite in Mitsuike Ana Cave.





B-type lava shelves with subsided original lava bridge. Shoiko Fuketsu Cave No.2.



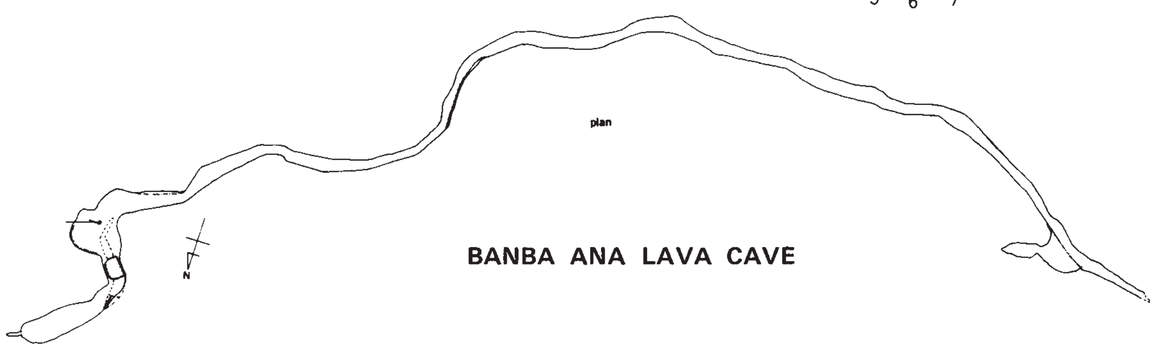
Gas blowout from sidewall in Shyoiko Fuketsu Cave No.1.

Mihara Fuketsu, Mount Mihara, Izu Oshima Island, Tokyo, Japan.

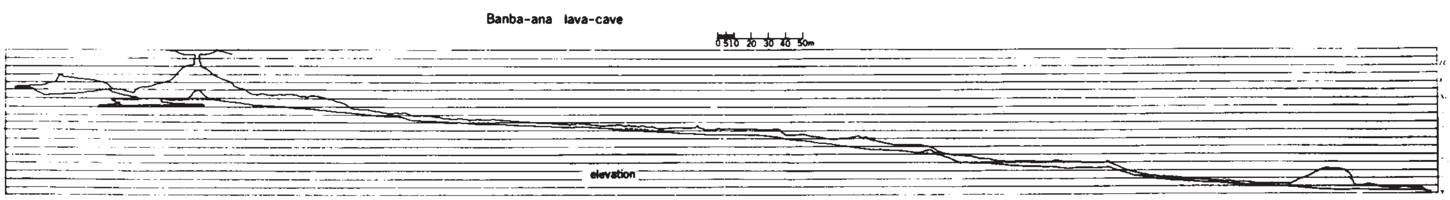
Yukido Cave, Daikon Island, Japan.

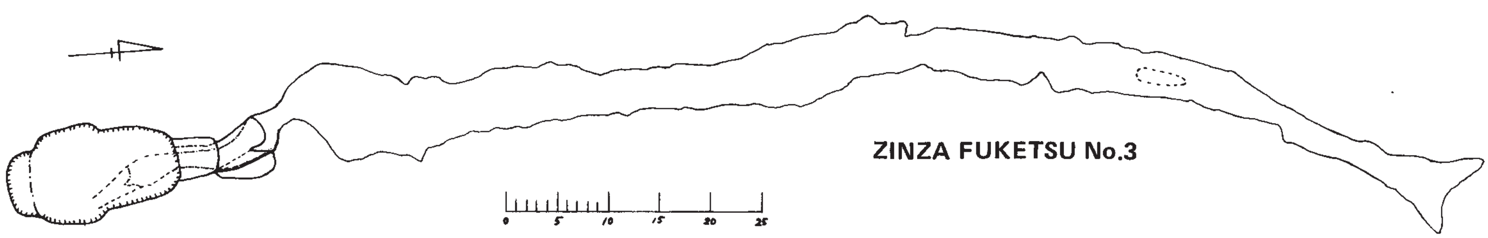
Showing several sectio
Lava Cave prior to its
another one

ZINZA FUKETSU No.1

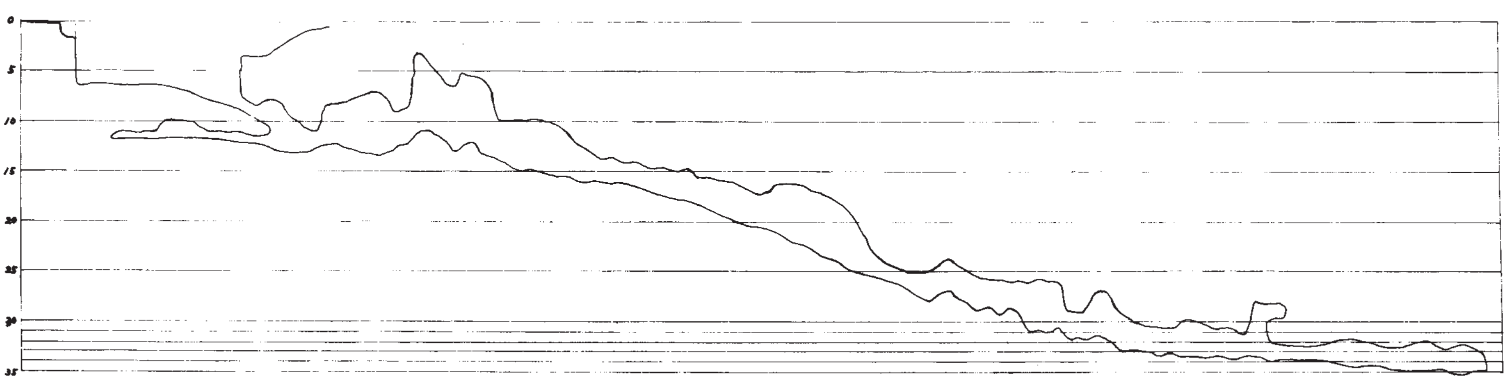


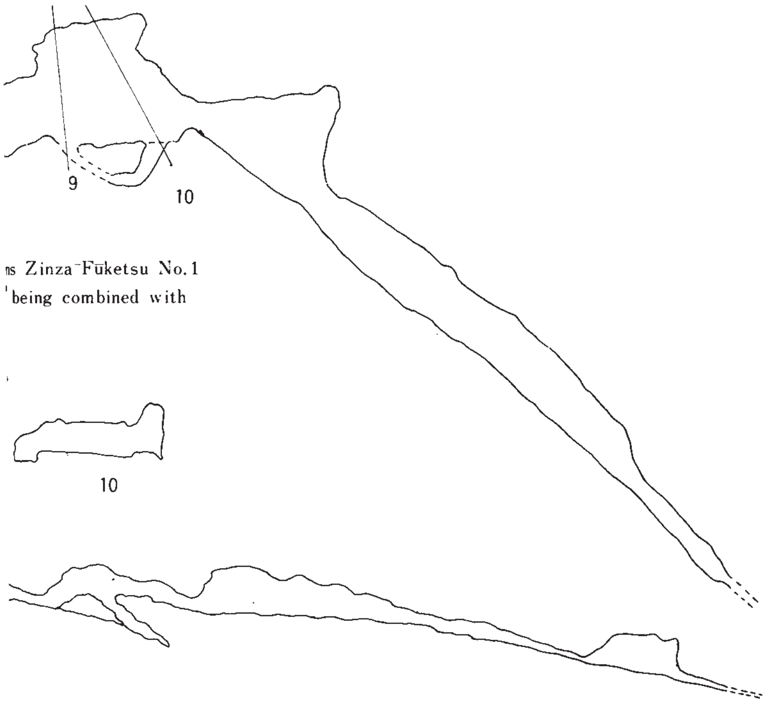
BANBA ANA LAVA CAVE





ZINZA FUKETSU No.3





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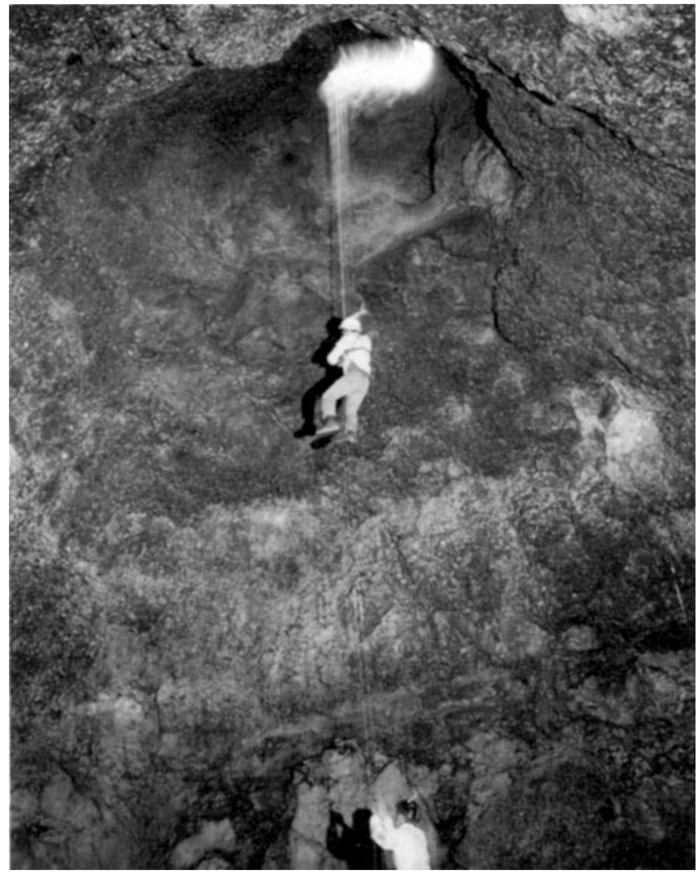
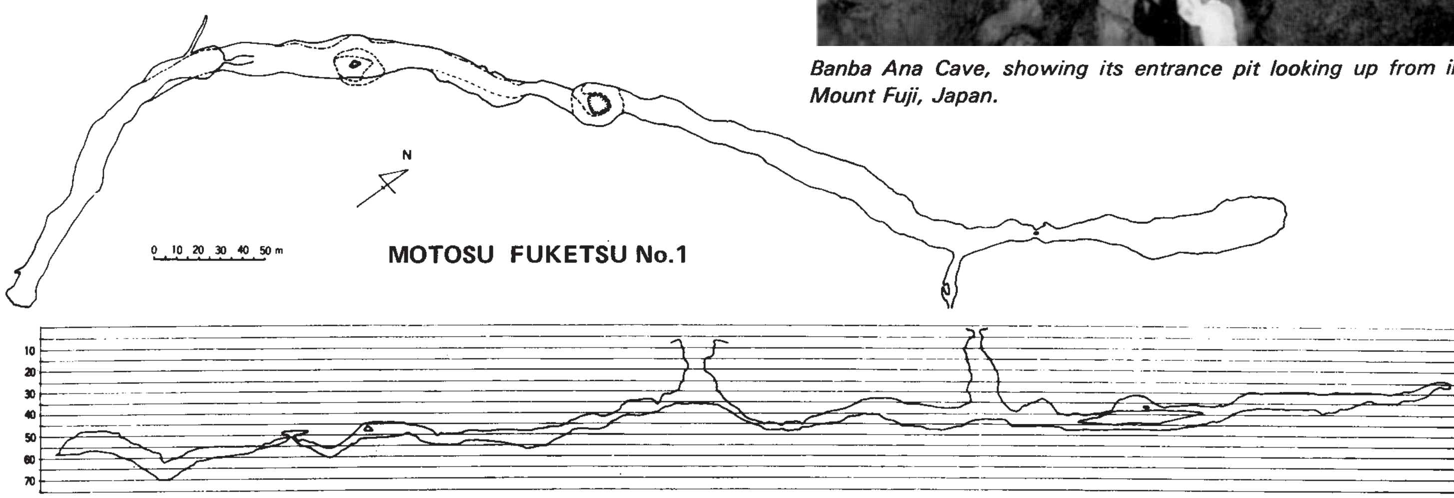
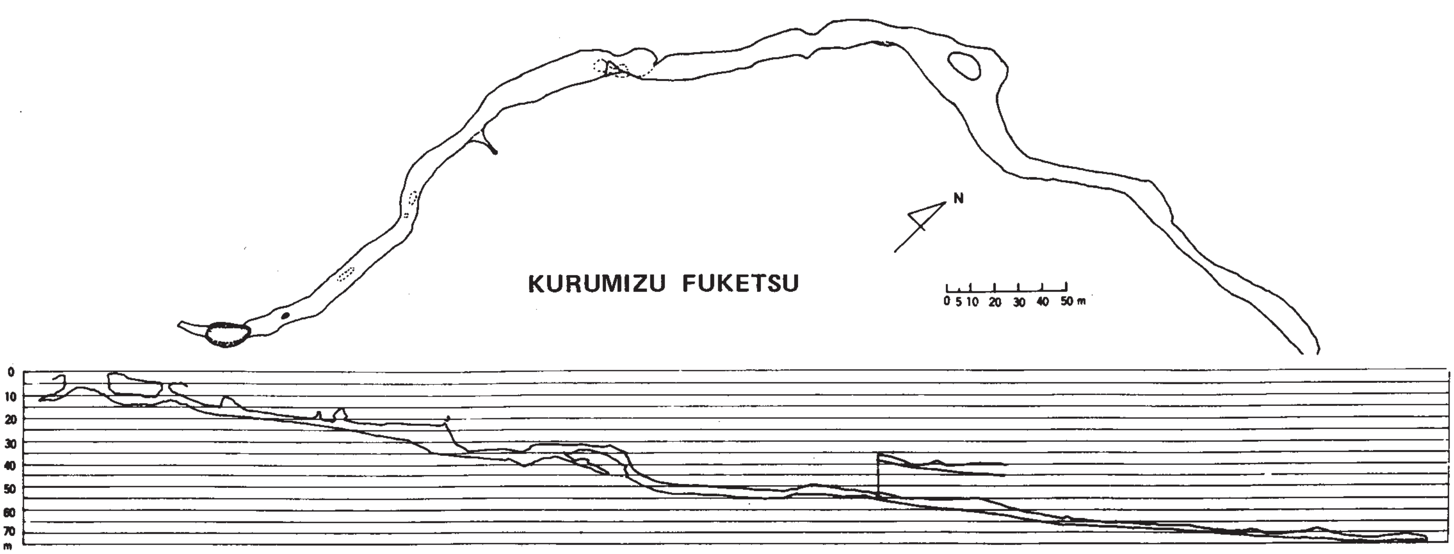
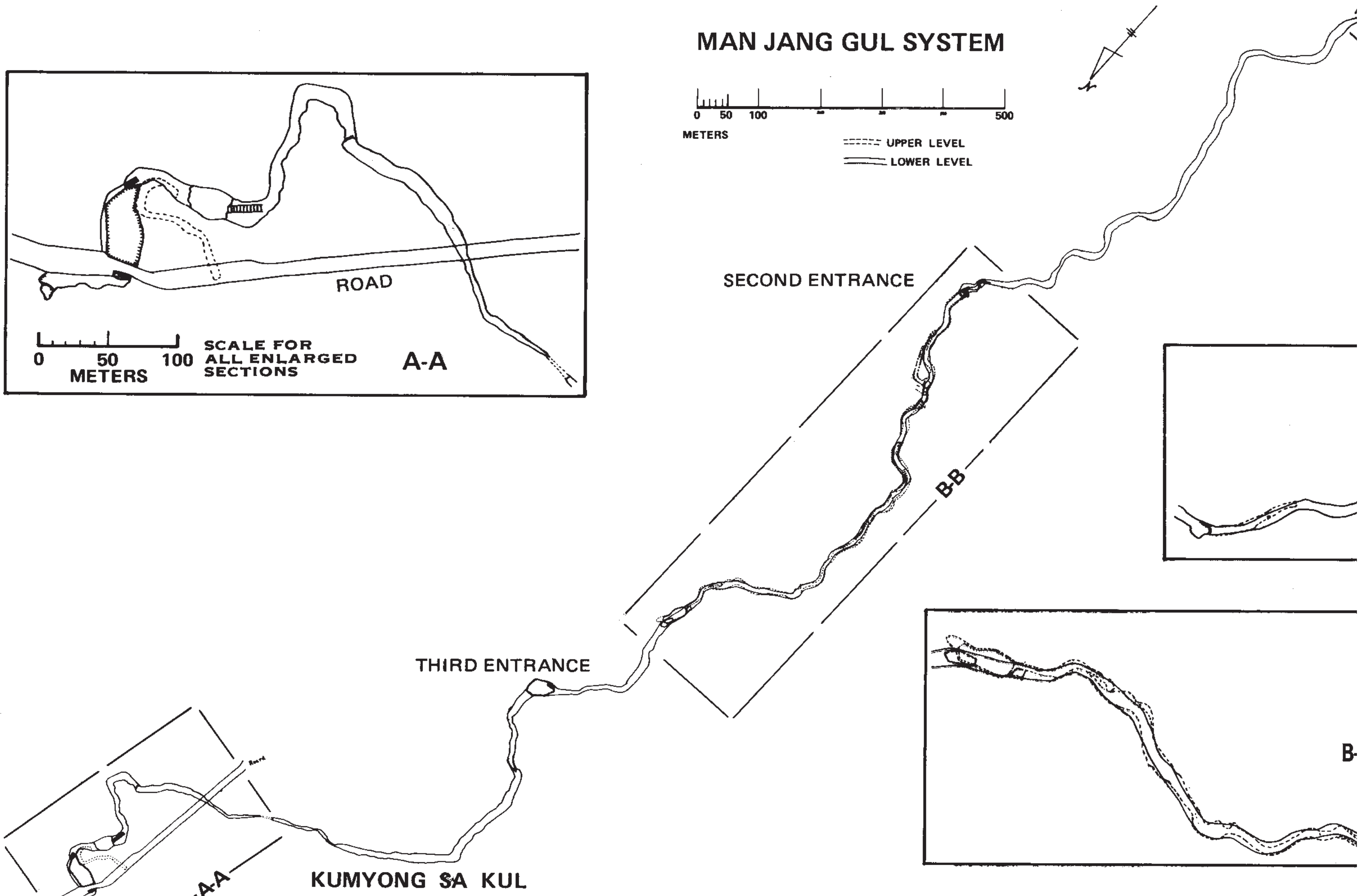


Banba Ana Cave, showing its entrance pit looking up from inside. Mount Fuji, Japan.







KOREA: LAVA CAVES ON CHEJU-DO (ISLAND)

Cheju-do (Island) consists largely of alkali basalt which erupted from Mt. Hanra. The latest eruptions took place in 1002 A.D. and 1007 A.D. In the southern part of this island, there formed a small "volcanic island" of andesite. Later, there occurred an upheaval, and now there are many "islands" in the southern district of the island surrounded by the basalt of Mt. Hanra.

In Korea, Mt. Hanra is said to have erupted in Pliocene or Pleistocene time. But judging from the erosion of the mountain and the weathering of the caves, we believe, from comparison with Japanese volcanoes, that it began to erupt about 20,000 years ago. If we think of the fact that Oahu Island came into existence about 3,000,000 years ago, Cheju Island is quite a recent one, and when we compare its caves with the weathering and ruined state of the oldest of Mt. Fuji caves (13,000 years old), it may be considered to be more recent. More precise geological mapping is needed.

CHINA: THE LAVA CAVES OF HEI RON CHYAN SUUN

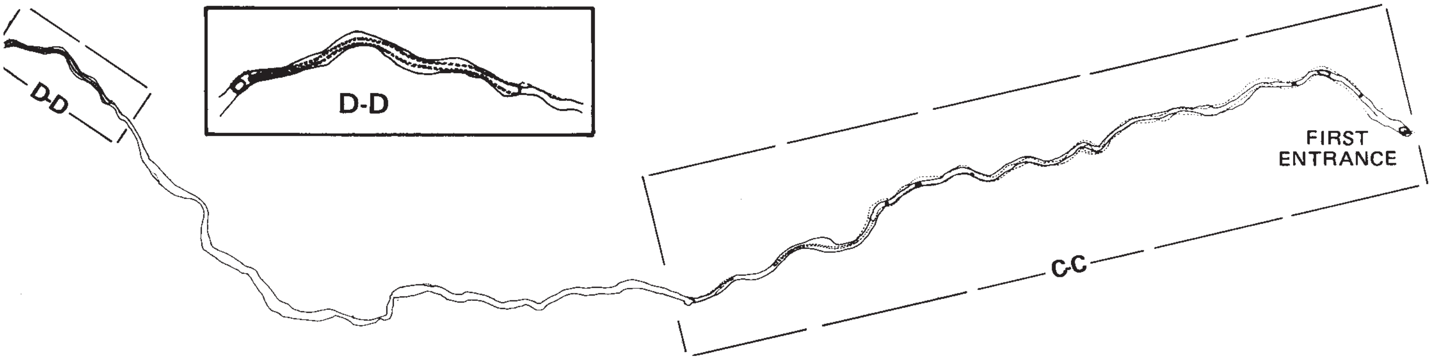
These lava caves were first introduced in the Chinese periodical *Geomorpholical Knowledge* in January 1981. They are at the upper fork of Mu Tan Chyan River; northeastern China, 110 kilometers southwest of Mu Tan Chyan Su (city) in Hei Ron Chyan Suun, and 13 kilometers southeast of Fuo Ko Sum Rin which is near Puo Fu (lake). Here are craters with basalt lava erupted 4,000 to 8,000 years ago. Lava caves of various sizes were discovered here in June 1980. They range from 10 meters long to 500 meters long. The width is 3 to 11 meters, and the height is 1 to 4 meters.

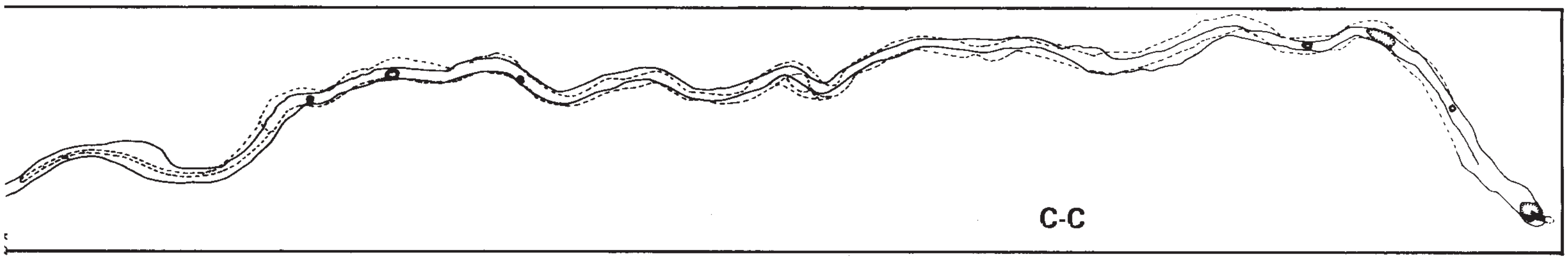
The lava ledges are B and D types, and besides ropy lava flows, lava stalagmites, and lava falls, there exists the same type of lava ball here that is found in Man Jang Kul (Cave) in Korea. Also found are those with lava hanging from the tips of stalactites. The number of caves was not mentioned.

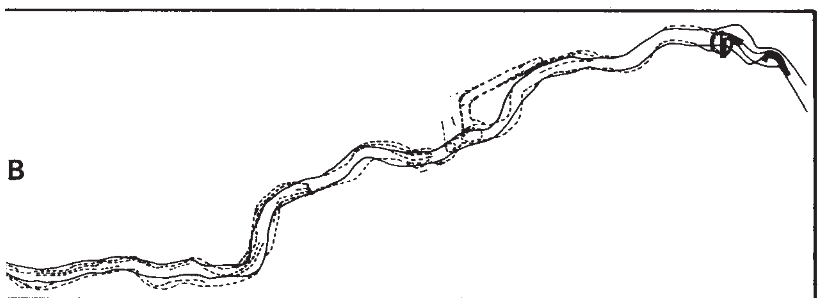
FEATURES SEEN IN THE LAVA CAVES IN EAST ASIA REGION

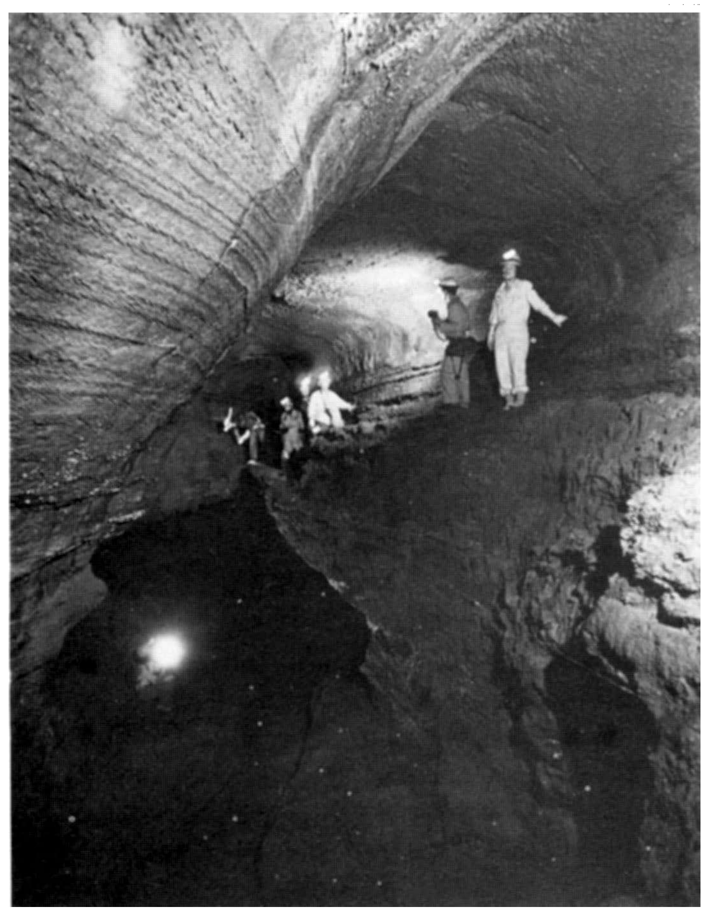
The lava in which caves are found in Japan is the aa type lava, but in Korea and China is the pahoehoe. In the Mt. Fuji area, the caves contain A-type lava ledges.

In Japan, these can be seen in seven of the caves, but in

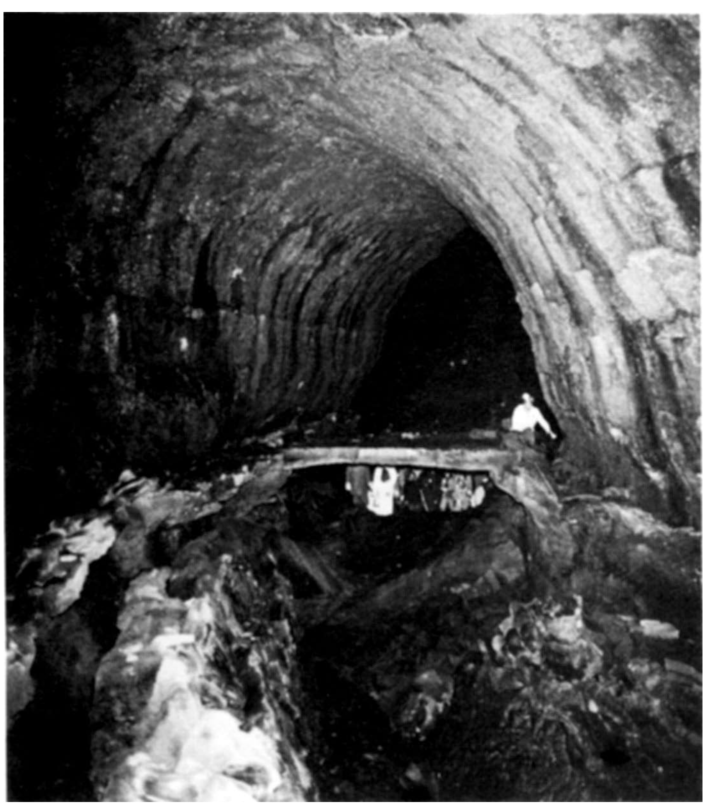






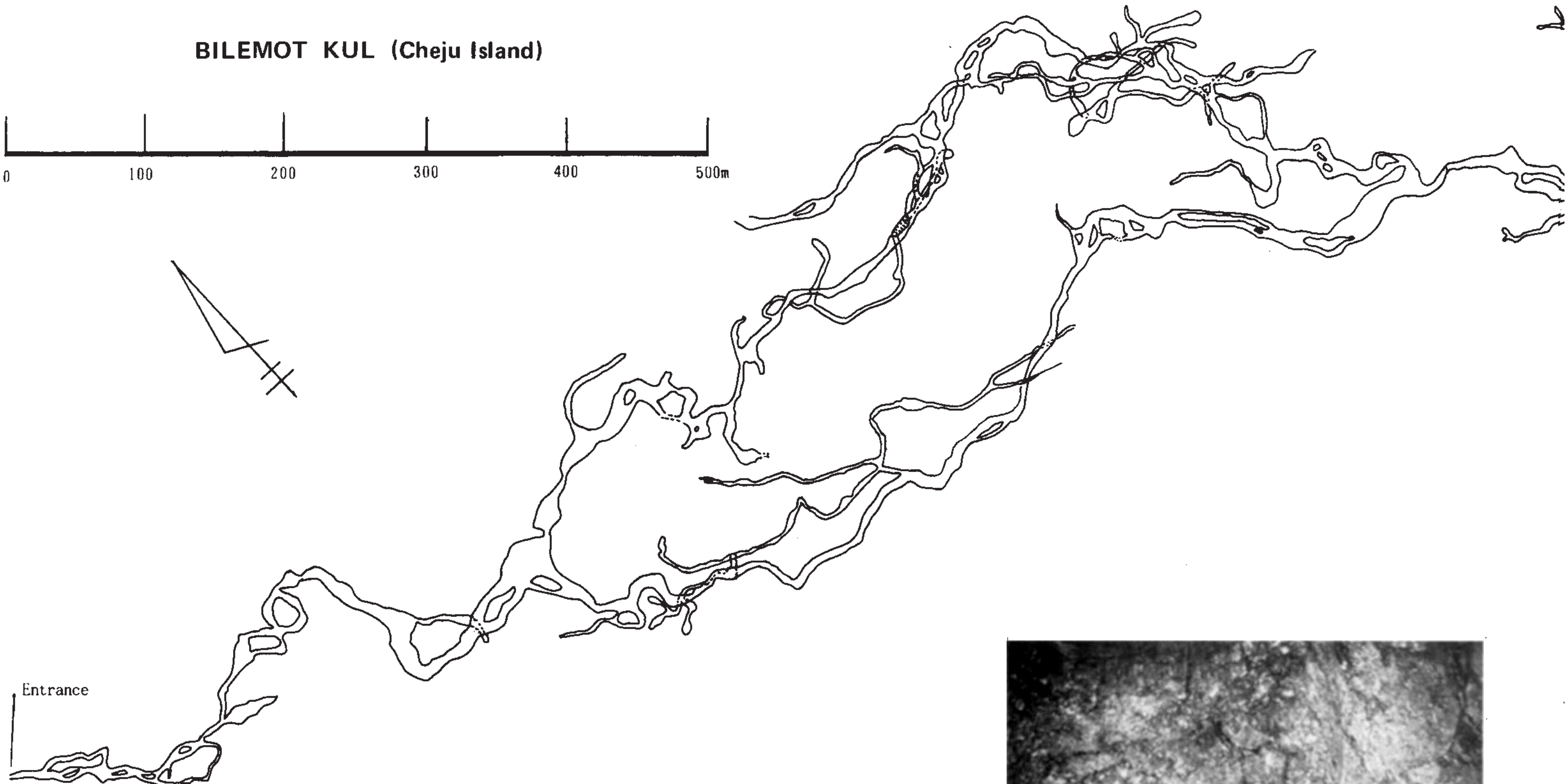


Bilemot Kul Cave, Cheju Island, Korea.



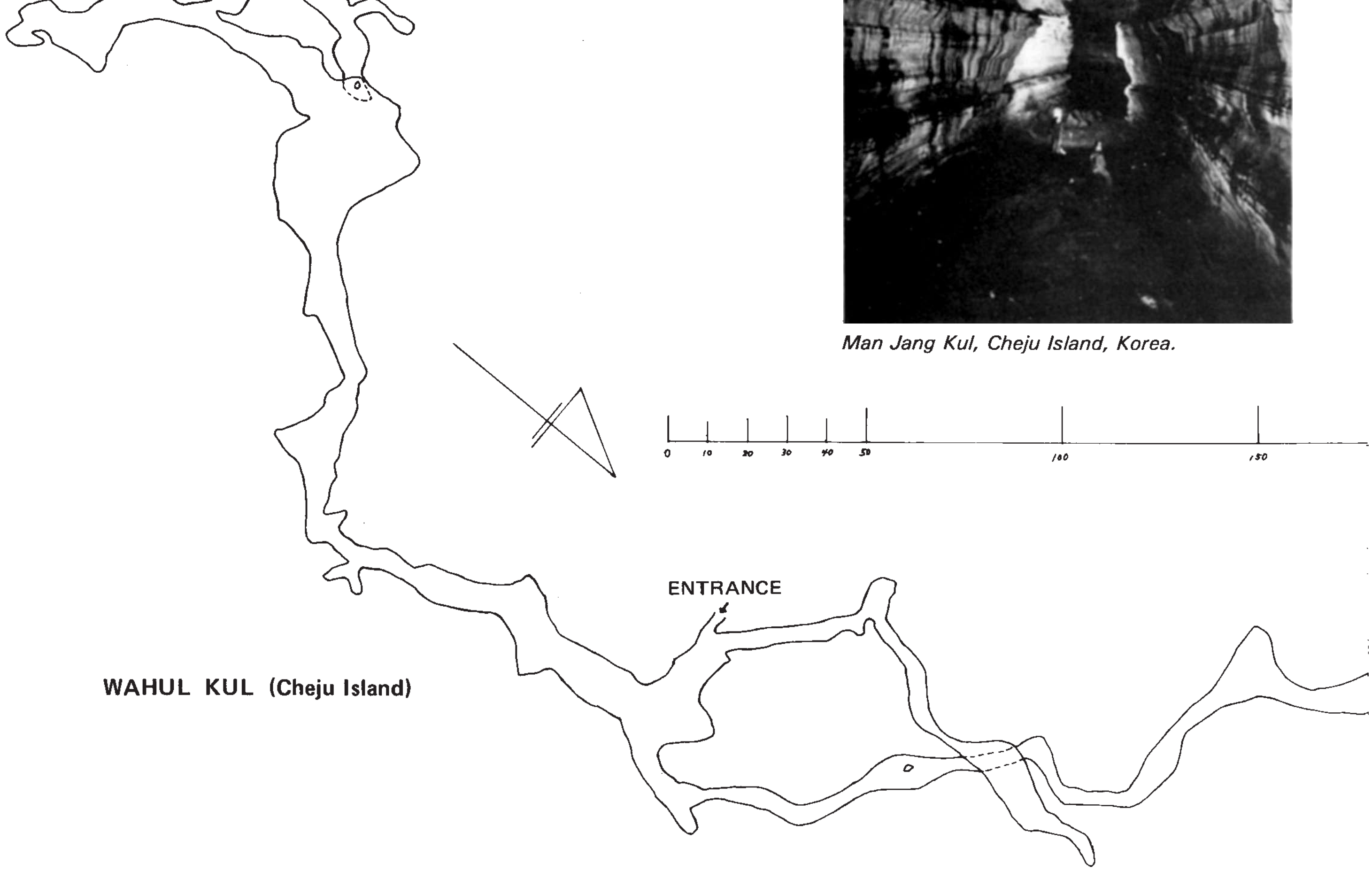
Lava bridge in Man Jang Kul, Cheju Island, Korea.

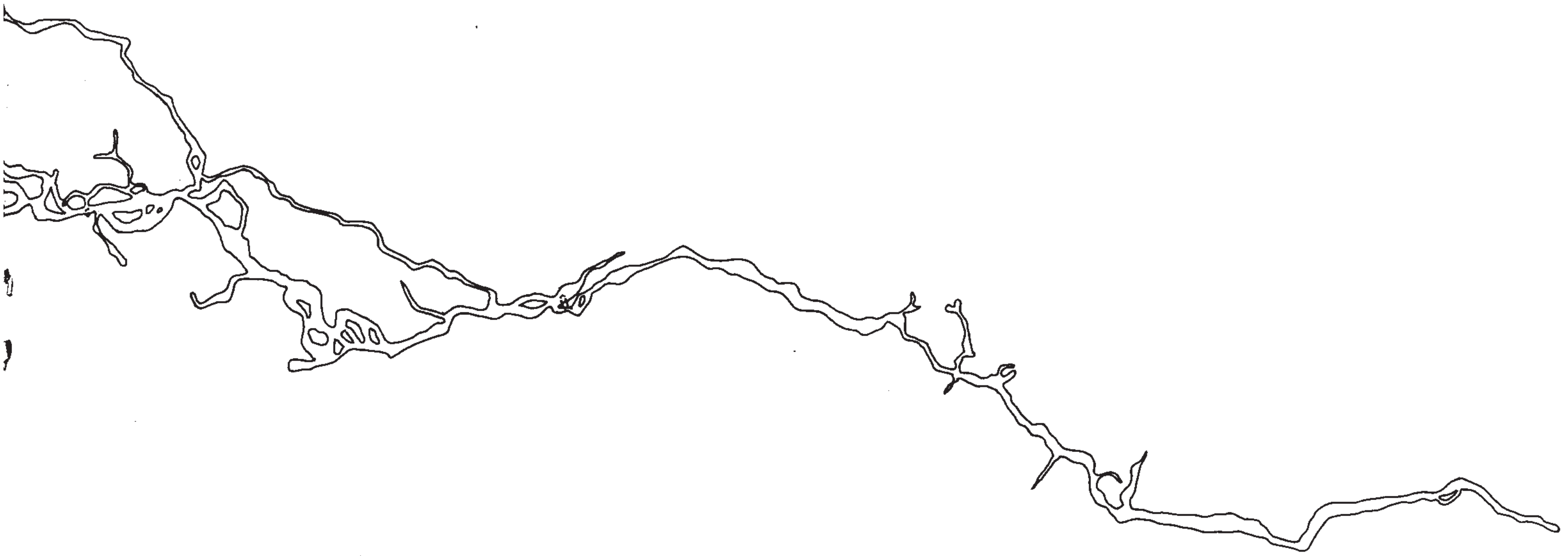
BILEMOT KUL (Cheju Island)



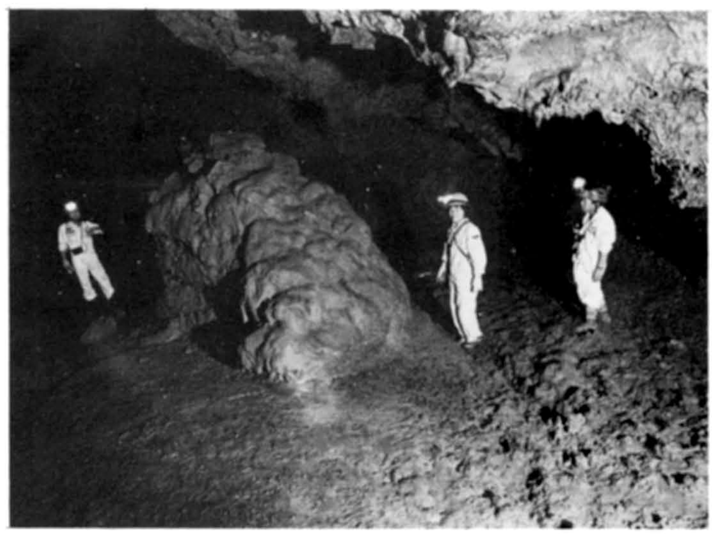

Man Jang Kul, Cheju Island, Korea.

WAHUL KUL (Cheju Island)

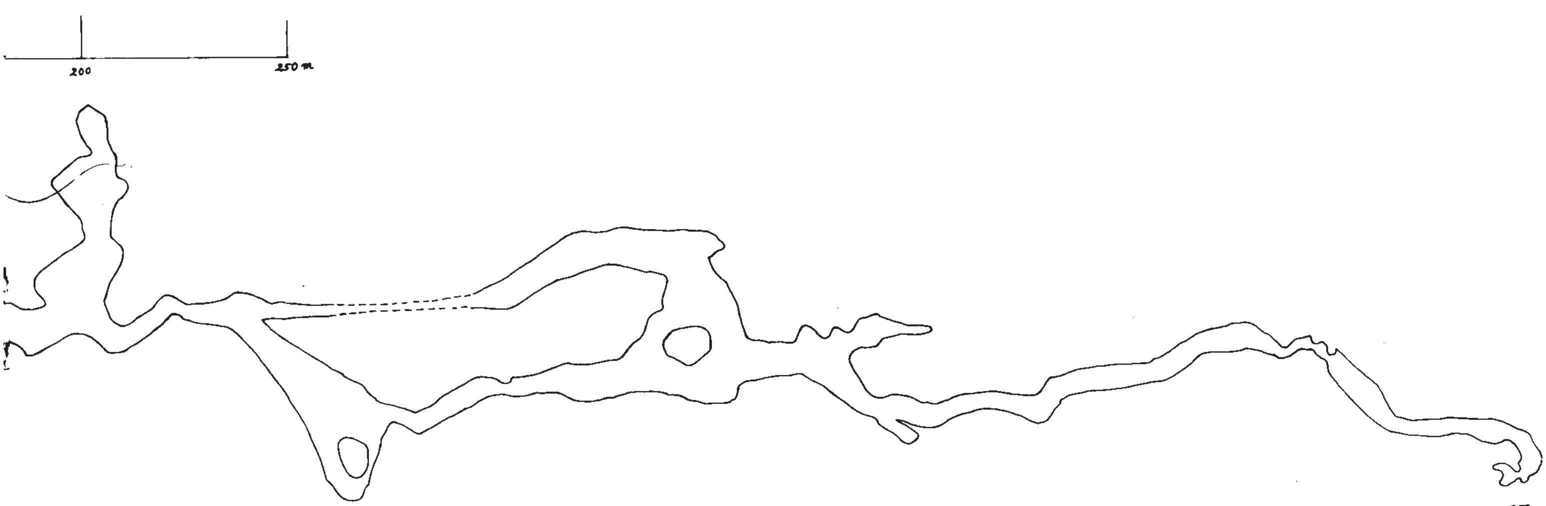




Bilemot Kul, Cheju Island, Korea.



Lava ball in Bilemot Kul, Cheju Island, Korea.



