August 1972

1972: Proceedings of the International Symposium on Vulcanospeleology and its Extraterrestrial Applications: A Special Session of the 29th Annual Convention of the National Speleological Society White Salmon, Washington, 16 August 1972

William R. Halliday

PROCEEDINGS
of the
INTERNATIONAL SYMPOSIUM ON VULCANOSPELEOLOGY
and its
EXTRATERRESTRIAL APPLICATIONS

A Special Session of the 29th. Annual Convention
of the National Speleological Society
White Salmon, Washington 16 August 1972

Auf Stein gez. v. P. Brugier. Gedr. v. J. Lier.

LA CUEVA DE LOS VERDES

Cover photograph: The traditional calcareospeleologist's concept of lava tube caves, evidently sketched by someone who had never seen one, to illustrate Hartung's monograph on the geology of Lanzarote and Fuerteventura (see page 43).

Printing note: Pages 22, 23, 24, 37, 38, 41, and 42 were foldouts in the original, 11 by 15 inches (about 28 by 38 cm) in size. Special attention will be required to print those pages from the PDF file at their orginal magnification.

The cave map that appears on pages 22 and 23 can be downloaded in assembled form as a separate PDF file. The same is true of the map on pages 24 and 25.

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Chairman and Editor

A Special Publication of the Western Speleological Survey

in cooperation with the

National Speleological Society

Seattle

1976

EDITOR'S INTRODUCTION AND APOLOGY

At this 1972 symposium, I publically commented on the long delays which have lessened the value of published proceedings of all-too-many other symposia. Worse, I vowed that no such delays would happen this time. My apologies!

Still worse, borrowed tape recorders failed their intended mission of preserving the exact texts of papers and the subsequent discussions. The former have been reconstructed reasonably well, --I think-- but the various unsystematic notes of discussions proved too fragmentary to be very useful. This was a serious and regrettable loss. Especially pertinent were comments of several speakers who have been unable to find speleogenetic sheer planes previously described by Ollier and Brown. Discussion of the Harters' classification also was especially important. The existance of rift caves (such as Crystal Ice Cave, Idaho) and of surface tube caves was overwhelmingly accepted, but there was no concensus on whether trench and semi-trench caves should be differentiated. Other debate centered around their classification of several specific as rift caves (some held that rifts rarely were cooperative in aligning themselves neatly down-slope), and whether the names of the Harter classes were unnecessarily confusing.

As a result of the reconstruction necessary under these circumstances, the proceedings as published here differ slightly from the actual program. Yet the reconstruction was planned to preserve both the content and the flavor of the meeting. In my opinion, it was successful in this. A small amount of explanatory material has been added for clarity; this is primarily in the Harter papers. Some speakers whose work was evolving especially fast preferred to not to submit now-outmoded texts; their contributions are reflected by abstract only. Unfortunately, production costs required omission of many photographs included in various papers. Others proved unsuitable for black and white reproduction, and your editor was forced to resort to substitution.

Unsurprisingly, the symposium did not cover all issues current in this new and rapidly evolving field. Pseudokarstic piracy of flow units was barely touched-upon. Downcutting by intratubal flows received little more mention. Few if any of the theoretical models seemed to envisage any lava tube formation in pre-existing steep-walled stream courses: a bit of a disappointment to this editor who fancies that he sees evidence of all of these in perplexing Dynamited Cave, Washington, and elsewhere. Perhaps more surprisingly, successive deposition of lateral coatings in rifts such as that described by Jim Papadakis seems to have been considered to be exclusively the result of vertical shifts in the level of molten lava, with no consideration of successive longitudinal flow: clearly a major factor in the geologic history of the island of Hawaii.

But these are minor omissions. The wealth of data accumulated through this symposium is impressive. Today, more than three years after the event, its significance is manifest if only by the continuing need for publication of these proceedings.

Again my apologies that its appearance has been delayed so long.

William R. Halliday
Director,
Western Speleological Survey
Seattle
20 December 1975

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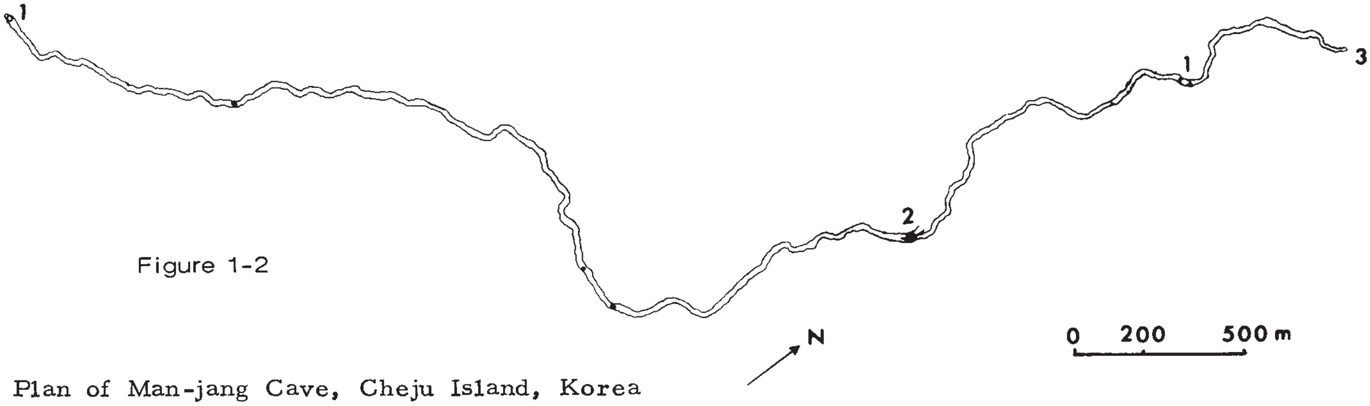