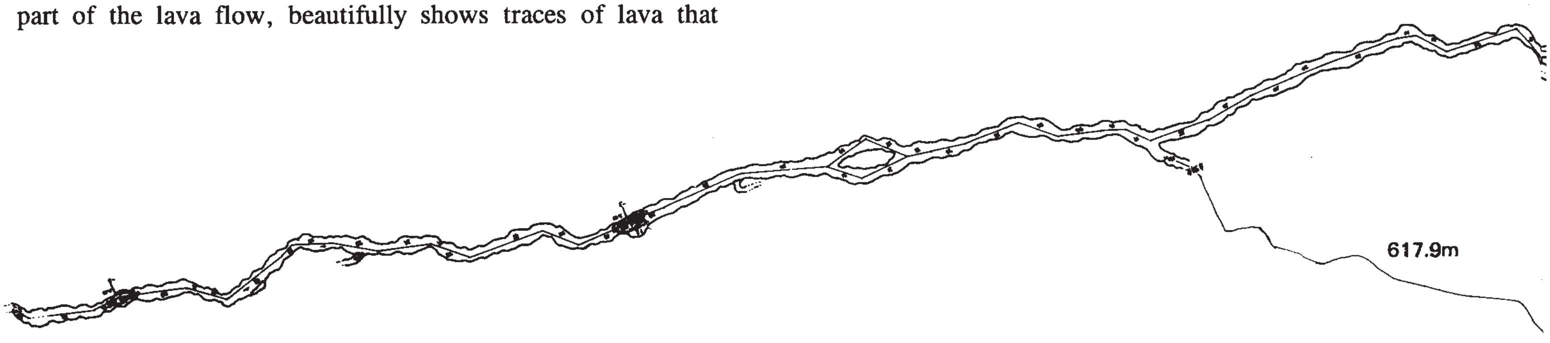
only one cave has an A type lava ledge. This type is caused by secondary flows of somewhat low temperature lava, which flowed into the caves, and after it flowed out, the lava which remained on both sides of the wall curled off and formed into a snake-shaped pipe. When the lava is very hot and soft, this does not occur, and a B-type lava ledge forms instead.

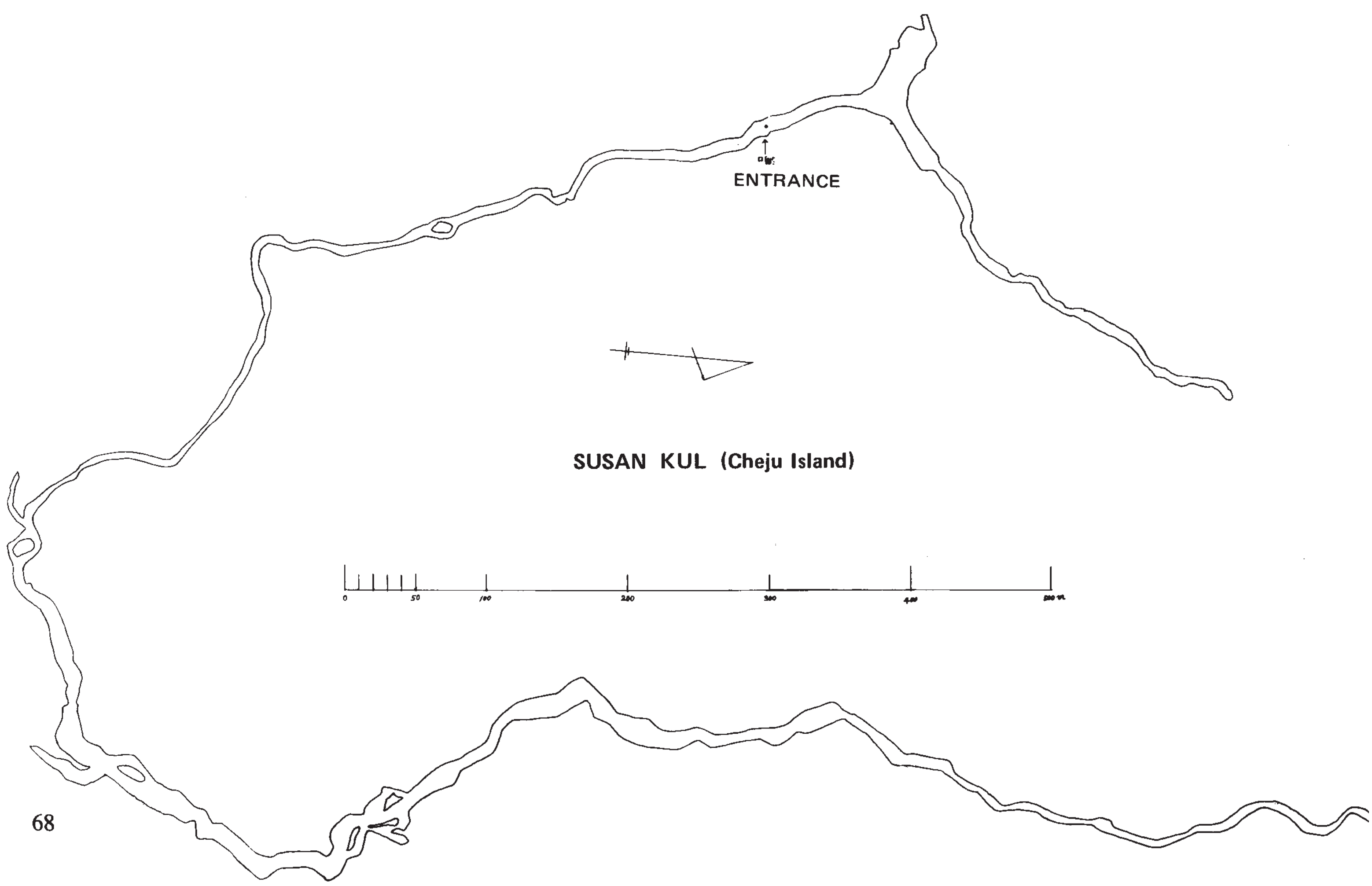
In Japan, three lava balls can be seen in Mitsuike ana (Cave) and two in Hachijo Fuketsu lava cave; in Korea, 21 are in Man Jang Kul (lava cave) and three in Bilemot Kul lava cave. The biggest of these is seven meters in the longest diameter, and 5.2 m in the shortest, and 2.5 m in height. There is also one in Susan Kul. The most notable ones are in Man Jang Kul.

When we look at these lava balls, we understand that the condition for the formation of these balls is that when they fall from the ceiling, the flow of lava on the floor must be slow. The lines on the sides of lava balls in Man Jang Kul show that the lava balls had sunk into the floor and subsidence and flow made these lines on the lava balls. One lava ball, on the surface part of the lava flow, beautifully shows traces of lava that flowed in two different directions, one to the right and the other to the left.

On Mt. Fuji, in Motosu Fuketsu No. 1 Cave, Zinza Fuketsu No. 1, and Karumizu Fuketsu, the "grape-type" lava stalactites can be seen. This is caused by the action of gas which dispersed small pieces of lava into a state of spray, and these particles stuck together one after another in a cluster of stalactites.

In Japan, siliceous stalactites can be seen in 13 of the caves of Mt. Fuji. The longest stalactites are 30 centimeters in length, but most of them are about 5 centimeters long. They are not seen in other places in Japan. In Korea, they have been found only in Man Jang Kul, Handul Kul, and Bilemot Kul. In some





SUSAN KUL (Cheju Island)

caves, siliceous stalagmites also are present.

Cross-sections show a concentric state. Formation of these stalactites and stalagmites is as follows: when gas is suddenly cooled, silicate which is contained in the gas forms particles. Later these are carried by water that has soaked through the lava, and they are deposited just like calcite stalactites.

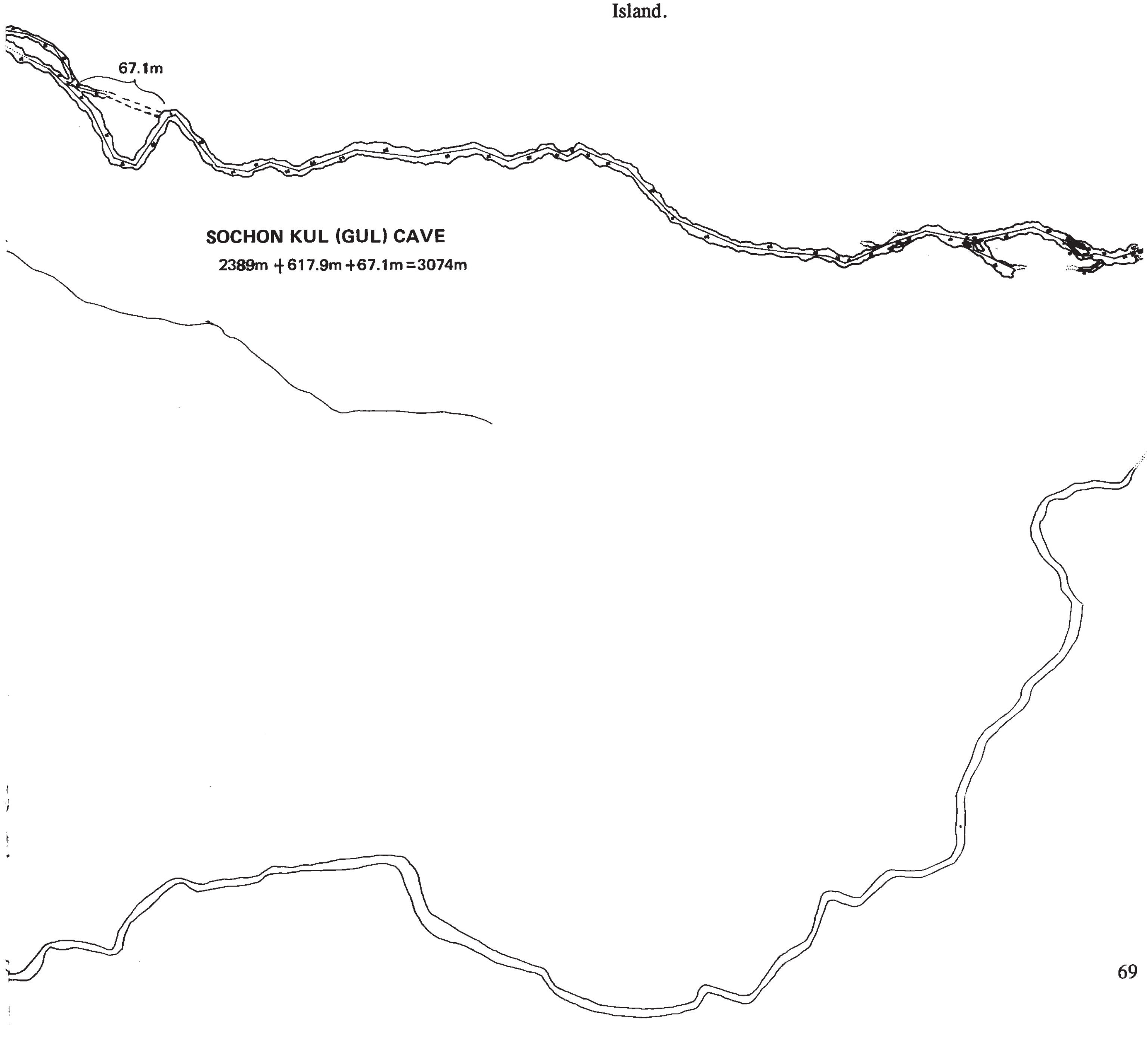
Other siliceous deposits are chemically similar to siliceous stalactites. In the USA, they have been reported by C. Larson as coralloid speleothems in Round Mountain Cave (Oregon). In Japan, they can be seen in nine of the lava caves of Mt. Fuji. In Korea, they are found mostly in Bilemot Kul (Cave). In Man Jang Kul (Cave), Handul Kul (Cave), and in Susan Kul (Cave), a few of them are present.

These are formed when the secondary lava flowing into the cave is suddenly cooled and the gas which gushes out from the lava hits against the side wall and the silicate contained in the gas sticks to the side wall.

Sometimes they are found in foam-like holes of lava, especially in Bilemot Kul Cave, on the walls and ceiling, where gas broke through into the cave. Generally, the color is white, but sometimes the surface is oxidized and is black. They vary in shape from mushroom-type to coral-type.

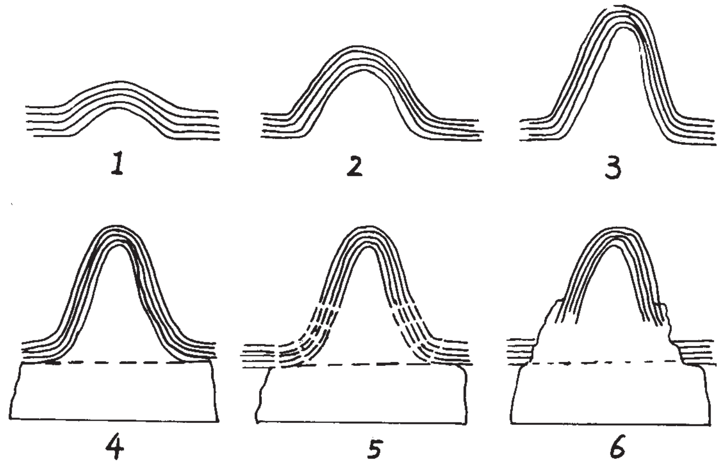
In Japan, calcareous sublimates can be observed in some of the lava caves in Aokigahara lava flow in Mt. Fuji; in these lava caves, a siliceous deposit does not exist at all. As this lava flow is a rather recent one which erupted in 864 A.D., there may be some lime still remaining in the country rock. In the case of Korea, calcareous sublimates cannot be seen at all.

In Japan, there are no tubes-in-tube in the caves of Mt. Fuji. A small one is found in Hachijo Fuketsu No. 1 in Hachijo Island.



LAVA CAVES ON CHEJU ISLAND

	Lava flow and cave name	Length (meters)	Elev. (meters)
	*** Pyoseonri lava flows, Mount Hanla**		
1	Bilemot Kul	11749	245
2	Man Jan Kul	8927	120
3	Susan Kul	4674	110
4	Sochon Kul	3074	150
5	Michon Kul	1695	100
6	Wahul Kul	2066	200
7	Handul Kul	1400	80
8	Kunchokit Kul	910	80
9	Shinchang Kul	850	20
10	Yuktigi Kul	800	70
11	Kumyong Sa Kul	705	60
12	Kyeosae Kul	414	10
13	Sangyong Kul	380	15
14	Imemolu Kul	350	70
15	Kyeotsae Kul	250	10
16	Kaenegi Kul	200	30
17	Kyeyomul Kul	170	10
18	Hwangkukm Kul	140	20
19	Jaeamchun Kul	114	10
20	Hyupjae Kul	109	20
21	Pognamumit Kul	100	30
22	Kumyong Bat Kul	/	10
23	Kumyong Jeol Kul	/	10
24	Jagun Chogit Kul	/	/
25	Kum Rung Kul	/	/
26	Buzong Kul	/	230
27	Konaebong Kul	/	/
28	Han Dam Kul	/	/
	*** Ha Hyo Ri & Cheju lava flows, Mount Hanla**		
29	Mosimeol Kul	80	460
30	Kaeng Saengi Kul	45	280
31	Dotjae Pognamu Kul	80	30
32	Jolong Kul	50	30
33	Yeo Woo Kul	/	/
34	Nam Sogak Kul	/	/
35	Dot Lyanug	/	/
	*** Hanlasan lava flows, Mount Hanla**		
36	Kulin Kul	380	780
37	Yong Jin Kul	/	1450
38	Tong Kwae Kul	/	1530
39	Dung Tojin Kwa Kul	/	1750
40	Pyeong Kwae Kul	/	1600
41	Sang Kwae Kul	/	1450
42	Neol Bun Sang Kwae Kul	/	1700
	*** Sihungri lava flows, Mount Hanla**		
43	Songdang Kul	850	250
44	Dukchon Kul	190	180
45	Konaengie Sul Kul	/	/



Model showing the growth of laminations and the lining partition.

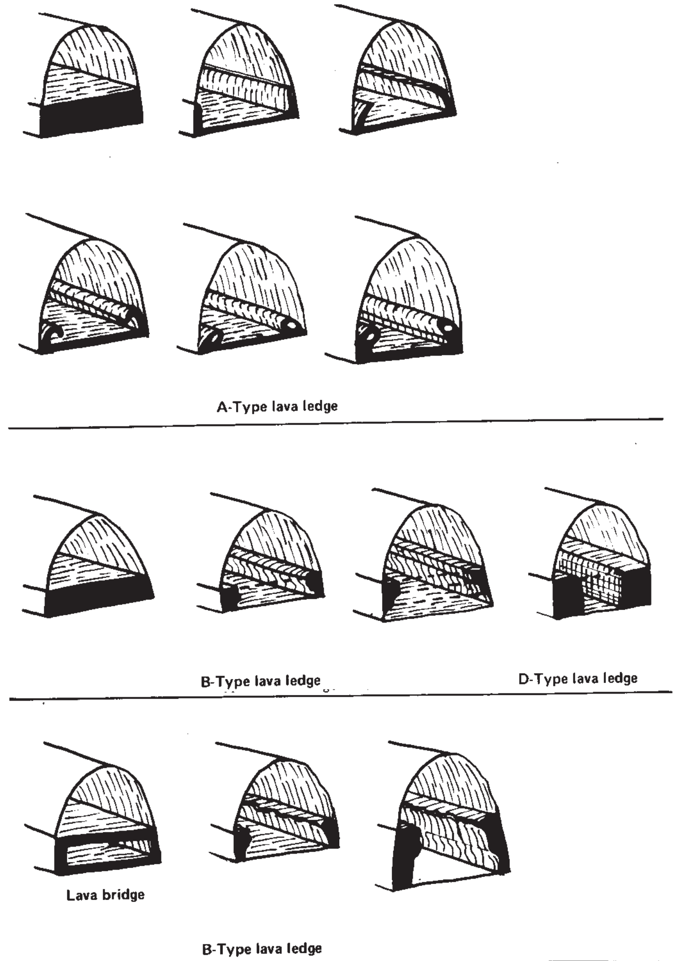

Laminations in Inusuzumiyama Fuketsu Cave No. 1, Mount Fuji, Japan


A-type lava ledge in Narusawa Komori Ana No. 1, Mount Fuji, Japan.

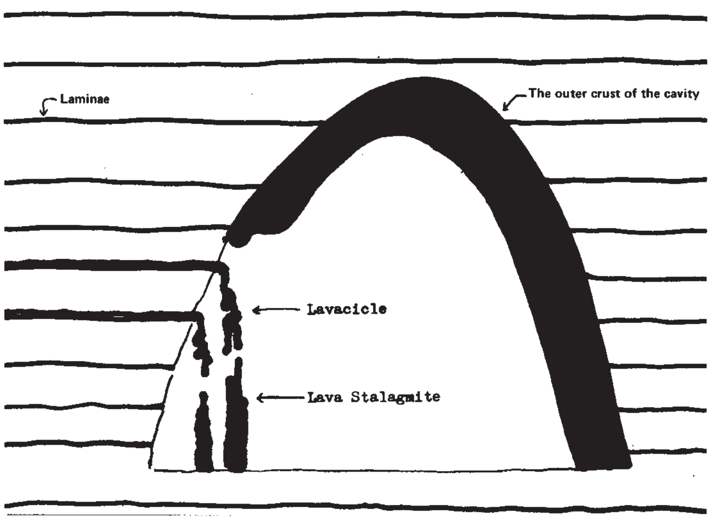
On Cheju Island, a very long one (over 300 meters long) has been found in Sochon Kul (Cave). Man Jang (Kul) and Bilemot Kul (Cave) each has one tube-in-tube.

Laminae can be seen only in the following six lava caves on Mt. Fuji, namely, Inusuzumi-yama No. 1 Cave, Mujina-ana (Cave), Mitsuike-ana (Cave), Zinza Fuketsu No. 1 Cave,

A-type lava ledge in Shoji Ja Ana (cave), Mount Fuji, Japan.



C-type lava ledge, Uzura Ana (cave), Mount Fuji, Japan.



Cross section of lava cave and lava flows.

Push out lava stalactite, Bilemot Kul, Cheju Island, Korea.

Motosu-Fuketsu No. 1 Cave and Karumizu-Fuketsu Cave. There are none in the caves of Cheju Island.

In Japan, lava stalagmites exist only in Mitsuike-ana (Cave) in Mt. Fuji. The biggest is 191 centimeters in height, and there are 137 which are over 5 centimeters in height.

On Cheju Island, there are four in Bilemot Kul (Cave) and in Susan Kul (Cave) about ten can be found. Formerly, there were two in Sochon Kul Cave, but they were stolen. In Man Jang Kul (Cave), there were many, but at present there are none.

Japan has only two small lava bridges in the caves of Mt. Fuji. Cheju Island has beautiful lava bridges in Man Jang Kul (Cave). Susan Kul (Cave) has lava bridges extending as long as 20 meters, and Sochon Kul has 300 m.

A coffin in Sochon Kul (Cave) shows clearly the process of origin of this type of feature.

The coffin in Prince Albert Cave (Washington) was formed when the surface of the secondary lava flow hardened and later when the inside lava flowed out, it formed the coffin as a tube-in-tube.

But when the lava was flowing, the ceiling which had hardened, collapsed, and was carried away by the moving lava, then the walls of tube-in-tube were pushed outward and made wider, and in the Sochon Kul Cave, the part which is stuck and pushed upward can be seen.

In Japan, lava stalactites of various forms are found in Mitsuike-ana (Cave) of Mt. Fuji. In Hachijo Fuketsu Cave on Hachijo Island, there are five others. There are no other examples in Japan.

On Cheju Island, Bilemot Kul (Cave), Man Jang Kul (Cave) and Susan Kul (Cave) have some. The ones in Man Jang Kul are pipe stem types. One of them is about 90 centimeters long. It is not as narrow as the one in Pisgah Crater Cave (California).

These stalactites are laminated. Hot lava which infiltrated into the thin lava layer kept dripping and formed them. Columns formed by joining of stalactite with stalagmite can be seen in Mitsuike-ana (Cave) in Japan and Bilemot Kul (Cave) and Susan Kul (Cave) in Korea.

THE STUDY OF THE FORMATION OF THE CAVES

When we look at the vertical section of Zinza Fuketsu No. 1 Cave in Mt. Fuji, it can be understood that the cavities are connected to each other and become longer and longer.

As one cavity joins with another, gas moves from one cavity to another. The following caves contain evidence of this:

1. The grape-type lava stalactites (Motosu-Fuketsu No. 1 Cave, Karumizu-Fuketsu Cave, and Inusuzumi-yama Fuketsu No. 1 Cave on Mt. Fuji).

2. Speleothems resembling eolian ripple marks on lava ledges (Man Jang Kul in Korea).

3. Speleothems of lava drops which ran down against the wall impelled by gas (Man Jang Kul).

4. Stalactite bent by the movement of gas.

5. Stalactite on the ceiling that shows many straight parallel lines (Shyoiko Fuketsu No. 1 Cave, Japan).

When we examine the laminae in Mitsuike-ana (Cave), it is

CHEMICAL QUANTITATIVE ANALYSIS OF SILICEOUS SPELEOTHEMS IN LAVA CAVES

Place	Mt. Hanra (Korea)		Mt. Fuji (Japan)	
Cave name	Man Jang Kul	Man Jang Kul	Komakado Fuketsu	Ohno Fuketsu No.2
Form	Powder	Lamella	Coralloid	Stalactite
SiO_2	33.07	49.39	36.81	37.54
Al_2O_3	0.04	0.19	27.07	30.20
Fe_2O_3	0.12	0.18	1.48	0.28
MnO	0.00	0.01	0.00	0.00
MgO	14.4	8.66	2.11	0.28
CaO	0.89	11.6	1.47	1.23
Na_2O	0.26	0.22	1.07	0.87
K_2O	0.02	0.03	0.29	0.19
H_2O	44.41	5.80	16.42	15.22
Ignition loss	6.61	20.05	11.87	13.77
Total	99.8	96.1	98.9	99.58

clear that the outer crust of the cavity hardened quickly into a crust; around the crust, there is a thin lava layer, which sometimes flows on as one thick plate.

When this outer crust breaks down and laminae are exposed, these laminae seem to have separated from each other as they flowed and traces of scratches can be observed between the upper and lower layers in Mujina-ana (Cave).

Also in Zinza Fuketsu No. 1 Cave, laminae are pushed up by gas, some parts are destroyed. They are identical with what is called the Plug in Kitty-Pooh Extension (Oregon), Ice Rink Cave (Washington) and Dynamited Cave (Washington).

In those lava caves which are near the surface, cavities exist under surface swellings where lava is pushed up by gas. There are four such caves on Mt. Fuji.

Ripple marks on a lava ledge, Man Jang Kul, Cheju Island, Korea.

Lava ball in Mitsuike Ana (cave), Mount Fuji, Japan.

Considering these phenomena, we must say that gas has much to do with the making of caves. In Shyoiko Fuketsu No. 1, when we examine the place where gas explosively broke through the wall of the cave, we can see how rapidly the lava has hardened. Also, when we look at pipe-like stalactites, it can be understood that, when the drops of lava are dripping, it cannot be formed unless its surface quickly becomes hard.

When a lava cave is made, first of all successive flat cavities are formed by gas. At the bottom of the cavity, the floor moves on with the least resistance, so the floor itself sinks and the cavities are connected, and thus they may form an enormous cave. In this way, very long caves are formed.

Features of Three Kinds of Lava Caves

We have examined caves in the three kinds of basalt caves, and they do not show much difference. But in the lava caves of Cheju Island and those in China, caves in alkali basalt have some characteristics:

1. There was much flow of lava, and generally the caves having the above conditions are very long caves.

A. The lava on the walls of the cave has luster and is smooth, and many caves show that the floor moved down and sank rapidly, that is, the lava was of high temperature and had no coking property.

B. As the amount of lava eruption was great, the lava caves are generally very long, as in the case of Cheju Island, which is a volcanic island, and because gas from the sea water was added to the lava, in the case of Man Jang Kul (Cave) in Korea, 51 cavities were joined together producing a system 8,927 meters in length.

2. In these alkali basalt caves, laminae cannot be seen on the sides. We may consider that this depends on the nature and quality of lava.

3. A lava bridge is big and long, so the coking property has something to do with it. According to the chemical analysis table, SiO_2 here is less than in those in Hawaii, and it has much fluidity.

As in the case of high-alumina basalt in the lava in Mt. Fuji, each lava flow has different chemical components. Inusuzumi-yama lava flow has the softest basalt erupted from a shield volcano, which is called Mt. Inusuzumi, halfway up to Mt. Fuji. So here there are many very long caves and also caves with complicated planes.

Because there are caves in which the side walls have collapsed and laminae can be seen, it is probable that there was much fluidity of lava. Even if the lava flow is the same, the impression we get when we go into the caves can be completely different according to the condition of the movement of lava or the difference of time when the eruption occurred.

Generally speaking, the caves near the flat part of the summit are close to the surface, and they are complicated and small. But the cave which formed where the lava did not move but stayed, are simple, big and long.

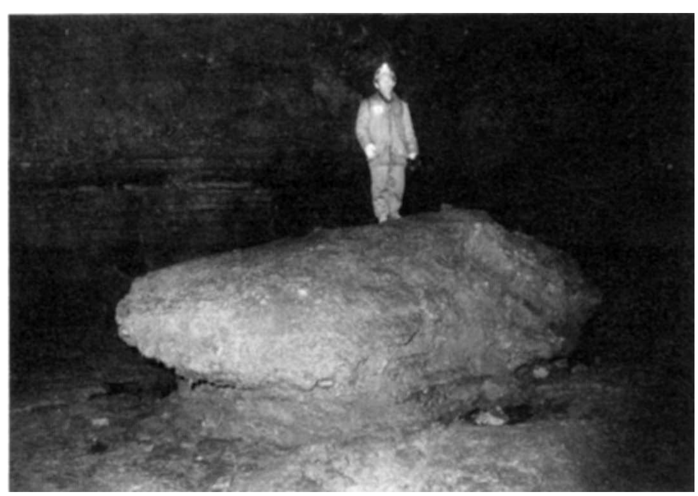
In Aokigahara, where the number of caves is the greatest, the lava flow is typical aa lava. So A type lava lege is found only in this lava flow and in that of Mt. Aso.

It is not certain whether it is due to high-alumina basalt, but in Pinwill's Cave (Australia, North Queensland) A type lava ledge is present. This A type lava ledge is formed in a snake-like shape under both the side walls of the cave. Some of them are hollow.

As I have mentioned above, a small difference in the chemical component of basalt gives every cave some different features.

ACKNOWLEDGEMENT

The report on the lava caves on Cheju Island is the result of joint investigation with Dr. Hong Shi Hwan, head of the Speleological Society of Korea.



Lava ball in Man Jang Kul, Cheju Island, Korea.

LAVA CAVES OF AUSTRALIA

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ABSTRACT

During the Cainozoic, there was widespread basaltic igneous activity in eastern Australia, but only the relatively young (post Miocene) lava field provinces in northeast Queensland and western Victoria have numerous, well-preserved lava caves (over 40 in northeast Queensland and over 50 in western Victoria). The northeast Queensland caves are large, simple in plan and cross-section, and are concentrated in particular groups; each group represents a lava tube system. In general, the Victorian caves are smaller and often more complex, especially in plan, and they tend to occur in isolation. A range of origins and geomorphic settings is represented by the Victorian caves, including tubes in flank flows, valley flows, lava plains and channel overflows, as well as spatter cone shafts and roofed lava channels.

Isolated, older caves are also present in eastern Australia. Early Miocene lava in southeast Queensland contains a small lava tube, and a very small cave in early Oligocene basalt in New South Wales may be a lava tube remnant.

INTRODUCTION

During the Cainozoic, there was widespread basaltic igneous activity in eastern Australia (Figure 1), in a band up to 300 km wide, extending 4,000 km from Tasmania to Torres Strait and beyond (Stephenson, *et al*, 1980). Volcanism commenced in the Late Cretaceous (approximately 70 Ma) and continued through the Cainozoic at a nearly constant rate (Wellman and McDougall, 1974a). More than 50 igneous provinces have been recognized, activity in each generally lasting less than 5 Ma and resulting in lavas covering a region 50-200 km across. The extruded rocks range from mafic to felsic in composition, with basaltic types predominating (Wellman, 1978). The provinces are generally of either the lava field (areal) type, with a diffuse eruptive area, or less commonly the central volcanic type, in which flows are extruded from a well-defined vent area.

Lava tubes are present in basalt flows within six of the areal Cainozoic provinces in eastern Australia, five in Queensland, and one in Victoria (Figure 1). Some of the Victorian caves have been known since the mid-19th century, and Ollier and Brown (1965) reviewed much of the information known about them. Most of the Queensland examples have only been described fairly recently, and new caves are still being found. The present review gives a general description and comparison of all known lava caves in Australia, concentrating on those formed by volcanic action. The term "lava tube" as used herein refers to a cave formed as an internal lava conduit within a flow, whereas the general term "lava cave" encompasses any cave within a lava flow, however it was formed. Lava caves which owe their origin to groundwater or stream action are only briefly mentioned in this review, and caves in pyroclastic deposits interbedded with flow are excluded from this discussion.

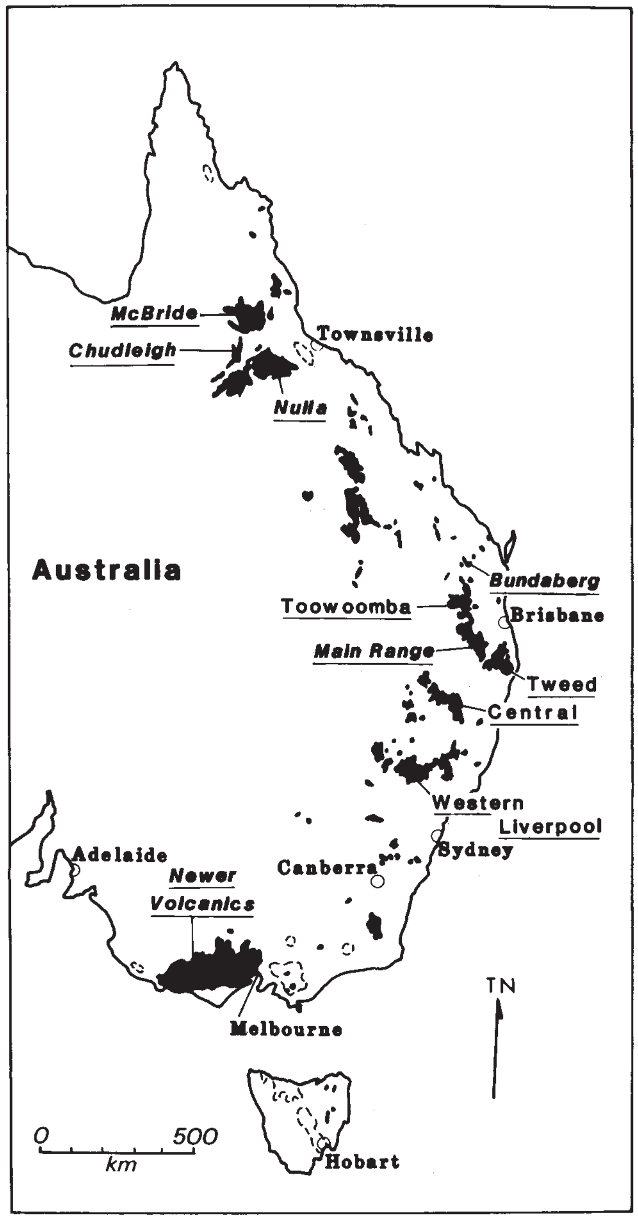

Figure 1. Cainozoioc volcanic areas in eastern Australia; dashed lines enclose areas too small to show clearly at this scale. Modified from Stephenson et al. (1980). Provinces named in italics contain lava tubes; provinces labelled in roman script contain basalt caves formed by the action of streams or groundwater.

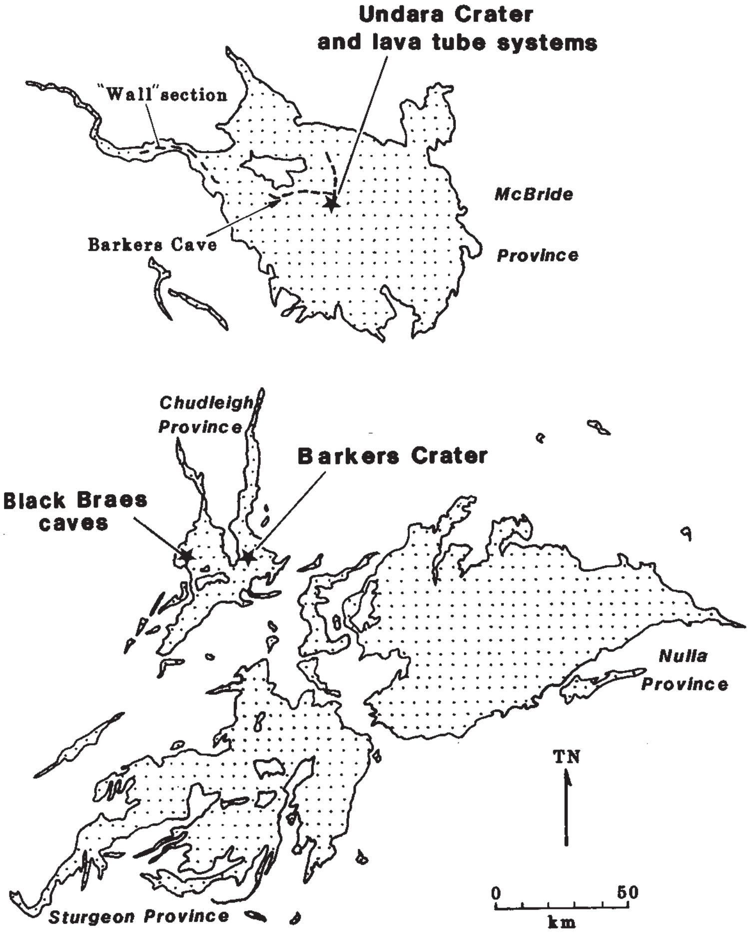

Figure 2. North Queensland volcanic provinces, with major lava cave areas

NORTHEAST QUEENSLAND

In northeast queensland, there are 12 main volcanic provinces, most being lava fields. Volcanic activity has been intermittent since Paleocene-Eocene time, with a major period of volcanism extending from five Ma almost to the present. The age of the youngest eruption is somewhat uncertain, but the Toomba flow in Nulla Province overlies carbonaceous sediments that yielded a radiocarbon date of 13,000 years (Stephenson, *et al*, 1980). Three of the northeast Queensland provinces are known to have lava tubes: McBride, Chudleigh and Nulla (Figure 2).

McBride Province: The largest and best-known lava caves in Queensland are associated with Undara Crater in McBride Province. This province is roughly circular, with a diameter of 80 km and consists of a broad lava plain with numerous cones; there are 164 known vents (Stephenson, *et al*, 1980). As a whole, the province forms a broad volcanic dome with Undara Crater as the highest point. Two long lava flows, both 190,000 years old, extend from Undara Crater, one reaching 90 km to the north and northwest, the other extending 160 km to the west-northwest and west (Figure 2). The great length of these flows is attributed to continued high effusion rates and favorable topography which resulted in channeling and the formation of efficient, heat-insulated lava tubes, able to maintain a supply of fluid lava over long distances (Stephenson, *et al*, 1980; Atkinson, *et al*, 1977). Usually, low viscosity is not believed to be a factor.

The lava tube system in the Undara basalts extends north of the crater for 4 km, and then splits into two, following the course of the flows (Figure 2). The system is marked by a series of elongate depressions and well-preserved lava tubes. In the western flow, these extend perhaps 35 km (Atkinson, *et al*, 1977), their continuation is the "wall" section, a narrow ridge 35 km long, up to 20 m high and 70-300 m wide (Stephenson and Griffin, 1976). Although no caves have been found in the "Wall," it is believed to have formed above a pre-existing stream channel and apparently represents an undrained lava tube (Stephenson, *et al*, 1980).

The elongate depressions associated with the lava tube system are conspicuous from the air because of the dark green vine-thicket vegetation growing in them, and they allow the course of the lava tube system to be traced easily on air photos. The depressions are 50-100 m across, with elevated rims, and probably represent former lava ponds that have drained and collapsed after crusting over (Stephenson and Griffin, 1976; Atkinson, *et al*, 1977).

Although closely related to the lava caves, the depressions seldom give access to them. Entrance to the caves is usually effected via narrow, less obvious depressions 30-60 m wide caused by roof collapse. There are 27 caves known in the area (Grimes, 1977), and undoubtedly more remain to be discovered. Tunnel-like in appearance, the caves are up to 21 m wide and 13 m high, and are unbranched to once-branched in plan. The longest cave, Barkers Cave (Figure 3, Figure 4), is just over 900 m long and ends in a lake (Grimes, 1977); other caves terminate downflow with collapses or a downward curve of the ceiling to the floor. The maximum slope of any cave is 3°, and the average slope of the whole lava tube system is 1° or less. Most caves have silty floors, but in some, the original lava floor is exposed and shows ropy surfaces and gutters. Lava linings on the walls often have lava stalactites and lines marking former lava levels. The basalt above the tube roofs is exposed in some entrance collapses, and indicates that the caves were initiated by roofing of running lava channels, apparently by crusting (Atkins, *et al*, 1977).

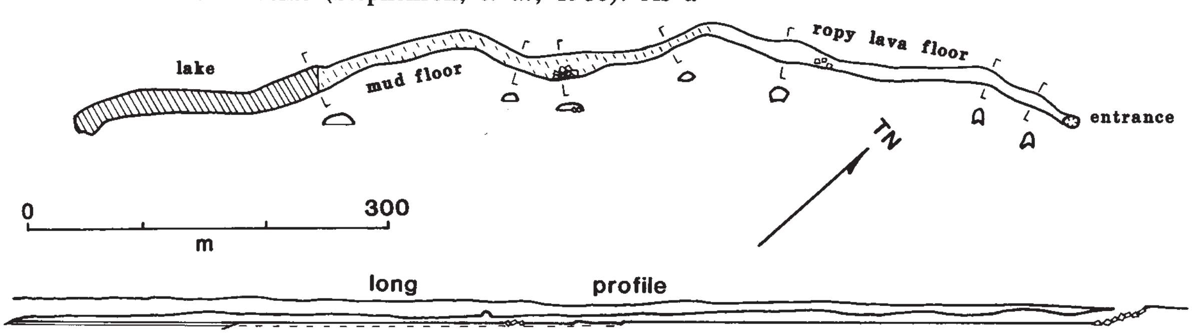

Figure 3. Barkers Cave, McBride Province, north Queensland (see Fig. 2 for location). From Grimes (1977).

Four species of bats roost in the caves, and two (*Miniopterus schreibersii* and *Eptescicus pumilus*) use some of the caves as maternity sites (Grimes, 1977). Guano deposits on the floor of Taylor Cave have yielded the phosphate minerals taranakite, struvite and brushite (Hamilton-Smith, 1978).

Chudleigh Province: This province forms a broad irregular upland characterized by partly dissected lava plains between numerous pyroclastic cones (Stephenson, *et al*, 1980). The flows extend down former river valleys; one traveled over 100 km down a valley from Barkers Crater (Figure 2). The exact age of the lavas is uncertain, but they are likely to be Pliocene or younger. Lava tubes are present in flows from Barkers Crater and from a volcano 6 km west of Black Braes homestead (Figure 2).

There are seven caves near Black Braes, ranging in size from small overhangs to a large cave 300 m long, 20 m wide and 7 m high (Grimes, 1978). In plan, the caves are unbranched or once-branched, and some contain large mounds of rubble fallen from the roof. Lava stalactites are occasionally present on walls and roofs. Associated with the caves are a number of irregular shallow depressions up to 5 m deep, with flat floors. Some of these depressions appear to be related to the caves, and may represent partially drained lava ponds, by analogy with the larger depressions at Undara described above. Three species of bats roost in the caves (200,000-300,000 are present at one site), and *Miniopterus schreibersii* uses one cave as a maternity site (Hamilton-Smith, 1978).

Figure 4. Barkers Cave, McBride Province, north Queensland; note lines on walls marking former lava levels.

From Barkers Crater, a lava channel extends some distance, bounded by raised levees of lava, and caves have apparently former where sections of the channel have roofed over (Shannon, 1974). Five caves are known, with a total length of 250 m, and a maximum height of 10 m and width of 15 m; bats are present.

Nulla Province: This province comprises a wide area of lava plains with 25 vents (Figure 2). The youngest flow (Toomba flow) is less than 13,000 years old and shows original pahoehoe surface textures and negligible soil development (Stephenson, *et al*, 1980). Some short caves are present in this flow, but have yet to be described in detail.

SOUTHEAST QUEENSLAND

Bundaberg Province: This province includes an area around Coalstown Lakes comprising 125 km of basalt flows and three pyroclastic cones; the flows continue down a river valley for a total distance of about 140 km (Grimes, 1979; Ellis, 1968). Lakes occupy two craters in one of the cones. The lavas have a total thickness of up to 20 m, and are 0.6 Ma old (Wellman, 1978).

A single cave, Dundurrah Lava Tube, is known from the Coalstown Lakes area; it is 50 m long, and up to 4 m high and 15 m wide. The cave shows two generations of benches next to the walls, as well as well-preserved wall linings and lava drips, and a large pillar separates the main tunnel from a small anabranch. The roof of the cave appears to have formed by welding of a fragmentary crust (Grimes, 1979). Bats (Miniopterus sp.) roost in the cave.

Main Range Province: The Main Range Province comprises a sequence of nearly horizontal Tertiary volcanics up to 90 m thick, forming the Great Dividing Range in the area (Stevens, 1965). The lavas probably issued from fissures along the highest points of the range, and are dominantly basaltic in composition, with some trachytes. Radiometric dating has given ages of 22-24 Ma (late Oligocene-early Miocene) for the volcanics (Webb, *et al*, 1967).

A small cave (Holy Jump Lava Cave) is present in the upper part of the sequence (Webb, 1979). It has 60 m of passage up to 5 m wide and 2 m high, and consists of portions of lava tubes in two superimposed flows (Figure 5). Part of the lower tube shows wall linings and lava drips, but elsewhere the cave has suffered extensive breakdown, and only small sections of the original walls are present. Secondary silica mineralization (chalcedony, opal-A, opal-CT) encrusts the walls in places and the bat guano on the floor contains gypsum and taranakite (Webb, 1979). Forty centimeters of laminated mud covers the floor of the easternmost part of the lower tube (Figure 4). Two species of bats roost in the cave, and there is an abundant insect fauna, including an endemic species of pseudoscorpion (Muchmore, 1982).

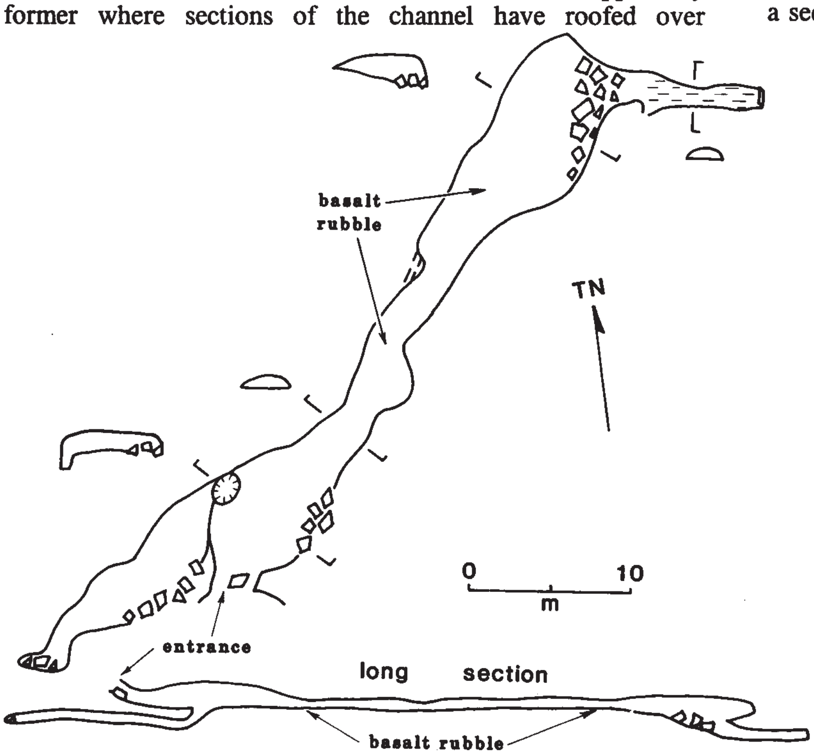

Figure 5. Holy Jump Lava Cave, Main Range Province, southeast Queensland.

Toowoomba and Tweed Provinces: Late Oligocene-early Miocene caves in both these provinces in southeast Queensland (Figure 1) contain caves which have not formed by volcanic action. The cave within the Bunya Mountains in Toowoomba Province has about 45 m of passage; the entrance chamber is 10 m wide and 2 m high (Graham, 1971). Groundwater erosion of vesicular basalt along well-developed joints appears to have caused this cave to develop (Willmott, *et al*, 1981).

Natural Bridge in Tweed Province consists of a single large chamber 46 m long, 26 m wide and 6 m high, with waterfall cascading through a hole in the roof. This cave probably owes its origin to erosion behind the waterfall (Willmott, *et al*, 1981). Bats (*Miniopterus schreibersii*) roost in both caves.

NEW SOUTH WALES

Central Province: Ten kilometers south of Glenn Innes in Central Province is a small basalt cave, 10 m long; nearby basalts have been dated as early Oligocene (33-34 Ma; Wellman and McDougall, 1974b). This cave is tubular in shape and not related to joints or vesicular zones in the basalt (J. Taylor, personal communication). Thus, it seems possible that the cave was originally a lava tube; identifying wall and floor features have presumably been destroyed by weathering.

Western Liverpool Province: Five caves are known in this province, in basalts of early Oligocene age (Wellman and McDougall, 1974b). The largest cave has 70 m of passage, including an entrance chamber 20 m wide and 12 m high (Osborne, 1979). The caves all appear to have formed by groundwater erosion of zeolite-rich amygdaloidal basalt (Osborne, 1979).

VICTORIA

A large Cainozoic volcanic province occupies much of western Victoria and part of southeast South Australia (Figure 6), with a total area of approximately 15,000 km^2; it contains basalts collectively referred to as the Newer Volcanics (Joyce, 1975). This province has more than 400 points of eruption, none of which grew to any great size, most being less than 100 m high. The volcanics are predominately lavas, and only 1% of the total volcanic material is fragmentary (Ollier and Joyce, 1973). Although there are some late Miocene eruptions (McKenzie, *et al*, in prep.), the main period of vulcanicity probably commenced in the late Pliocene, and continued into the Holocene (McDougall, *et al*, 1966). Physiographic features, such as tumuli and lava caves, are well preserved and the most recent flows are characterized by a distinctive hummocky, rock-strewn topography known as "stony rises" (Ollier and Joyce, 1973).

Over 50 lava caves have been found in the Newer Volcanics in Victoria and South Australia, at the localities shown on Figure 7. These will now be described area by area, starting in the northeast.

Parwan: A single lava tube with 240 m of passage is present at Parwan. Basalts 25 km to the east-southeast are 2.5-2.7 Ma old (McDougall, *et al*, 1966), and the flows enclosing the cave

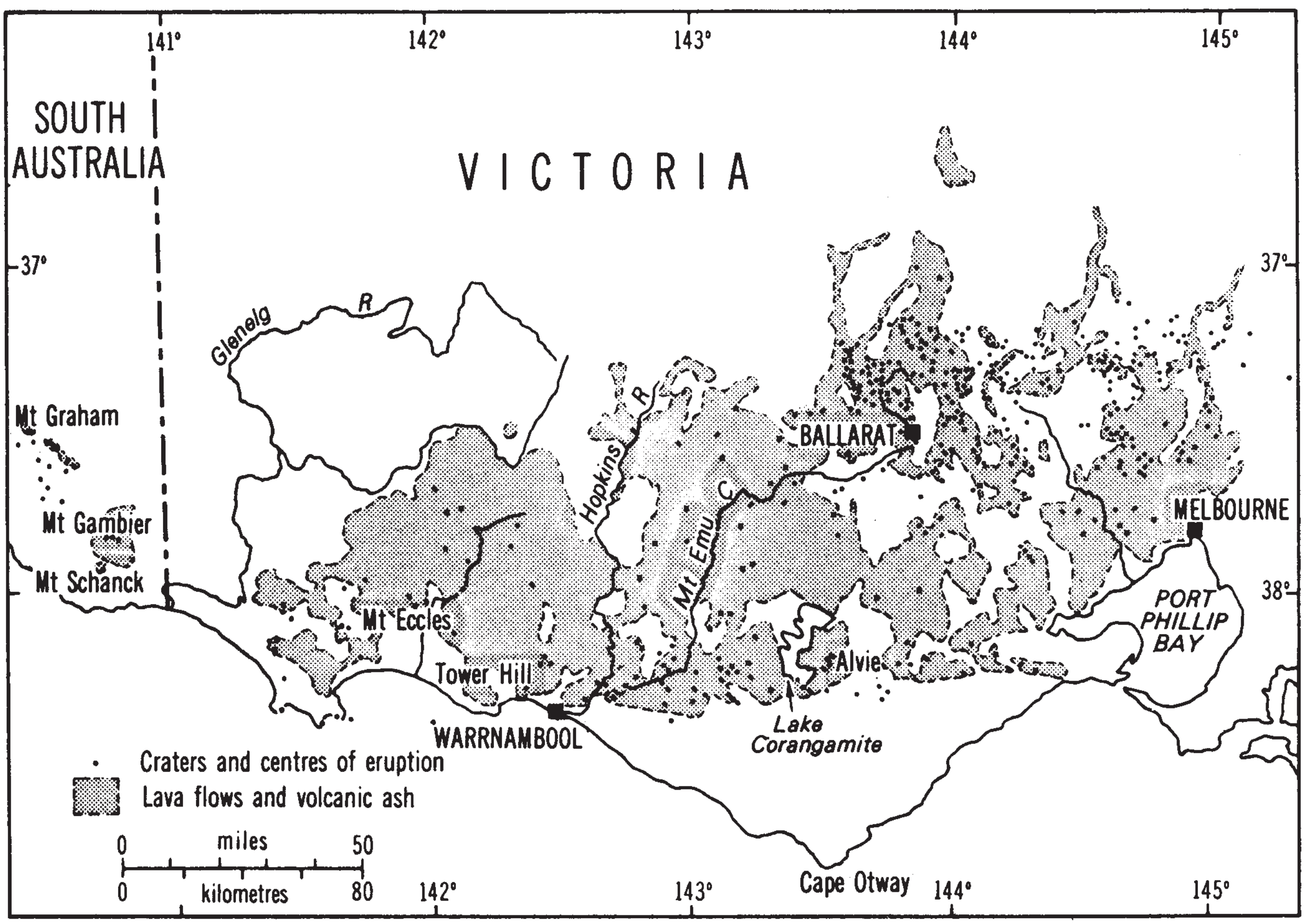

Figure 6. Extent of Newer Volcanics in western Victoria and southeast South Australia, showing eruption points. From Laseron (1972).

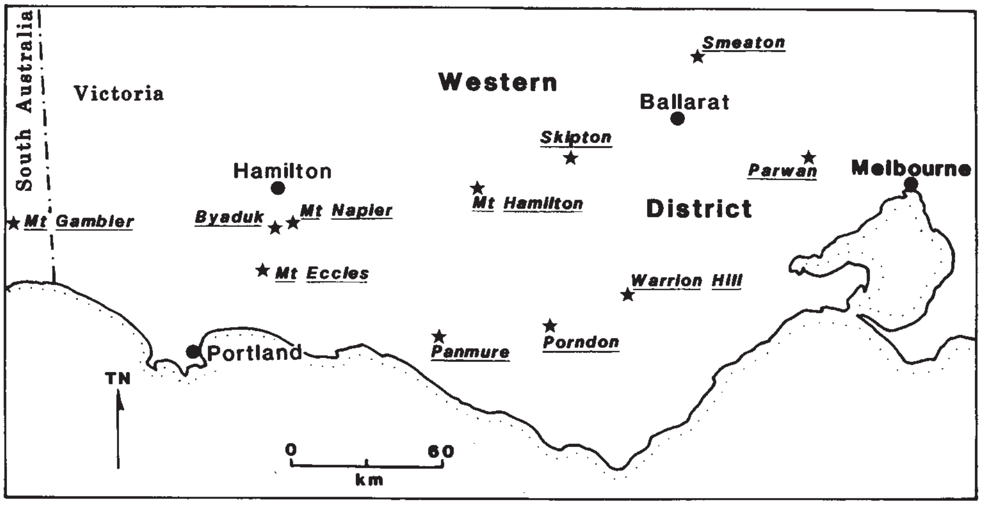

Figure 7. Lava cave locations in western Victoria and southeastern South Australia indicated

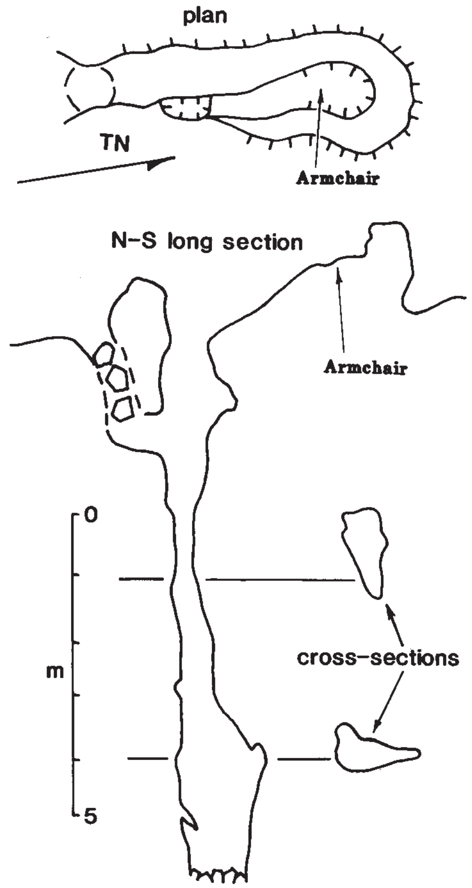

Figure 8. Armchair Shaft, near Smeaton, western Victoria. From Smith (1980a).

are probably of similar age. The cave is a simple tube up to 15 m wide but averaging only 1.5 in height; there is extensive collapse in places, but portions of the original roof, covered with short lava stalactites, are still present. The floor is mostly covered with clay, and is 8-10 m below the ground surface, indicating that the basalt flows at this locality are thicker than elsewhere in the vicinity, perhaps filling a river valley (Rees and Gill, 1959).

Smeaton: Near Smeaton there is a large composite ash cone, Mt. Kooroocheang, which has on its southwest flank a prominent radial dike and two hornitos. One of the hornitos has an open shaft 9 m deep and up to 1.5 m wide (Figure 8). A peculiar channeled lip on the up slope side of the hornito appears to be a "lid" of sticky lava that was flipped open when the hornito erupted, and has given the cave its name of Armchair Shaft (J. Hillis, personal communication; Smith, 1980a). The walls of the shaft are lined with well-preserved spatter and lava stalactites. The second hornito, 100 m up slope of the first, has a vent almost completely filled with a convex plug of basalt (J. Hollis, personal communication).

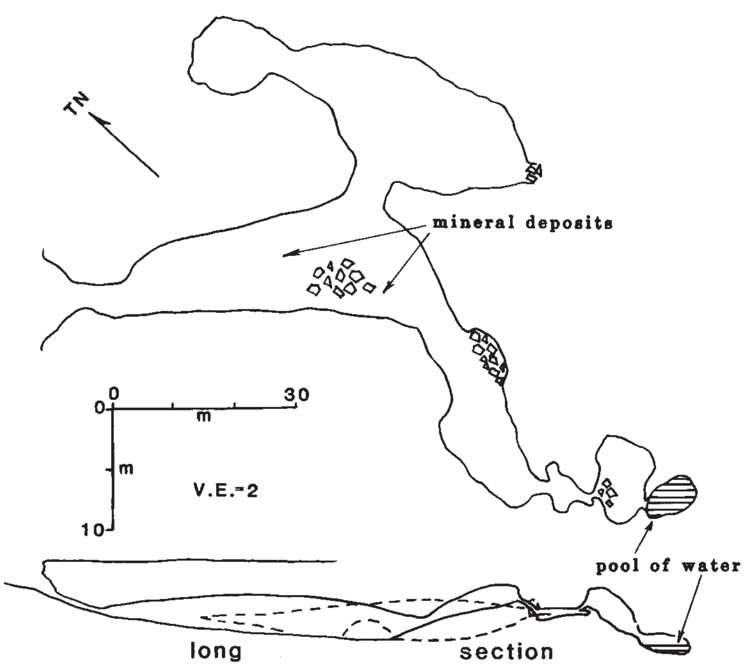

Figure 9. Skipton Cave, western Victoria. Redrawn from Ollier (1963a).

Skipton: One large lava cave is known at Skipton (Figure 9). Although it has only 150 m of passage, this cave contains one of the largest chambers in Victorian lava caves (50 m long, 15 m wide and 5 m high; Ollier, 1963a). The cave has suffered extensive collapse, but original wall linings are well preserved in places, and parts of the walls are covered with small stalactites of opaline silica (Figure 10). The lowest chamber in the cave has a permanent lake which is pumped for irrigation. Bats were recorded in Skipton Cave in 1866 (Selwyn and Ulrich, 1866), but had disappeared by 1895 (Fletcher, 1895). Possible reasons for the desertion include human interference or a change in the cave climate, perhaps linked to the clearing of the forest on the surface above (Simpson and Smith, 1964). Bones in the guano in the cave indicate that the bats were *Miniopterus schreibersii*, and the cave was probably a maternity site for this species (Simpson and Smith, 1964; Hamilton-Smith, 1968). The insect fauna living in the guano consists of six species (Hamilton-Smith, 1968); these survived the vanishing of the bats and consequent change in food supply, but may have been recently exterminated by human interference. The guano has been mined for fertilizer, and yielded a number of unusual phosphate minerals, newberyite, struvite, brushite, hannayite and taranakite (Pilkington and Segnit, 1980; W. Birch, personal communication).

Mt. Hamilton: At Mt. Hamilton, three lava caves are known (Figure 11), one of which has 1,200 m of repeatedly branching passages, making it the longest and most complex lava cave in Victoria. The total distance between the

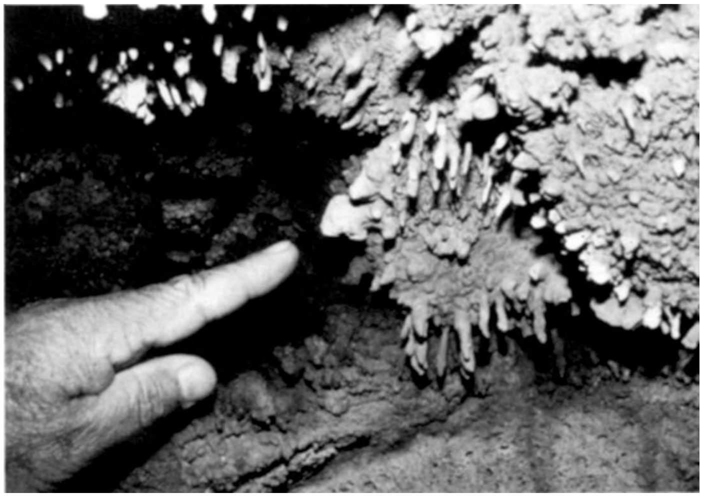

Figure 10. Stalactites of opaline silica, Skipton Cave, western Victoria.

northernmost and southernmost extremities of this cave is 30 m (Ollier, 1963b). The entrance is a narrow collapse, and the cave passages are semicircular in cross-section, being up to 8 m wide and 4 m high. Domes are present occasionally, and there are abundant lava stalactites. Laminated clay deposits occur both in cavities in the basalt and on the floor of the cave, and gypsum stalactites and crusts are found on the walls. Sub-fossil mammal bones have been collected from several parts of the cave; 26 species have been identified, three of these being prehistoric and a further 12 no longer found in Victoria (Wakefield, 1963, 1964b).

The other two caves at Mt. Hamilton are at the same level as the first, and each consists of 50-60 m of more or less straight passage (Figure 11. The westernmost cave contains extensive alluvial fill, which is unusual for lava caves in Victoria (Ollier and Joyce, 1968).

Warrion Hill: Around Warrion Hill, five caves have been discovered, up to 50 m long. These are simple in plan and quite shallow, apparently running inside hummocks on the lava flow surface (Fran, 1971).

Porndon: Near Porndon, there is an unusual volcano, Mt. Porndon, comprising scoria cones overlying a "disc" of lava 3 km across, with a distinct wall-like "ring barrier" formed at the edge (Skeats and James, 1937; Ollier and Joyce, 1973). This disc, in turn, overlies extensive basalt flows containing two lava caves.

Arch cave, the bigger of the two, is a straight tunnel 100 m long, with a symmetrical cross-section up to 15 m wide and 9 m high (Figure 12). Just outside the entrance, there is a small arch left by the collapse of part of the tube roof. The walls have a well-preserved lava lining with some small lava stalactites, and along the base of the walls on either side of the cave, are lava benches 40-60 cm high and 30-40 cm wide, representing peeled-off wall linings (Ollier and Joyce, 1978; Smith 1980b).

The second cave is distinguished by the large mound of putrefying rubbish occupying most of the entrance. Bats (*Miniopterus schreibersii*) roost in both caves (Hamilton-Smith, 1965; Smith, 1980b).

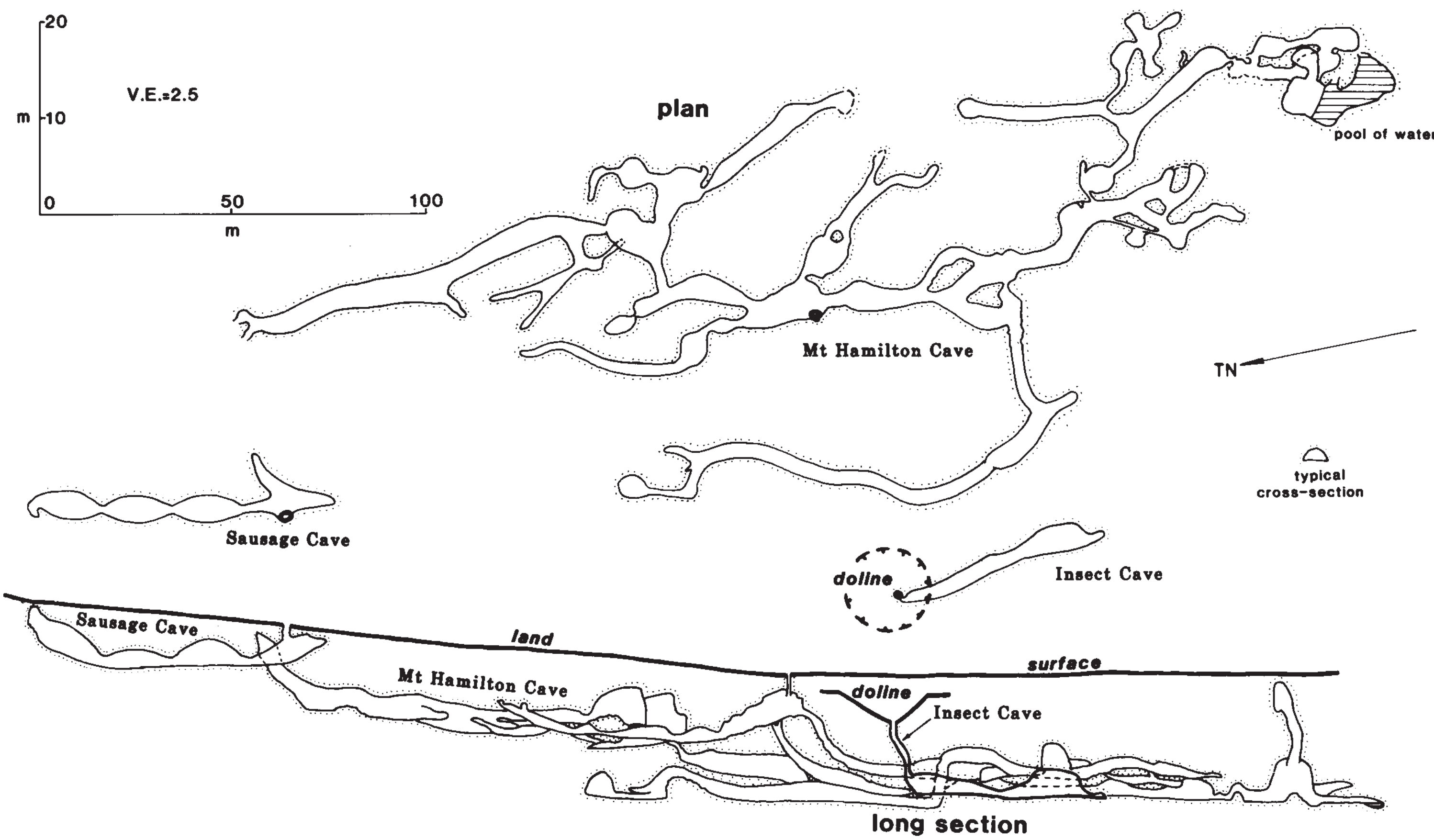

Figure 11. Mt. Hamilton caves, western Victoria. Modified from Ollier (1963b) and Ollier and Joyce (1968). Note that previously published long sections of Mt. Hamilton Cave had erroneous vertical scales, and as a result Fig.1 in Ollier and Joyce (1968) showed Insect Cave as being deeper than Mt. Hamilton Cave; these mistakes are corrected in the present diagram.

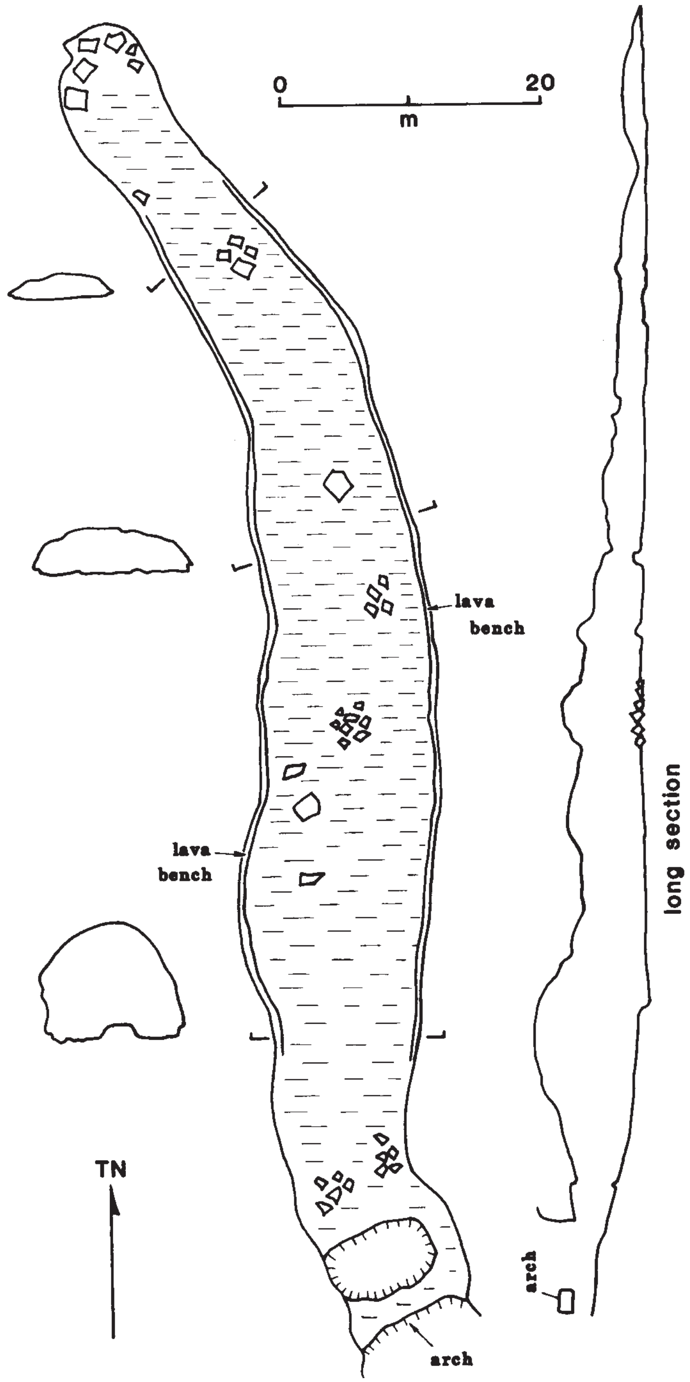

Figure 12. Porndon Arch Cave, western Victoria. From Smith (1980b).

Figure 13. Porndon Arch Cave, western Victoria; note lava bench formed as a peeled-off wall lining.

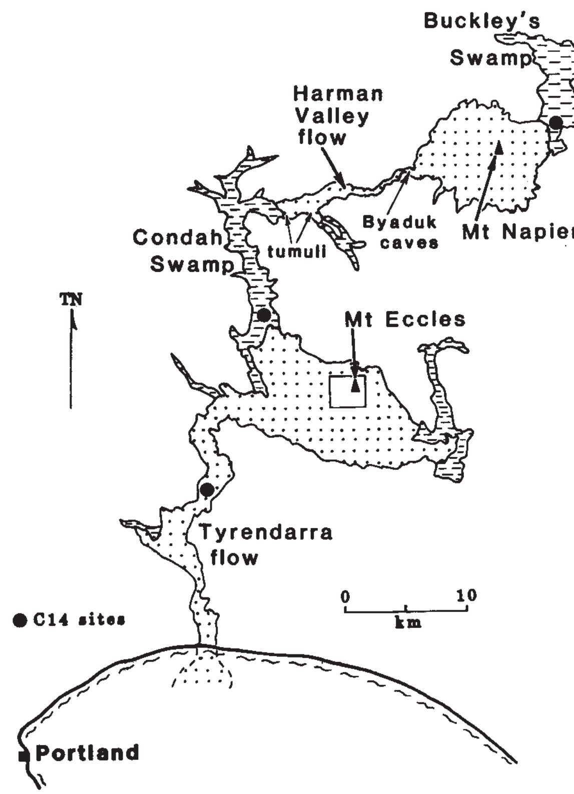

Figure 14. Lava flows and swamps surrounding Mt. Napier and Mt. Eccles, western Victoria (for location see Fig. 7); area around Mt. Eccles shown in more detail in Fig. 21. Radiocarbon dating sites shown by black dots. From Gill (1979).

Panmure: The lava cave at Panmure consists of a tube-like passage that bifurcates into two subequal, nonparallel branches, with a total length of about 100 m. The cave used to be entered by a small hole at ground level which led down steeply, but adjacent quarrying has enlarged the entrance slightly (Gill, 1944). The cave is probably in a flow erupted from a volcano 16 km to the northeast about 0.57 Ma ago (Ollier and Joyce, 1968; McDougall, *et al*, 1966), and bifurcates upstream. It is a roosting site for *Miniopterus schreibersii* (Hamilton-Smith, 1965).

Mt. Napier: Mt. Napier is a multiple scoria and spatter cone resting on a broad lava dome approximately 10 km across (Joyce, 1976). Buckley's Swamp to the northeast (Figure 14) originated when flows from Mt. Napier blocked drainage in the valley; a radiocarbon date of 7,000 years from the base of the peat in this swamp gives an approximate age for the eruptions (Gill and Elmore, 1973).

There are two small blister caves on the northwest flank of Mt. Napier, and on the western flank, close to the crater, are two more caves. One of the latter is in a small done of lava in line with a lava channel, and has a cross-section in the form of a pointed arch (Joyce, 1976). The walls of both western caves

Figure 15. Needle-like stalactites in a cave on the western flank of Mt.

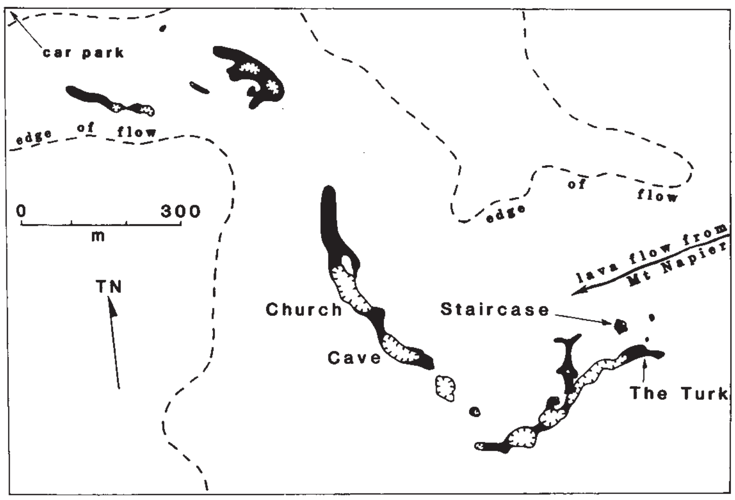

Figure 16. Byaduck Caves, near Mt. Napier, showing caves (solid shading) and collapse dolines (for location see Fig. 14). Modified from Ollier and Brown (1964).

display groups of needle-like stalactites, 1 mm or less in diameter, some of which are inclined downstream.

About 2 km west of Mt. Napier is a scoria cone 25 m high. A lava canal, starting as a lava tube 10 m long, runs southwest from the cone of 400 m, with a natural bridge 50 m from the tube section (Gill and Elmore, 1974). Two other caves, up to 20 m long, are close by.

Byaduk: The Harman Valley flow (Figure 14) extends 24 km from Mt. Napier down a river valley (Ollier and Joyce, 1973). Near the end of the flow are a number of exaggerated tumuli, up to 10 m high and 20 m across (Ollier, 1964a), and nearer the volcano are the Byaduk lava caves. These caves follow the center of the flow, and are upstream of the first point of constriction, where the lava is only 0.2 km across (Figure 16). The basalts have a total thickness of at least 20 m (The maximum depth of the caves), and have a very low gradient, 1.5° or less (Ollier and Brown, 1964; Ollier and Joyce, 1973).

Nineteen caves are known in the area (Matthews, 1979), but many are grouped in interconnected systems opening to the surface at collapse entrances, and arches and natural bridges are common. The collapse dolines contain a striking dark green vegetation easily visible from the air and are characterized by abundant ferns (20 species), mosses (62 species, one unknown elsewhere in Australia), lichens and liverworts (Beaglehole and Learmonth, 1957).

Church Cave (Figure 18) is the longest cave, with 400 m of passage up to 15 m wide and almost as high. In places, the floor of the cave has cracked into slabs with spaces below, apparently as a result of fluid lava draining away beneath a crust on the last flow through the cave (Ollier and Brown, 1964). There are two levels of lava tube within Church Cave (Figure 18); other caves at Byaduk belong to either one of these levels. The deeper caves have ceilings 7 m below the surface and floors about 20 m deep; The less common, shallower caves have floors less than 4 m below ground level. Most of the Byaduk caves are simple or once-branched in plan, but some of the shallower caves have anastomosing branching patterns (Taylor, 1971).

Although the Byaduk caves have collapsed extensively, original wall roof and floor features can still be seen in many places and are well preserved because of the youthfulness of the caves. The Turk (Figure 16) illustrates many of these features. The wall lining shows drips and wrinkles and along the base of one wall is a roll of lava, apparently a combination of a peeled-off lining and a bench from a former lava level. The floor is composed of original lava, broken into fragments about 1 m across. Some of the fragments have bumped against each other and developed upturned edges. The inner portion of The Turk has an unusual asymmetric cross section, in contrast to most of the Byaduk caves, which are quite symmetric tunnels.

In Staircase (Figure 16), horizontal lava "tidemarks" along one wall resemble a set of steps, and mark successive levels as the lava surface subsided (Ollier and Brown, 1964). Another wall in the cave is well decorated with unusual lava stalactites, which project up to 30 cm from the wall as complex drooping "hands," some coated with opaline silica. One of the shallower caves contains lava stalagmites, which are rare in Victorian lava caves (Ollier and Joyce, 1968).

Three of the caves have yielded mammal bones, apparently the remains of animals eaten by owls. The fauna, of the 25

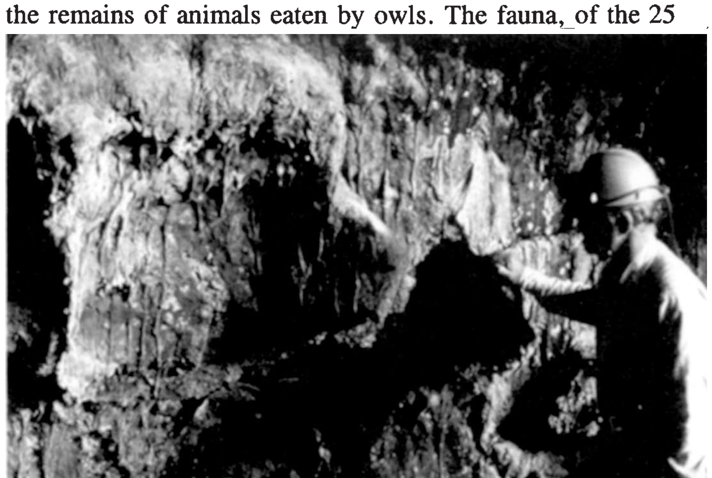

Figure 17. Wrinkles and drips on wall lining in The Turk, Byaduck, western Victoria

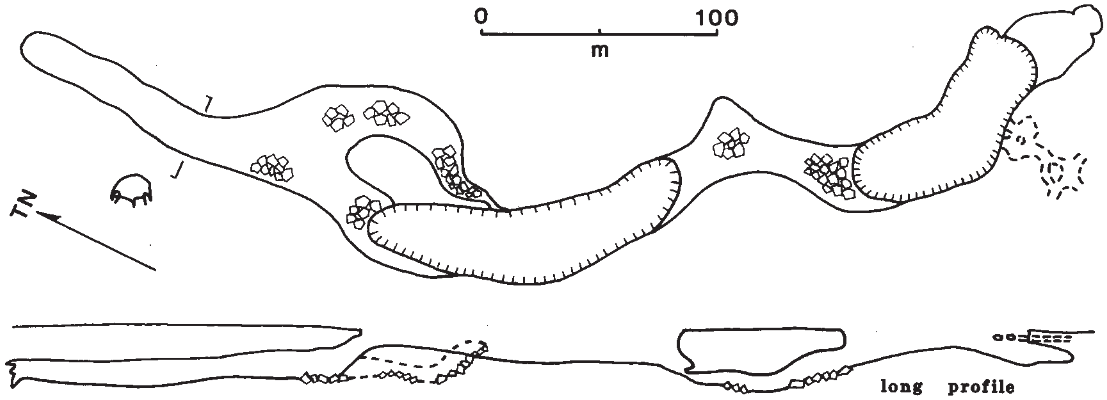

Figure 18. Church Cave, Byaduck; dashed outline shows shallower section of cave (for location see Fig. 16). Modified from Ollier and Brown (1964).

Figure 19. One of the collapse entrances to Church Cave, Byaduck, western Victoria; characteristic doline vegetation, dominated by ferns, visible in foreground.

species, is a modern one (Wakefield, 1964a, 1964b). One cave serves as a roosting site for *Miniopterus schreibersii* (Hamilton-Smith, 1965).

Mt. Eccles: Mt. Eccles is surrounded by an area of lava about 10 km wide (Figure 14), from which the Tyrendarra flow runs west and south 40 km to the coast, with a further 16 km submerged on the continental shelf (Joyce, 1976). A radiocarbon date on wood from a stream bed buried by this flow (Figure 14) indicates that the lava is about 19,000 years old (Gill, 1979). Condah Swamp (Figure 14) was presumably formed because of blockage of the valley by flows from Mt. Eccles. Peat at the base of this swamp gave a date of about 6,000 years. (Gill, 1978).

The main volcano at Mt. Eccles is a steep-walled elongate crater containing Lake Surprise (Figure 21). From the north end of the crater, a lava channel runs out into the lava plain where it splits into two branches, which extend up to 4 km from the crater (Joyce, 1976). These channels vary from 80-220 m wide and 4-12 m deep, and in places have levees comprising successive thin flows. At least 14 lava caves are associated with the channels (Matthews, 1979), although only a few have been mapped and located accurately (Figure 21). Most of the caves run more or less perpendicular to the channels; some branch complexly and connect the channels to large collapse dolines (Franz, 1980). The largest cave, with 45 m of passage, is Tunnel Cave (Figure 22), and this has an almost perfect arch-like cross section with intact walls, a low lava bench and a thin covering of earth over a flat lava floor. The entrance section of Tunnel Cave supports a flora of ferns, mosses, lichens and algae, zoned according to light intensity, humidity and moisture, with lichen and algae occurring furthest into the cave (Johnson, *et al*, 1968). Tree roots hang down from the walls and ceiling in the high humidity areas of the cave, up to 17 m below the ground surface, and probably belong to *Eucalyptus viminalis* (Johnson, *et al*, 1968).

The smaller caves along the channels have well-preserved internal features (e.g., gutters, tidemarks and lava stalactites), and tree roots are often abundant in them (Figure 24).

Southward of Mt. Eccles, along the line of the main crater, is a series of spatter cones (Figure 21). The alignment of these points of eruption may indicate fissure eruption, or, less likely, adventitious cones on a straight lava flow (Ollier and Joyce, 1973). From one cone, a steep-sided lava channel 10-18 m wide runs about 2 km west (Figure 21); this has a 30 m roof section, Gothic Cave, so called because of its "gothic arch" cross-section (Joyce, 1976). The cave passage is about 7.5 m high, and the wall lining consists of more or less vertical contorted layers of lava, behind which are sub-horizontal layers in the lava of the channel wall (representing successive thin levee flows) (Figure 25). The vertical layering apparently formed as the open channel filled, subsided and filled again, leaving a lining on the walls of the channel each time. The linings gradually grew in from the sides until they joined in the middle, making a complete roof over the lava channel. This roof later sagged to give the contortions in the layers. Harter (1978) described similar examples from lava caves in the USA. Mammal bones collected from Gothic Cave were identified by Wakefield (1964a, 1964b), and represent 24 species (two of which are no longer found in the area).