Figure 1-2

Plan of Man-jang Cave, Cheju Island, Korea

Scale 1:20,000

Reduced and simplified from 1:2,000 map by
Speleological Society of Korea, courtesy Larry Peterson

(1) collapse inks apparently segmenting system

(2) main entrance, leading into main part of system and also into unmapped segment estimated to be about 1,800 m long

(3) apparent lower end of cave; 380 m to next cave.

Figure 1-1: Ignimbrite blister cave. Photo by Dr.Anthony Sutcliffe.

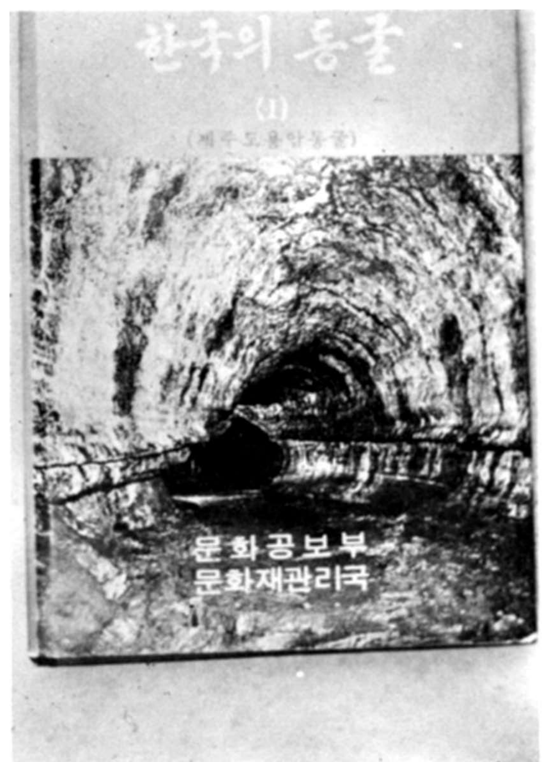

Figure 1-3: Korean Caves: Manjang Cave (Red Dragon Cave) on Cheju Island, published by Korean Ministry of Information and Cultural Preservation.

Moderator's Remarks
by
William R. Halliday
Symposium Chairman

Welcome to the International Symposium on Vulcanospeleology and its Extraterrestrial Applications -- to our knowledge the first such meeting ever held, and certainly long overdue.

Because of the large number of papers submitted, participants are hereby notified that I intend to be ruthless in maintaining our schedule so that at least a little time will be available for discussion of each paper.

As will be seen as we proceed, there are some minor changes from the preliminary program. Perhaps the most important of these are the title and content of Alan Hatheway's paper. Frank Howarth and Alan Swanson have consulted and decided to reverse the order of their papers.

I bring you the greetings of a few would-be participants unable to attend, and others interested in the symposium but overwhelmed by obstacles of time, distance, and obligations. Jim Papadakis is in the middle of the busiest part of the tourist season of his Crystal Ice Caves, and has sent us a multimedia presentation in absentia. Alan Howard telephoned yesterday expressing regrets at being swamped by the Apollo program and that his paper must be read in abstract only. This will be done by Will White of Pennsylvania State University, Chairman of the N. S. S. Section on Geology. Bernie Joyce sends trans-Pacific greetings from "Down Under;" his paper will be read by W. R. (Ted) Livingston, state geologist of Washington. Stuart Peck is engaged in field work in British Honduras; his will be read by a fellow temporary Canadian biologist, Russell Harmon. Transatlantic greetings are expressed by Messr. s Wood and Mills; their notable report will be read by Eugene Kiver, Professor of Geology at Eastern Washington State College. Anne Atkinson personally brings the compliments of her fellow Australian vulcanospeleologist, Neville Stevens, and will present their joint paper. And northwestern vulcanospeleologist Charles Larson, who as convention chairman thought for a while he was going to get away with delegating all the work to others, will present Alan Hatheway's provocative paper.

I am specifically authorized to express the compliments of the Grupo Vulcanoespeleologico of the Tenerife Mountain Club, with headquarters at La Guancha, Tenerife, which I recently visited. Its members were delighted to learn of the growing world-wide interest in their favorite topic.