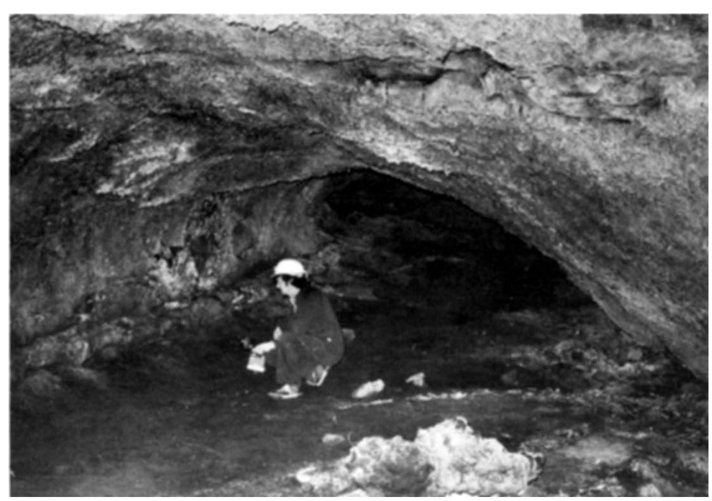

Figure 20. The Turk, Byaduck, western Victoria; note asymmetrical

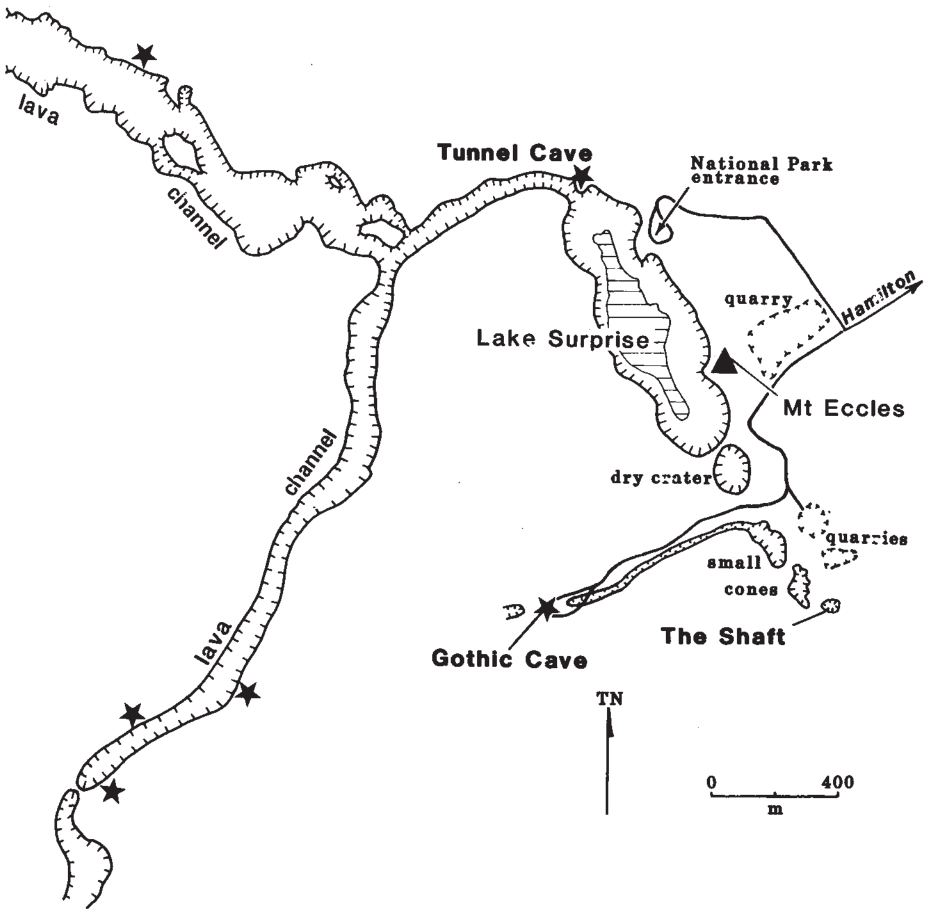

Figure 21. Mt. Eccles area, showing caves (indicated by stars), cones and channels; for location see Fig. 14. Modified from King and Spurgeon (1980).

Another of the spatter cones south of Mt. Eccles has an open vertical vent, known as The Shaft (Figure 21, Figure 27). The cone is about 10 m high, but the vent is 23 m deep, extending below the level of the surrounding plain and widening at depth (Ollier and Joyce, 1973). It is lined with abundant lava stalactites and floored by large boulders of vesicular basalt.

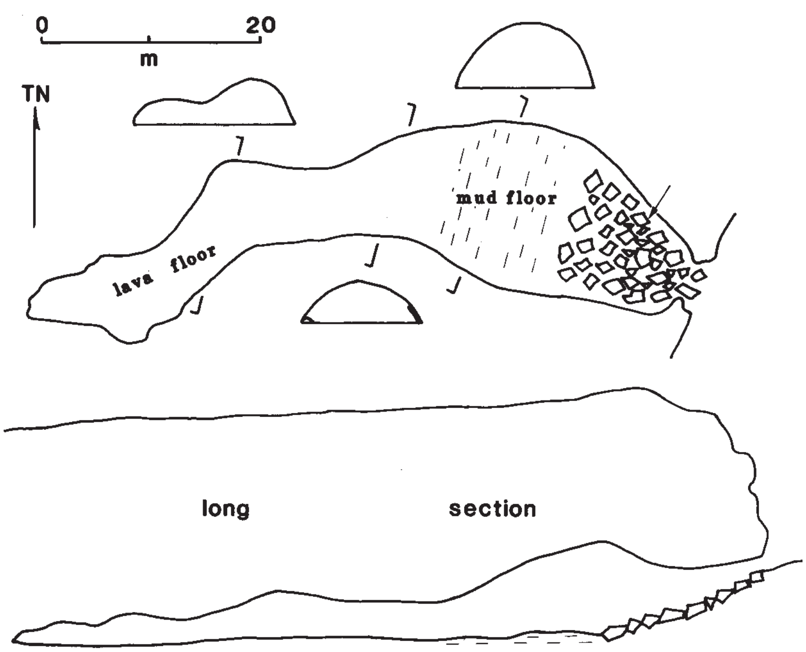

Figure 22. Tunnel Cave, Mt. Eccles area (for location see Fig. 20). Modified from Johnson et al. (1968).

Another small cone nearby had an open vent 10 m deep (Ollier, 1964b) but this has been filled in by a local farmer.

SOUTH AUSTRALIA

The Mt. Gambier volcanic complex (Figure 6) comprises a close knit series of composite maars with a complicated history of eruption around 4,000-4,300 years ago (Blackburn, *et al*, 1982). During the first period of eruption, two basalt sheets were extruded, and several small lava caves are known from the bases of these lava flows (Sheard, 1978). One of the largest caves was 10m long and 2.5 m wide and high, and contained lava stalactites; it was destroyed by a natural landslide in 1977 (Sheard, 1978).

TASMANIA

Several tiny caves, up to 10 m in length, have been found in Tertiary basalts near Mole Creek, central Tasmania (Anon., 1970). They appear to be the result of groundwater erosion of zeolite-rich amygdaloidal basalt.

CONCLUSION

From the foregoing descriptions, it can be seen that the two most significant groups of lava caves in Australia are in basalt flows within areal igneous provinces in western Victoria and northeastern Queensland, and that there are a number of differences between the caves from each state. The northeast Queensland caves are large, simple in plan and cross-section, and are concentrated in particular areas; each area represents a lava tube system. In general, the Victorian caves are smaller and often more complex, especially in plan, and they tend to be scattered and isolated from each other. Even where several caves are present in the same area, they are usually completely unrelated, except at Byaduk, where most of the caves were probably part of a single lava tube system. Indeed, the Victorian lava caves represent a range of origins and geomorphic settings including spatter cone shafts, roofed lava channels, and tubes in flank flows, valley flows, lava plains and channel overflows.

These differences probably reflect differences in the rate of discharge and viscosity of the basalt magma in the two areas, also influenced by the topography of the land surface beneath the flows. The great length of the northeast Queensland flows apparently resulted from a very high rate of effusion of low viscosity lava, coupled with topography which favored channeling and the formation of efficient, heat-insulated lava tubes, able to maintain a supply of fluid lava over long distances. In Victoria, it would appear that this favorable combination of circumstances rarely occurred.

Figure 23. Drips marking successive lava levels in small cave off one

ACKNOWLEDGEMENTS

Thanks are due to L.K.M. Elmore and a number of members of the Victorian Speleological Association (Particularly Nick and Sue White, Dave Smith and Rudi Frank) for provision of photographs and information.

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Figure 24. Unnamed cave off lava channel, Mt. Eccles area; note tree roots.

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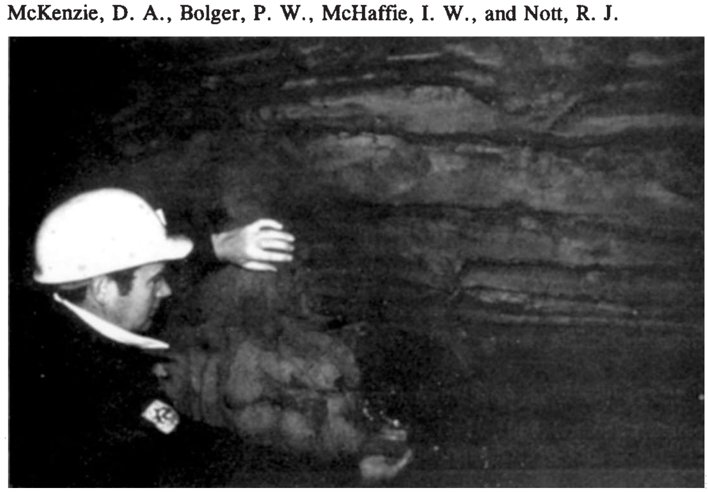

Figure 25. Wall lining in Gothic Cave, Mt. Eccles; section has cracked off revealing subhorizontal layers in lava of channel wall, representing sucessive thin levee flows.

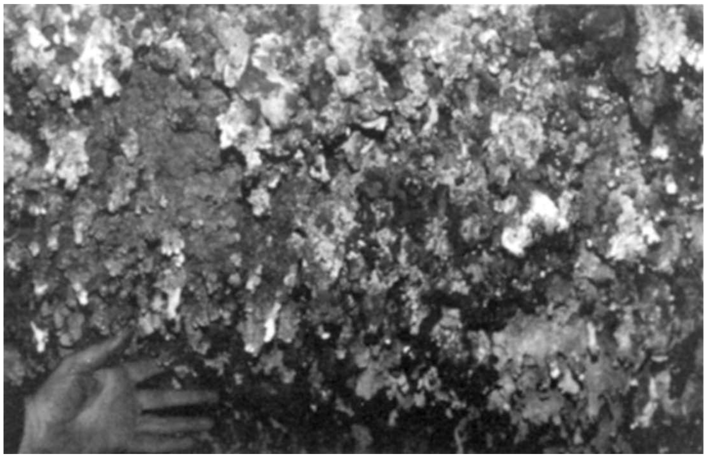

Figure 27. Complex lava stalactites, thinly coated with opaline silica, in Staircase, Byaduck, western Victoria.

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Figure 28. Entrance to the Shaft, Mt. Eccles area, western Victoria.

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VOLCANOKARST IN THE CULTURE AND LANDSCAPE OF EASTER ISLAND

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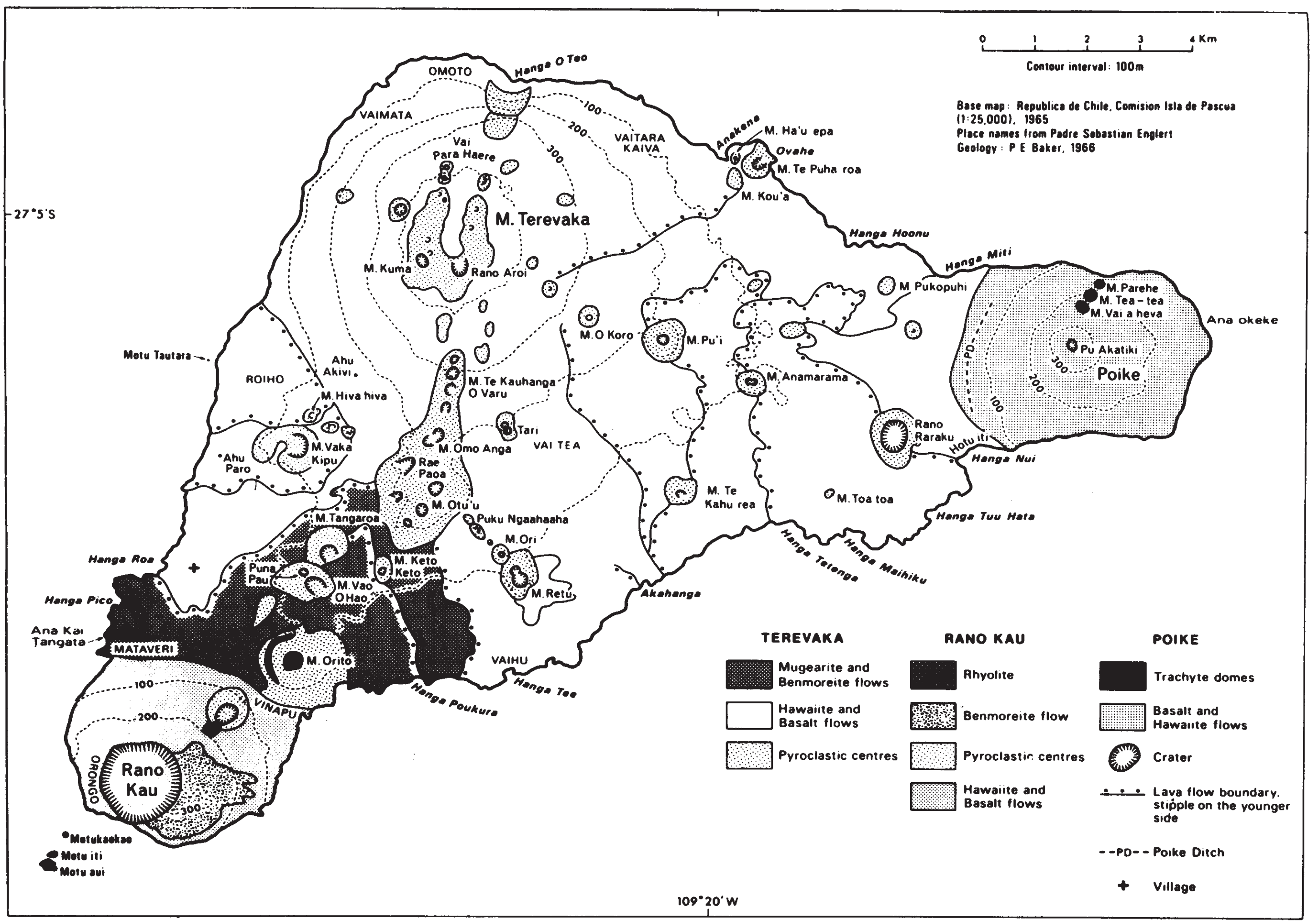
ABSTRACT

Volcanokarst is intimately interwoven with the human history of Easter Island. While the caves have been a focus of some archaeological investigation, they have been little studied in their own right. The island is entirely volcanic, and lava tunnels are well developed in tholeiitic flows which emanated from several vents. The Roiho olivine basalt flow from the small cone of Maunga Hiva hiva is particularly rich in caves. There is limited cave development due to piping of volcanic ash.

INTRODUCTION

In the popular medias as to the archaeologist, Easter Island has long been shrouded in mystery. According to folk memory, one Hotu Matua had a vision which led him to dispatch six scouts from his ancestral home of Marae Renga to look for an "island full of holes." Ever since, caves have added to the enigma of the world's most isolated outpost of humanity, a place best known for the giant human statues or *moais* which occur in various parts of the island, notably on the temple platforms of *ahus* which fringe the coastline. The first systematic investigations of the caves by Europeans were those of Thompson (1889), Routledge (1919), and Lavachery (1935). A geologist reported further caves in 1937 (Bandy, 1937). A Catholic missionary, Father Sebastian Englert, visited many caves during his years on the island (Englert, 1948). After his



Geological map of Easter Island after Baker et al (1974).

epic Kontiki expedition drifted too far to the north to land on Easter Island, Thor Heyerdahl mounted a prolonged archaeological investigation in the 1950s (Heyerdahl, 1958, 1976, Heyerdahl, et al, 1961). Heyerdahl published a map which recorded the location of 43 caves visited by his expedition, and the probable location of further 17 caves reported by islanders (Heyerdahl, 1958). Other caves were located during geological research in the 1960s (Baker, 1967). A further 30 caves not recorded on Heyerdahl's map were explored in 1976 (Kiernan, 1976). The object of this contribution is to briefly consider the human history of Easter Island and the role caves have played, and to review the extent of the volcanokarst.

The isolation of Easter Island is reflected in an ancient name: Te Pito o te Henua-naval (centre?) of the earth. The Dutchman Jacob Roggenveen, is believed to have been the first European to sight the island on Easter Day, 1722. The stone age Rapanui people were next visited in 1770 by the Spaniard Don Felipe Gonzales. The speedy disappearance of the gifts and stolen items led the Spanish to presume that secret hideaways lay beneath the open landscape. An account by Aguera (1770) noted that "most of the natives . . . dwell in underground caves . . . the entrances to which are so narrow and inconvenient that I have seen some of them introduce themselves in the opposite manner to what is natural, beginning by projecting their feet and the head last." In 1774, Captain James Cook saw few people and thought that the islanders must have been hiding in caves, but his men were refused admittance when they tried to examine the boulder piles which they believed hid the entrances. This network of caves was later dramatically demonstrated to La Perouse when the islanders suddenly appeared all over the barren landscape to greet his ship as if they had been spawned by the earth itself. The visitors were permitted to enter some of the caves. But as the years drew on, the owners of the caves and those who knew their locations, were decimated by outsiders and by internal strife.

Public awareness of the tragic recent history of Easter Island is overshadowed by that of the mysteries posed by its statuary and prehistoric culture. Following internecine strife in his ancestral home, Hotu Matua's small band voyaged to a triangular island 21 x 14 km in extent, with a circumference of 47 km, and an area of 160 km^2. Their first residence lay in caves at Anakena. Rising to 511 m, at the same latitude as Brisbane (lat. 27°10'S; long. 109°20'W), Easter Island lies on

Carved human skull from an Easter Island cave.

the southern margin of the southeast trades, which blow from October to April and leave the grasslands to bend in waves before more variable winds at other times of the year. The mean annual temperature today is 22°C and 100 mm of rain soaks rapidly into the porous volcanic soil to become accessible only in a few springs, caves and crater lakes, and in a single surface stream.

Since settlement, the island has been converted to grassland, and sheep in particular have done much to change the "heaven on earth" witnessed by Roggenveen and La Perouse's garden, to what Gossett (1938) described as an island whose "whole aspect . . . is one of barrenness, loneliness and dreariness."

Heyerdahl asserts that the first inhabitants were skilled stonemasons who ignored timber and who arrived from South America, perhaps as long as 2000 years ago. This thesis rests upon the pre-Inca style statues and the Inca-like stonemasonry of the Vinapu site on Easter Island, the latter dating from about AD 800. Much of this early construction was dismantled to retrieve building materials during later cultural phases. However, there is considerable cultural unity with Polynesia. Radiocarbon dating indicates that man from southeast Asia had reached the Solomon Islands by 5 kyrs. BP, and New Caledonia and Fiji by 3 kyrs. BP. He reached the Marquesas by AD 400 and extended into the Easter Island, Hawaiian and New Zealand extremities of the Pacific triangle after AD 500. Megaliths remained behind in the Marquesas, Tonga, Easter Island, and also on the coast of Peru. Did some of the South American culture come from the Pacific? Heyerdahl cites a radiocarbon date of AD 380 from Easter Island and recently discovered coral and obsidian eyes which fit some of the moais and appear to be of South American affinity. Perhaps Easter Island welcomed settlers from both east and west.

The people encountered by Roggenveen appeared to comprise two groups. Some were red haired and tattooed, their ears deformed like those of the moais through elongation of the lobes by heavy weights. These people were the Tu'uaro and Hotuiti people (variously referred to as the "long ears" or "thin" people) who tilled the thin stony soils. Among them were the Hanaueepe ("short ears" or "fat" people — again depending upon the authority consulted) who fished the seas around Easter Island. While Heyerdahl argues that South Americans were the first migrants, it is generally argued that the "long ears" arrived first. It seems clear at any rate that the short-eared Hotu Matua was part of a second wave. The islanders then dwelt in rush huts, fished, and cultivated sweet potatoes. The existence of the moais implies a high degree of social organization for enormous energies were diverted away from food production.

The carvers were still at work in AD 1470. But in the 17th-18th century, strife broke out, possibly due to diminishing crops during the Little Ice Age (McCall, 1981). Weapons are absent from archaeological deposits prior to AD 1680, but suddenly obsidian spear points littered the ground. The "short ears" resisted the demands of the "long ears" to help clear the soil of rocks, promoting what was probably the only major battle prior to the arrival of the Dutch. Hundreds of skeletons with broken bones and carved skulls attest great violence and are to be found in the caves and elsewhere. The Rapanui fled underground, often using the foundations of their former reed houses for construction purposes in the caves. Food production ground to a halt and starvation took over. The sufferings are reflected in wooden carvings of emaciated figures with protruding ribs which have been found in this island's caves.

The old deities were of little assistance. Strangers arrived in great ships. Violence met despair and compounded it. The moais were overturned, probably around the 1860s. Now the seasonal arrival of terns became important to the diet of the Rapanui. The tern came to be worshipped. Hereditary kingship was replaced by a system of annual competition to obtain the first egg laid on the islets off Rano Kau coastline. When Europeans first arrived, this new cult of the bird-men was still ascendant. Yet another cultural development was superimposed upon the palimpsest of the island's caves.

Caves were quite vital to the Rapanui economic system, described by Ferdon (1958) as "steal trading" by virtue of which "any available object is insecure as far as its owners is concerned." Ferdon continued: "The secret cave in Easter Island culture represents the one secure place for whatever kind of property an islander wishes to keep. It is not going too far to say that the ownership of secret caves for the hiding of persons and property emerges as one of the most characteristic features of Easter Island culture. In the decadent late period, caves were probably as important to the Easter Islanders in their daily lives as were the famous ahu images in the middle period. Since secret caves or caches may be accidentally found by another, they are guarded by dangerous personal spirits called akuaku who have the power to disable or kill any trespasser — the need for some sort of spiritually protected 'warehouse' is a functional necessity for the preservation of family heirlooms and capital assets."

VOLCANOKARST IN THE LANDSCAPE: CAVE EXPLORATION

Thompson (1889) observed that "natural caves are numerous, both at the coast and in the interior of the island." His was the first European party in pursuit of archaeological relics to explore caves on Easter Island (Heyerdahl, 1976). He recognized caves that were "worn by the action of waves" as opposed to others which were "due to the expansion of gasses in the molten lava and other volcanic action." He continued:

"Many caves were reached after difficult and dangerous climbing and were found to contain nothing of interest, while others of traditional importance were inaccessible from below, and we were not provided with ropes and the necessary appliances for reaching them from above. Some of the sea-worn caves are of considerable extent, but generally difficult to access and affording little of interest except to geologists. The caverns produced by volcanic agencies are found throughout the island and some were traced through subterranean winding to an outlet on the bluffs overlooking the sea. They were generally quite dry. The rainwater falling upon the surface occasionally finds its way between the cracks or joints in the solid rock, but these gloomy passages and chambers lack grandeur from the entire absence of stalactites and decorations of carbonate of lime. No glistening and fantastical forms of stalagmitic decorations exist here to excite the fancy and create in the imagination scenes of fairy-like splendour. The feeble rays of our candles were quickly absorbed by the sombre surroundings, heightening the apparent extent and gloom of the recesses."

The archaeology of these caves also drew the attention of Katherine Routledge in 1914, whose party "daily examined such caves and grottoes as came under our notice," but she too complained of her "inability to reach the most thrilling of the caves, which are halfway up the great sea cliffs," (Routledge, 1919). In her footsteps came a Franco-Belgian expedition in 1934 (Lavachery, 1935).

Many caves were known to the late missionary Father Sebastian Englert. Among a number of notable explorations by Father Sebastian was that of the 400 m long Ano o Keke at the eastern end of the island. Father Sebastian's Rapanui housekeeper and her sister-in-law were keen cave hunters who greatly assisted him in his documentation of Easter Island's antiquities. His book on the island recorded the use of caves for residential purposes, for burial and for refuge. He referred also to the:

"Secret caves which were the property of particular families and only the most important persons in a family knew the entrance to their respective secret cave. These served as hiding places for valuable things, such as inscribed tables, rongo-rongo or statuettes. The secret of the exact location of the entrance is buried in the graves with the last survivors of the old times." (Englert, 1948).

Although Father Sebastian had failed to gain access to any of these family caves, the Norwegian party under Thor Heyerdahl which spent several months on Easter Island in the mid 1950s confirmed not only that they existed, but that they continued to be respected and maintained by the islanders. Within such caves the archaeologists found carvings of wood and stone, often wrapped in or sitting upon reed mats, together with some stone containers and skeletal remains of forebears. Other caves contained fish shells; bird, rat and turtle bones, amulets of bone and shells, and needles of human bone. Considerable ceremony was attached to entry into the caves. Even after the ceremonial transfer to Heyerdahl of one cave's contents, the former owner retained the cave itself "in case of war." Indeed, long after burial in the Hanga Roa village cemetery had become compulsory, there were still instances of elderly islanders stealing away to die alone in their family caves. Only the few remaining descendants of the "long ears" maintained family caves.

Subsequent archaeological studies to which I do not have access have presumably continued some investigation of caves. However, while caves are abundant and many are easily found, this is not always the case. Small entrances in steep cliffs provide a natural difficulty exploited in the selection of secret family caves. Entrances to other caves used to store family treasures or provide refuge during the fighting, were deliberately hidden:

"Atan . . . pointed straight to the ground at the tips of my toes. I saw there a small flat stone half covered with sand and loose straw, exactly like 10 million others nearby." (Heyerdahl, 1958, p. 226).

Easter Island is characterized by countless billions of scattered rocks, any of which might deliberately cover caves. Although Heyerdahl doubted the veracity of some guides who failed to locate alleged caves, it is as well to remember how frequently cavers manage to lose caves in the bush without the additional obstacle of their being deliberately hidden. On Easter Island in 1976, I was myself extended the utmost hospitality and friendliness by the Rapanui, but on the other hand, there was zero cooperation as far as caves were concerned — indeed, the very existence on the island of *any* caves whatsoever was strenuously denied, even though entrances lay agape for all to see around the outskirts of the village. Whether the veil of silence was due to a continued desire to protect family caves or perhaps to debunk any suspicion of the old beliefs still being held remains open for debate. Alternatively, it may be noteworthy that on my departure, I was taken aside by armed officials and thoroughly searched. I record the fact not in protest, but in appreciation that the authorities apparently no longer intend to permit the sort of archaeological plundering which has robbed Easter Island of too much of its heritage.

And perhaps before any speleologist risks trampling underfoot the sensitivities of the Rapanui, it may be as well to recount an anecdote recorded by Heyerdahl (1958, p. 210).

"I had said that sometime in the future, it would be possible to find the secret caves and tunnels of the island by going over the ground with a kind of cavity detector. This had made a strong impression on Lazarus. As we rode along, he pointed out several areas in which such an apparatus would be effective because there was supposed to be secret caves under the ground, of which the openings had been lost. He declared with dismay that the first person to bring the apparatus to the island would get rich simply by walking among the houses in the village. A secret cave 300 yards long, which had belonged to one of the last kings, ran underground to the sea from an unknown spot near the most northerly houses. It was found by a man who brought up some gigantic spearheads from the cave, but the aku-akus "bit and pricked him night after night until he died."

Preoccupation with the search for family caves and archaeological deposits has meant that caves have been under valued as remarkable landforms in their own right. Heyerdahl's (1958) account reflects on the morphology and size of some of the non-secret lava tunnels:

"Later we visited several of these huge caves with room after room like pearls on a string running down through the underworld. Their entrances were all so skillfully walled up that no one could get down through the narrow funnels cut with sharp angles or zig-zags, in which any assailant would be completely helpless. There was water in some of the largest caves; two of them had regular subterranean ponds and right down at the bottom of a third we found a walled well of ice cold water surrounded by a stone pavement and a well built terrace some ten feet high."

Although caves have been mentioned by at least two geological workers on Easter Island (Baker, 1967, Bandy, 1937), the only other paper known to the writer which specifically focusses upon the caves is his own brief review of his limited explorations in 1976, which may have introduced Easter Island to the speleological literature for the first time (Kiernan, 1976). This exploration focussed upon the Roiho flow, the lava flows to the east and south, a small area on the northwest slopes of Rano Kau, and also upon the piping caves of Rano Aroi and sea caves around Hanga Roa. As intriguing as secret caves may be to archaeologists and treasure hunters, they provide only a sidelight to the story of Easter Island and its caves, for the island abounds with more obvious and less sensitive entrances. This is accurately reflected by Heyerdahl's comment that "on the first day, we were in and out of caves from morning to night," and as Gossett (1938) observes, the shore of Easter Island is "honeycombed with caves in the lava."

VOLCANOKARST IN THE LANDSCAPE: THE LAVAS AND SOME CAVES

Easter Island lacks continental rocks. Although conglomerate was recorded by Braun (1924), the material he described is a tuff. But for some calcareous sand at Anakena, the traditional landing place of Hoto Matua, and also at an equally picturesque beach 2 km to the east, the island is entirely volcanic. It is surrounded by oceans 4,000 m deep. The island's geology is described by Baker (1967), Baker, et al, (1974), Bandy (1937) and Gonzales, et al (1974).

The basalts of Easter Island are tholeiitic but range between quartz normative and olivine tholeiites (Baker, et al, 1974). They are low in MgO, but high in T; Zr and total iron. A low K content is also characteristic. Three large volcanoes — Poike, Rano Kau and Maunga Terevaka —stand at the corners of this triangular island. About 70 lesser eruptive centers are known. Much of the coastline comprises high cliffs on the flanks of the cones, but to the south it is formed by a single flow only a few meters thick. Although various caves have been entered both by islanders and visitors, I am unaware of any cave inventory, and the following only scratches the surface of what is already known, but which seems to be mostly unrecorded.

(i) Poike: Poike is a stratovolcano from which a K/Ar assay of 3MyBP has been obtained. Poike comprises the oldest section of Easter Island. Trachyte is associated with the parasitic domes of Maunga Vai a heta, M. Tea-tea and M. Parehe, but the northern cliffs are highly porphyritic basalts of hawaiites with plagioclase phenocrysts. Aphyric lavas lie to the southwest. Poike was formerly a separate island. Lava caves occur right around the Poike coastline, the best known lying on the northern side.

Ana o Keke (Cave of the White Virgins; Cave of the Sun's Inclination) lies east of Katiki volcano. Its small entrance lies in a steep sea cliff. This cave contains about 400 m of passages, some of which are narrow and wet. Human remains lie in a dry inner chamber. Young girls were confined in the darkness of this cave to bleach their skin to match the fairness of the gods. Here their religious training included learning to recite from the rongo-rongo, wooden tables with now undecipherable hieroglyphics of which no more than 20 are known. Several girls are reputed to have survived a smallpox epidemic by virtue of their isolation in Ana o Keke, only to die of starvation when there was no one to bring them food.

In this same area lies a residential cave. A spring supplies the water which is fed into the massive mouth of a giant head carved into the rock wall nearby. Other caves and a spring from a deep fissure lie east of Maunga Tea-tea. Further caves occur on the southwest side of Maunga Vai a heva, in the sea cliffs on the southeastern extremity of Poike, and at least one on the island of Marotiri.

(ii) Rano Kau: At the western extremity of Easter Island stands Rano Kau. Its impressive caldera of 1.5 km diameter contains the large lake from which this volcano derives its name. Sea cliffs of 300 m mark its western flank. Thin basaltic lava flows are interbedded with pyroclastic material at the base of Rano Kau and are overlain by more differentiated lavas. Benmoreitic flows form the upper caldera wall. These break into flat slabs which were used to construct the Ahu Viahu.

White trachyte and rhyolitic obsidian are associated with a parasitic center on the northeastern slopes, and rhyolites with the "birdman" islands of Motu iti, Motu nui and Motu kao kao. The obsidian of Maunga Ourito and Maunga Otu is generally a clear, greenish brown glass with a conchoidal fracture. Man has scattered the obsidian widely across Easter Island in the form of stone tools.

One of the best known caves of Rano Kau is Haka-Rongo-Manu (Cave of Listening for the Birds). This lies partway down a steep sea cliff below Orongo. During the bird-man phase, it was here the Rapanui waited for the arrival of the first manu tera tern (Sterna fuscata) to reach the bird-man cliffs. Still other caves occur around the northeast crest of Rano Kau, and numerous other rumored caves were presumed by Heyerdahl to lie in the sea cliffs, particularly in the Rikiriki-Vinapu area. A number of caves occur on Motu nui, some of which contain human bones. Two were visited by Routledge. In another, Heyerdahl found statuettes, including a red head with a goatee beard.

(iii) Maunga Terevaka: Rising to 511 m on the northern corner of Easter Island is the complex fissure volcano of Maunga Terevaka, the island's highest summit. Flows up to 15 m thick occur here, and K/Ar assays of up to 300 Kyrs. BP indicate this to be the most recent of the large volcanoes. A U-shaped system of ridges open to the north comprises coalesced pyroclastic cones, the largest of which is Rano Aroi. Rows of craters extend south-southwest from the southern slopes of Maunga Terevaka to Maunga Otu'u, the hard, dark lavas of which are much favored for stone tools, including carved fishhooks. A further line of eruptive centers extends west-southwest from the western flank of Terevaka to Rano Raraku where a wave-cut notch in the southeast rim about 1 km from the present coastline may mark a high sea-level stand, probably of Last Interglacial age.

The moais were carved from the yellowish-brown sideromelane tuff of Rano Raraku. This center originated as a submarine vent which discharged palagonitic tuff and ash of plagioclase, olivine, clinopyroxene and opaque oxides. Basaltic xenoliths and scoriaeous fragments occur in a calcareous cement. Carving projects were occasionally abandoned due to xenoliths, although many of the inclusions were then utilized for stone tools. Most of the lava flows are of hawaiite composition. A pale aphyric flow from Maunga Hiva hiva near Roiho is an olivine tholeiite. It contains phenocrysts of olivine and is more alkaline than the other lavas of Easter Island. Further to the southwest are lavas which are similar in composition to those of Rano Kau, but which appear to have been emitted from the Terevaka complex; their origin is not clear. In this area lies the 100 m high and 300 m side cone of Puna pau. All the maroke or top-knots which adorned many of the moais and symbolized red hair or headgear were fashioned from this scoriaceous rock, which is blackish when fresh, but weathers to bright red color.

Over 80% of the known caves of Easter Island lie in the Maunga Terevaka lavas. Ana Hotu Matu (Hotu Matua's Caves) lie in a small gully in the Anakena Valley. These spacious chambers are traditionally believed to have sheltered Hotu Matua's party when they arrived at Anakena before the first reed huts were constructed. They are still occasionally slept in by islanders. Nearby stand the moais of the Ahu Anakena, the first of which was re-erected by William Mulloy during the

Small lava cave with entrance steps and retaining walls, near Akahanga.

Norwegian expedition, and the others by Rapanui archaeologist Sergio Rapu.

The coastal strip from just west of Anakena to a point west of Maunga Kuma is a highly restricted zone in the management plan for the Parque Nacional Rapu Nuie (Zentilli, 1977). Motu Tavake (cliff to the Tropical Bird; Lazarus' Cave) lies in this area at Omohi, west of the Hanga-o-Teo plain and at the foot of Vaimataa. It is difficult to reach, its entrance being a narrow squeeze hidden under a projection in a 50 m sea cliff. Sculptures were collected from this cave by Heyerdahl. Nearby is one of several snake carvings known on the island, in part of the world where snakes are unknown.

The entrance to a family cave recorded by Heyerdahl (1958) as "Mayors Cave No. 2" is a horizontal crack which lies 20 m from the top of a 100 m sea cliff near the Ahu Tepeu. Within it he found numerous stone carvings, some of which he speculated may have come from the nearby Ahu to be hidden in the cave during the wars. This cave lies amid the mugearite and benmoreite flows of Rano Aroi.

Various other caves have been reported around the coast facing slopes of Terevaka. Two family caves are reputed to lie above Vaitara Kaiva, another is known in a cliff at Hanga Hemu and another at Hango-o-teo. Many more caves lie in the Maunga Ha'u epa — Maunga Te Puha roa — Maunga Kou'a to the east of Anakena, and at inland locations between here and Rano Raraku. At the latter location a cave in the rock face is reputed to contain three sections, each of which was maintained by a family. Another cave lies at Hotuiti.

Along the coastline between Poike and Rano Kau are a number of caves, some of which contain human remains (Kiernan, 1976). Secret caves have also been reported in this area (Heyerdahl, 1958). One of these is supposed to be at Vinapu and another at Hanga Maihiku. "Santiago's Cave" (Heyerdahl, 1958) is entered via a narrow hole in an overhanging 10 m sea cliff and was found to contain family skeletons and stone sculptures. A residential cave near an ahu in this locality has well constructed stone steps leading into it (Kiernan, 1976).

A more moderate sized cave lies in the sea cliffs west of the airstrip. In the area of mugearite and benmoreite flows nearby lies Ana Kan Tagata (Cannibal's Cave). Various secret family caves are rumored to exist beneath the Hanga Roa Village, not

Sinkhole on the lava flow from Maunga Hiva hiva at Roiho.

all of which are taboo. Heyerdahl examined at least three of the caves in this area. "Mayors Cave No. 1" lies just inland of the route from the village to the leper station, and two or three others, including "Enriques Cave" in the vicinity of the Ahu Paro. In this general area, what appears to have been an old residential cave, now shelters sheep, as indeed do many of Easter Island's caves (Kiernan, 1976). "Wizards Juan's Cave" lies east of the road about 11 km south of the leper station.

Raakau ("Atan's Cave") is named for the moon. Its hidden entrance was shown to Heyerdahl, who collected many of the sculptures which lay on reed mats: "here were curiosities which would make any art dealer tear his hair in excitement . . . fabulous underground treasure chamber." The cave lies north of Puna pau. There are numerous small shelter caves in this general area. Off the western coastline on Motu Tuatara are two burial caves, in one of which a member of the Norwegian party found red hair on a human head.

However, by far the most densely cavernous single area on Easter Island appears to be the olivine lava flows from Maunga Hiva hiva at Roiho (Baker, 1967; Kiernan, 1976). Baker remarks upon "the extraordinary ramification of lava tunnels and tubes which occupy its interior." The surface of this triangular-shaped flow, which covers about 3.5 km^2, is pockmarked by enclosed depressions about 10 m deep. Some have coalesced to form small pseudo-uvalas, the largest of which measures about 200 x 50 m. An entrance through talus beneath the low cliff at the northern end gives access to a spacious cavern 10 m high, but inadequate lighting equipment prevented full exploration of this cave by Kiernan (1976). Caves frequently open off either end of a single sinkhole formed partway along a tunnel. Farther to the west, a lofty passage extends from a 4 m high entrance in another sinkhole. At least 20 cave entrances occur in this vicinity. Some contain old man-made terraces, while in others stone walls have been constructed, presumably to block off passages and alcoves.

VOLCANOKARST BY PIPING

A final series of caves in the Terevaka area is of quite different origin. Surface water is scarce on Easter Island. Springs below sea level were sometimes drawn up directly by the Rapanui, and sometimes intercepted by wells dug in beaches. Precipitation rapidly sinks into the porous volcanic ash, sometimes to reappear as springs where it is brought to the surface by basalt flows. Pools of water in lava tunnels must also have been important, to judge from the artificial channels and collecting depressions carved in the stone floors of some caves. Some pools near entrances are today fouled by stock. Some surface water is also held in crater lakes. The only surface water is also held in crater lakes.

The only surface stream is that which flows from the crater lake of Rano Aroi. Here piping of volcanic ash has produced a large underground conduit. Partial collapse has produced a 10 m-deep gully, spanned by natural bridges. Bandy (1937) recorded that many of these caves were large enough to admit a man on horseback, but by 1976, much of the system had collapsed to leave the gully spanned in only four places (Kiernan, 1976, 1980). These may be the only penetrable caves on Easter Island which are the product of running water.

OVERVIEW

The lava tunnels of Easter Island are of Tertiary to late Pleistocene age and are formed in fluid pahoehoe lavas of tholeiitic composition as exemplified at Roiho. Detailed speleogenetic studies have not been undertaken, but a few general comments are possible. The lava in which some of the caves are formed is layered. It is difficult to escape the argument of Ollier (1975) that if the lava in the tubes has eroded the layers, as appears to have occurred in some cases here, then the layers must predate the tubes. Thus, in at least some cases here, the hypothesis of Ollier and Brown (1965) seems preferable to formation by the crusting over of surface channels as described by Peterson and Swanson (1974). Evidence exists within those caves observed by the writer for fluvial-type downcutting by prolonged lava mobility after the roof has developed. Flat floors are common and suggest incomplete drainage in some cases, as do convexities in the longitudinal profile of cave floors probably formed due to pressure differentials in the liquid lava rather than degassing. But while some passage infilling by congealed lava has occurred at a late stage, the size of the tunnels and moderate gradient suggests fairly rapid flowage of the fluid rock. Elongate chambers are often linked by low roofed crawls. This form may be related to the formation of flow units (Nicholls, 1936) and/or hydrostatic pressure.

Concentric shelling of the lava parallel to cave roof profiles is commonly exhibited at cave entrances. The tunnels are exposed both by surface collapse due to subaerial erosion and also through truncation of lava flows by marine erosion. Angular blocks on the cave floors reflect secondary breakdown and are most common near entrances. Some tunnels are known to reach 400 m in length. Only small lava stalactites are known to the writer, most little more than botryoidal.

Piping of volcanic ash has resulted from the rapid absorption of rain into the soil, and the overflow of the Rano Aroi crater lake. These piping caves are best developed along the course of the Rano Aroi stream, but a similar process of spring flushing is responsible for micro caves elsewhere, particularly when resistent lava intercepts the passage of underground waters through the pyroclastics.

Similar differential erosion of the pyroclastic and lava rocks by the sea has developed broad, shallow caves around various parts of the coastline. Some shallow caves inland, particularly around Rano Raraku, may be due to marine erosion during former high sea level stands. Differential erosion by subaerial processes has also been responsible for some shallow rock-shelter caves elsewhere on Easter Island.

The caves of this lonely island have attracted negligible attention from speleologists. Instead, they have provoked some interest from archaeologists seeking to resolve a popular enigma. The caves of easter Island form a palimpsest upon which is recorded the human experience of man's loneliest and most remote outpost. It is this which provides perhaps the greatest fascination in the netherworld of Hotu Matua's "island full of holes."

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VOLCANISM AND CAVES OF MT. ETNA: A BRIEF REPORT

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INTRODUCTION

Mt. Etna towers in the middle of the Mediterranean area. It is the greatest active volcano in Europe; it is well known throughout the world for its activity since ancient times. Many scientific and popular papers about it have been produced in past centuries. It is rich in volcanic caves of different types and represents the only volcanic cave area on continental Europe. But the region as a whole is scarcely known in the world of international vulcanospeleology.

Notwithstanding the difficulties of presenting an exhaustive picture of Mt. Etna's volcanism from a speleological angle, this paper aims to outline a vulcanospeleological portrait of the area through a summary of geographical, geological and historical notes on the region, and a brief description of some of its most significant caves. Some considerations on cave formation theories are added as well.

GEOGRAPHICAL AND HISTORICAL NOTES

Mt. Etna rises to a height of 3,350 m asl on the eastern coast of Sicily, isolated from other mountain systems. It is primarily of Tertiary age. In the north, the Alcantara Valley segregates Etna from the Peloritani Range, and the high Simeto Valley marks the western limit between Etna and the Nebrodi Mountains. South of the volcano lies the Catania Plain, formed by recent alluvial deposits of the Simeto, Dittaino and Gornalunga Rivers. Mt. Etna slopes down to the east into the Ionian Sea, through a series of still active NNE/SSW and NNW/SSE faults, which cause recurrent seismicity in the area.

The surface of Mt. Etna is more than 1,250 square km wide, and its average diameter is about 45 km. Built-up centers of population form a continuous belt around the volcano, at its feet and on its flanks, up to a height of almost 1,000 m. The region is intensely populated (more than one million inhabitants). Catania, which lies at the seaside between the plain and the southernmost limit of Mt. Etna, is the main town.

The origins of Catania are uncertain: many archaeological findings show that a village existed in this area in prehistoric ages, and the town was already an important trade center and port in Greek and Roman times, some centuries B.C.