Astronaut, former N. S. S. member, and calcareospeleologist Karl Henize sends his regrets, mentioning that vulcanospeleology is a part of the current training of American astronauts. Also expressing regret are John Guest and Anthony Sutcliffe of London, both of who have major articles scheduled in a forthcoming vulcanospeleological issue of Studies in Speleology, the notable international publication of the Pengelly association in England. I commend this publication highly to anyone unfamiliar with it. Anthony sends this slide of a type of volcanic cave unknown in the western hemisphere, showing one of a number of numerous ignimbrite blister caves in the Mount Fantale region of Ethiopia (Fig. 1-1). *

Even without considerations of its extraterrestrial applications, vulcanospeleology suddenly has come into its own. This has occurred so rapidly that communications have lagged badly, which is why we are here today.

This symposium obviously will not even solve some of the most superficial unanswered questions, like the location of the world's longest lava tube cave -- the Canary Islands, Cheju Island, Korea, where Manjang Cave (Fig. 1-2) has been the subject of a recent book (Fig. 1-3), Hawaii, Skamania County, Washington, or elsewhere. Answers to that and many more important questions will evolve only in the course of systematic field work. But at least we can begin here. Already from the convention guidebook (Halliday, 1972), it is evident that the terms "lava tube" and "lava cave" are not synonymous. I would suggest that any skeptics in the audience take a look at the map of Dead Horse Cave (Fig. 1-4). Much needed is standardization of nomenclature for example defining such basic terms as "lava tube", "lava tube system", and "megasystem".

Today we seek common ground long overdue.

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* After the symposium was completed, Mr. J. W. Simons, president of the Cave Exploration Group of East Africa expressed keen regret that a communications gap in their organization had prevented their submission of a major paper on the noteworthy lava tube caves of Mount Suswa. A preliminary report on these caves appeared in Volume 1, no. 1 of Studies in Speleology.

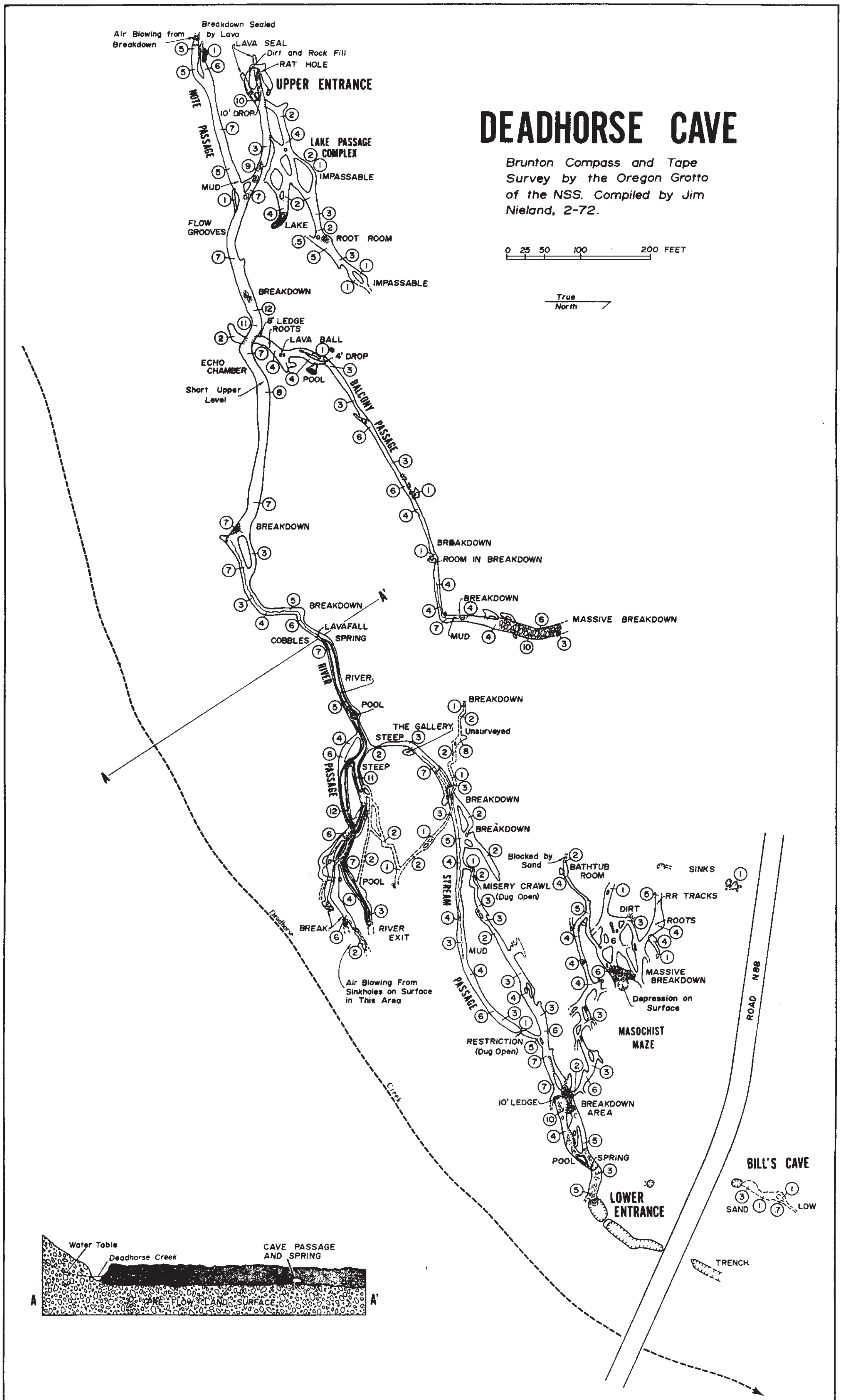

DEADHORSE CAVE
Brunton Compass and Tape Survey by the Oregon Grotto of the NSS. Compiled by Jim Nieland, 2-72.
0 25 50 100 200 FEET
True North
UPPER ENTRANCE
LAKE PASSAGE COMPLEX
NOTE PASSAGE
BALCONY PASSAGE
RIVER PASSAGE
STREAM PASSAGE
MASOCHIST MAZE
LOWER ENTRANCE
BILL'S CAVE
ROAD N88
Deadhorse Creek
Water Table
CAVE PASSAGE AND SPRING
PRE-FLOW LAND SURFACE
A
A'

Figure 1-4

FEATURES OF LAVA TUBE CAVES OF THE PACIFIC NORTHWEST:
A Photographic Presentation

Beth Wolff
Oregon Grotto of the National Speleological Society

EXPANDED ABSTRACT

Many lava tubes formed in the Pacific Northwest during the recent volcanic activity. The resulting caves have been found to have a wide variety of speleothems and distinctive markings. This photographic presentation is based on visits to many lava tube caves in the Pacific Northwest, with specific observation and compilation of the features thereof. In addition to features described in the Convention guidebook intrusive lava dripstone speleothems are seen in one Klickitat County cave (Fig. 2-1), and deeply buried lava tube caves are present in southern Oregon.

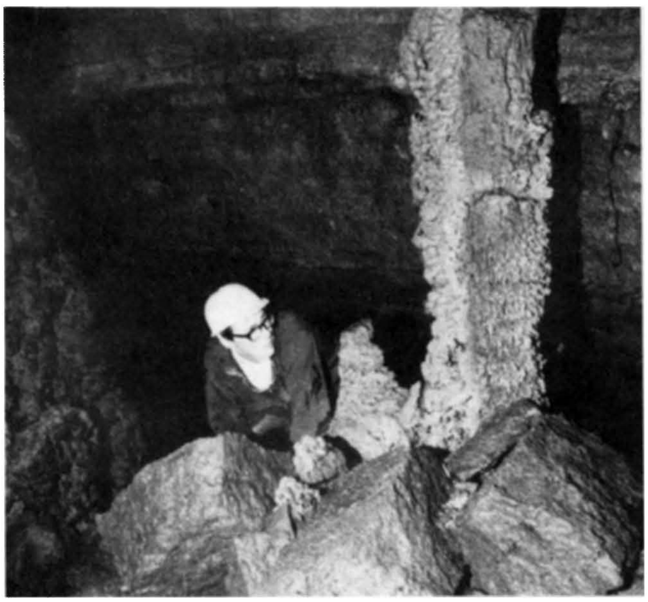


Figure 2-1: Intruding lava dripstone speleothems in a Kilickitat Co. lava tube. Halliday photo.

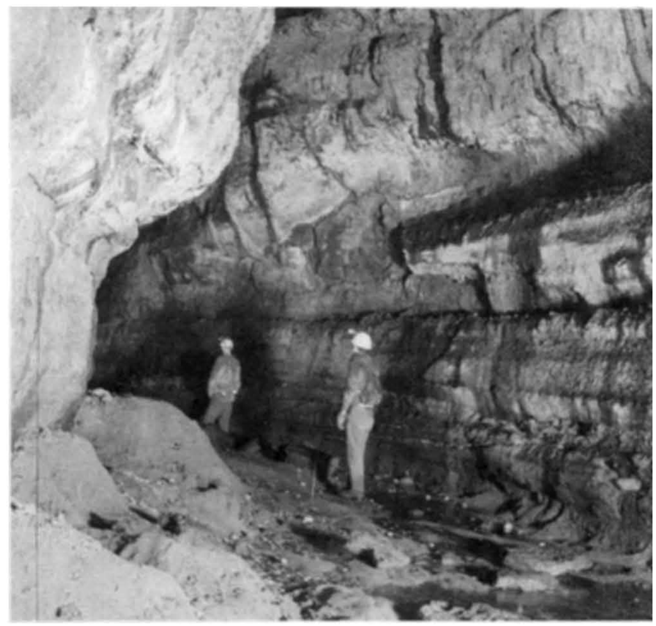


Figure 2-3: Main passage, Ape Cave, southwest Washington. Halliday photo.