The town suffered many destructions caused by eruptions and earthquakes. In recent historic times, it was partially flooded by lava during the great 1669 A.D. eruption, and completely razed by the 1693 A.D. earthquake. Nevertheless, Catania was rebuilt by the Duke of Camastra, and from then onwards, it has been growing larger and larger, to the size and importance of today.

VOLCANIC CAVE FORMATION: WHERE AND WHY

Though volcanic areas and rocks are very common on the Earth's surface, volcanic caves are formed only in zones where a distension type of volcanism occurs and basic lavas are the final volcanic products. Compression volcanism results from remelting of more or less deep batches of crustal rocks with a high silica percentage, and therefore, generating acid high viscosity lavas, incapable of fluxion. Distension volcanism in contrast, is fed through distension fissures, directly from the subcrustal mantle, thus producing very fluid lavas, capable of flowing and forming caves. This is the situation at Mt. Etna, though some complexities exist in its case.

Mount Etna: Structure and Evolution: The structure of Mt. Etna is very complex, since it is a multiple stratovolcano built up by intercrossing products of several volcanic units, active in different times and places.

Today's Etna is "a distension fissure-fed volcanic region with centralized structure" (Romano, 1979), rather than a single volcano; therefore, it is advisable to have a glimpse of its evolutional history for a better understanding of the subject. Different subsequent stages can be distinguished in the volcanic activity of the area:

A. First eruptive events: These date back to about 7/500,000 years ago, and occurred in the form of a submarine fissure eruption in the northern side of a shallow gulf closed to the north and the west by the Peloritani/Nebrodi sliding nappes, and to the south by the tectonic block uplift of Mts. Iblei. The submarine lavas were erupted on an underlying horizon of bluish clays of the "Sicilian" age (mid-Quaternary). Gradually they filled the gulf. Also, subaerial fissure eruptions occurred to the west at this stage.

The evidence of these ancient volcanic events can be traced in the pillow-lava and hyaloclastite horizons of Aci Castello and Aci Trezza, and in subaerial lava outcrops in the SW area (Paterno, Biancavilla and S.M. di Licodia).

B. Basal volcanism: An irregular tectonic uplift marked the beginning of this stage, which pushed the sea south, and eastward and resulted in a sloping basement whose height ranges from sea level (south) to about 700 m (NE) and 1,000 m asl (NW). Evidence of this stage is identified in several volcanic centers of Mt. Etna, such as the Calanna and Trifoglietto I Volcanoes to the east (Zafferana and Milo area), and the Paterno Volcano to the west. Also in the NW area, a high terrace of basal lava outcrops on the Alcantara River, east of Randazzo (Romano and Guest, 1979).

According to Cristofolini, et al (1977) and Romano and Sturiale (1981), at least two additional centers were active in this period: the Monte Po Volcano to the south (Pedara/Tardaria) and the Pernicana Volcano to the north.

C. Trifoglietto unit: The diffuse fissural activity of previous stages was gradually transformed to a central type of activity. After the cessation and eventual calderic collapse of the previously mentioned volcanic centers, a new and gigantic edifice gradually built up, the Trifoglietto unit. Not less than five volcanic centers were more or less contemporarily active in this unit: the Trifoglietto I, the Serra Giannicola Piccola, the Vavalaci, the Belvedere and the Zoccolaro Volcanoes. Evidence of these centers is found in the intercrossing lava and cinder beds and massive vertical dikes outcropping from the steep walls of Valle del Bove.

In fact, the activity and subsequent description of these volcanoes resulted in the impressive calderic collapse of Valle del Bove, a complex of coalescent calderas open eastward some 8 km wide (N/S axis) per 6 km long (E/W axis), incised for more than 1,000 m (at its deepest point) on the eastern bank of Etna.

Though the origin of this gigantic scar is still controversial (somebody even proposed a glacial origin! . . .), the presence of extensive lahar outcrops downslope eastward could be interpreted as the evidence of multiple phreatic explosions which eventually created and gradually enlarged and deepened the depression.

D. Mongibello unit: "Mongibello" is Etna's name in Sicilian speech. It is a Latin/Arab composite word, which sounds somewhat like "the pre-eminent Mountain" or "the Mountain itself." This unit was formed on the western flank of the pre-existing Trifoglietto unit, when the main volcanic axes shifted to NW from Trifoglietto to Mongibello.

The Mongibello unit surrounds the present central volcanic conduit and is featured by a strato-volcanic conical edifice rising from 1,800 to 2,900 m asl. The summit of this cone was truncated by two subsequent calderic collapses: the Ellittico caldera (filled by subsequent Leone eruptions), and the Leone caldera (unfilled and open on the NW Valle del Bove rim).

A further calderic collapse, termed the Piano caldera, marks the transition to Modern Mongibello. Some consideration on C14 dating led volcanologists to date the last collapse back to 2,000/2,500 years ago. The filled Piano caldera is today towered by the steep summit cone, consisting of thin lavas and pyroclastic rocks.

It can easily be seen that during the evolution of Etnean volcanism, the main activity center has gradually migrated from SE to NW. The remnants of the diverse volcanic centers are roughly ranked along a directrix which links the first submarine effusions with the summit apparatus of today's Etna.

Also, the chemical composition of lava changed somewhat during the volcanic axis shifting. The former transitional basalts and basalts of tholeiitic affinity of the first eruptive events changed through the alkaline basaltic series of the basal lavas up to the supersaturated elements (mugearites and benmoreites) of some centers in the Trifoglietto unit; and back again toward undersaturated terms, up to hawaiites, basic mugearites and alkalic basalts of modern Mongibello (Romano, 1979).

This led scholars to the conviction that Mt. Etna has not an actual magma reservoir, but is fed by different distension fissures. Furthermore, it is supposed (Romano, 1970) that some tilting occurred in the cracked crustal blocks floating on the underlying mantle, thus segregating portions of basal magma in the interstices, which in turn resulted in a gravitary differentiation of evolution of the erupted lava.

PRESENT VOLCANIC ACTIVITY

Mt. Etna performs an almost continuous activity of a mixed kind, with prevailing effusive events. Its summit complex apparatus (the Chasm, the NE crater, the Western Chasm or Bocca Nuova, and the SE crater) maintains a permanent fumarolic activity with recurrent explosive events. The last effusive eruption from the Chasm was in 1964. Effusive activity is very intense and recurrent on the flanks of the mountain and is performed through abundant effusions of aa lava which is fluid and rather degassed, and flows for remarkable distances.

The last eruption occurred in March 1981: a very fluid lava flow, emerging from NNW/SSE fissures gradually elongating from 2,550 m to 1,100 m asl on the northern side of the volcano. The lava moved downslope NNW for some 7.5 km, and reached the bed of the Alcantara River at about 600 m asl after crossing woods, orchards and vineyards. The flow severely threatened the town of Randazzo and buried large segments of the Etna ring-road and ring-railway, the state road from Fiumefreddo to Randazzo and the state railway from Giardini to Randazzo.

DIFFERENT ERUPTION TYPES OF MT. ETNA

According to mainly phenomenologic considerations, Etna eruptions can be distinguished into four main classes (Rittmann, 1963):

i. Terminal eruptions: All explosive and/or effusive phenomena, characterizing the eruption, are performed through the terminal apparatus.

ii. Subterminal eruptions: All explosive phenomena (emission of ash clouds, cinders, bombs and molten lava spatters) are performed through the summit apparatus, while outpourings of lava occur through one or more "bocca di forno" (arched boccas resembling oven mouths — Cucuzza-Silvestri, 1967) on the banks or at the base of the summit cone (between 3,300 and 3,000 m asl).

Nevertheless, in some subterminal eruptions, the outpouring of lava occurs at a really lower height, when fluid lava flows for some distance downslope beneath a thin crust of pre-existing solid lava, before coming onto the external surface through a rootless vent. This singular type of subterminal eruption can be easily recognized because of the absence of explosive activity in the vent; the lava outflow is only coupled with launching to a short distance of molten lava spatters, which, when falling to the ground, build up the typical welded spatter cones termed "hornitos."

iii. Lateral (or radial) eruptions: These eruptions are preceded by explosive activity in the summit apparatus, with violent emission of ashes and solid material. Magma coming from the main volcanic conduit becomes laterally wedged towards the surface through weakness trends, and the eruption is performed through an eruptive fissure in the flank of the volcano; this fissure is almost always radially oriented as to the main volcanic axis.

The explosive activity is performed in situ through the upper end of the fissure, where one or more ranked cinder cones (regular or crescentic or broken) are built up, while lava flows from the downslope end.

The activity of the summit apparatus in this stage is restricted to emission of fumes and ashes, due to internal collapses, and the end of the eruption is generally followed by a quiescent period, the duration of which is somewhat related to the violence, duration and discharge of the previous eruption.

iv. Eccentric eruptions: All explosive and/or effusive phenomena occur through adventive eruptive systems, which open onto the flanks of the volcano. Since accompanying activity in the summit apparatus is missing, magma is supposed to come onto the surface through a feeding fissure or dike independent of the main volcanic conduit. Most of Etna eruptions in historical times can be classed as subterminal or lateral ones.

CAVE FORMATION ON MOUNT ETNA

Factors contributing to cave formation on Mt. Etna are its distension fissure-fed volcanism, the chemical composition of its lava (alkalic basalts, hawaiites and mugearites) and the relevant temperature and fluidity, and the favorable topographical and environmental conditions (slopes ranging everywhere from 10° to 20° gradient and lack of natural obstacles or large water masses). In comparison to the caves of some other volcanic areas, the caves of Etna are small and of moderate extent.

It is remarkable that the great majority of Etna's lava flows consist of true aa lava, the pahoehoe being restricted to persistent subterminal "leaking" activity (such as the 1614/1624 A.D. eruption). In spite of this, thanks to the average slope gradient, lava can maintain a significant flowage capacity even below 1,000° C, when other lavas elsewhere, in normal conditions, have already started the final general congealing. Therefore, most lava tube caves on Mt. Etna are actually in aa lava rather than pahoehoe.

In addition to the rheogenetic surface caves (lava tube caves; Licitra, 1978/b, 1982/b), several rheogenetic fissure caves (eruptive fissure caves) and pneumatogenetic explosive caves (hollow welded spatter cones and hornitos) can be found on Mt. Etna. The writer did not succeed in identifying pneumatogenetic expansion caves (lava blisters), probably because the chemical composition of lava and/or the environmental conditions do not permit such caves to be formed. Nevertheless, some scholars reported caves of this kind along the coastline, between Capo Mulini and Pozzillo, probably generated by expanding seawater steam after the incandescent lava entered the sea.

VULCANOSPELEOLOGICAL RESEARCH AND STUDIES

Man's interest have been excited by volcanic phenomena of Etna since ancient times, either for superstitious purposes or for scientific ones. Ancient Greeks believed that Vulcan's smithy was located inside Etna, and that the God of Fire there prepared his father, Jupiter's thunderbolts. A legend also tells that the naturalistic philosopher Empedocles (5th century B.C.) spread the rumor that he had been called by the Gods, and then he hurled himself into Etna's crater. But Vulcan, offended by this lie, shot forth from the crater one of Empedocles' bronze boots, thus letting people know the truth. Today, a hillock just below the summit crater is named "philosopher's tower," in memory of this legend.

As early as 1359, Giovanni Boccaccio cited the Etnean cave Grotta di Talia (untraced by us) with these words: ". . . and a pelting was heard of subterranean waters, coming from the melting of Etna's snow reservoirs . . ." But the scholar who first positively took an interest in the caves of Etna was Anton Giulio de' Amodeo, nicknamed Filoteo. In his work "Topographia" (1591), he quoted many caves visited by himself, and described some of them. Nevertheless, only one of these caves has been identified by the GGC, and recorded in the Catalog files as "Riconco di Monte Dolce" (Si/CT/1110).

Many more or less definite citations of the caves of Etna can be found in the literature of the subsequent centuries, though the descriptions are often exaggerated and defiled by a good amount of folk beliefs and superstitions. The Dutchman Athananasius Kircher asserted (in Mundus Subterraneus, 1678) that he had visited a cave on Mt. Etna, capable of lodging 30,000 "homines."

The scholar Wolfgang Sartorius von Waltershausen described (1880), among others, the Grotta delle Palombe and published a sketch of it. It is remarkable that this cave, which shows a sheer 8 m vertical entrance pit, was already descended and explored some 100 years ago.

In the first decades of the present century, some volcanologists produced contributions concerned with Etnean caves, and formulated hypotheses on their genesis, but a methodical plan of speleological research was launched only about 50 years ago by Dr. Fracesco Miceli, a CAI Etna member, and founder of the G.G.C. In fact, Miceli found and described some fifty caves and laid down the foundations of the Mt. Etna Caves Catalog or Cadastre in the course of his more than thirty years of speleological activity. The G.G.C. carries on Micheli's work. It owns the topographical data of almost 200 caves. Descriptions and maps of many of these caves also have been compiled.

In 1975, to celebrate the CAI Etna centenary, the G.G.C. published a volume by Fabio Brunelli and Blaco Scammacca, Volcanic Caves of Sicily," containing the description and survey of the first 25 caves recorded in the Oadaster files, in addition to general information on vulcanospeleology.Also organized was a successful International Seminar on Lava Caves (August 27-29). The relevant Proceedings, published by

G.G.C. in 1977, represent a milestone in vulcanospeleological literature.

In addition to the G.G.C. of CAI Etna, the Speleological Group of CAI Giarre (founded in 1976) and the Group for Archaeological and Speleological Research of Acireale (founded in 1979) are today carrying out successful research on Etna caves. Although "official" science is not actually interested in volcanic caves, these groups can count on some supporting scientific organizations: the Volcanology and Geology Department of the Institute of Earth Sciences (State University of Catania) and the International Institute of Volcanology of Catania (National Research Council).

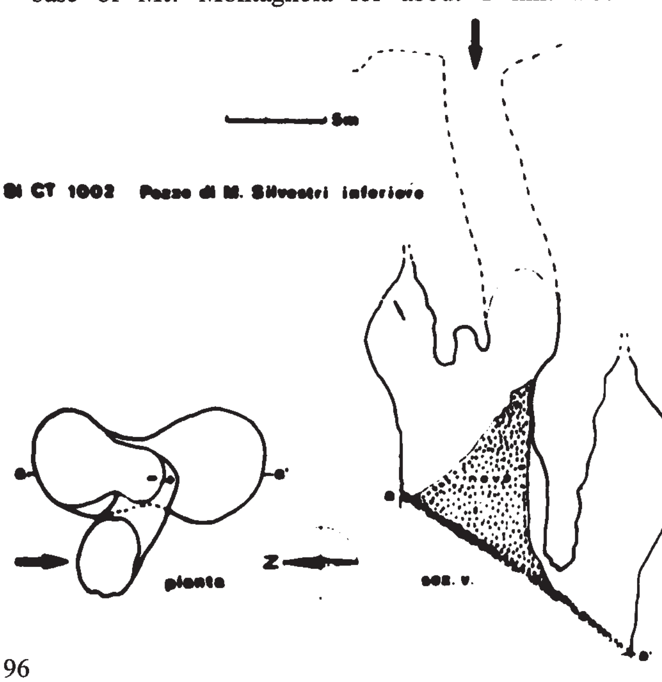
SOME VOLCANIC CAVES OF MOUNT ETNA

Etna caves are numerous and extremely varied, and many of them are located in true aa lava flows. Therefore, it is thought convenient to report brief descriptive, historical and morphogenetic quotations of only five significant rheogenetic caves, to give a general idea of the role of Etnean caves in the classification and study of volcanic cave formation.

I.1. Rheogenetic Fissure Caves (group 1.2)

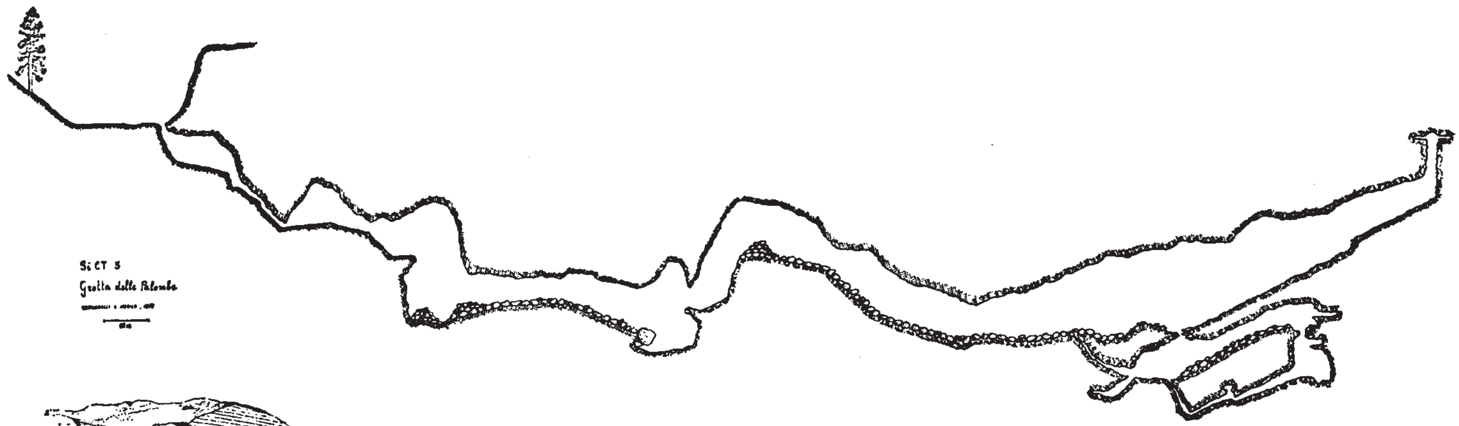
i. Pozzo di Monte Silvestri Inferiore (Lower Mount Silvestri Pit — Si/CT/1002): This is a vertical cave 31 m deep. It is shared by two subsequent pits with only 12 m planimetric range. The cave is in the eastern eruptive apparatus of the 1892 lateral eruption. The cave is deservedly well known, though its size is modest. In fact, in recent times, the Pozzo di M. Silvestri Inferiore has been quoted by scholars as a model to define the "eruptive conduit" type in some descriptive classifications. In addition to this, it is well known to non-experts because of its easy access; it is located a short distance from the road through an easy 100 m path.

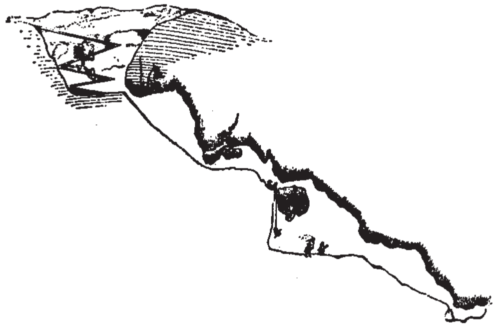
The 1892 eastern eruptive apparatus is formed by an eruptive fissure cracked out at about 2,000 m asl southward from the base of Mt. Montagnola for about 1 km. Four main explosive centers were here formed on the fissure, from its upper end downwards: Upper Mt. Silvestri, Lower Mt. Silvestri, Mt. Silvestri III and Mt. Silvestri IV. The first two are regular cinder cones, the third is a crescentic, while the fourth is a regular welded spatter cone with an explosive pit some 20 m in diameter and 40 m deep. Lava flowed southward from a large bocca situated between the third and the fourth cone on the western side of the fissure, and eastward from two pseudo-boccas situated some 200 m away ESE from Mt. Silvestri IV.



The cave entrance is located in the center of the bowl-shaped crater of lower Mount Silvestri, and consists of a cylindrical subvertical conduit about 2 m in diameter, which sinks down through unconsolidated materials (cinders, ashes, loose lava spatters) accumulated during the explosive activity of the crater. The inner part of the entrance pit is coated with a lava plaster 5 to 10 cm thick, and leads to a 12 m vertical bell-shaped inner pit, contained in the eruptive fissure itself. Its vertical walls, 5 m apart, are coated with a skimmed lava plaster also.

A complete report, including the description, topographical





Querschnitt der Grotta delle Palombe bei Nicolosi.

survey, morphology and genetic considerations of this cave, was submitted by G. Licitra and F. Cavallaro to the XIII National Speleological Congress held in Perugia in 1978.

ii. Grotta delle Palombe (Si/CT/1003): In 1669, the southern flank of Etna was the scene of its largest eruption in historical times; the eruption "of the Monti Rossi," lasted 122 days. After a strong local earthquake which destroyed the small village of Nicolosi, immediately west of the village itself, at 850 m asl, the ground cracked on March 11 with formation of a large explosive/effusive fissure more than 1 km long, trending N/S, from which flowed a large lava flow which reached and entered the sea at a distance of about 15 km, after having flooded the villages of Mompilieri, Belpasso and Misterbianco and the western part of the town of Catania. The medieval Ursino Castle (XII century A.D.), built up on the cliffs at the seaside, today is almost 1 km from the sea itself. The quantity of emitted lava is estimated to be about 1.0 cubic km (Romano and Cristofolini, 1980), and the pyroclastic materials ejected around the fissure vent formed a broken cinder cone whose twin tops, more than 200 m high, were named Monti Rossi (Red Hills), because of their color.

In addition to numerous lava tube caves formed in this flow (not specifically mentioned in this paper), a pit-cave named Grotta delle Palombe, was left in the bottom of a small bowl-shaped crater, at the northern end of the fissure vent. It is a mixed type cave, with a 35 m depth and a planimetric range of about 150 m.

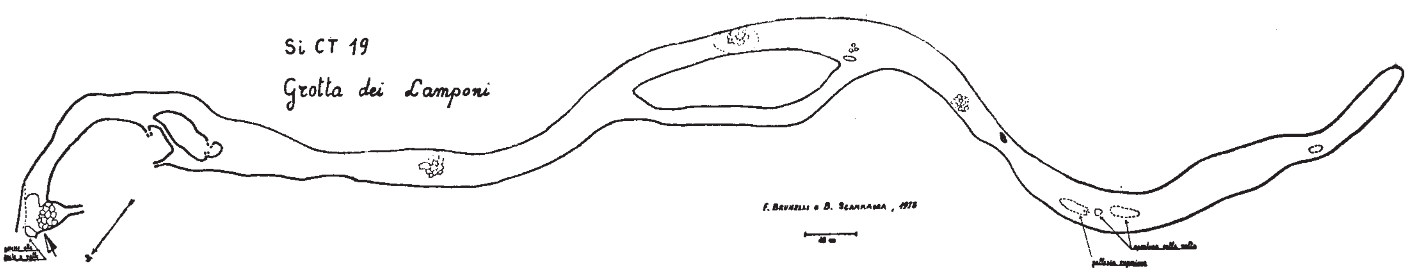
The Grotta delle Palombe is undoubtedly the most studied and best known cave by Etna scholars. It was mentioned in 1773 by Patric Brydone, and was visited at the end of the same century by the naturalist Giuseppe Recupero. A report of the exploration carried out by Mario Gemmellaro was published in 1858 by his brother Carlo. Even Sartorius visited this cave up to the same point as M. Gemmellaro did (the edge of the 17 m pit), and left an accurate description and a longitudinal cross-section of the cave in his work "Der Etna" (1880); this represents perhaps the first attempt to topographic survey in a volcanic cave anywhere in the world. The cave was completely mapped in 1969 by Domenico Condarelli and Pietro Nobile, and this map (cross-section), with the cave description, was published in the volume Volcanic Caves of Sicily, by Brunelli and Scammacca (1975).

The entrance of Grotta delle Palombe is formed by a bell-shaped pit 8 m deep, at the head of which a cavern 5 m wide per 13 m long is located. From the southern end of the cavern, a sloping 40 m passage leads to the edge of a 17 m vertical pit. The cave lengthens southward from the head of this pit between the walls of the eruptive fissure, about 3 m wide, through several collapse zones.

1.2— Genetic Considerations on Eruptive Fissure Caves

These two caves are both of the rheogenetic fissure type, namely they were generated by lava flowing inside and through an eruptive fissure.

This kind of genesis operates in two subsequent steps. In the first step, molten lava, pushed onward by endogenetic forces, opens a way to the surface through weakness trends, thus generating eruptive phenomena. In the second step, when the



endogenetic push shifts to lower heights or diminishes and eventually ceases, a lowering of lava level occurs inside the fissure.

In case the fissure walls are well cemented and large collapses do not close the fissure, after the lava sinks down, an elongated narrow hollow is left, with parallel walls, which is termed rheogenetic fissure cave (Licitra, 1978/c —1981/b).

II.1 — Rheogenetic Surface Caves (group 1.1)

Lava tube caves are widespread on Etna, thanks to its basic lava and to its mainly effusive activity. Yet the moderate fluidity of Etna lava (in comparison with the Hawaiian and Icelandic lavas) manages to form caves with modest planimetric range; the Grotta dei Lamponi, the longest known lava tube cave on Etna, has a planimetric range of only 700 m.

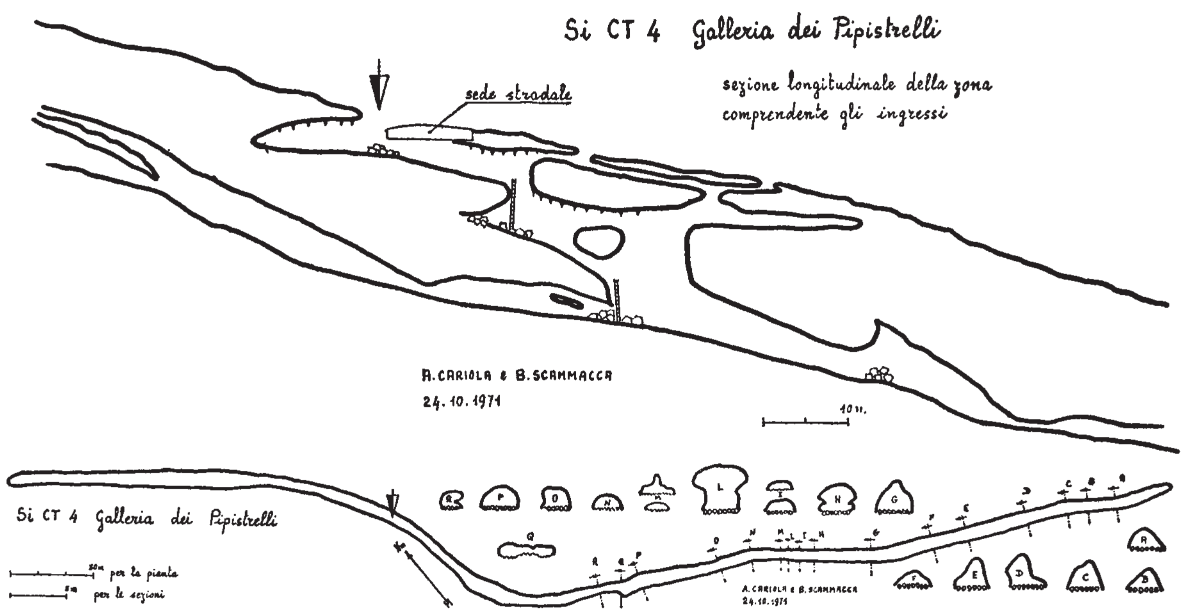
Notwithstanding this, a wide range of different morphological features can be observed in Etna lava tube caves: circular, elliptical, triangular or irregular traverse cross-sections; round or gothic arched and flat roofed passages; loose or welded cinder floors and pahoehoe or slab floors; multi-storied, braided and coalescent tubes; lateral benches and shelves, detachment laminae, glassy linings, etc. It is, therefore, possible to carry out a wide set of systematic comparative studies of lava tube caves on this volcano.

i. Grotta dei Lamponi — (Si/CT/1019): This cave is situated at 1,750 m asl on the northern flank of etna, in the lava flow of the eruption which lasted from 1614 until 1624. This large lava flow, named "Lava dei Dammusi," was made by an enormous number of small pahoehoe flows rather than a single significant flow (as the 1669 flow), and is supposed to have been due to a persistent subterminal "leaking" activity (Romano and Guest, 1979). The Grotta dei Lamponi was explored for the first time in 1965 by some members of CAI Linguaglossa. It is a long, almost unbraided lava tube, which can be entered through a collapse hole in the roof, situated two-thirds of the way downslope from the upper end. The entrance divides the gallery into two different segments. In the upper segment, the gallery shows a moderate gradient, an almost regular elliptical cross section, and is separated from the surface by a rocky cover ranging from 2 to 4 m average thickness. The floor is made of welded cinders, but in some places, it is hidden by lava blocks collapsed from the ceiling. A large skylight looks into the lava tube at its upper end, and a minor collapse hole affects the tube roof some 40 m downslope from the skylight. A minor branch diverges to the left (looking downslope) from the main tube into a narrow and spiny crawlway, which rejoins the main tube after some 5 m; one small tributary tube a few meters long can be seen on the left wall of the gallery just at the main entrance.

In the segment downslope from the entrance (not yet mapped by G.G.C.), some 120 m long, the gradient increases considerably and the gallery plunges into the body of the lava flow. The lower end of the cave is segregated from the surface by a rocky cover about 70 m thick.

Some large lateral horizontal shelves can be noted in this section of the lava tube. In the writer's opinion, a large mass of lava ponded (see Romano and Guest, 1979) and started congealing inside the tube during the active flow, but the increasing hydrostatic pressure exerted by additional lava arriving from the source vent succeeded in clearing some passage downslope, thus abruptly emptying the molten lava reservoir. The horizontal shelves could be the remnants of the supposed underground lava reservoir. The grotta dei Lamponi and other caves in the "Lava dei Dammusi," were carefully surveyed in 1976 by a joint team (SMCC and Leicester University, U.K.), headed by Dr. Chris Wood, with G.G.C. cooperation.

ii. Grotta dei Tre Livelli —(Si/CT/1004): This cave is located on the SSE flank of Mt. Etna, at 1,725 m asl in the 1972 A.D. lava flow. It was discovered in 1964 during the construction of the road from Zafferana to Cassa Cantoniera dell 'Etna. It is probably the best example of a lava tube cave on Mt. Etna.



The Grotta dei Tre Livelli shows three superimposed flow galleries, connected by two pits 5 m each; there is a vertical range of about 8 between the upper and lower end of the lowest gallery. The total length of the cave is almost 500 m. It is possible to trace back the steps that featured the operation and evolution of the active flow, through a skilled study of the surface features and of the three galleries of the cave. In fact, while the flow front gradually proceeded downslope, the flow level stabilized at a lower height inside the lava tube, and then started being covered by a solid crust, thus forming the subsequent level.

The lowest gallery of the cave contains interesting features: the floor is formed by welded cinders (uplifted welded slabs in the vicinity of the upper end), and very long lateral shelves and curled detachment laminae can be observed along the walls. Furthermore, the gallery is almost unaffected by collapse.

iii. Grotta dell'Intraleo Cave —(Si/CT/1007): Like the preceding ones, this cave shows special features that can involve interesting studies. The Grotta dell'Intraleo is located at 1,325 m asl on the western flank of Etna, at the foot of Mt. Intraleo. The parent flow is thought to have been formed by the 1595 A.D. eruption but the date is uncertain for lack of documentation on this eruption; the local parish archives (main sources of news about ancient eruptions) were almost completely destroyed by the 1693 A.D. earthquake.

This lave tube cave is elongated downslope westward from the base of Mt. Intraleo. It has two segments separated by a large collapse hole some 12 m wide by 3 m long. Many morphological features induce the belief that the collapse occurred just at the end of the active flow. In the first segment of the cave, up slope just before entering the collapse hole, the floor is lifted in the middle and a 20 m crawlway passage runs beneath it. It is thought that the discharge of lava increased after a solid crust had formed on the flow surface inside the lava tube, and it caused the crust to be cracked and lifted up and the small inner passage to be formed.

The cave segment downslope from the collapse hole displays evidence of the evolving and final stages of the flow. It is a braided tube, divided into three divergent (in space) and subsequent (in time) branches, with gradually lowering flow levels from the left to the right. Furthermore, another large gallery a few meters long is situated beneath the floor of this second cave segment. This gallery, featured by very large detachment laminae, marks the last stage of the active flow, before the final congealing of lava and collapse of the tube roof upstream.

A complete report concerning the Mt. Intraleo and Gallobianco lava flows and their caves will be submitted by Dr. C. Pandolfo, G. Puglisi and the writer to the forthcoming National Speleological Congress of Italy in Bologna at the beginning of September 1983.

II.2 — Genetic Considerations on Lava Tube Caves

The study of the previously outlined rheogenetic surface caves, of many other lava tube caves of Etna, and some observations in the Raufarholshellir lava tube, Iceland (visited in August 1980), induced the writer to the conviction that some misunderstandings and an essential equivocation do affect theories concerning lava tube cave formation, since almost all authors dealing with this topic enunciated their general genetic theories based on the study of a single cave or lava field. Therefore, although the concerned theories are generally valid in the observed cases, they often conflict with other theories based on observation of other caves and/or lava fields.

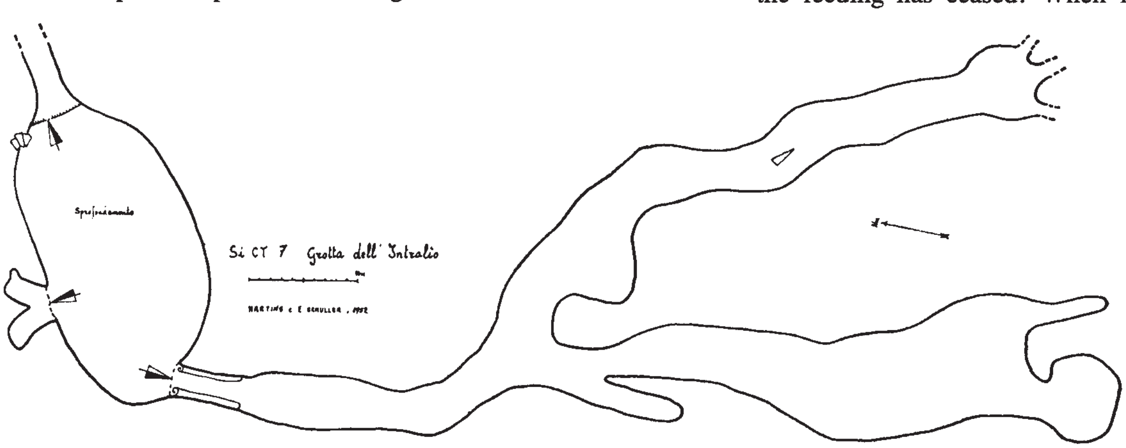
In the writer's opinion, the problem must be examined from a theoretical angle, to gain widespread applicability, as it was already indicated by Poli (1959), Ollier and Brown (1965), and Rittman (1977).

In fact, the first flow of lava on the surface is always by gravity. But owing to the thermal loss to the air and to the ground, the molten lava becomes restricted to a channel and then chilled, forming a solid crust, beneath which the flow continues under hydrostatic pressure (exerted by additional lava arriving from the vent) with hardly any further thermal loss.

Yet the flowage level inside any active lava tube always tends to lower, both through diversion into new flow units at the flow front and/or remelting and erosion of the flow bed, thus restoring gravitative flowage conditions inside the tube with further thermal losses in the gaseous space. This causes the cycle to be repeated over and over.

Thermal compensation is the factor permitting the flow motion, either by gravity or by hydrostatic pressure, while the flow is fed. The active lava flow preserves its heat because any thermal loss is continuously balanced by the incoming of new molten lava at a higher temperature, and thus the flow mobility is maintained.

As a consequence, lava tube caves are actually generated DURING the active flow operations, through the gradual lowering of flowage level/bed inside the tubes, instead of being caused by drainage of still molten lava from the tubes AFTER the feeding has ceased. When feeding from the source vent ceases, the thermal compensation mechanism ceases its operation, and damping down of the flow is almost immediate. Only minor segments of tubes in very fluid lava flows can be actually formed by final drainage of still molten lava, and for a really short extent.



CONCLUSIONS

These notes on the present situation of vulcanospeleological studies on Etna are necessarily concise and full of gaps, as it is impossible to condense in a few pages a wealth of studies and research involving many scholars and many decades of theoretical and observational studies.

In any event, the writer hopes he has succeeded in outlining a comprehensive view of present local knowledge. This is continuously increasing, thanks to the numerous and different caves which can be found and studied on Mt. Etna, and thanks to the eruptions which occur with a certain frequency, thus making possible the observation and study of the actual operation of active lava flows.

The International Symposium on Vulcanospeleology and the Round Table of Lava Tube Cave Formation, which will be held in Catania in September 1983, celebrating the 50th anniversary of the Etna Caves Cadaster, will provide a significant opportunity for comparison and review of the previous studies, of achieved knowledge, and future programs of research and study.

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THE WORLD'S LONGEST LAVA TUBE CAVES

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INTRODUCTION

Since lava tube caves began to be mapped in large numbers, numerous claims to possession of the world's longest have been advanced by cavers from various countries. Among the caves for which this distinction has been claimed are Ape Cave, Washington (Halliday, 1962); the Cueva de los Verdes, Canary Islands (Montoriol and de Mier, 1974); Kazumura Cave, Hawaii (Gagne and Howarth, 1975); Leviathan Cave, Kenya (Simons, 1976); Man Jan Gul, South Korea (Anon, 1981); and Bilemot Gul, South Korea (Ogawa, 1982).

Conventionally, the ranking of the above mentioned and other long lava tube caves would be based on their published lengths. Unfortunately, some of the caves involved have conflicting published length figures; even more unfortunately, the mappers have used different standards in defining cave length and cave limits. Uncritical acceptance of the published figures would lead to a list in which the lengths given for different caves would not be truly comparable; thus the ranking would be meaningless. It is evident that a single set of standards and definitions must be adopted for a meaningful ranking of the caves in order of length to be possible.

The Problem of Segmentation

The most important controversy among lava tube mappers is whether intact lava tube segments separated by collapse trench should be counted as the same or different caves. Figure 1 illustrates diagrammatically eight possible caves bearing on this controversy.

Figure 1A shows a single passage cave divided by a typical collapse entrance. Korean, Spanish, or British cavers would almost certainly count this as a single cave. American, Canadian, or French cavers would most likely count it as two. This difference of opinion would lead to two alternative length figures differing by a factor of about two. Moreover, of the mappers who would count this as a single cave, some would include the collapse in the cave's length and some would not.

Figure 1B is a more extreme case of Figure 1A. Some of the mappers who would count 1A as one cave would count 1B as two. Probably some would count even 1B as a single cave. In this case, if the collapse trench were counted, it would nearly double the cave's (or caves') length.

The same mappers who would count 1A as one cave would probably count 1C as one also; others would count it as three. But would anyone count the largely collapsed system in 1D as a single cave for the sake of its four tiny intact segments? Probably not. This is what is known as a reduction ad absurdum. If one is not to count extreme cases like 1D as entire caves, where is the line to be drawn? Standard definitions are the only answer.

The diagrams on the right side of Figure 1 illustrate some cases to be considered in formulating standards on segmentation. Figure 1E illustrates the least controversial possible case. A collapse at one end of a passage obviously leaves the cave intact. The case in Figure 1F is almost equally clear. Everyone, I think, would agree that a collapse which can be bypassed via intact passage does not segment the cave.

Figure 1G illustrates the nub of the problem. Several points of view are possible here. First, one could view the left hand case as a single cave, despite the segmenting collapse. One would then have to decide where to set limits on how much collapse can be part of a cave, or be forced to count extreme cases like 1D as caves. Second, one could adopt some such rule as that a collapse of the full passage width segments the cave. One would then have to count the right hand case of 1G as two caves, something most cavers would be reluctant to do. The best compromise between these two points of view I have seen is the international standard as adopted here; see below for details.

A more difficult problem, and one that has yet to be satisfactorily settled, is illustrated in Figure 1H: a collapse that does not include the full passage width, but leaves an overhang on one or both sides. If the collapse in this example does segment the cave, what then about a much smaller skylight collapse? If it does not segment the cave, what then about a case where the overhang is less than half a meter?

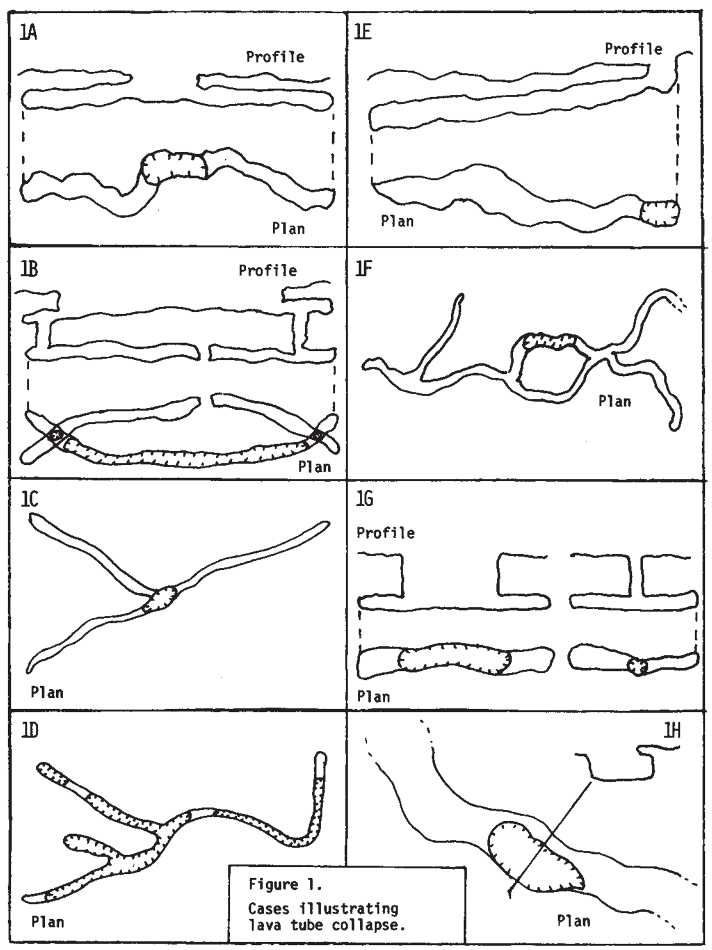


Figure 1.
Cases illustrating lava tube collapse.