Figure 2-2: Entrance to Mowich Creek Cave, Oregon. Wolff photo.

Figure 2-4: Big Room, Dynamited Cave, southwest Washington. Halliday photo.

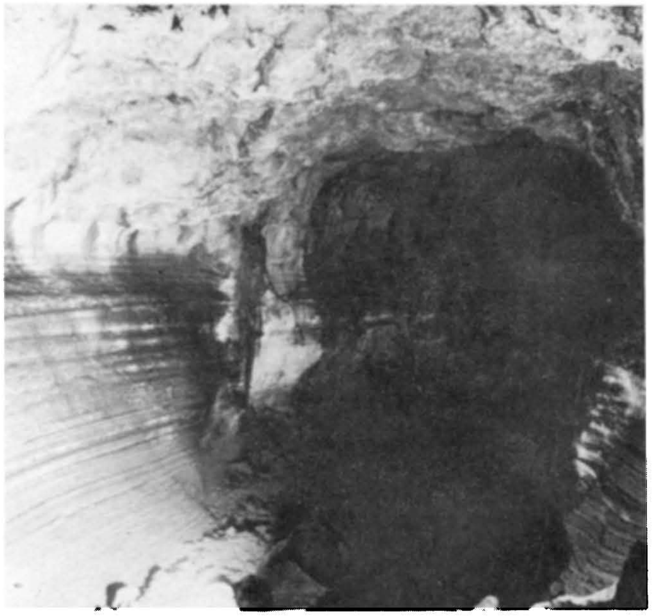


Figure 2-5: Multiple lateral grooves in a southwest Washington lava tube. Halliday photo.

Figure 2-8: Multiple levees and tube-in-tube in Prince Albert Cave, southwest Washington. Larson photo.

Figure 2-10: Lava stalagmites in a southwest Washington lava tube. Halliday photo.

Figure 2-6: Levees in a side passage of Ape Cave, southwest Washington. Halliday photo.

Figure 2-9: Lateral coatings in Dynamited Cave, southwest Washington. Halliday photo.

Figure 2-7: Lava stalactite in a southwest Washington lava tube. Halliday photo.

LAVA TUBES AT PISGAH CRATER, CALIFORNIA

Russell G. Harter
Southern California Grotto of the National Speleological Society

Pisgah Crater lava field is in the Mojave Desert of southern California, about 175 miles northeast of Los Angeles. Little weathering has occurred since the lava erupted, and there is almost no vegetation. Because of the quality of preservation, and numerous lucid examples of lava features, the locality is an excellent area for the study of flow features in basaltic lava.

At least two hundred lava tube caves are present. Most of the caves are small; only 22 are greater than 100 feet in length. The longest are SPJ (about 1,500 feet), and Glove Cave (1,100 feet).