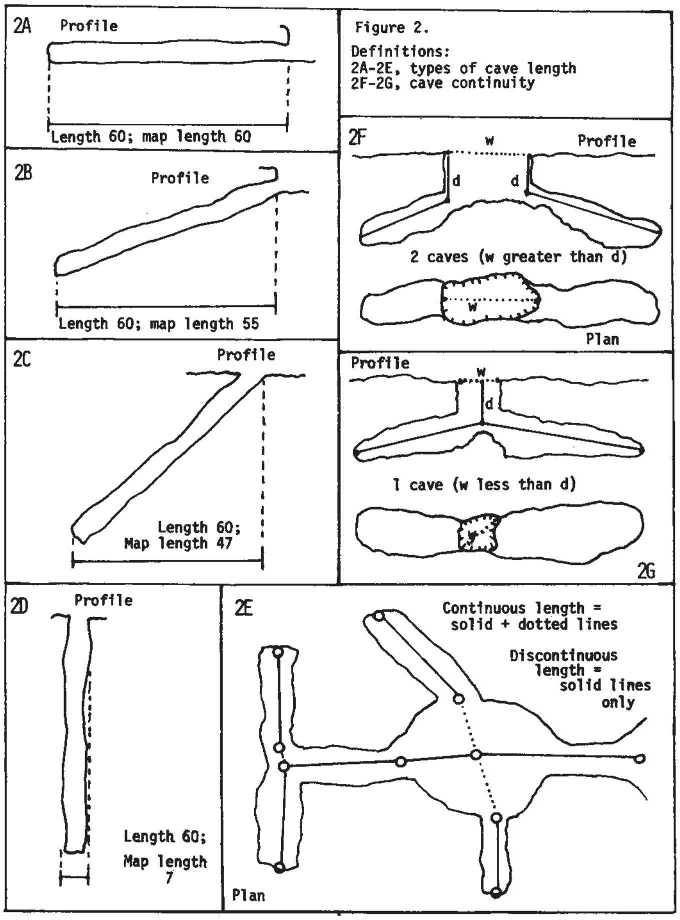


Figure 2.
Definitions:
2A-2E, types of cave length
2F-2G, cave continuity

The Problem of Length Definition

Other controversial aspects of cave length have to do with just how "length" is defined with respect to a cave. To begin with, I think most or all cavers would agree that a cave's length is the total length of all passages, and not just the "main passage" length as some geologists would have it. Another standard that is widely, though not universally accepted is that a cave's length must be determined by mapping, not estimation, to bear comparison with other lengths.

What is done with the mapping data to determine cave length? In the case of some mappers, particularly those of the eastern United States, the first step is to reduce the raw length data, as measured in the cave, to horizontal and vertical components and to count only the horizontal components. This is illustrated in Figure 2 (A-D). Length determined in this way is called projected length or map length. In figure 2A, the map length is 60 units, the same as the unreduced length figure, since the cave is perfectly horizontal. In Figure 2B, the map length is 55; in Figure 2C, 47 feet; in Figure 2D, the "length" of the 60-unit pit is 7 units. To my mind, counting map length as the "true" length of a cave is unrealistic to the point of absurdity. A cave passage, like a stick or any other rigid object, does not shrink and expand depending on whether it is horizontal, vertical, or at an angle. The distance from one end to the other is the same in each case. The length of a cave passage is measured along the long axis of the passage. This is also carried slope length or linear development. All the cases in Figures 2A-2D have the same length, 60 units. Slope length is used by cave mappers in most parts of the world. Reduction of slope length to map length is, of course, an essential step in the preparation of a plan view map. However, it must be remembered that it is only a mathematical abstraction useful in cartography, and has no constant relationship with the true length of a cave.

In caves that slope very little, the map length may be only slightly less than the true length. If the cave is very long, however, even a small percentage difference can be important. A case in point: the most recent list of longest caves of the world (NSS News, October 1982), lists Friars Hole, USA, at 66,000 m, in seventh place under Sistema Ojo Guarena, Spain, at 67,000 m, in sixth place. It is not unlikely that the figure for Friars Hole is map length and that for Sistema Ojo Guarena is slope length. In this case, if the slope length of Friars Hole were only 2 percent higher than its map length, it would be 67,320 m and would take sixth place.

Most other variations in length standards have relatively minor effects, but one can be significant at times: continuous vs. discontinuous length. These concepts are illustrated in Figure 2E. The solid lines represent discontinuous length; the solid plus dotted lines represent continuous lines. In the case of large rooms, the difference can be considerable. Either form seems defensible, but a single standard must be adopted nonetheless.

International Standards

Like other cave mappers, I have personal opinions on how cave length should be determined. I could here proceed to codify these, but lacking any authority other than mine, they would stand no more chance of universal acceptance than anyone else's opinions. Fortunately, there exists an International Commission on the Greatest Caves, presently headed by Claude Chabert, whose job it is to set standards for cave mapping. Their preliminary recommendations were published by Chabert (1979) and Chabert and Watson (1981); from this I have extracted the following list of basic standards for lava tube mapping. Some statements have been reworded for clarity or applicability to lava tubes, but the principles are those of Chabert and his colleagues. See the discussion above the definitions of terms.

*1. **An open collapse pit is part of the cave if and only if its greatest horizontal dimension (width, length, or diagonal) is less than its depth.*** See Figures 2F, 2G. By this definition, the collapse in 2F is not part of the cave, but that in 2G, is part of the cave. Depth in this case is considered to be the depth that would be added to the cave if the pit were considered part of the cave; in other words, the vertical difference between the lip of the pit and the first in-cave survey stations.

*2. **A cave is a continuous subterranean cavity; any discontinuity such as a collapse where one must leave and then re-enter a cave, divides that cave into two caves, whose lengths must NOT be counted together.*** This is a corollary of (1) above, and a crucial point which must be accepted in order for a standard list of long caves to be possible. A related point is that caves linked only by artificial tunnels must be treated as separate caves; however, natural passages enlarged or re-excavated by cavers count as part of the cave.

*3. **For ranking purposes, a cave's length is continuous linear development***, or the distance traveled by a caver to explore all parts of the cave. As a corollary, portions of the

TABLE 1 SOME CAVES AND CAVE SYSTEMS OMITTED FROM LIST

Cave/Cave System	Claimed Length, m	Reason Omitted	Location
Ainohou Ranch Cave	7,110	Segmented	Hawaii
Ubuwumo bwa Musanze	4,560	Segmented	Rwanda
Offal Cave	3,400	Unmapped	Hawaii
Kalmanshellir	3,000	Unmapped	Iceland
Catwalk Cave	2,420	Segmented	California
Cueva de Gallardo	2,250	Segmented	Galapagos
Cueva de San Marcos	2,130	Two caves	Canary Is.
Cueva de Felipe Reventon	2,000+	Unmapped	Canary Is.
La Cueva	2,000+	Unmapped	Canary Is.

TABLE 2 CAVES LISTED WITH REDUCED LENGTH

Cave/Cave System	Max. Claimed Length, m	Listed Length(s)	Reason
Man Jang Gul	13,268	4,632	Segmented
Leviathan Cave	11,152	9,152 2,071	Segmented
Cueva del Viento (system)	10,002	7,922	Segmented
Cueva de Los Verdes	6,100	2,565	Segmented
Susan Gul	4,700	4,674	Overestimate
Gruta dos Balcões	3,200	2,650	Overestimate
Socheon Gul	3,074	2,186	Segmented

TABLE 3 WORLD'S LONGEST LAVA TUBE CAVES

	Cave	Length, m	Vertical Range, m	Location
1.	Bilemot Gul	11,749	---	Cheju Do
2.	Kazumura Cave	11,713	261	Hawaii
3.	Upper Leviathan Cave	9,152	408	Kenya
4.	Cueva de las Breveritas	7,922	261	Canary Is.
5	John Martin Cave	6,400 ?	---	Hawaii
6.	Cueva de Don Justo	6,315	143	Canary Is.
7.	Susan Gul	4,674 ?	---	Cheju Do
8.	Man Jang Gul	4,632	---	Cheju Do
9.	Ape Cave	3,904	210	Washington
10.	Duck Creek Lava Tube	3,674	76	Utah
11.	Falls Creek Cave	2,797	126	Washington
12.	Gruta dos Balcoes	2,650	43	Azores
13.	Cueva de Los Verdes	2,565	29	Canary Is.
14.	Kaumana Cave	2,544	---	Hawaii
15.	Dynamited Cave	2,388	108	Washington
16.	Pot o' Gold Cave	2,250	---	Idaho
17.	Socheon Gul	2,186	---	Cheju Do
18}	Mitsuike Ana	2,140	70	Japan
19}	Gypsum Cave	2,140	---	Idaho
20.	Lower Leviathan Cave	2,071	57	Kenya
21.	Catacombs Cave	2,000	---	California

cave no caver has passed through, such as unclimbed domes and undescended pits, cannot be counted.

4. For ranking purposes, a cave's depth is the difference in elevation between the highest and lowest points reached by cavers in the cave.

5. Only accurately surveyed caves can be ranked; where the survey is unfinished, only that part which is surveyed qualifies.

One problem not addressed directly in these standards is that illustrated in Figure 1H, where a collapse sink leaves an overhang. One of the Commission's principles that may apply is that in a horizontal entrance, the cave begins at the innermost point of the drip line. Unfortunately, this does not seem to help much. This problem is one that should be addressed by the Commission at the earliest date possible. In the meantime, this list will count caves like that in Figure 1H, where it is possible to remain under the overhang while passing the collapse without undue contortion, as single caves.

Criteria for Inclusion

The intention of the list given here is to include every continuous lava tube cave with 2,000 m or more of mapped passage. In most cases, it has been possible to determine whether the caves on the list are segmented, although in some cases, the information has been hard to find. Since there are no lava tubes in the eastern United States, I assume that all the lengths given are linear development rather than map length. In some cases, this has been confirmed.

Two caves are listed which may be segmented, but are being given the benefit of the doubt pending confirmation. Favre's map of John Martin Cave does not show collapses clearly, but in a conversation with John Martin, I received the impression that his cave will probably prove to be segmented when detailed information becomes available. No map or photographs of Susan Gul have yet been published, so its nature remains unconfirmed.

A number of lava tube caves with lengths claimed in excess of 2,000 m have been omitted from the list for reasons connected with the standards set above. In most cases, these caves were either segmented or unsurveyed. In one case, the Cueva de San Marcos, the cited length was the total of two caves with entrances near each other on a cliff face, but not even connected by collapse trench. The more important of the omitted cases are given in Table 1.

In segmented systems, all segments more than 2,000 m long have been listed. So far, only one system has proven to have two such segments; the Leviathan System in Kenya. Originally, it was thought that the Leviathan System was segmented in two places, but data kindly supplied by Jim Simons show that only the lower of these two, "Pottery Collapse," actually segments the cave (see Figure 3). Simons' data is admirably thorough and might serve as a model for other cave mappers. A number of the caves on the list are the longest single segments of cave systems which in toto are considerably longer. Some of these are compared in Table 2 below.

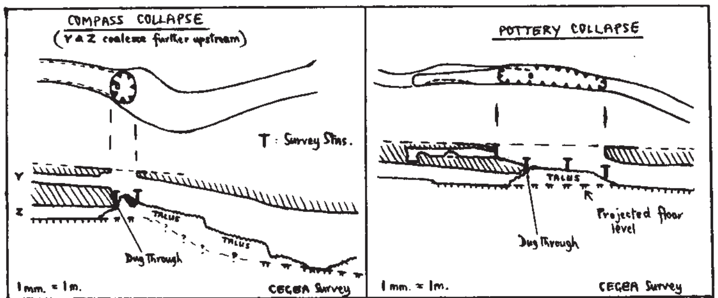
List of the World's Longest Lava Tube Caves

The list which follows is only as good as the data which I received from all over the world. Numerous changes have been made from past lists, and future editions will undoubtedly reflect more additions, changes, and corrections. Kazumura and Upper Leviathan caves are both incompletely mapped, so changes in the ranking of the "top three" may be expected. It is likely, however, that Upper Leviathan Cave will retain its position as deepest known lava tube cave for some time. The position of Catacombs Cave at the bottom of the list is probably permanent, unless new passage is discovered.

Sources of length data and published maps:

1. Ogawa, 1982 (length); map.
2. Wood, 1981 (map, length, and depth).
3. Simons, personal communication, 1982; map not yet available.

LEVIATHAN CAVE, CHYULU HILLS, KENYA



COLLAPSE HOLE DIMENSIONS (metres)	Compass Collapse		Pottery Collapse	
LENGTH (Parallel to passage direction)	6 m.		26 m. (Total)	
WIDTH (⊥ to passage direction)	7 m.		3-5 m. (Av. 4m)	
DEPTH : Maximum to projected floor level	11 m.		9 m.	
: At dig 'bottoms'	9 m.	Av. 7.3m.	6.5 m.	Av. 6.5m. & 5.6m.
: Highest points on talus	5.5m.		3 & 5 m.	
: Below downstream edge of collapse (i.e. lowest point on talus)	7.5 m.		8 m.	

Figure 3. Leviathan Cave collapse dimensions (drawn by Jim Simons).

4. Wood and Mils, 1977 (map, length, and depth).
5. Favre, personal communication, 1982. Map on file, unpublished.
6. Montoriol, Romero, and Montserrat, 1980 (map, length, and depth).
7. Ogawa, personal communication, 1982; map not yet available.
8. Crawford, 1980 (recalculation of length); map.
9. Halliday, 1978 (length, depth); map.
10. Green, 1976 (map, length); 1978 (depth).
11. Nieland, 1975 (map, length, and depth).
12. Montserrat, personal communication, 1981; map on file, unpublished.
13. Montoriol and de Mier, 1969 (map, length, depth of system). Only longest segment listed here.
14. Wood, 1986 (map only). Length given here is estimated from map; when known, true length will be greater.
15. Crawford, 1975 (composite length and depth); only partial maps are available.
16. Ireton, personal communication, 1978.
17. Crawford, 1982 (re-calculation of length, map).
18. Ogawa, personal communication, 1982. Map on file, unpublished.
19. Vance, 1978 (map, length).
20. Simons, personal communication, 1982. Map not yet available. This is the section of cave below Pottery Collapse.
21. Peck, 1976 (map, length).

Concluding remarks:

The study of the world's lava tube caves has hardly well begun. Most volcanic areas have not even been checked by cavers. Even the best-studied areas will, undoubtedly, yield additional caves that qualify for this list. Several of the caves listed here are certain to be extended by further exploration. I encourage all cavers living in or near volcanic areas to explore and map their lava tubes, to adhere to the international standards, and to communicate the results to me for inclusion in future editions of this list.

Simons (1978 and in litt.) has suggested the formation of a separate list of longest lava tube cave systems, where caves divided by collapse would be added together. I am unable to undertake such a list myself, but offer my support and encouragement to anyone who feels sufficiently energetic and meticulous to do so. Much presently unpublished data would have to be gathered to even make a start. Such a listing would have to set standards of its own, answering questions such as: Would collapse trench be counted in the length, or only intact passage? If the former, it would be hard to beat the 28,500 m Bandera Crater Lava Tubes in New Mexico (Hatheway and Herring, 1970). Would a system consist of caves separated by collapse only, or would systems segmented by lava seal or breakdown choke, necessitating return to the entrance and overland treks, be included? Would cave segments so short that they individually would not qualify as true caves, be counted in the length? and so forth.

Discussion:

Giuseppe Licitra (Sicily) remarked that he prefers to consider systems segmented by collapse as single caves, but systems segmented by lava seals as separate caves. My reply: this standpoint may well be defensible scientifically, but if everyone adheres to their personal opinions and ignores the international standards, no cooperative length ranking will be possible.

Takanori Ogawa (Japan) corrected my length figure for Bilemot Gul. The original figure of 12.4 km did have a source, but much recent searching has failed to disclose it. Ogawa's figure may be considered authoritative.

Fred Stone (Hawaii) pointed out that the cave measurement standards presented here need further refinement. He mentioned cases where the survey line zigzags from wall to wall; where a collapse entrance has a significant overhang, or a floor is deep at one end and shallow at the other; or where cavers might excavate an originally shallow collapse pit until its depth exceeded its width. I agree that these and other problems need to be addressed; nonetheless, these standards are far better than the chaos we had before, and hopefully, Chabert and his commission will continue to work on them.

Acknowledgements

I thank all the cave mappers from many countries who have contributed data for this and previous editions of this list, most of whom are cited by name above. Over and above these, I owe a special vote of thanks to Bill Halliday, who assisted greatly in compiling the data and made most of the international contacts that made such a list possible.

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A SCIENTIFIC RATIONALE FOR VULCANOSPELEOLOGY

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Vulcanospeleology is the exploration and scientific study of caves in volcanic rocks. It is a recently developed branch of speleology, born from the worldwide eagerness of cavers to search for new caves, even in apparently unlikely places, far from any outcrops of soluble rock. Some volcanic caves have been known and explored for centuries, but only in the last 20 years has there been a serious undertaking to prospect for, explore, and scientifically study caves in the world's major volcanic provinces. This short experience has shown that there is a remarkable assemblage of caves in volcanic rocks, the principal forms being vents and pits, cracks, and lava tube caves. Cavers have also come to learn that it is the basaltic terrains that contain the greatest abundance of large cave forms.

Exploration and mapping activities by specialist caving groups, such as the Cascade and Oregon Grottos of the NSS, the Cave Exploration Group of East Africa, Gruppo Grotte Catania, and others, have contributed to the considerable growth in knowledge regarding the forms and occurrences of volcanic caves. Professional geologists, on the other hand, until very recently, looked upon volcanic caves merely as curiosities. That was until the need arose for terrestrial analogies of the volcanic landforms of the lunar surface, and eventually of the surfaces of the other inner planets of the solar system. Sinuous rills were thought to have probably originated from lava tube collapse, and this stimulated research into the geology of terrestrial lava tube caves, and subsequently, into the processes of lava tube construction and operation as observed for the first time in detail during the 1969-74 Mauna Ulu flank eruption of Kilauea Volcano, Hawaii. Other scientists participating in the program of observations of the Mauna Ulu activity were, in turn, struck by the importance of lava tubes in transporting fluid lava to sites distant from the vent, and by the apparently important role played by lava tubes in the building of Hawaiian-type shield volcanoes. Unfortunately, other volcanic caves have not stimulated as much professional interest. But as time goes by, more and more local geological problems are being solved by exploration and careful study of vents, pits and cracks. Thus, vulcanospeleology has progressed by means of steady amateur study, and by means of a series of coincidental scientific discoveries which have drawn in professional earth scientists.

It is now time to take stock of our position — to ask what has been learnt in 20 years of volcanic cave study, and to point out to cavers the goals to be pursued within a comprehensive scientific framework. The components of this framework are listed below.

1. Basalt, and other cavernous volcanic rocks, cover a larger surface area of this planet than any other rock type, and in these volcanic terrains (including ocean floors), caves are large, abundant, and diverse landforms, worthy of study in their own right.

Outside of caving circles, few realize just how extensive, diverse and abundant volcanic caves are. We need only to cite a few examples here to illustrate this point. There are lava tube caves in Korea and on Hawaii Island that range up to 12 km in length, but these are just isolated segments of caves which may ultimately be found to be 20 or 30 km long (certainly this is probable on Hawaii). On mainland USA, collapsed lava tube caves are known to extend for 40 or 50 km (Green and Short 1971), while a partly cavernous lava tube originating from the Undara Volcano, North Queensland, may have had a length in excess of 100 km (Atkinson, Griffin and Stephenson 1977)! The lava tube cave, Cueva del Viento, Tenerife, is a three-dimensional passage maze, as complex as any limestone cave (Wood and Mills 1977), and Dynamited Cave, Washington, contains significant vertical development (Halliday 1963). The world's largest natural pits are volcanic (for example, Trou au Natron in the Tibesti Mountains, North Africa, has a depth of 1,160 m), while a number of the world's great volcanic rifts (for example, the Great Rift of Idaho, and Hawaiian rifts) may eventually be descended to depths of hundreds of meters. Even exogenetic forces have formed caves of significant length and depth in volcanic rocks, as exemplified by the 214 m cavern complex of Officer's Cave, Oregon (Parker, Shown and Ratzlaff, 1964), while endogenetic caves are known to exist on the ocean floors. Of particular importance, caves are not an isolated phenomenon in volcanic terrains, and in basalts especially, there is a group of cave-related landforms (collapse dolines, natural bridges, gorges, sinks, etc.), forming a distinct non-solutional, karst-like geomorphology.

2. The study of volcanic caves, and the landforms derived from them, help to explain landforms on the surfaces of the other planets.

Extra-terrestrial landforms cannot be studied on the ground, but terrestrial equivalents may provide the necessary insights into the evolution of such landforms. Terrestrial volcanic terrains, such as the Snake River Plain, Idaho, appear to be directly analogous in surface morphology to many volcanic regions on the Moon, Mars, Mercury and Venus (Greeley, 1977), while the Hawaiian shield volcanoes appear to be comparable with the great lava shields of Mars. Mention has already been made to the belief that sinuous rills are collapsed lava tubes (see, for example, Greeley 1972), and rifts and pits are being examined to provide insights into comparable extra-terrestrial landforms (as in Greeley 1977). More important, as will be explained later, tube-fed lava flows may have played a fundamental role in the development of plains and shields on earth, and by implication to have been an important process in the formation of comparable parts of the surfaces of the other inner planets.

3. Exploration of pits and cracks reveals details of the internal "plumbing of volcanoes, and aids an interpretation of their deep stratigraphy.

The exploration of volcanic pits, vents and cracks is exceedingly dangerous because of the fragile nature of the wall rock, but it provides the volcanic caver with the opportunity for vertical exploration, and it can provide solutions to problems of the local geology which cannot be discovered on the ground surface. Much is now known about the geology of the Great Rift, Idaho, partly because it is examinable in all three dimensions (King 1977). This author, amongst others, has descended smaller rifts, vents and hornitos on Mt. Etna, Sicily, in order to solve specific problems relating to the local stratigraphy (Wood 1976). Others have described in this symposium the descent of a pit in the Ka'u Desert, Kilauea Volcano, Hawaii. This pit, and others on Hawaii Island, display a stratigraphy ranging over hundreds of meters in vertical extent, a thorough examination of which would reveal much about the various styles of eruption which have built up this volcano.

4. Detailed mapping of cave groups in specific lava flows enables the eruptive history of the flow to be worked out.

This author has undertaken two very successful studies of this nature. In an investigation of the small, monocyclic lava shield of Gullborg, Iceland, (Wood 1978), analysis of lava structures, and surveyed relationships between the lava tube caves, open lava channels, and major flow units enabled an interpretation of the genetic history of the volcano to be made. Similarly, in a collaborative study of the unusual 1614-24 lava flow, Mt. Etna, with R. Greeley and J.E. Guest (Wood 1978), he surveyed relationships between the lava tube caves and large terraces in the flow, providing details of their relative ages and the order of terrace formation.

5. Equilibrium flow of liquid lava through a lava tube may be a reason for the formation of long lava flows on minimal slopes, and thus for the development of basaltic plains and shields.

Geologists were much enlightened about the construction and operation of lava tubes following observations of the 1969-74 Mauna Ulu flank eruption of Kilauea Volcano, Hawaii. Amongst other things, these observations revealed that the lava tubes developed during this activity were highly efficient transporters of liquid flow, for the original temperature and mobility of the erupted fluid were only slightly reduced, even after flowing through more than 12 km of lava tube (Peterson and Swanson 1974). In a later study of lava tube systems, based upon the morphologies of lava tube caves (Wood 1978), this author also emphasized the efficiency of tube-fed flow, and drew attention to the similarities between the channel forms and activities of lava rivers and water rivers. It was proposed that, although this efficiency may be due in part to the low thermal conductivity of the cooled basalt rock, an important factor might be that, like a water river, a lava river may possess the capacity to adjust its channel, through erosion and deposition, in a direction that minimizes thermal and mechanical energy losses.

As this author has previously pointed out (Wood 1978 and 1981), the proposal implicit in these studies — equilibrium flow through a lava tube system — is far-reaching, for it infers that the tube-fed volcanic process may be a reason for the apparent anomaly of very long flows emplaced down minimal slopes. In theory, accumulations of these flows would form a low-angled lava shield if they were erupted from a single vent, or form an expansive lava plain if erupted from multiple vents. Indeed, it is well known that basaltic plains, such as the Snake River Plain, contain extensive lava tube caves on very low slopes, while studies of the Hawaiian shield volcanoes (Greeley, Wilbur and Storm 1976; Holcomb 1980; Wood 1981) have shown that lava tubes are very abundant, with many developed on slopes of a little as 1-1/2° (for example, this is the mean gradient of Kazumura Cave).

6. Studies of the discharge of liquid lava through a lava tube system may enable future calculations of the rate of effusion, or the duration of a dated vent effusion, to be worked out.

This author surmised in his previous paper in this symposium that if it could be established that certain passage forms in lava tube caves formerly transported full-bore flow, and subsequently drained off all the fluid fill, then it should be a relatively simple matter to estimate the mean discharge of the tube. Such a figure for a known tube would be most useful, and together with an estimate of the volume of the lava flow emplaced, a calculation of the duration of the effusive vent activity is possible. Similarly, if the period (duration) of the activity is known, it would be possible to calculate the mean rate of effusion from the vent. These obviously would be tentative figures, but they would be invaluable to a geologist attempting to understand the overall history of a particular effusive period of a volcano.

The biggest problem is the identification with certainty of tubes which carried full-bore flow, and which drained completely. This author believes that circular, or sub-circular, conduit-like passages, with or without conical ceiling stalactites, such as the passages making up parts of Kazumura Cave and Ainahou Ranch Cave, Hawaii (Wood 1981), are of the type necessary for this calculation.

*7. **Future knowledge of the formation and operation of lava tube systems may be a key to predicting the behavior of dangerously active lava flows.***

There have been attempts in the past to divert dangerously active lava flows by aerial bombardment, or through the construction of barriers in advance of the flow front. Wentworth (1954) considered why such attempts were not a great success, and modern knowledge of the morphology of active lava tube systems, gained principally from cave evidence, adds further insights into the behavior of active tube-fed lava flows.

On the basis of his own researches into lava tube caves, this author has proposed (Wood 1978) that an ideal lava tube system, feeding a simple tongue-shaped lava flow, or flow unit, comprises four morphological elements: (1) a long, sinuous, partly braided main feeder tube lying along the axis of the flow; (2) lateral complexes of smaller tubes, which transport liquid flow only when surges from the vent cause the axial feeder to overflow; (3) tube complexes overlying the axial feeder, left vacant because their flow has been captured by the underlying tube; (4) a delta-like region of smaller distributary tubes at the flow front. Elements 1 and 4 are common to all systems, while elements 2 and 3 may or may not be present.

This author proposes that this system behaves as follows: the axial feeder tube is an "adjusted" or equilibrium form, through which fluid lava is conveyed between the vent and the flow front without significant loss of heat energy or mechanical energy. At the flow front, where the velocity of the fluid passing out of the axial tube is checked, as a result of rapidly increasing energy losses, the stream rapidly agrades, dividing and subdividing into a myriad of smaller distributary tubes and channels, feeding lava to a broad delta-like front. It appears that as the lava front advances, the axial feeder tube elongates across earlier formed frontal deltas. The mechanism for this elongation is not known, though it is clear that very few of the vast number of distributaries of the older deltas are utilized, for competition between routes must cause most to clog, and the mobile fluid to be concentrated along the flow axis.

A more detailed description of this model is provided by this author elsewhere (Wood 1978), but this synopsis points to two important implications.

A. The model now shows that there is little benefit in attempting to divert dangerously active tube-fed flows, unless fluid can be drained away from the axial feeder.

B. Comparison with the work by Bates (1956) on water river deltas, suggests that the lava emerging from the end of an axial tube, at the front of an active pahoehoe flow, may be likened to a jet flow. Thus, the development of pahoehoe lava flows may be predictable and amenable to future quantification through the application of jet theory.

*8. **Studies of wildlife in lava tube caves aid the development of models of cave life evolution.***

Although the author is not a cave biologist, he recognizes that there are certain advantages to studying wildlife in lava tube caves, particularly caves situated on isolated oceanic islands. Howarth, for example, has shown that the rapid speciation of faunas in the Hawaiian caves holds important clues to the interpretation of the evolutionary process.

(References not received)

PERPLEXING FEATURES OF LAVA TUBE CAVES IN SEMI-ARID REGIONS OF THE WESTERN UNITED STATES

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ABSTRACT

Recent volcanism in the western United States has created impressive landforms. Most are explained, but some have escaped attention because of their scarcity and/or remoteness. These include apparent speleogens found in lava tubes of semi-arid parts of Oregon. These unusual forms have been speculatively termed speleogens, speleothems, etc. They have been explained as the result of steam pockets, erosion, kaolinization, and even as phreatic forms (the latter for their remarkable resemblance to similar forms in solution caves). This presentation will draw attention to these features, hopefully resulting in an explanation of these vulcanospeleological oddities.

The strange rock forms described herein first attracted the attention of Oregon Grotto members in 1967, following visits to the Saddle Butte Lava Tube System in southeastern Oregon. At that time, new and undescribed features in lava tubes were quite commonly encountered; vulcanospeleology was young. So beyond noting that they resembled genetic features of solution caves, little further attention was paid them. Then in 1974, Burns and Rattlesnake caves were examined and it became apparent that some geological process was altering the interior of these caves in a highly unusual way (see Figure 9). A year later, upon examination of Raven Pit Cave and latter the Kitty Pooh caves (and others), it became obvious that the unusual forms first observed in Baker, Owyhee River and Tiretube caves in 1967 were present throughout the system.

In Raven Pit (see Figure 1), nearly all the ceiling and wall surfaces are modified by weathering and the floor is blanketed with fine grain weathering products, probably several feet deep locally. It was there that it was first observed .that the weathering process was not limited to cave interiors. Raven Pit is a fairly well ventilated cave (there is a skylight in addition to a large entrance), and the weathered surfaces are distributed more or less evenly throughout and also in the walls of the adjacent collapse trench for a considerable distance outside the cave.

Figure 1. Eroded walls in Raven Pit Cave. Note the products of erosion on the floor.

Figure 2. Eroded basalt far inside Raven Pit Cave.

Following study of Raven Pit Cave, enough was known about subterranean weathering in the cave system to predict the existence of hollow breakdown blocks (had anyone cared to). In 1980, in a hitherto unknown branch of the system, two caves were found which contained even more bizarre shapes, including hollow breakdown blocks (see Figure 4). Two significant variations were found there, as well: (1) shapes which retain no pre-weathering surfaces or reveal any relation thereto (see Figure 5); and (2) honeycomb or anastomotic patterns which suggest differential weathering along some sort of control plane (see Figure 6).

With one or two exceptions mentioned below, until 1982, all recorded observations of the weathered forms were limited to the Saddle Butte caves. In 1982, examples of the same sort, including the honeycomb variety, were identified in the Benjamin Lake Caves about 120 miles west of Saddle Butte and

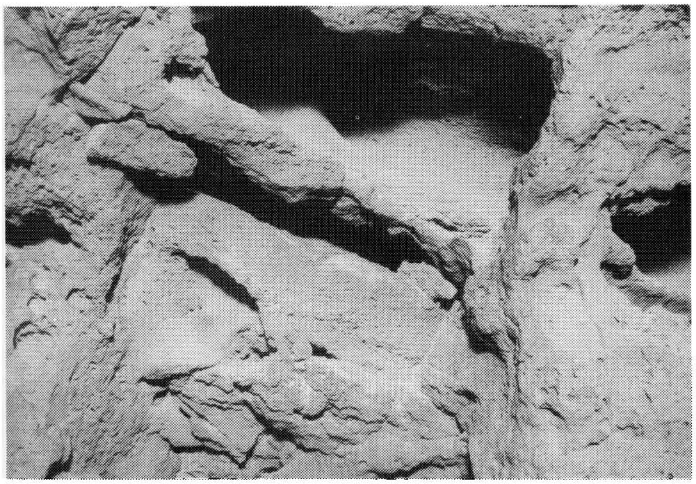

Figure 3. *Weathering recesses in wall inside Derrick Cave, Devils Garden lava flow, Newberry volcano, Oregon. Note penny at center for scale.*

Figure 4. *A hollow breakdown block. Interior was eroded away. Thunder Cave, Saddle Butte Lava Tube System, Malheur County Oregon.*

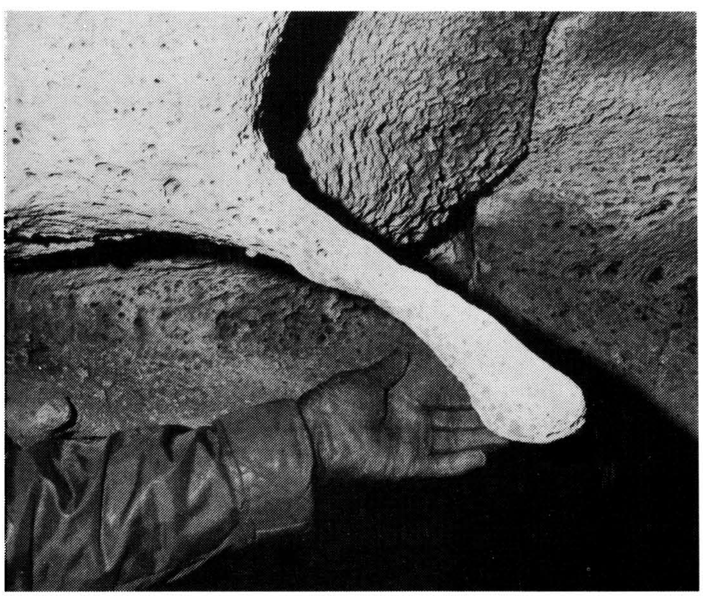

Figure 5. *A basalt projection remaining after surrounding material was removed by weathering. Often the resulting shapes indicate control by contraction cracks, or grain (direction of flow). Thunder Cave, Saddle Butte System.*

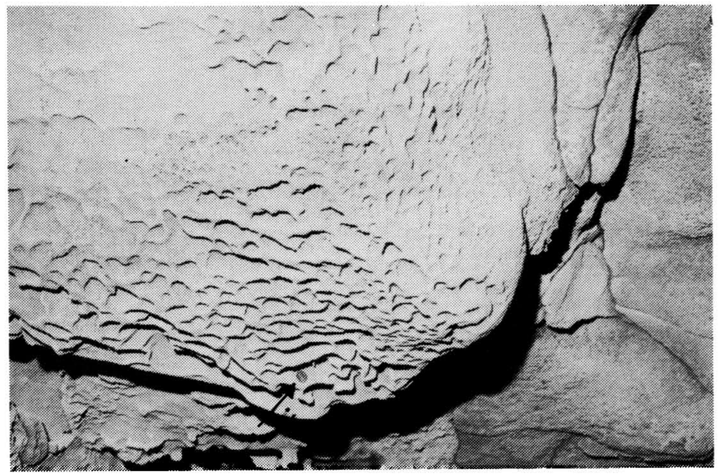

Figure 6. *Weathering of the ceiling leaves anastomotic pattern of many small pockets, Thunder Cave, Saddle Butte System, Oregon. Note penny, lower center, for scale.*

Figure 7. *Growth of crystals (probably gypsum) are wedging small shards of basalt off the ceiling in Lost Blowing Hole Cave, Saddle Butte System, Oregon. Note paper match for scale.*

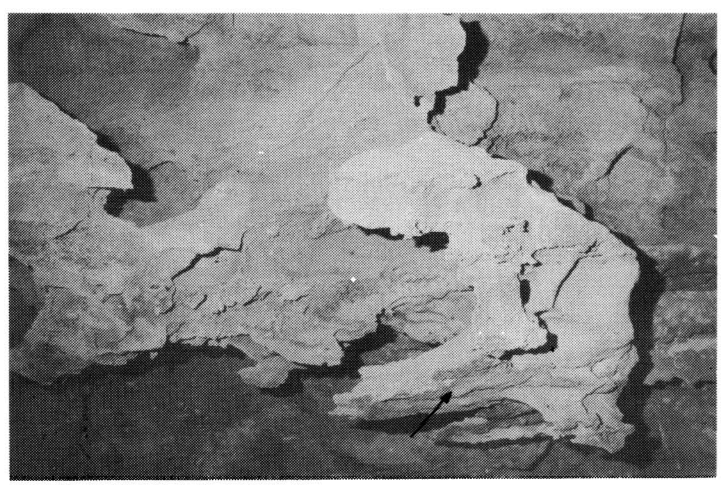

Figure 8. *Pendant remnant of weathered basalt outside the wall of Thunder Cave, Saddle Butte System, Oregon. Small patch of primary tube lining remains at lower right (see arrow).*

Figure 9. "Free standing" contraction cracks inspired the name Boxwork Room, in Rattlesnake Cave No.2, Saddle Butte System, Oregon. Weathering has removed as much as 2 feet of cave wall, leaving blades about one inch thick adjacent to contraction cracks. Blades projecting 26 inches from the wall (just above center left of this photo). Rattlesnake Cave, Saddle Butte System, Oregon.

in Derrick Cave, not far from Bend, Oregon. Also, there are similar forms in the Arnold System caves just outside Bend (Greeley 1971), in Horse Cave on the outskirts of Bend, and in Redmond Cave a few miles north. Examples have been found, in fact, in most lava caves east of the Deschutes River in Oregon.

Speleological literature regarding these forms is practically non-existent. The earliest extant observation is a brief 1962 description in Oregon Speleological Survey files of a "smooth sponge-like rock" in Horse Cave just east of downtown Bend.

There is as yet no satisfactory name for these weathered forms. In the abstract, I referred to them as "apparent speleogens," but now conclude that term is misleading. They are not, as some contemporary definition and usage of the term "speleogen" implies, an original feature of the cave boundary. In most cases, some small parts of the original cave boundary are retained, but for the most part, they are as different from the original cave boundary as are speleothems. Also, it may be that the prefix "speleo" itself is inappropriate because these forms are to be found outside of caves; for example, in the walls of collapse trenches and elsewhere on basalt faces protected from rainfall, for example in the walls of Crack-In-The-Ground adjacent to the Four Craters Lava Flow. "Petromorph" has been suggested, but contemporary definitions of that term, while contradictory, most often distinguish between the subject material and bedrock in which the cave formed. Until a better term evolves, I will refer to them as "weathered forms."

It now appears likely that most of the sediments in the Saddle Butte caves are the product of decomposition and disintegration of the basalt — weathering — and, to a lesser degree, tephra. Also, it is probable that most of the geologically recent breakdown is induced by weathering, and consequently, very insidious. Progressing west, into the ash shadow of Mount Mazama and other more recent volcanism, tephra probably predominates in cave sediments, though subterranean weathering products are present.

The forms described herein appear to be the result of weathering; physical disintegration and chemical decomposition, and may be related to hydration and transpiration by and of capillary groundwater over long periods of time. Requisite long periods of time would explain the seeming resistance of exposed boundaries of discrete blocks of basalt (see Figure 9) which, though occasionally drenched by rain waters, quickly dry in the caves' uncharacteristically low humidities. (On the other hand, there is a possibility that rainwater removes some constituent of the basalt adjacent to the exposed surfaces, causing the seeming resistance to attack.)

Contact with groundwater-bearing strata seems to be a requisite (e.g., hollow rocks are found only in contact with the floor fill, never in well aerated, isolated positions such as piled loosely atop other rocks). The transpiration of groundwater theory is further strengthened by:

1. The similarity of the weathered forms regardless of position, whether far inside caves or exposed to freezing temperatures (though sheltered from rain) in an adjacent collapse trench.

2. The process seems more active in basalt which is highly vesicular, a condition which improves its porosity.

3. No indication of seasonal variation has been found.

4. To date, the weathered forms in caves have been found only in arid climates where the caves have uncharacteristically low humidity (in the 50-60% range), a condition favoring transpiration. In and west of the Cascades, where rainfall is far heavier and cave humidities are typically at or near 100%, secondary minerals (principally silica) are deposited, but no weathered forms have been found.

The weathered forms described in this paper are located east of the Cascade Mountains in the State of Oregon. If it were not for the outstanding examples found in the caves of the Saddle Butte Lavatube System, their relative abundance might have escaped attention far longer. Surely similar examples of spelean weathered forms exist elsewhere. Hopefully, this paper will stimulate additional study.

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LAVA STALACTITES: TERMINOLOGY, SHAPE AND POSSIBLE ORIGINS

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A number of different shapes of lava stalactites exist, and the different shapes are readily seen to reflect different origins. Five types are identified and discussed herein, and additional types undoubtedly exist.

Due to the difference in origin, it is important to recognize the different types of stalactites in studies of lava tubes. Terminology must be standardized, or detailed descriptions given, in order for those who study lava tubes to communicate clearly with one another. These five types of lava stalactites are:

1. Common stalactites, remaining relatively unmodified from separation of the roof crust; sometimes called stretched stalactites.
2. Remelt stalactites.
3. Lavacicle stalactites (type locality is Lavacicle Cave, Oregon).
4. Spatter stalactites.
5. Candle-dip stalactites.

For purposes of this paper, the controversy of whether forms that are non-solutional can properly be termed "stalactites" is dismissed as unsubstantial.

Common Stalactites:

These are lava drips that remain from the initial separation of the roof crust from liquid lava below. Since such drips can be expected any time that solid lava (above) separates from liquid lava (below), they are conceptually the commonest form of lava stalactites. The surface includes many vesicles, and is characteristically quite rough.

Remelt Stalactites:

Lava stalactites, or drip pendants, are lava drips that result from remelting of the ceiling surface. They are distinguished from common stalactites in that the individual stalactites are more clearly shaped. The surface is also smoother, and has less vesicles. Very few vesicles appear on the glazed surface of mature pendants. Modification of common stalactites by remelting results in drip pendants. Drip pendants can also form as a result of remelting of other lava surfaces, such as casts or broken faces. Remelt stalactites are tapered and have roughly pyramidal bases. Thoroughly remelted surfaces trap vesicles behind the remelted layer. The gas pressure builds up until it is able to blow off the soft remelted layer, making blowout pockets. Blowout pockets are also known as "pull-offs."

Lavacicle Stalactites

Lavacicle stalactites are generally cylindrical in shape or only slightly tapered, with little or no widening at the base. They resemble soda straws, and occasionally have "lava helictite" forms. Lavacicle stalactites are typically less than one inch in length, but have been reported up to several feet in length. The term "lavacicle" appears to have been coined by Phil Brogan of Bend, Oregon in about 1923, and (according to him) was intended to pertain to both stalactites and stalagmites.

Lava stalactites of this variety were described by Dana (1889) and his description included drawings showing concentric rings on the outside of the stalactites. Dana offered no guess as to the origin of the rings, which he termed "transverse markings." A similar modern study of lavacicle stalactite mineralogy by Baird (1982) refers to growth rings," but offers no elaboration. The author asked Baird at the formal presentation of Baird's paper what the origin of the growth rings might be, but Baird insisted he had "no idea." Longitudinal grooves, as well as concentric rings, have been observed on the outside of lavacicle stalactites. Although he does not mention the rings or grooves, Perret's posthumously published book (1950) states that this type of stalactite is ". . . in part, at least, gas-impelled . . ."

Independently, and before knowledge of Perret's view, J.W. Harter III and the author concluded that lavacicle stalactites:

1. Are extruded by expanding gas bubbles.
2. The concentric rings represent minute pauses as the stalactite is extruded.
3. The longitudinal grooves, and slight tapering (increase in diameter toward the base) remain from the extrusion process.
4. Grow at the base, rather than at the tip.
5. Are not surface remelt phenomena.
6. Have "roots" extending up into the ceiling.

Also independently, Lawrence Chitwood concluded, after study of the stalactites in Lavacicle Cave, that they were extruded, and that there are small cavities in the roof above lavacicle stalactites.