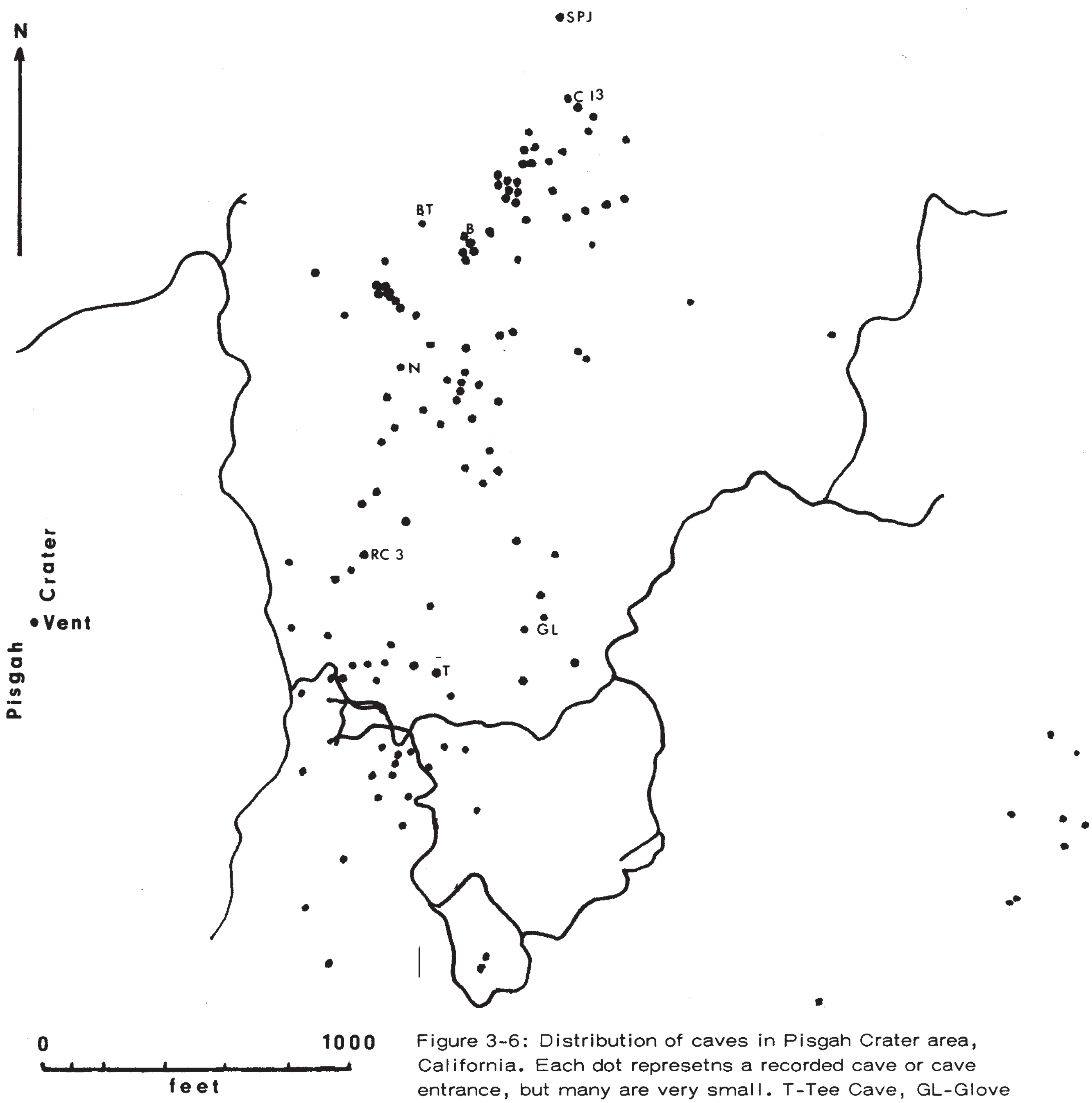


Figure 3-6: Distribution of caves in Pisgah Crater area, California. Each dot represetns a recorded cave or cave entrance, but many are very small. T-Tee Cave, GL-Glove Cave, curving lines are roads.

VENT

The Pisgah vent is apparently very unusual. Few cinder cones in the western United States have open vents. Usually they fill soon after the eruption ceases, with cinder which falls back into the hole. The result is a conical depression with rounded bottom, as Cinder Cone at Mt. Lassen, or Lava Butte near Bend, Oregon.

Pisgah Crater partly filled with a pahoehoe lake, which solidified in place and formed a flat. At least two vents passed up through this lava floor. One, toward the west, built a low cinder mound. This vent is completely filled. The other vent is toward the north of the crater floor, and is open for about 25 feet. It is not vertical, but is at a low angle to the flat crater floor and trends about N20E from the entrance. The inside is badly broken, and the low end is filled with loose rubble. The walls and ceiling are sintered cinder and spatter, implying that this vent structure predates the lava which later surrounded it. The vent does show signs of having been active after the lava was emplaced. Numerous fragments of spatter are found loose around the vent, where

Figure 3-1: General view of the Pisgah area flow with Pisgah Crater in distance. Don Rimbach photo.

Figure 3-2: Partially collapsed surface tube in Pisgah area. Don Rimbach photo.

Figure 3-3: Partially mummified remains of a mountain sheep in Pisgah cave in December 1962. Don Rimbach photo.

Figure 3-5: Interior of a pisgah cave. Don Rimbach photo.

they were evidently weathered loose from a poorly consolidated spatter cone or similar structure. The entrance to the vent is a sink which trends southward and ends abruptly about 30 feet from the entrance.