Lavacicle stalactites form stalagmites below them when lava drips to the floor. The stalagmites formed below lavacicle stalactites are composed primarily of bubbles of lava with large vesicles. By contrast, stalagmites formed under remelt stalactites are much smaller in size, and are composed primarily of solid lava drips. If they do not adhere to the floor, the lava drips can sometimes be found unattached. Unattached lava drips, incidentally, may be more rare than calcite cave pearls in limestone caves and they are similarly susceptible to theft.

Spatter Stalactites:

Spatter from molten lava that accumulates on the underside of a roof or other overhang can collect and drip, making stalactites. These stalactites are typically irregular and lumpy. They are found inside spatter cones, as well as in lava tubes.

Candle-Dip Stalactites:

These stalactites are larger in diameter and more massive than those described above. When a broken one is seen in cross section, it is found that the stalactite is built up of alternating layers of lava and large gas bubbles. The lava layers sometimes have a thin rind on the outer side from remelt. The candle-dip stalactites are named such because they appear to form by the lava level rising and falling repeatedly, coating the stalactites. The process is similar to candle-making where thin layers of wax are repeatedly added by dipping the candle into molten wax. Candle-dip stalactites are comparatively unusual. The author knows of two localities at Diamond Craters, Oregon, and one at Pisgah, California. In the caves at Diamond Craters, the candle-dip stalactites are in chambers that did not have large amounts of through-flowing lava. In the one cave at Pisgah, the candle-dip stalactites are located on one wall of a passage that had through-flowing lava.

DISCUSSION

Dr. William R. Halliday pointed out what might be considered an additional type of lava stalactite. Blade or ribbon-shaped stalactites have been noted in Lake Cave, Washington (Halliday 1963).

Donald Peterson and Lawrence Chitwood each expressed the opinion that candle-dip stalactites should not form in lava conduits, since they would be swept away by the flowing lava.*

Giuseppe Licitra expressed the opinion that volcanic gas emitted from lava as its flows cannot be hot enough to remelt the walls and ceilings of a lava tube. He said that remelt is evidence of combustion.

*Editor's note: They are present in the Lava Bridge System, Klickitat County, Washington, which contains other features typical of lava conduits..

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FORMATION OF LAVA CAVES IN JAPAN AND KOREA

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ABSTRACT

This paper consists of qualitative considerations of lava cave formation on the basis of interior observations of lava caves in Japan and Korea. The observations suggest that most lava caves are composed of unit caves, and cavities formed by floor flows with sinking. Each unit cave consists of gas bubbles that formed under cool skins of lava.

The lava cave formation theory proposed here can be explained in terms of rheological properties of lava flows and mixed phase flows in lava flows. In this theory, plasticity of lava is necessary for morphological maintenance and vertical development of lava caves. In addition the gases, the liquid, and the semi-solid lava in the mixed phase flows area regarded as volatiles in lava, molten basaltic lava and crusts of lava, respectively. It is considered that there are two main modes of lava cave formation. One is formation due to coalescence of unit caves in Newtonian lava flows. The other is formation due to floor flows with sinking in Bingham plastic lava flows.

1. Introduction

In this paper, the author proposes a mechanism of formation of huge lava caves such as Manjang-Kul (Lava Cave) on Cheju Island in Korea. When a huge cave is formed it is difficult to believe that the whole cave is formed instantaneously. Moreover, it is important to know how morphology is maintained in a cave which is in molten lava. It is necessary to discuss these problems when lava cave formation is considered more generally.

Theories of lava cave formation which have been proposed to date do not deal clearly with these considerations. It is apparent that in those theories, mixed phase flow of lava and rheology of lava area not considered simultaneously. Ogawa (1980) deduced from interior observations of lava caves that most of them are complexes of many smaller cavities. This is important in development of hugh lava caves. But in his report, a clear explanation of the mechanism was not made systematically. Moreover, contrary to his inference, it can be observed in Japan and Korea that a lava cave can be reformed as a single cavity.

The purpose of this paper is to describe qualitatively the formation mechanism of a lava cave in a closed system based on interior observation of lava caves in Japan and Korea. A closed system is defined by the presence of large gas bubbles in molten lava, out of contact with the atmosphere and the ground during the formative stage of lava cave development. These large gas bubbles are named unit caves in the sense that a larger lava cave is composed of many large gas bubbles.

As mentioned above, it is assumed in this paper that lava flows are the mixed phase flow, and the development of unit caves depends on the rheology of lava flows.

2. Interior observations.

Features illustrating the formation of lava caves are demonstrated by photographs taken inside lava caves in Japan and Korea.

Figure 1.

2.1 The mixed phase flow in lava flows.

The cross section of lava caves is worth notice because it is reminiscent of the motion of underwater gas bubbles.

Fig. 1 shows the example of a large circular cross section in Suisan-Kul (Lava Cave) on Cheju Island in Korea. This type of cross section is rare in Japan and Korea.

Fig. 2[1] shows a semicircular cross section in Mitsuike-Ana (Lava Cave) at the foot of Mount Fuji. This type of cross section is observed widely in Japan and Korea.

Fig. 3[1] shows a "shell-shaped" cross section in Megane-Ana (Lava Cave) at the foot of Mount Fuji. It is rare that this type of cross section is observed in Japan and Korea.

Fig. 4[1] shows a dome-shaped space, Banba-Ana (Lava Cave) at the foot of Mount Fuji.

Fig. 5[1] shows lava stalactites which all are bent in one direction, in Mujina-Ana (Lava Cave) at the foot of Mount Fuji. This suggest that gas passed through the lava cave when the lava stalactites had not completely solidified. In other words, the cave was filled with gas during this stage of lava cave development.

Fig. 6 shows a lava cave with a semicircular cross section. It was formed parallel to Yoshida-Tainai Lava Tree Mold at the foot of Mount Fuji. It seems that a tree mold was the source of gas supply to the lava cave.

From all this, it seems to suggest that gas in lava flows plays a very important role in the formation of lava caves. That is to say, some lava flow should be considered as a gas-liquid two-phase flow.

2.2 Lava flow lines.

Fig. 7 shows a very large cave wall in Manjang-Kul (Lava Cave). Judging from

[1] Editor's Note: This illustration could not be reproduced with adequate clarity for this publication.

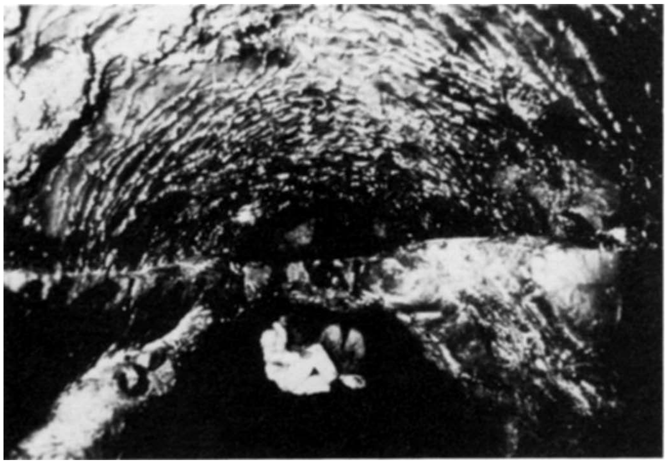

Figure 6

the morphology and the scale of the cross section, the wall seems to be influenced by factors different from the action of gas in lava flows. Fig. 8[1] shows lava flow lines on the side wall in Hundle-Kul (Lava Cave) on Cheju Island. Lava flow lines are not observed on the ceiling, but are observed on the side wall. This phenomenon is observed widely in Japan and Korea. From these facts it can be considered that formation of lava caves in a closed system is composed of two main modes.

2.3 Crust on the inner cave wall.

According to my observations of roof collapse and wall collapse in lava caves, there are some cases where something like a cave lining (termed *crust* here) is observed on the inner cave wall.

Fig. 9 [appearing as photo #24 in the accompanying paper by T. Ogawa] shows the crust on the ceiling in Mitsuike Ana (Lava Cave). Layered lava is observed on the right side. The crust is one thing, and the cave lining another. The crust is formed during lava cave formation. On the other hand, the ceiling is formed when lava caves serve as conduits for subsequent lava flows.

Fig. 10 shows crust on the side wall in Manjang-Kul (Lava Cave). From these two examples, it is considered that the morphology of the lava cave in a closed system is maintained by the crust.

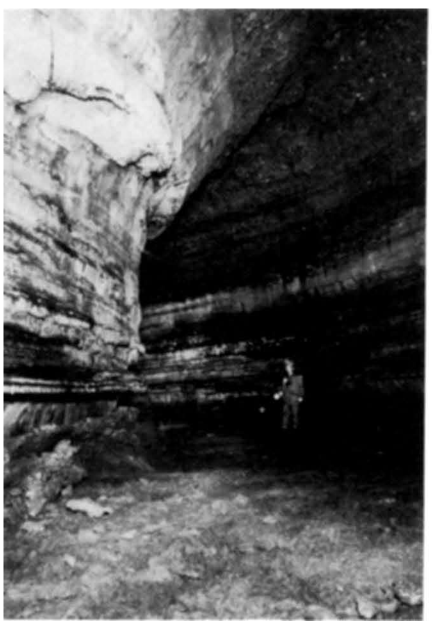

Figure 7.

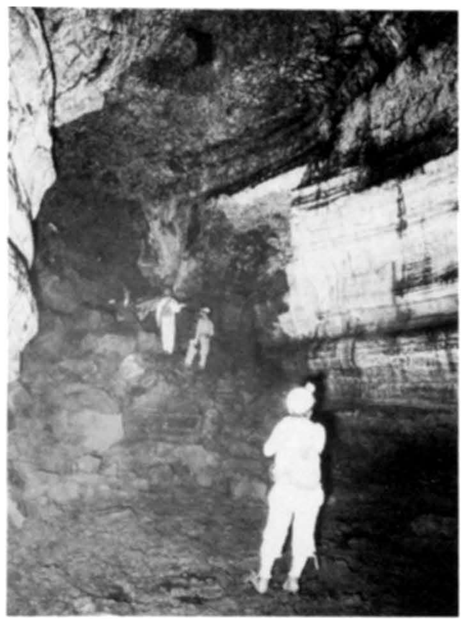

Figure 10.

Figure 13.

Figure 12

Fig. 11[1] shows crust with columnar joints in Megane-Ana (Lava Cave). Most of the joints in lava flows result from the strain that arises in the rock during cooling (Mcdonald and Abbot 1979). On the other hand, columnar joints cannot be observed in the crust on the inner cave wall. From this fact, it is considered that the crust on the inner cave wall is formed by another reason, different from the temperature difference.

2.4 Interconnection of unit caves.

Following the initial level of the lava flow lines visually, numerous discontinuous points of initial lava flow lines can be observed. The discontinuous points are the interconnection points of unit caves.

Fig. 12 shows interconnection points in Manjang-Kul (Lava Cave). The initial floor level of the rear unit cave is A, and that of the front unit cave is B; the level B is higher than A. When the floor level B sank to level A, these unit caves interconnected. This phenomenon seems to be very important to explain lava cave formation.

Fig. 13 shows scratch marks on the ceiling at the interconnection point in Manjang-Kul (Lava Cave). This photograph also supports the concept of floor flow with sinking.

3. Formation mechanism of lava caves.

It is reported (Sparks and Pinkerton 1978) that basaltic lava which, on eruption behaves as a Newtonian fluid will change to a Bingham plastic fluid. Moreover, the development of gas bubbles in each fluid will be described by using the concept of mixed phase flow that is widely observed in the field of chemical engineering and hydraulic engineering.

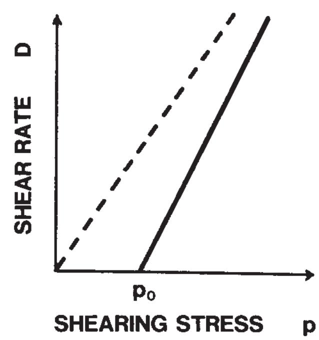

Fig.16 The ideal relation between shearing stress and shear rate.
p_0 : yield stress.
Solid line : a Bingham plastic fluid.
Broken line : a Newtonian fluid.

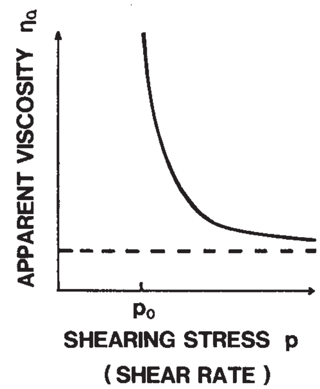

Fig.17 The ideal relation between apparent viscosity and shearing stress or shear rate.
Solid line : a Bingham plastic fluid.
Broken line : a Newtonian fluid.

3.1 Lava cave formation in a Newtonian fluid.

If a lava flow is a Newtonian lava fluid, the lava flow is regarded as a gas-liquid two-phase flow from the point of view described in section 2.1. That is to say, gases are volatiles in lava flows, and the liquid is molten basaltic lava.

Fig. 14 shows flow patterns for Newtonian gas-liquid two-phase flow in horizontal pipes (Wallis 1969). The flow patterns change from bubble flow to slug flow through plug flow as the gas flow rate is increased under a condition of constant liquid flow rate. In this paper it is assumed that the change of these flow patterns corresponds to the development of unit caves in lava flows.

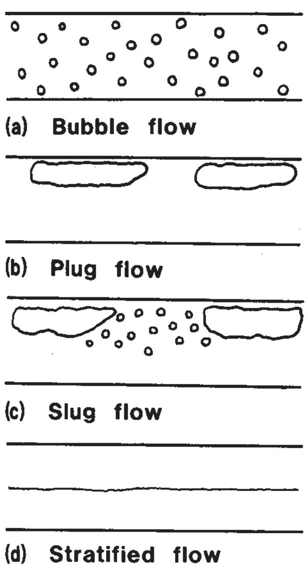

Fig.14 The flow patterns for the gas-liquid two-phase flow in horizontal pipes.

The flow pattern of lava flows near eruption vents may be bubble flow because it is difficult for gas bubbles in lava to accumulate into larger gas bubbles because of the influence of the morphology of country rocks under the lava flows, and also because of the difference between lava and country rock and atmospheric temperature. In this condition, the lava flows may be turbulent as in Fig. 15(a).

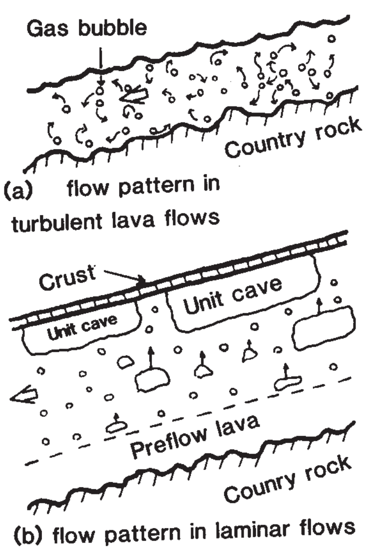

Fig.15 THE FORMATION OF UNIT CAVES

On the other hand, at the foot of a mountain the surface of country rocks is leveled by preflow lava, and the inside of the lava flow loses very little heat. In addition, the lava flow rate is decreased because of an increase of viscosity of lava and a gently-sloping mountainside. As a result, the lava flows change from turbulent flow to laminar flow.

In this stage, large numbers of gas bubbles that are supplied by subsequent lava flows coalesce into larger gas bubbles. Although the large gas bubbles rise because of the buoyancy of gas, the crust of the lava surface prevents the gas bubbles from escaping into the atmosphere. Meanwhile, the lava flow changes from bubble flow to plug flow and slug flow as in Fig. 15(b). The large bubbles in the gas-liquid two-phase flow grow to be unit caves as described above; unit caves in subsequent lava flows coalesce into those in previous lava flows. As a result, a large, long lava cave or a bigger unit cave is formed in a closed system. Where lava flows stagnate at depressions, dome-shaped lava caves are formed.

3.2 Lava cave formation in a Bingham plastic lava flow.

Pinkerton and Sparks (1978) reported that the 1975 Etna lava was a plastic fluid. In this paper, it is assumed that a lava flow is regarded as a Bingham plastic fluid which is an ideal plastic fluid.

As time passes, lava flows change in rheology from a Newtonian fluid to a Bingham plastic fluid. Crust (as in Figs. 9 and 10) is formed on the inner cave wall. The process of formation of the crust will be explained using the basic rheological properties of a Bingham plastic fluid as in Figs.16, 17 and 18 (Eirich 1956). The rheological properties of a Newtonian fluid are also shown in those figures.

Fig. 19(a) is a schematic drawing of a lava cave in layered lava. In the early stages of lava cave formation, the floor of

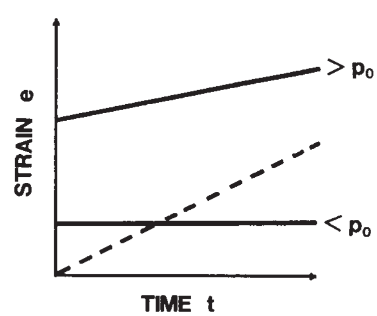

Fig.18 The ideal relation between time and strain.

Solid line : a Bingham plastic fluid.
Broken line : a Newtonian fluid.

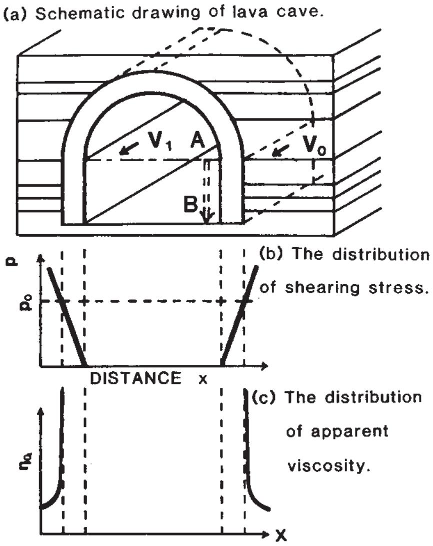

Fig.19 The formation of crust on the inner wall.

the unit cave is at the level of surface A. As time passes, the floor sinks to the level of surface B. Fig. 19(a) shows also that crust is formed on both the ceiling and the side wall.

Fig. 19(b) shows distribution of shearing stress at the level of surface A. This relationship is anologized from the plug flow in laminar flows of a Bingham plastic fluid in a circular pipe (Eirich 1956). The shearing stress is not established on the cave floor since there is no lava on it. The thickness of the crust depends on a yield stress for constant slope of the shearing stress. As evident from Fig. 16, since the shearing stress of the crust partition is under a yield stress, permanent deformation does not originate in the crust.

Fig. 19(c) shows the distribution of the apparent viscosity at the level of surface A. This relationship can be obtained from Fig. 17 and Fig. 19(b). Fig. 19(c) leads to the following: the crust partition acts as if it were a solid. And, as in Fig. 18, strain is constant with respect to time under the yield stress. It is considered, from the relationship described above, that the crust which has once been formed is stable to change with passage of time. This means that crust plays an important role in the morphological maintenance of lava caves in molten lava so that a hugh lava cave is completely formed. From the point of view described above, Bingham plastic lava flows are regarded as the gas-liquid three-phase flow. That is to say, gases are the volatiles in lava, the liquid is the molten lava, and the solid is the crust.

The floor flow with sinking is a unique phenomenon in Bingham plastic lava flows. Such a phenomenon can be explained as follows: since the shearing stress is not established on the floor surface of lava caves, the flow rate, V_1, of the floor is faster than that, V_0, in layered lava, namely the vertical component of V_1 is larger than that of V_0, and then floor flows with sinking are generated. At the same time, since the crusts

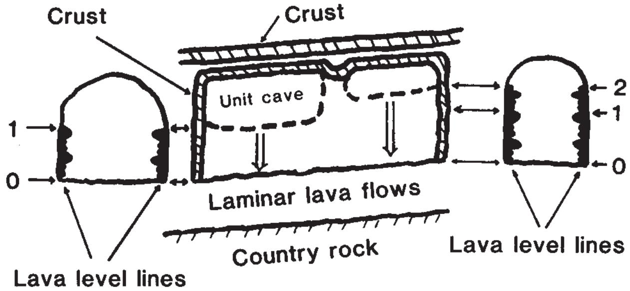

Fig.20 lava cave formation due to floor flow with sinking.

on both side walls are formed continuously (by similar reasoning to that described above), the cave walls are extended vertically, and then the cross section of a lava cave is elongated. As a result, separate lava caves in lava flows will interconnect due to floor flow with sinking, and consequently a lava cave in a closed system is developed in the direction of the lava flows as in Fig. 20.

In addition, the crust is formed on the floor partition at the same time, but it may be destroyed generally by vertical vibration of the free surface.

4. Consideration.

The outline of the discussion about the formation of a lava cave in a closed system is summarized in Table 1. As indicated there are four combinations of factors influencing the formation of lava caves. In this table, both rheological properties and states of motion of lava flows are considered as factors in cave formation.

4.1 The case of a fixed mode.

The first mode in this case represents lava flows which are Newtonian fluids and stagnate. It is considered, for example, that when lava flows stagnate at a depression, dome-shaped lava caves are formed. Banba-Ana (Lava Cave), Fig. 4 is an example.

The second mode is the case where lava flows are Newtonian fluids and flow. In this case, tunnel-shaped lava

Table 1 The modes of lava cave formation in a closed system.

		RHEOLOGICAL PROPERTIES OF LAVA FLOWS	
		A NEWTONIAN FLOW (TWO-PHASE FLOW)	A BINGHAM PLASTIC FLOW (THREE-PHASE FLOW)
THE STATE OF MOTION OF LAVA FLOWS	STAGNATION	Bubble flow →Slug flow or Plug flow (Formation of unit caves) ▽ Dome shaped lava caves	No development of unit caves; Sporadic lava caves
	FLOWAGE	Bubble flow → Slug flow or Plug flow (Formation of unit caves) ▽ Tunnel shaped lava caves	Lava caves due to the floor flow with sinking

caves are formed, without lava flow lines. These are sometimes observed in Japan and Korea.

The third mode is where lava flows have been Bingham plastic fluids since the lava was erupted, and stagnate. In this case the unit cave is not formed because of the crust; and then a lava cave cannot be formed in Bingham plastic lava.

4.2 Cases of changing from one mode to the other.

In this section, cave formation will be described when a mode changes in the direction of the arrow indicated on the border among each mode in Table 1. From my interior observations of lava caves in Japan and Korea, there are numerous cases in which the second mode changes the fourth mode. In this case, lava flow lines could be observed on both side walls, if it were not for the cave ceiling.

It is seen in Fig. 7 that it is necessary to change from the second mode (formation of the ceiling partition) in order to form such a huge cave as Manjang-Kul (Lava Cave).

Next, the morphological maintenance of lava caves in Newtonian lava flows will be considered. In this case, since the crust cannot be formed, quench hardening of the whole lava flow is necessary for morphological maintenance. However, this quench hardening may not be effective for cases which are located in thick lava with very low thermal conductivity (Swanson 1973). Moreover, quick cooling due to the atmosphere from skylights is also considerable, but this effect may be restricted locally, and then the cave partition distant from the skylights will be destroyed due to the decompression of the internal pressure of the cave.

In order to overcome this difficulty, it would be advisable to assume plasticization of the inner cave wall in Newtonian lava on the basis of the idea of the reference 3. In this case, since the floor flow with sinking is not generated, lava may hardly flow. But crust has not yet been discovered in a cave which may be formed in a Newtonian lava flow such as Suisan-Kul (Lava Cave).

Acknowledgements

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ESSAY ON GENETIC CLASSIFICATION OF VOLCANIC CAVES

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Vulcanospeleology, the study of caves formed in volcanic rocks, reached a great importance in the '70s as a result of interpretation of their analogies to extraterrestrial morphologies (Moon, Mars).

A thorough study of volcanism is required for rational planning of vulcanospeleological research; it allows the formulation of volcanic caves, based upon their main speleogenetic processes, and is an essential instrument for these studies.

An essay on genetic classification of a theoretical kind, which can be applied to whatever cave generated by volcanism is therefore suggested. This classification is based on the effects of flowing lava and expanding gases; both these factors are actually common to every volcanic manifestation and are independent of local features of volcanism.

Different types of caves are described in connection with their position in the classification, and their genetic processes are outlined.

RATIONALE

Speleological studies are supported by different interacting disciplines, which explain speleological phenomena, or extract from them their relevant investigational field. A remarkable position among these disciplines is held by vulcanospeleology, which studies volcanic caves.

These caves often show a striking morphological analogy with karstic caves generated by chemical and mechanical erosion in limestone rocks, though they greatly differ from the latter for obvious reasons. Their genetic processes are quite different from those generating karstic caves; they are formed in such a short time that their formation velocity can be considered near instantaneous. Furthermore, their formation is contemporary with that of the engulfing rock, and is controlled by the same factors, thus they were defined syngenetic by Montoriol-Pous and De Mier (1970), as contrasted to caves generated by erosive or tectonic or other phenomena in a pre-existing rock. The latter were defined epigenetic by the same authors.

Like karstic caves, volcanic caves have been well known too, and used by people since the most ancient times. They were explored and described and studied by excursionists, travelers and naturalists. But for a long while, they met a marked disinterest in the scientific world, and were always considered as simple morphological peculiarities of volcanic environments.

Vulcanospeleology gained importance for scholars only at the beginning of the '70s, when its role became evident as a key in the interpretation and analogical study of extraterrestrial morphologies, photographed by space satellites. Many specialists started exacting studies, both on solid lava fields and extant volcanic caves, and also on active lava flows during eruptions. They formulated new genetic theories and suggested complex classifications which do not entirely agree. Many doubts remain because of scanty availability of comparative terms and because of limits due to over-generalization based on local evidence.

In addition to a thorough knowledge of volcanism, in all its aspects, a simple and rational classification of volcanic caves, based upon valid and generally applicable genetic considerations, is needed for correct planning of studies in the vulcanospeleological field. It does simplify a general systemization of all such caves, regardless of location, whatever morphology they display, however they are formed.

The aim of this paper is to propound such a classification and to link the fundamental cave types herein considered with their genetic processes.

Caves hollowed out in volcanic rocks by speleogenetic factors other than volcanism have been intentionally excluded, as they are in the general category of epigenetic caves.

TYPICAL VOLCANIC FACTORS CONTROLLING CAVE FORMATIONS

Volcanic manifestations characterizing each eruption are numerous, of a varied nature, and are so much dissimilar, one from another, in time and space, as to form the investigation field of a proper discipline.

The grounds for these differences must be investigated in the polygenetic character of volcanism. One may be of distension type in crustal divergence areas, or of compression type in subduction areas. Many intermediate types occur.

In turn, the primary differences are reflected in chemical and mineralogical composition of the erupted materials, in their physical conditions at the moment of eruption, in their way of spread and emplacement in the external environment, and in the resulting morphological features.

In different parts of the earth, scholars have undertaken studies of genetic and systematic problems of volcanic caves — mainly of lava tube caves — but they have been involuntarily affected by the local set of interacting factors which characterize the volcanism of a given area (or type), and differentiate it from others.

As a consequence, systematic arrangements or genetic theories often do not succeed in meeting a vulcanospeleologist's requirements in Japan, or Victoria, or Sicily, when they were elaborated through studies carried out in Icelandic, or Hawaiian, or Northwest American caves. Therefore, it is necessary to loose the volcanic cave systematics from the particular morphogenetic bonds connected with local volcanism, especially as they often are further complicated by single topographical and/or environmental features.

A classification of volcanic caves should be linked only with the most general volcanic features common in every eruption, viz:

1. The shifting of coherent volcanic material, more or less fluid, moved by gravity and/or by hydrostatic pressure and/or by endogenetic pushes (originated by the steam pressure of the engulfed gas).
2. The action of gases, when their volume and steam pressure reach such a power that irreversible deformations are caused in the engulfing molten lava or volcanic deposit or rock.

These actions are limited to primary volcanism. When a speleologically appreciable gap is thus formed in the rock mass, it results in a syngenetic cave, namely a cave generated by the same phenomena which controlled, more or less contemporarily, genesis and emplacement of the engulfing rock.

GENETIC CLASSIFICATION OF VOLCANIC CAVES

In the light of the previous considerations, and of others reported in earlier papers (Licitra 1978(a), 1978(b)), the writer introduced a genetic classification upon typical volcanic factors controlling cave formation, in the third Gruppo Grotte Catania Speleology Lecture Course in 1975.

In this classification, caves are divided into two primary classes, concerned with the peripheral speleogenetic action. Each class in turn is divided into two groups, according to the place and/or way of operating of the speleogenetic action.

Caves generated by flow of lava are classed as rheogenetic (from ancient Greek "rheo" = flow), whether the flow occurs on the surface, in an active lava flow (rh. surface cave) or through pre-existing rocks, when lava flows to the surface through an eruptive fissure and next flows downwards (rh. fissure cave).

On the other hand, the class of pneumatogenetic caves (from ancient Green "pneuma" = blow, breath) action of gases, whether they are volcanic gases released by lava, or induced ones, generated by masses of water, snow or ice contacting hot volcanic gas or lava.

MAIN VOLCANIC CAVE TYPES CONSIDERED IN THE CLASSIFICATION

The main volcanic cave types are hereinafter reported, in connection with the classification mentioned before, and their relevant genetic processes are outlined.

1.1 Rheogenetic Surface Caves

This group includes the most widespread, best known and most studied volcanic caves on a world scale. They are reported as lava tube caves or lava tunnels or galleries; they were also termed emptying out tunnels by Cucuzza-Silvestri (1977) and vary in a wide range of forms and sizes. Lava channels also are classed in this group; in spite of their small importance in speleology, they play an important role as intermediate stage in the formation of lava tube caves, and are valuable terrestrial analogues in studying morphogenesis on the Moon and Mars.

Different hypotheses exist on the formation of rheogenetic surface caves (Licitra, 1977) and it is needless to repeat them all here. According to many ruling opinions, their formation should occur through drainage of still-molten lava from a lava tube (or roofed channel) when the feeding of the flow at the source vent ceases. But it is more likely that a lava tube hollows as a result of gradual lowering of the flowage surface (and bottom) of flowing lava during its active phase (viz. when the flow is being actively fed by lava pouring out from the vent) than at the end of the effusion. In fact, if one considers the high viscosity of lava when compared with other fluids, and the modest temperature interval (1,000/1,000 degrees) within which it maintains a significant flowage capacity, it is very unlikely that such a significant drainage can occur even in water-like fluid lavas, as to generate long caves such as the "Kazumura Cave" of Hawaii.

The lowering of the flowage level could operate either by evacuation through division of lava into new flow units in the flow front, or (more likely) by simple lowering of the flowage bed, through remelting and erosion of the tube bottom (Finch 1943).

Also, some geomorphic features of lesser speleological interest must be classed in this group, such as those surveyed and described by Montoriol-Pous and De Mier (1970) in Grindvik lavas, Iceland; large traverse fractures gaping across the flow direction, corresponding with an underlying slope incretion (cavidades fractogeneticas) or collapse holes of small dimensions (cavidades embudiformes) or blind sections of tube unroofed by collapse (cavidades serpentiforms);or even bowl shaped subsidence holes, as Alae Crater, Hawaii, described by Swanson and Peterson (1972).

If the downward reflux is not followed by conduit collapse, a vertically developed hollow is formed, with parallel walls. This is defined as a rheogenetic fissure cave (Licitra 1978(c); 1981). The more effusive the activity, the lesser the collapse is probable.

2.1 Pneumatogenetic Explosive Caves

Caves engendered by gas explosions are classed in this group, whether the exploding gases are volcanic or phreatic.

In addition to diatremas, which are of limited importance from a speleological angle (they somewhat resemble Mexican sotanos, originated by tectono-carstic phenomena), hornitos are included in this group. They are tall welded spatter cones, with a hollow core, built up by spatters of molten lava splashed by gurgling gas bubbles, around a rootless vent from which very fluid and partially degassed pahoehoe lava emerges.

Rheogenetic surface or fissure caves are frequently found beneath hornitos or at their base.

2.2 Pneumatogenetic Expansion Caves

This type of cave is not very widespread and is generally associated with rheogenetic surface caves Furthermore, this is the only type of volcanic cave which has been noticed in volcanic rocks other than basic lava flows. A pneumatogenetic expansion cave occurs when two different factors are interacting:

i — presence of abundant gases, the steam pressure of which is incapable of completely overcoming the resistance of the engulfing material;

ii — volcanic products (basic lava, or ignimbrites) too viscous to allow the engulfed gases to be released, yet plastic enough to be warped by the gas pressure before the stiffness of the solid state has been attained.

Caves of this type are called blister caves by English authors, and cavidades cutaneas by the Spanish Montoriol-Pous and De Mier (1970), and may be formed when a lava flow enters a large quantity of water (lakes, sea) or buries a marshy ground (such as Myvatn, Iceland). Such caves have been noticed in Iceland, in Australia and at the foot of Mt. Etna along the Ionian coastline.

Perhaps the most remarkable type of pneumatogenetic expansion cave has been surveyed and studied in a prehistoric ignimbritic deposit at Fantale Volcano, Ethiopia. Gibson (1974) ascribes the formation of such blister caves to expanding gases and steam held beneath wrappings of ashes and viscous rhyolitic lava scraps, at very high temperature, after red-hot ash flow has halted.

Although no information is available in this report, such caves might be found in the Valley of the Ten Thousand Smokes, Alaska, in the ignimbritic deposit laid down in 1912 by Katmai Volcano.

CONCLUSION

The theoretical classification presented in this paper, based upon general speleogenetic factors of volcanism, should simplify and assist collection and interpretation of observational data.

By this classification, it is actually possible to ascertain how very dissimilar local morphologies may be related to one another and traced back to a single genetic pattern. Thus, the risk is avoided, that an excessive subclassification of syngenetic caves (due to seemingly different morphological and/or dimensional standards) leads to misclassification of caves generated by the same processes into different classes or groups.

The researcher's task then, will be to ascertain the set of local factors (chemical, physical, topographical, environmental, etc.) and the degree of interacting relationships, which control the specific morphogenesis of each cave.

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CONSERVATION OF LAVA CAVES: EXAMPLES FROM AUSTRALIA

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ABSTRACT

The problems of the management and conservation of lava caves and their associated features differ from those of karst caves. Some features mostly peculiar to lava caves include a generally simpler plan with regular, large, tunnel-like cross-section; entrances often large and relatively easy to use; for these reasons, often relatively safe for visitors; speleothems formed rapidly at the same time as the cave without any later growth; later internal changes restricted to infilling by rock-fall, collapse, and sometimes the accumulation of fine sediment washed or blown in; streams or pools of water uncommon; more than one level of passage uncommon; generally dark rock walls making lighting and observation difficult.

In Australia, most lava caves are little known, and are visited mostly by speleologists and occasional research workers interested in geology, botany and other sciences. However, several cave groups are better known, and have come under pressure from other visitors. Caves have also been threatened by rubbish dumping, deliberately blocked up by farmers, or distributed by nearby quarrying.

Some caves have recently been developed for tourist use, and several will be described in detail.

Studies of the problems of conservation of lava caves have recently been made a part of surveys by the Queensland and Victorian Divisions of the Geological Society of Australia sponsored by the Australian Heritage Commission (de Jersey and others 1976, Joyce and King 1980, Willmott and others 1981). In these reports, the young volcanic areas and their caves have received special attention and the incorporation of several cave groups into new National parks and similar reserves has begun.

INTRODUCTION

When "Conservation of Caves" is under discussion, perhaps most of us think of caves in general, and if asked, we would admit we had a mental image of one or more limestone caves at the back of our mind. Limestone caves are, of course, most common and perhaps most in need of conservation. However, it may be worthwhile considering whether lava caves need a different approach, and whether they pose different problems of conservation.

In this discussion, we probably need some definition of conservation first. Perhaps looking after caves, their preservation, restoration, and management would all be aspects of conservation. We need to consider who goes into caves and who might want to do so in the future; what they do there, and with what effect on the cave; who should be in charge of the cave. These matters we will discuss at the end of the paper.

However, first we will mention some features of the Australian lava caves, adding to those covered in the earlier paper, and relevant to any discussion of conservation. We will try to highlight aspects which are different from those of other (limestone) caves, and so may pose different conservation problems, or lead to different ways people may look at and experience lava caves.

* * *

Many lava caves in Australia have been adversely affected by man's presence. Some examples are: graffiti at the entrance to Skipton Lava Cave; secondary school children's graffiti in Parwan Cave; candle wax on floor of Skipton Cave, and farm rubbish in a collapse in the lava flow near Mt. Eccles.

Cave entrances have also been blocked up to protect stock, and keep out visitors; in one case, a farmer bulldozed the entrance to several small caves in an area just outside the boundary of a national park.

It is often thought that lava caves are less easily damaged than limestone caves, but many of them contain interesting and often fragile features worthy of preservation such as — needle-like stalactites, near Mt. Napier, the "Hands," ("lava stalactites" Staircase Cave, Byaduk), aragonite crystals in Mt. Hamilton Cave; lava drips on the cave's wall at Mt. Eccles, a ropy flow entering a cave at Mt. Napier, and layers of guano and minerals in the floor of Skipton Cave; several rare minerals have been found in this cave, guano mining was carried out in the nineteenth century, and now collectors have removed much of the mineral material.

Many lava caves also contain fauna and flora worthy of consideration such as: spider webs behind the lava lining in Skipton Cave, and fungae on the wall of Skipton Cave.

In the nineteenth century, this cave contained a bat colony, which may have been forced out by increasing dampness in the cave, probably related to tree clearing when the area was settled. The insect fauna of this cave survived the departure of the bats, but recently became extinct, probably because of floor compaction due to visitors' trampling.

Today, several lava caves in western Victoria have bat colonies; one is a maternity cave. At certain times of the year, any entry into such caves may be harmful to the bats.

The collapses of Byaduk contain large tree ferns which do not occur elsewhere on the dry lava plains; 20 ferns and 62 mosses are recorded. Many tree ferns have been removed for sale. The dumping of several cars in one of the collapses was little recompense. Also noteworthy are roots in ceilings of caves and sub-fossil bones found in Mt. Hamilton Cave.

* * *

"March 99" graffiti, Skipton Cave.

When drawing up conservation strategies for lava caves, their present relationship with man-made features must be taken into account, such as windmill pumping from a cave pool at Skipton, and stone fences, such as on the Byaduk flow.

Man's impact may not always have been disastrous; the entrance to Panmure Cave was made more accessible by quarrying near the entrance collapse. However, in many areas, quarrying of scoria or cinders in the volcanic cones or quarrying the stone of the flows, poses problems to the general conservation of the volcanic features of the area.

Major pressures for the preservation of many of the volcanic features of the area have begun to yield fruit recently, with the declaration of the Mt. Napier area and the Byaduk Caves as a state park.

Some graffiti may be so old as to be worthy of preservation. Those in Skipton Cave date back to 1899.

In any management plan, first priority must be removal of unsightly (and smelly) rubbish. Often dead farm animals are included in the rubbish dumped.

Management may involve provision simply of access roads and signs, or included better facilities such as car parks and camping areas, with a ranger in attendance, and signposted walks, as at Mt. Eccles National Park. Some lava caves are easily opened for tourist inspection merely by provision of steps, and clearing roof-fall from the floor.

One cave on private land is run as a tourist cave, catering mainly to school bus parties. The owner collects an entrance fee, which is being saved with the idea of putting in lights and installing a toilet system. This is the cave with many graffiti, excavated rare minerals, lost insect fauna, and candle-wax on the floor.

Some caves are so remote they might just be left alone, such as the Undara lava tube system, Queensland. The owner of the property with several of these caves, who contracted histoplasmosis from the bats in the cave, has actively discouraged visitors to the caves, and opposes the entry of the caves on the Heritage Commission Register.

SUMMARY

We can generalize and say that limestone caves are generally evolving systems in which the caves may be increasing in size and number (although any one cave may be filling in by collapse or deposition of sediment). On the other hand, lava caves are decaying systems — if material is carried in or the roof collapses, if stalactites are damaged or removed, there is no replacement. In the short-term time-scale, probably on the human time-scale, such caves may be thought of as static, unchanging — most have been in existence, little altered, for several hundred to several thousand years. Human interference may speed change, however, and rapidly alter or infill a lava cave.

In many other ways, lava caves are like other caves, with problems of littering, problems of physical damage by collectors, by trampling, by developers installing lighting or steps or guide rails or signs; this in turn leading to alterations to cave temperature and ventilation, perhaps to alteration of cave water quality (even if it is only present as drips and puddles) because of farming practice nearby, waste disposal, tourist car parking and the leakage from toilets; finally, general problems arising from over-use or sometimes any use.

Our approach to these problems might be — in order of decreasing control — protection (e.g., gating), conservation by management, "open-go?" If we reject the latter approach, we might argue for at least some caves to be fully protected (even from speleologists, even from scientist-speleologists, perhaps?). However, in this discussion we should probably concentrate on the management of lava caves for the use of the spectrum of visitors ranging from family day-trippers to dedicated scientists from distant lands.

It might be useful to ask ourselves:

"Why do people decide to go to a cave?

"What do they hope to experience?"

"What do they actually experience?"

"Can this experience be varied, to their advantage, or to the cave's advantage?"

"Are there alternative or substitute experiences which could be made available?"

We cannot answer most of these questions without some survey of visitors and potential visitors. We might guess that people decide to visit lava caves for many reasons — they are visiting

Spider web behind lining, Skipton Cave.

a park or reserve and see a signpost or read a leaflet; they read about it on a map, tourist literature or popular semi-scientific literature (e.g., a geographical magazine); they are told about it by others who have been there; they go as a group with a leader (e.g., a school group, scout group, speleology club); they visit the cave again after one of the above.

They may be hoping for some sort of aesthetic experience (the quiet, the dark, a semi-claustrophobic thrill); the satisfaction of curiosity, scientific or otherwise; a social or group experience (e.g., young couple, family group, holidaying teenagers); just the satisfaction of having been (as with the T-shirt saying "I climbed Ayers Rock"); because everyone else is going; or perhaps they just see the queue at the entrance and join it.

They may actually be scared, experience real claustrophobia, panic part-way through a conducted tour on a one-way route, get wet or dirty, fall and sprain an ankle, cut their head in the dark, quarrel with their companions, be caught littering or breaking off stalactites.

Porndon Rubbish Cave.

We could arrange to vary the experience with lighting, steps, guide rails, a cave nature trail with markers, an official cave guide to lead tours, plus explanatory literature display boards, interpretive centers, extra features in the cave such as stuffed wombats or plastic bats, spot-lit statues of bush rangers, perhaps selections from the soundtrack of the film "2001."

We could arrange alternative experiences — a surface nature trail briefly entering or just looking into caves, as an audio-visual display, a strip through a simulated cave made of rocks, plastic and cardboard (especially suitable for the handicapped or elderly —or should they have a suitable cave developed for them?

Obviously, the conservation of lava caves requires more study. There are certain features of lava caves — their general rarity but sometimes local abundance; their nature as decaying systems; their ready accessibility and general suitability for the casual visitor which pose special problems.

Solutions may include:

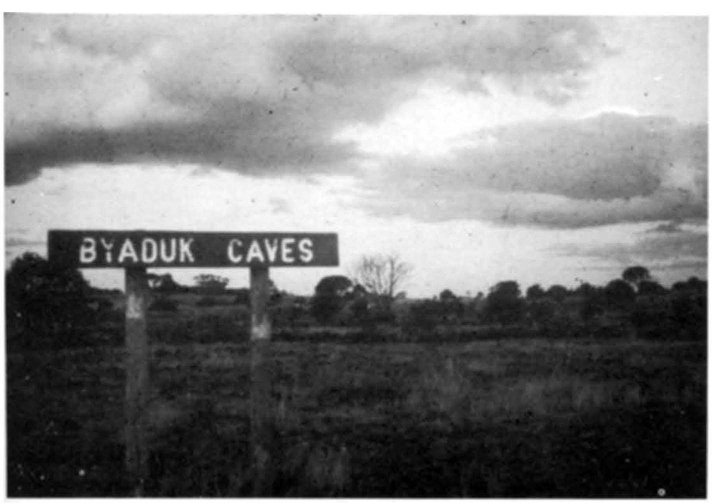
1. Complete protection of certain caves (such as those with fragile or scientifically-important features such as bat colonies or rare minerals) by gating, prohibiting access to the surrounding area, keeping the cave location generally as secret as possible.

2. Conservation of certain caves by proper management; relating caves to the general volcanic environment, so that they are seen as just one aspect of the young volcanic activity of the region; this may be best done in national parks established for this purpose.

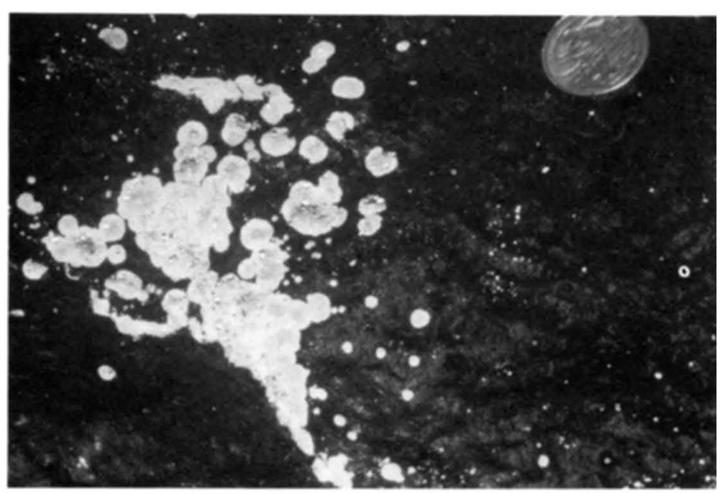
3. Perhaps one-access to certain caves (e.g., those with simple plans, no fragile features); if on private land, with the cooperation of the land owner; and as a means of reducing demand and assisting in the first two methods.

Recent moves in Australia for the entry of caves and similar features on the Register of the National Estate; the government-commissioned listing of sites of geological and geomorphological interest in each state; and moves toward increasing the numbers of national parks and similar reserves; all give some hope for the future. Comments are welcome.

(References not received)



Car park at Byaduk Caves.



Porndon Rubbish Cave.

CONSERVATION OF HAWAII'S SPELEOLOGICAL RESOURCES

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Hawaiian caves have long been known to have significant cultural and archeological values. Discoveries within the last decade have revealed important additional values in biology, paleontology, and geology. More recently, widespread publicity among national and international caving groups has emphasized the recreational and aesthetic values of Hawaiian caves. These seven major values represent a relatively rich resource which is matched by few cave areas elsewhere in the U.S., or even in the world. Unfortunately, conflicts arise among the various groups utilizing and attempting to preserve these resources. The unique values of Hawaiian caves, and the immediate nature of the threats to them by increased visitation, require that urgent and positive actions be taken to ensure their continued survival as a global scientific resource (Howarth in press; Howarth and Stone 1987).

Archeological and Cultural Values

The archeological importance of Hawaiian caves is great, as they hold a wealth of knowledge, documenting the cultures of the native Polynesians prior to European contact. Uses of caves by the early Hawaiians included shelter, habitation, food storage, water catchment reservoirs and crypts (Emory *et al.* 1969; Bonk 1969). For native Hawaiians today, these caves still have considerable cultural value, with traditional guardians ("kahunas") keeping watch over some important burial caves. Antagonism of the local people by thoughtless cavers, so common in other regions, would cause irremediable damage in Hawaii, and must be avoided.

Interestingly, the near-pristine condition of many Hawaiian lava tubes is partially due to a fear of burial caves by local residents, which has kept visitation at a low level until recently. Looting of pre-historic sites by artifact hunters is a serious problem, which has desecrated many sites already, partly in response to the publication of cave locations in archeological publications. However, up to now many caves have escaped this looting because of remoteness and lack of published locations.

Biological Values

The biological and evolutionary significance of Hawaiian caves has only been realized over the past decade, with the discovery in 1971 by Howarth (1972) of a cave-adapted fauna, now represented by over 50 species from all over the main islands. Maciolek's discovery of aquatic cave-adapted crustaceans on Maui (Maciolek and Brock 1974) led to the finding of over 20 aquatic species. New cave-adapted species are still being found regularly.

The evolutionary significance of Hawaiian cave-adapted species is immense: 1. They served as a bellwether for a more intensive search for troglobites in lava tubes and tropical caves with highly rewarding results. Past theories of cave adaptions, based on the presumed restriction of troglobites to the temperate zones, were no longer valid, and a new era of study and theorization was begun (Howarth 1980; Howarth 1982). 2. The isolated island characteristic of Hawaii allows for study of adaptive shifts, by which cave-adapted organisms evolved from native Hawaiian groups, much as other organisms have evolved to exploit novel habitats (Howarth 1981). These relationships are not often as clearly demonstrated in the more complex faunas of continental areas. Adaptions displayed by Hawaiian cave animals are truly remarkable, presenting such anomalies as underground tree crickets, blind planthoppers, a terrestrial water treader, and the ultimate of adaptive shifts, no-eyed, big-eyed hunting spider. 3. Environmental studies can be done, comparing cave species with their closely related surface relatives, revealing the effects of adaption to diverse habitats (Ahearn and Howarth 1982). Additional biological values of Hawaiian cave organisms, already known or remaining to be discovered, contribute to their great biospeleological potential.

It was fortunate that the biological survey of Hawaiian caves began before organized sport caving developed here. Our field data show that, other factors being equal, species diversity and population levels of cave organisms is inversely proportional to the level of visitation and human disturbance. For example, immature cixiid planthoppers and cave moths feed solely on living roots that penetrate the cave roof. If roots do not reach the floor, or are severed by human traffic, the dislodged nymphs starve. As a result, populations of these two species and their predators often reflect the level of human disturbance. Furthermore, hazardous refuse, such as carbide and batteries is detrimental to cave life. Tobacco smoke contains a powerful insecticide that can harm, or kill cave invertebrates in relatively enclosed caves.

In 1971, Joan Aidem discovered bird fossils on Molokai in sand dunes, followed by Howarth and Gagne's discovery of fossil bird skeletons in Maui lava tubes (Olson and Wetmore 1976). Since then, numerous species of hitherto unknown fossil birds have been discovered on all the islands including flightless ibises, rails and geese. Over 30 new species are known, with new finds occurring regularly, necessitating an ongoing revision of our knowledge of the evolution of bird life in the entire Pacific island region (Olson and James in press). These fossils, so crucial to understanding evolution of Hawaiian birds, are extremely vulnerable to destruction by unaware cave visitors.

Geological Values

In 1971, Mauna Ulu, a new volcanic vent, began erupting in earnest, and for the first time modern geologists had a front row seat during the formation of a shield volcano. They quickly realized that lava tubes, which form by the crusting over of pahoehoe lava channels, play an important role in the formation of volcanic shields by efficiently conveying lava great distances through the insulated interior of a lava flow (Peterson and Swanson 1974). This discovery catapulted lava tubes from mere geologic curiosities to valuable scientific resources.

Additional geological values derive from the formations within lava tubes: lavacicles, driblet spires, and other structures and mineral deposits which give clues to processes of lava tube formation and evolution. These deposits also add to the aesthetic values of lava tubes, but as in limestone caves, they are vulnerable to accidental breakage and vandalism.

Human Impact on Cave Resources

Cave conservation elsewhere provides possible solutions to conservation problems in Hawaiian caves. Cave exploration as a sport began in earnest in the last century in Europe, to some extent in America, and elsewhere. It has mushroomed in popularity in the last few decades as a result of increased leisure, improved techniques, and increasing ease of travel. Everywhere caves have experienced increased use and abuse by humans. As caving pressure increases, so does human impact; vandalism, accidental breakage and trampling, pollution, et al. Unchecked, these impacts irreversibly damage biological, paleontological, archeological, geological and aesthetic resources (Stitt 1977). Five stages can be recognized: **1.** local use, **2.** discovery, **3.** escalation of caving, **4.** resource destruction becomes critical, **5.** cave protection begins in order to preserve what little remains.

Caves share with other discrete habitats such as montane bogs and sand dunes a vulnerability to human traffic. However, scientists studying surface habitats often need only go a few hundred meters away from a well-worn trail to find relatively undisturbed study sites. In caves, however, traffic is narrowly confined, and unless there is access control, study areas will be trampled or vandalized.

In addition, caves have been closed to researchers because of increasing conflicts with exploration parties. Many caves have entered the last phase with little left to preserve. In England, for example, Britton (1976) lamented that: "In the entire country, no cave now exists which has a man-sized entrance and undisturbed biology or [paleontological] sediments."

Impacts on Hawaiian Caves

Until recently, principal impacts on Hawaiian caves have resulted indirectly from clearing forest land, construction of roads and buildings, and use as dump sites. For example, cave entrances on Hawaii island have been illegally bulldozed shut by well-meaning but misinformed construction workers who were unaware of the rich resources thus destroyed.

Hawaii is now in the discovery phase (No. 2 above) with recreational use increasing dramatically. However, this is rapidly escalating to the next stage in which use will exceed carrying capacity. Popular accounts of recent expeditions have generated more visits (e.g., Wood 1980), and several expeditions from North America, Asia and Europe are planned within the near future. Even though these groups represent responsible experienced cavers, without special training they are not likely to be sensitive to local resources and management problems in Hawaii. Unique values of Hawaiian caves makes them particularly sensitive to visitor pressure, and makes a special protection imperative.

PROTECTION AND MANAGEMENT STRATEGIES FOR HAWAIIAN CAVES

1. Protection from destructive land use practices. It is not practical to save all caves from destruction from improper land use, but through workable management schemes including alternatives, the significant caves may survive without undue economic loss. For example, on Kauai, caves with significant biological and archeological values are being protected within a golf course by a management agreement between the county and the developers. Land managers, environmental agencies, and environmental groups must be kept informed of cave resources.

2. Caves in the national parks. Currently, Hawaiian Volcanoes National Park has realized the need for a management plan for the caves there. This realization resulted from a rapid increase of requests to visit the lava tubes, stemming from articles in international caving journals. The park is developing a management plan and beginning a survey to determine which lava tubes require restricted access due to scientific values.

3. Protection for caves outside the parks. Additional efforts by the caving community are necessary to extend protection to scientifically and culturally important caves outside the parks. A Hawaii Cave Conservation Task Force of the National Speleological Society is presently being formed by representatives of groups concerned with preservation of the unique values of Hawaiian caves.

Preservation of Hawaiian cave resources requires a concerted effort by the caving community at large, without which the efforts of the task force will have limited effectiveness. Recognizing this need, in July, 1982, the Board of Governors and the Biology Section of the National Speleological Society passed the following resolution:

Whereas, Hawaiian caves, including lava tubes, have unique internationally recognized important values to science, especially in the fields of biology, archeology, paleontology and geology; and,

Whereas, Many of these important scientific resources are particularly vulnerable to unrestricted recreational caving; and,

Whereas, Once destroyed these values cannot be recreated; and,

Whereas, Popularizations of the sporting potential of Hawaiian caves in mass media encourages recreational caving by the general public; and,

Whereas, The National Speleological Society recognizes these problems elsewhere in the United States;

Therefore, be it resolved that the National Speleological Society urges all cavers to assist in the conservation of Hawaii's cave resources; and,

Be it further resolved that the Board of Governors encourages all N.S.S. members and all cavers visiting Hawaiian caves to exercise special caution to prevent the destruction of these resources; and,

Be it resolved that the National Speleological Society opposes the publication in the popular press of articles describing the sporting potential *or locations* of sensitive caves; and,

Be it resolved that the National Speleological Society supports the efforts of the Hawaii Caves Conservation Task Force, the National Park Service, the Bernice P. Bishop Museum and others in their efforts to conserve Hawaii's cave resources.

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BIOTA OF VOLCANIC CAVES: AN INTRODUCTION

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In recent years, cave biologists have been more and more of the opinion that troglobites, or so-called "obligate cave fauna," are primarily inhabitants of the network of fissures, interstices, and small cavities that is more-or-less continuous throughout large areas, rather than existing in isolated cave populations (for discussion see Husmann, 1967; Culver, et al, 1974; Henry, 1979; Crawford, 1981; and below). In view of this, one might expect that the most diverse and abundant troglobitic faunas will be found in regions where this widespread subterranean habitat has certain favorable qualities. Among these might be availability of moisture and food, and the size and interconnectivity of the "living spaces."

Clearly, a crevice system with no connection to surrounding cavities, or a material like clay, with many available spaces but all of them microscopic, is not likely to support animal life. Both these factors — size and connectivity of spaces — are reflected in the permeability of a medium to groundwater, which can be measured. Permeability is an intrinsic quality of a medium analogous to electric resistivity, and is proportional to the rate at which groundwater, under a given set of conditions, can pass through it. Its dimensions are length squared. Brown, et al, (1975) gives the permeability ranges of most common bedrock and sediment types. Three materials show maximum permeabilities near the top of the scale, or about 0.152. They are gravel, limestone, and basalt. Since both limestone and basalt contain caves, their subterranean faunas can be investigated. Both kinds of cave should be expected to have diverse and abundant troglobitic faunas, and that expectation is proving to be justified. Oddly, though, the large subterranean faunas of basaltic terrain remained almost unsuspected until very recently.

Although a few troglobites were described from volcanic caves as early as the 1930s, only a handful had been reported before the late 1960s. Beginning in 1966, lava troglobites were described individually in increasing numbers from Japan, Korea, Idaho, Washington, and elsewhere. Then Leleup (1967) reported the presence of an entire fauna in the Galapagos Islands. In quick succession, Ueno, et al, (1970, 1971) reported large subterranean faunas from volcanic caves in Japan, Howarth (1972) from Hawaii, and Peck (1973) from western North America. Thus, volcanic cave biology blossomed from nothing to a substantial subject in an extraordinarily short time.

Currently, the Galapagos fauna is being published in the Resultats Scientifiques, Mission Zoologique Belge aux Iles Galapagos et en Ecuador (1968-date); the Japanese fauna in the Bulletin of the National Science Museum, Tokyo (Volume 13, 1970, to date), and the Hawaiian Fauna in Pacific Insects (Volume 15, 1973, to date). The North American results are scattered in many journals. About 40 lava troglobites have been described from Japan; 13 from the Galapagos; 24 from Hawaii; and 16 from Washington, Oregon and Idaho, with many more awaiting description. Species described include the fish *Luciogobius albus*, Regan (Japan), and *Caecoqilbia galapagosenis*, Poll and Leleup, as well as such diverse invertebrate groups as earwigs, flatworms, harvestmen, true bugs, actinaria (Japan), and pseudoscorpions, beetles, and crickets, collembola, spiders, mites, and numerous millipede and crustacean species.

Even in these four studied areas, probably the majority of the fauna awaits discovery. Almost nothing has been done on the cave biology of most of the world's volcanic areas. In many cases, the caves themselves have not been explored. The subject is ripe for anyone interested in primary discovery.

VOLCANIC CAVE ECOLOGY — DIFFERENCES FROM SOLUTION CAVES

Many of the ecological differences between volcanic and solution caves arise from differences in physical structure. One of the chief distinctions of lava tube caves in this respect is their comparative shallowness. Limestone caves often have a considerable overburden; by comparison, the thickest overburden known for a lava tube is 45 m (Nieland, J. and E., 1975) and most have considerably less, in the neighborhood of 1-10 m. Seepage water penetrates readily to these depths by means of joints and fissures, carrying dissolved and fine-particulate organic matter from the soil which supports heterotrophic bacteria on the cave walls and ceiling. In many cases, this bacteria (in Washington chiefly Actinomycete) forms thick deposits known as *lava tube slime* (Staley and Crawford 1975; Stanley and Staley 1975; Howarth 1973). Lava tube caves in forested areas commonly have tree roots penetrating their shallower passages through ceiling fissures. In Hawaii, this phenomenon is so pronounced that Hawaiian caves have thick and extensive "hanging curtains" of roots, sometimes even obstructing passages. Several Hawaiian troglobites, including a millipede and a Cixiid bug, are known to feed directly on living tree roots and many scavenge dead roots. In Washington, the troglobitic millipede *Lophomus skamania* feeds on living roots at least occasionally, and some other species are suspected to do likewise. The chief trees penetrating lava tubes with their roots in southern Washington are Douglas Fir and Ponderosa Pine; in Hawaii, several tree species have been cited. Of course, caves in treeless areas such as southeastern Oregon and the Galapagos are denied this energy sources.

Another consequence of the shallow overburden, along with the comparative shortness of the caves, is increased variability in microclimate. It has been reported many times that deep solution caves maintain a nearly constant temperature and other climatic conditions. Not so lave tubes. Benedict's studies (1974, 1977 and others) of Malheur Cave showed definite penetration of surface temperature through the 2-7 m thick overburden, but even more effect from temperature exchange via the entrance of the descending cave, warmer air moving outward along the ceiling and cooler air inward along the floor. In this case, the effect is ameliorated by the presence of a large thermal lake; temperature variations in other lava tube caves may be expected to be even greater. This is borne out by more random observations by myself and others. Just what effect this variation has on cave biota has not been elucidated in detail. Kamp (1973) suggests that ice cave populations of *Grylloblatta* spp. move out of the cave proper when onset of sub-freezing temperatures lowers the relative humidity. In most volcanic caves, the variation appear to be such that the cave is always habitable, yet significant variations do occur and might well influence the behavior and ecology of the affected fauna.

A very important difference in the ecology of volcanic and solution caves is a direct consequence of their mode of formation. Solution caves form as conduits for phreatic and vadose underground waters, and a large proportion at some time receive water from surface streams which carries large quantities of organic matter and surface-water fauna. This is the major organic input for these caves and it is definitely pulsed, coming in cycles dictated by seasonal stream flow variation, storms and floods, etc. By contrast, the major organic inputs of most volcanic caves are continuous and vary relatively little. The mode of formation of volcanic caves is unrelated to hydrology, and relatively few contain streams at all; even fewer receive large quantities of stream-washed organic matter.

The entrance floras of solution caves are undoubtedly of interest, though they seem to have been little studied. Yet, the plant communities in volcanic cave entrances, particularly of collapse sinks, have unique features which relate to the physical nature of basaltic lava. As related above, basalt flows are sufficiently young that mature water-retaining soil profiles have not developed on the surface. As a consequence, the surface in most volcanic cave areas is rather xeric or desert-like, regardless of the actual climate, because rainwater sinks rapidly into the bedrock without leaving a reserve to be tapped by plant roots.

As an example, consider Cheju Do, the volcanic cave area of South Korea. The annual rainfall on the north side of the island is 130-200 cm, comparable to that of the west slope of the Cascade Mountains in Washington, which feeds innumerable surface streams and supports a dense, lush and moist coniferous forest. In comparison, the interior of the Cheju Do has little surface water during most of the year and the surface is bleak, treeless, and desert-like, though much groundwater exists at depth. The collapse sinks associated with lava tubes present an astonishing contrast. For instance, the two collapse entrances of the cave So Cheon Gul are each only about 10-15 m in long diameter. Recorded from them are 27 species of fern and eight species of tree, as well as climbing vines and undershrubs — indeed miniature jungles. Photographs of the area show the barren lava surface with clumps of dense forest in the collapse sinks as in flower pots (Crawford, 1982).

The same phenomenon occurs in the Undara area of Australia, where lava tube systems are plainly evident from the air by the vivid contrast between the tropical rain forest in the collapse trench and the desert scrub of the surrounding plain (Stevens and Atkinson, 1976). The explanation of this phenomenon is two-fold. First, the lower level of the collapse brings the flora physically closer to groundwater, and perhaps almost in contact with perched groundwater on the "country rock" underlying the lava tube floor. Second, the enclosing walls of the collapse help retain humidity by limiting the penetration of rain and sunlight. This latter effect can be prominent even in a true desert climate (e.g., Fern Dome at Jordan Craters, Oregon [Larson, 1977]). In forested lava tube areas, such as the Mt. Adams area in Washington, the effect is less noticeable but still evident, since the surface vegetation is distinctly xerophytic (roots above groundwater), whereas that on the floors of collapse sinks and trenches includes phreatophytic species (roots in groundwater).

VOLCANIC CAVE ECOLOGY — SIMILARITIES WITH SOLUTION CAVES

Despite the differences in energy sources and environmental conditions between volcanic and solution caves, their community structure and bioenergetics are broadly similar, although of course numerous individual differences exist. The food chains of volcanic caves, as typified by Howarth's (1973) for Kazumura Cave, Hawaii, and mine (figure 1) for Deadhorse

Cave, Washington, show no consistent difference from those published for solution caves, except in such details as the nature of energy sources and taxonomy of the biota. This is perhaps to be expected, as both are examples of ecosystems supported by organic input from outside and colonized in similar ways by biota with similar characteristics.

Another point of similarity is that volcanic and solution caves in the same region usually have very similar troglophilic and trogloxenic faunas. I can state this from my own experience with regard to the caves of the Cascade Mountains of Washington; species lists published by Ueno, et al, (see above) for Japan and Korea also support this conclusion. Even a few of the same troglobitic species occur in both volcanic and solution caves; I know of three examples. In Hawaii (island of Kauai), the terrestrial amphipod *Spelaeorchestia koloana* has been collected in three lava tube caves and one of the Hawaiian Islands' rare limestone solution caves, formed in an ancient calcareous sand dune formation (Bousfield and Howarth, 1976). The Leiodid beetle *Glacicavicola bathysciodes* occurs in many lava tube caves of southern Idaho and also in limestone caves of adjacent Wyoming (Peck, 1981). The isopod *Salmasellus steganothrix*, originally known from karst groundwater and one limestone cave in southern Alberta, has been identified in the lava tube Deadhorse Cave in southern Washington, some 750 km away (J.J. Lewis, personal communication, 1981).

BIOGEOGRAPHY AND EVOLUTION OF TROGLOBITES IN BASALT

One reason why cave biologists formerly gave no consideration to caves in basalt is that it was assumed that such caves were too short-lived to permit the evolution of troglobites. This assumption may not be entirely valid; some cave-bearing basalts in Oregon may be one million years old or older (E.M. Benedict, personal communication, 1982). However, it is true that most of the best known lava tubes are only a few thousand years old. It is widely assumed that most lava tubes collapse fairly rapidly on a geologic time scale, although there seems to be little published data in support of this assumption. In any case, many lava tube caves containing troglobites are far too young for the species to have evolved in those caves. Kaumana Cave, Hawaii, contained several troglodyte species when it was only 90 years old (Howarth, 1972). To explain this, Howarth (1972, 1973) postulates "dispersal from one lava tube to another" via joints, aa clinker, vesicles, etc. Unfortunately, Howarth's wording implies something he clearly did not intend — the passage of individual animals from one cave to another via the small cavities between caves. Such dispersal would undoubtedly be so slow as to take several generations at least, and this in turn implies that migrants to a new cave would come directly from populations in the surrounding lava, not those in other caves.

Pahoehoe basalt formations, particularly those containing caves, generally consist of a succession of relatively thin flows rather than a single thick flow. The central massive phase of each flow is relatively impermeable; most of the permeability of basalt is concentrated near the flow contacts, and arises, in order of importance, from: scoria and other loose material; large loose blocks (like those observable on most recent lava flow surfaces); partings between flows; horizontal and vertical contraction joints; gas vesicles; cave passages; mechanical fractures; and tree casts (Brown, et al, 1975). For a diagram of these factors viewed as habitat, see Figure 2. Thus, a basalt formation contains a series of permeable layers, each presumably penetrable to troglobitic fauna. In these layers, particularly the upper ones, are the same major energy sources as present in caves: roots and organic solutes in seepage. The extent of cave passage habitat is minor in comparison to the total extent of the interflow permeable layers, particularly as most of a cave is empty space which does not constitute habitat for crawling invertebrates. A given area of the permeable layer occupied by scoria, joints, etc., must have much greater surface area than the same area occupied by a cave passage; this additional surface area is available for growth of slime, and colonization by troglobitic fauna. Howarth's implication that some of the Hawaiian troglobites have their main populations in penetrable caves is unproven and seems unlikely, at least for species known from two or more caves. The presence of a troglobitic species in more than one cave is in itself evidence that this species is able to enter, and therefore to colonize, the interflow layers. In my study area in Washington, there is much evidence that cave "populations" are minor adjuncts to the much larger populations in the surrounding lava.

I suggest, moreover, that the surface ancestors of some troglobitic species in basalt may have colonized the interflow layers directly, via joints and openings from the flow surface or erosional scarps, particularly those that have been enlarged by roots. This invasion mechanism seems especially likely for those species whose primary food source is roots. Such species would have colonized caves secondarily from the interflow layers. It should be mentioned here that most lava tubes intersect the interflow layer (as shown in Figure 2) due to erosion of the pre-flow surface by flowing lava in the active tube; thus, there is easy communication between the two habitats. Other species may have colonized caves first and the interflow layers secondarily, as Howarth suggests.

The rapidity with which subterranean fauna can colonize new lava flows is best demonstrated by the Hawaiian results, but is also evident in other regions. The Mt. St. Helens "Cave Basalt" in Washington, for example, is less than 2,000 years old and has been colonized by a few troglobites even though no other cave-bearing lava flow is closer than about 26 km. Thus, the subterranean fauna of a given volcanic region is supplied with new habitat at intervals as long as that region continues to produce basaltic lava. Even after volcanism has ceased, basalt can retain its permeability for long periods. The Miocene Columbia River Basalts of eastern Washington are 6-16 million years old and are still so permeable as to contain the dominant groundwater resource of the state. Admittedly, the climate of eastern Washington is relatively dry and soil formation correspondingly slow. Howarth (1973) and Bousfield and Howarth (1976) feel that in most maritime climate of the Hawaiian Islands, lava flows that are a few million years old have decomposed and silted up to the extent that the habitat of subterranean fauna is destroyed. This may be true, but I would like to see such conclusions supported by geologic evidence such as groundwater permeability, usually easy to obtain. I suspect that even in very old basalts some areas may retain enough permeability to support troglobites. Ultimately, geologic processes will render these accessible subterranean habitats fragmentary and isolated, whereupon additional geographic speciation of troglobites may be expected.

I conclude with a speculation based on the known layered

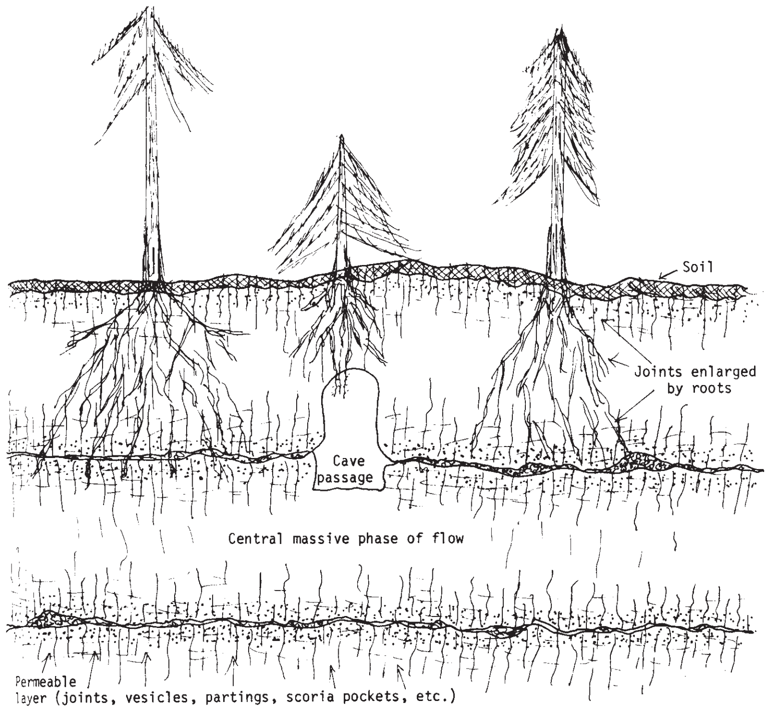

Figure 2. SUBTERRANEAN HABITATS OF BASALT

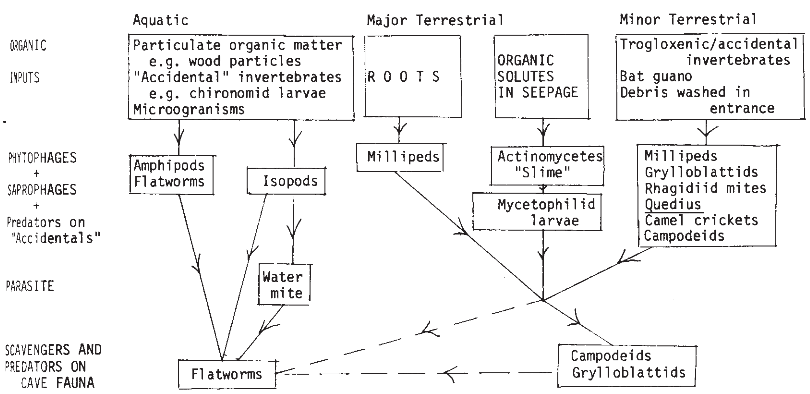

Figure 1. HYPOTHETICAL FOOD WEB FOR DEADHORSE CAVE, WASHINGTON

structure of subterranean habitats in basalt. The different layers in a given basalt formation will obviously have differing environments; the lower layers will have successively less organic input, and also less variable climate. The lowest layers will likely be saturated by groundwater, but there may be one or more unsaturated layers below the highest one in some areas. The central massive phase of each flow makes horizontal migration far more likely than vertical. Therefore, it seems possible that the interflow layers of a basalt formation will have different, and successively more depauperate, faunas, only the uppermost of which is generally accessible to cave explorers.

In addition to the still barely-touched study of subterranean fauna in volcanic caves, then, is the completely untouched study of the fauna of deeper basalt layers and of basalts containing no caves, such as the vast Columbia River Basalts (see above) and the Deccan Basalts of India. It is an extraordinarily promising field for future investigation — assuming, that is, that human ingenuity proves equal to the problem of developing suitable techniques.

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ERUPTIVE IMPACTS OF MOUNT ST. HELENS ON LOCAL BAT POPULATIONS

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INTRODUCTION

Mt. St. Helens, a volcano in Washington State, USA, erupted after a 123 year dormant period, resulting in displacement of material by landslide and vent explosions. Losses of most wildlife species could not be estimated because pre-eruptive data were non-existent. (USDA 1981). However, pre-eruptive bat data do exist. Here I present data on pre-eruptive locales which were important sites of concentrated bat activity and post-eruptive data and status of the above sites. Sites include nursery colonies, male roost areas and hibernacula.

METHODS

Pre-eruptive records are from Senger (1974), Adler (1976), and Perkins (1979). Post-eruptive data are personal records, USGS and USFS personnel communications, and members of the Oregon Grotto of the National Speleological Society, most notably J. Nieland, A. Purcell and B. Taylor.

Data area is divided into two segments for ease of discussion: (1) winter records from the blast area and south of the mountain; and (2) summer records from the blast area and from south of the mountain.

Site	Location	Use	Pre-erupt. Sp. Noted	No.	Post-erupt. Sp. noted	No.	Status
Mine Tunnel	B	H	UND	UND	-	-	D
Bat Cave	S	H	Pt Me Ml Mv My	80 2 4 19 1	Pt UND UND UND UND	80 UND UND UND UND	UNC UND UND UND UND
Spider Cave	S	H	Pt Ml Mv My	40 3 12 1	Pt UND UND UND	35 UND UND UND	UNC UND UND UND
Flow Cave	S	H	Pt	10	pt	3	UNC
Ape Cave	S	H	Ml Mv My	2 11 9	- - -	- - -	? ? ?
Ole's Cave	S	H	Pt	40	Pt	35	UNC
Little People's Cave	S	H	Pt	1-5	UND	UND	UND
Beaver Cave	S	H	Pt	2	-	0	?

TABLE 1. Pre and post-eruptive winter records of bats on Mt. St. Helens (winter). B=blast area; S=south side of the mountain; H=hibernaculum; UND=undetermined; UNC=unchanged; D=destroyed; MFT=mud flow threatens; MFI=mud flow inundated; Pt=Plecotus townsendii; Me=Myotis evotis; Ml=M. lucifugus; Mv=M. volans; My=M. yumanensis.

Site	Location	Use	Pre-erupt. Sp. Noted	No.	Post-erupt. Sp. noted	No.	Status
USFS Residence	B	NC	Ml	20	-	-	E
YMCA Camp	B	NC	Ml	30	-	-	E
St. Helens Lodge	B	NC	Ef	15	-	-	E
Swift Village	S	NC	My	50	My	55	UNC
Swift Village	S	NC	Mv	35	Mv	30	UNC
Crane Lake	S	NC	My	12	-	-	E
Merrill Lake	S	MR/F	Ln	25	UND	UND	UNC
Kalama Springs Campground	S	MR	Ml	?	UND	UND	UNC
Ape Cave	S	SW	Myotis Ml	500 ?	UND UND	UND UND	UNC UNC
Moss Springs	S	MR/F	Mc Me Ml My Ln	1 4 1 1 1	- - - - -	- - - - -	E E E E E

TABLE 2. Pre and post-eruptive records of bats on Mt. St. Helens (summer). B=blast area; S=south side of the mountain; NC=nursery colony; MR=male roost; F=feeding/drinking area; MFI=mud flow inundated; UND=undetermined; UNC=unchanged; E=extirpated; Me=Myotis evotis; Ml=M. lucifugus; Mv=M. volans; My=M. yumanensis; Mc=M. californicus; Ef=Eptesicus fuscus; Ln=Lasionycteris noctivagans; SW=Swarming area.

RESULTS

Results indicate bat activity sites in the blast/mud flow paths were eliminated.

Mine Tunnel. Entrance to this probable hibernaculum was most likely filled or blocked with debris from ash and tree blowdowns.

Spirit Lake. The three nursery roosts along spirit Lake are presently under three to 60 m of blast material. If bats had arrived prior to May 18, 1980, their survival is highly questionable. If arrival was post-eruption 1980, problems would have occurred in finding an alternate roost site. Present data indicate the colonies were eliminated.

Crane Lake. This site was inundated by mud flows of the same and later dates. Status of the colony, which roosted in a hollow tree is presently unknown. Alternate roosts (buildings, bridges, old growth trees) are available within 8 km of the lake. Survival of this small colony is likely.

Moss Springs. Inundation of this site by mud flows was the second course change for Pine Creek in less than 15 years. The upper flow route was altered by an earthquake in the late 1960s which allowed the formation of Moss Springs. This site was especially rich in bat diversity and roost sites.

Rerouting of water courses north and south of the mountain will probably redistribute remaining non-colony summer bat populations. Survival of these individuals will be heavily dependent on adequate roost sites near new water courses and/or insect populations.

Hibernacula and other bat activity sites outside the blast/mud flow paths are relatively intact. Populations appear to be at pre-eruption level, at least for P. townsendii. Myotis sp. has been at Little Red River Cave since the eruption. No other sightings have been reported to me.

A positive note is the return of a nursery colony of about 20 P. townsendii to Powerline Cave this spring. Red Zone closures probably resulted in a lower disturbance factor allowing the bats to re-occupy the roost which was abandoned about 1967. Continued human exclusion here may result in continued use of this site.

It will be interesting to note if large numbers of Myotis sp. will again swarm at the Ape Cave entrance this fall.

CONCLUSION

Bat losses due to the May 18, 1980 eruption and subsequent activities include at least three nursery colonies, one forage site, and one probable hibernacula. Unaffected were two nursery colonies, two forage sites, and four hibernacula. Further protection of bat populations surrounding the mountain may be necessary for populations to grow enough to repopulate extirpated areas.

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A COMPARISON OF THE TROGLOBITIC HARVESTMEN FROM LAVA TUBES AND LIMESTONE CAVES

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Some of the harvestmen known from lava tubes in the states of Washington and Idaho are comparable to the world's most specialized limestone cave troglobites. These lava tube species include Speleomaster lexi, Speleomaster pecki, and Speleonychia sengeri described by Briggs (1974) and discussed in Peck (1973). In order to apply a measure of cave adaptation to these harvestmen, the important troglomorphisms have been quantified and shown to be reduced or absent in related epigean species.

The harvestmen troglomorphisms selected for this comparison include increased tarsal segment counts, loss of the retina and lens, loss of the eye tubercle, depigmentation, relative lengthening of the second leg, and smoothening of the scute (carapace). All but the latter troglomorphism were applied to Australian cave harvestmen by Hunt (1972). An additional troglomorphism used by Hunt, the elongation of tarsal claws, was not used in this study because claw measurements are seldom reported by taxonomists. A specialization score for a troglobite was obtained by assigning numerical values to the troglomorphisms and selecting the most closely related epigean so that a difference between the sums for these species could be determined. The more objective values used were the sum of the tarsal segments for legs one to four and the ratio of the second leg length to the body length. A less objective score had to be assigned for relative depigmentation, loss of the eye tubercle, and scute smoothness. The maximum score for these troglomorphisms was set as follows: no pigment- 5, no eye tubercle - 20, and smooth scute - 10. Relative loss of eyes was not used in the specialization score because only harvestmen with a complete loss of eyes were considered sufficiently troglobitic for this study. If the related epigean is assumed to resemble the ancestral stock from which the troglobite evolved, subtracting the specialization score for the epigean gives emphasis to derived troglomorphisms.

A world-wide literature search yielded ten cave harvestmen more specialized by this measurement than the least specialized of the above three lava tube species (see Tables 1 and 2). These were found in limestone caves in Europe, Venezuela, Mexico and United States. The European troglobites include: Dinaria vjetrenicae Hadzi, Travunia troglodytes (Roewer), Travunia anophthalma (Absolon and Kratochvil), and Arbasus caecus (Simon), which are redescribed in Roewer (1935); Buermarina patrizii (Roewer[1956]); and Paralola buresi (Kratochvil, Balat and Pelikan [1958]). The venezuelan troglobite is Phalangozea bordoni (Munoz Cuevas [1975]) and the Mexican troglobite is Hoplobunus inops (Goodnight and Goodnight [1971]). From the United States, the troglobites are Phalangodes armata (Tellkampf [1844]), and Tolus appalachius (Goodnight and Goodnight [1942]). The lack of highly specialized harvestmen from Africa, Asia and Australia may be due to insufficient collecting, but the lack from islands is probably related to land mass size and youth. Lava tube harvestmen in this study are listed with locality data and related epigean species.

TABLE 1. Leading cavernicolous harvestmen.

	Maximum Tarsal Segment Count	2nd Leg to Body Length Ratio	Eye Tubercle	Scute	Pigment	Related Epigean Total	Relative Score
Peltonychia leprieuri (Italy)	3-5-4-4	3	0	0	0	19	epigean
Dinaria vjetrenicae (Yugoslavia)	5-12-4-4	10	10 (very low)	10 (smooth)	5	19	41
Travunia anophthalma (Dalmatia)	6-14-4-4	Unreported--assume 10	20 (none)	10	5	19	54 (?)
Travunia troglodytes (Dalmatia)	4-9-4-4	8	20	5 (faint areas)	5	19	40
Arbasus caecus (Pyrenees)	3-11-4-4	Unreported-assume 8	20	10	5	19	46 (?)
Buemarina patrizli (Italy)	3-6-3-4	6	10	10	5	61	28
Vima sp. and *Trinella* sp. (Trinidad)	9-24-7-9	12	0	0	0	61	epigean
Phalangozeabordoni (Venezuela)	12-28-8-8	15	20	5	5	61	40
Hoplobunus barretti (Morelos)	5-9-7-7	2	0	0	0	30	epigean
Hoplobunusinops (Tamaulipas)	8-15-8-8	10	5 (small)	5	5	30	34
Hypothetical ancestor	3-5-4-4?	2?	0	0	0	18	epigean
Paralola buresi (Bulgaria)	4-6-5-5	6	20	10	5	18	27 (?)
Bishopelia lacinosa (Southeastern USA)	4-7-5-6	3	0	0	0	25	epigean
Phalangodes armata (Kentucky)	5-8-5-6	9	5	10	5	25	28
Tolus appalachius (Tennessee)	5-10-5-6	8	0	10	5	25	24

Speleonychia sengeri Briggs 1974:207. **Known Localities:** lava tubes near Trout Lake, Skamania County, Washington. **Related Epigean Species:** *Yuria pulchra* Suzuki of Japan. This is the nearest known representative of the family Travuniidae to which *Speleonychia sengeri* belongs.

Speleomaster lexi Briggs 1974:210. **Known Localities:** lava tubes near Shoshone, Lincoln County, Idaho. **Related Epigean Species:** *Cryptomaster leviathan* Briggs of the Oregon Coast is the nearest known representative of the family Erebomastridae to which *Speleomaster lexi* belongs.

Speleomaster pecki Briggs 1974:212. **Known Locality:** Boy Scout Cave, Craters of the Moon National Monument, Butte County, Idaho. **Related Epigean Species:** as for *Speleomaster lexi*.

In conclusion, comparing these highly specialized lava tube harvestmen with the most specialized limestone troglobites strengthens the argument that "the internal environmental conditions (of lava tubes) have attracted, isolated and supported faunas in the same way as have those of limestone caves." (Peck, 1973) Other recent workers have made similar suggestions (for example, see Howarth, 1972). This comparison study also shows the necessity of including the related epigean and presumably ancestral stock in measuring the derived aspect of cave adaptation. Tropical troglobites, such as those in Mexico and Venezuela, would have much higher specialization scores were it not for the pre-existing troglomorphisms in tropical epigeans. As expected, the Travuniidae in European caves, characterized by Vandel (1965) as "living fossils," produced the highest specialization scores.

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TABLE 2. Lava Tube Harvestmen.

	Maximum Tarsal Segment Count	2nd Leg to Body Length Ratio	Eye Tubercle	Scute	Pigment	Related Epigean Total	Relative Score
Yuria pulchra(Japan)	4-6-4-4	3	0	0	0	21	epigean
Speleonychia sengeri (White Salmon, Washington)	4-17-4-4	5	10	10	5	21	38
Cryptomaster leviathan (Oregon Coast)	5-15-5-6	3	0	5	0	39	epigean
Speleomaster lexi (Shoshone, Idaho)	9-22-8-8	7	5	10	5	39	35
Speleomaster pecki (Craters of the Moon, Idaho)	7-16-5-7	7	5	10	5	39	23