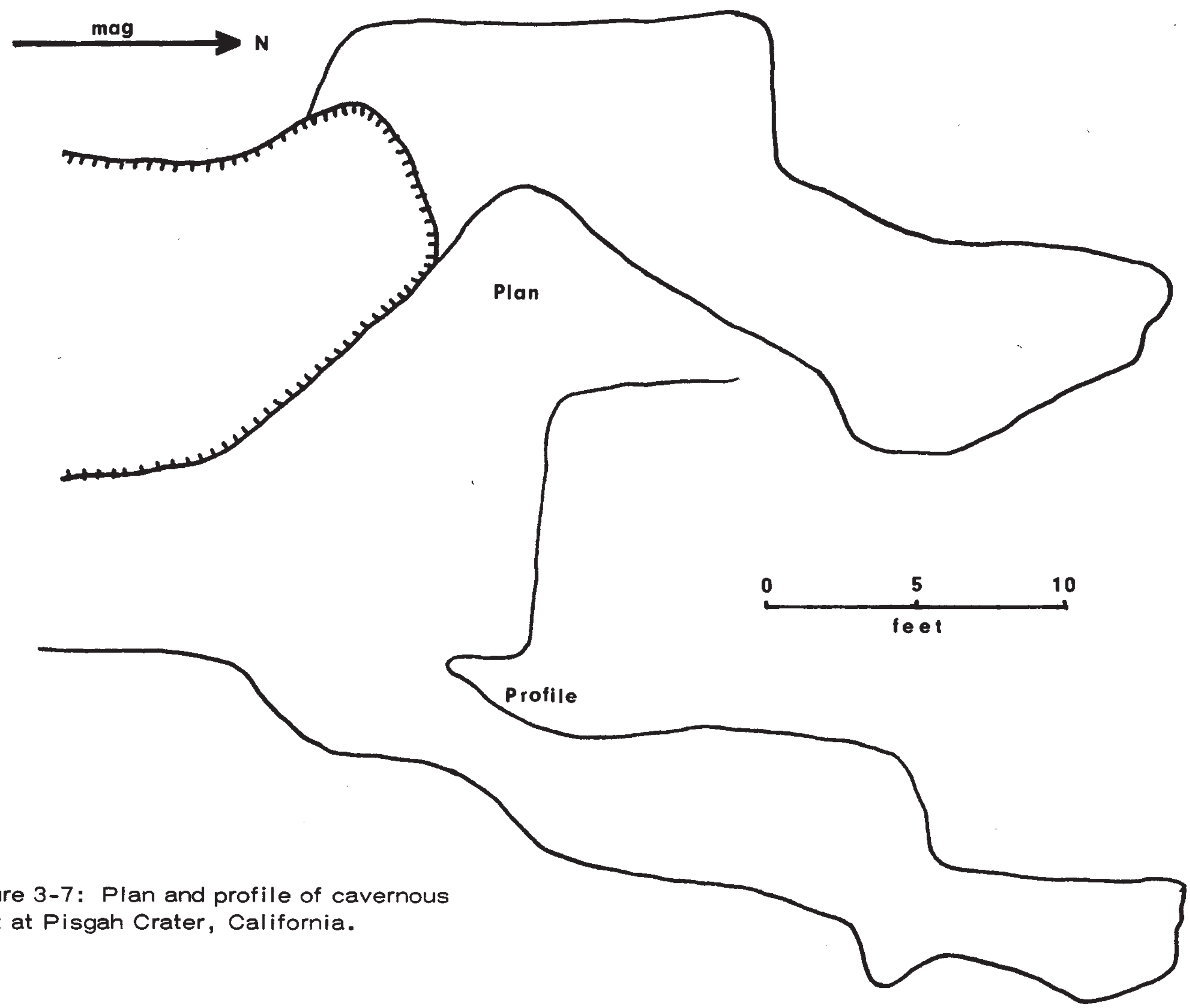


Figure 3-7: Plan and profile of cavernous vent at Pisgah Crater, California.

GLOVE CAVE

Glove Cave is the longest, and perhaps the best known cave at Pisgah. It apparently has been known for many years. The lower section, however, may have first been entered less than 15 years ago. In this section are bones of a mountain sheep which were undisturbed until recently (Fig. 3-7). Since 1965 or 1966 the bones have been vandalized, trampled, and carried off. Their age has not been determined. When first found, skin and a hair were present so they may be very recent. How the sheep got into the cave is unclear; the bones are almost 280 feet from the entrance and the first 75 feet are so low that it could not have walked upright through that section.

Glove Cave has a total of 1,100 feet of passage. It consists mostly of a single passage, but has some complexities. Three entrances are present within a distance of 125 feet. The uppermost entrance is at the uphill end of a collapse. The middle entrance is in the same collapse. The lower entrance is a smaller, separate collapse. The upper collapse fell partially while there was still flow in the tube, and the connecting passage between the upper and lower sections of the cave is partly the lava's route through the breakdown. The tube is buried for most of its length, and its flow origin is uncertain. Near the entrances, the only overlying lava is some which overflowed through gaps in the roof. Uphill from the entrances, later flows have covered the tube. Downhill from the entrances, the tube is buried by its own lava.

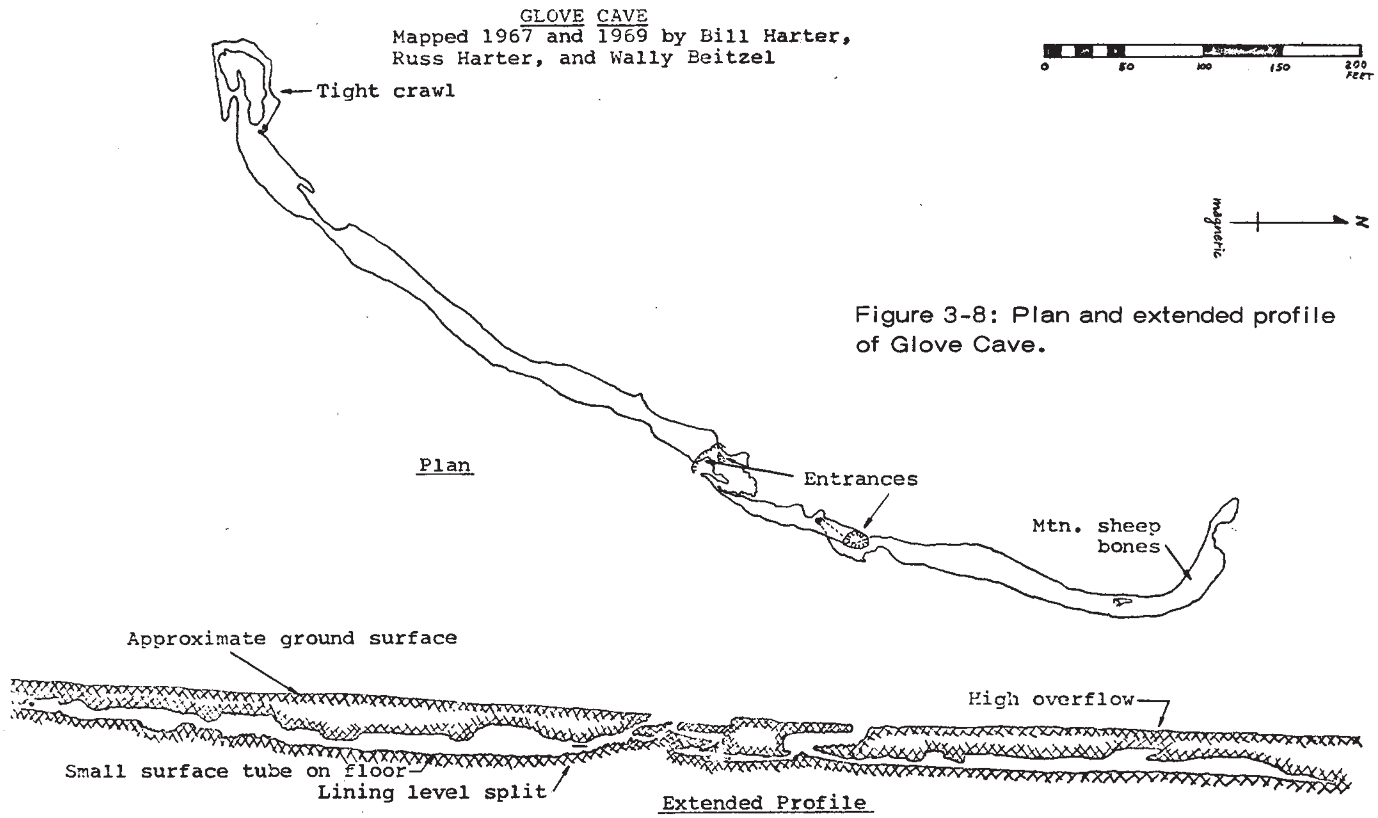


Figure 3-8: Plan and extended profile of Glove Cave.

The section of the cave downhill from the lower entrance is true trench. It split into two levels near the entrance and the upper level plugged. The lower level is now a passage three to four feet high. The two levels join further into the cave, and form a single large passage. The walls are massive and the cross-section is square. The trench shelf is present on one wall only, at a spot near the passage end.

The upper section of Glove Cave is semi-trench. Its walls are thin layers of lava which overflowed to the sides of the stream, building gradually. The upper section of the cave, unlike the shorter lower section, has much breakdown. Some of the breakdown occurred at an intermediate stage, and large blocks on the floor were washed over with lava flowing through the tube.

A loop of surface tube connects to the upper end of the semitrench passage. The main flow came through the semitrench, and an overflow from it fed the surface tube. Two surface tubes flowed in different directions from the rise chamber, and both of them later connected back to the main semitrench.

"B" CAVE

B Cave is a small but moderately complex lava tube cave. Its total length of passage is about 545 feet . The greatest depth below the surface is about 20 feet. The cave is the drained lowest portion of a local lava distributory system. This system is a small part of a much larger distributory system that includes at least 87 caves. Most are smaller than B Cave, but a few are larger. B Cave is our permanent field camp. There are a table and two chairs at the upper of the cave's two entrances.

The complexity of passages is caused by a succession of lava streams that flowed over and beside one another. Primary directions of lava movement are shown by arrows on the map (Fig. 3-9). The first stream of the series made the lowest or third level. Its walls are levees, built up by thin sheets of lava that overflowed to the sides. This makes it a semitrench lava channel. One small stream flowed into this channel from the east. The main channel split and rejoined. A portion of the west wall gave way, forming another branch. The lava tubes contined downhill, but plugged when the presently-open portion finally drained. Just uphill of the present upper entrance, the first channel overflowed through the roof. This fed the second-level lava stream. Its outer surface chilled, making a thin crust that arched over the entire stream. This is a surface tube. Its channels began to diverge, but two of them reconnected, making another semitrench.

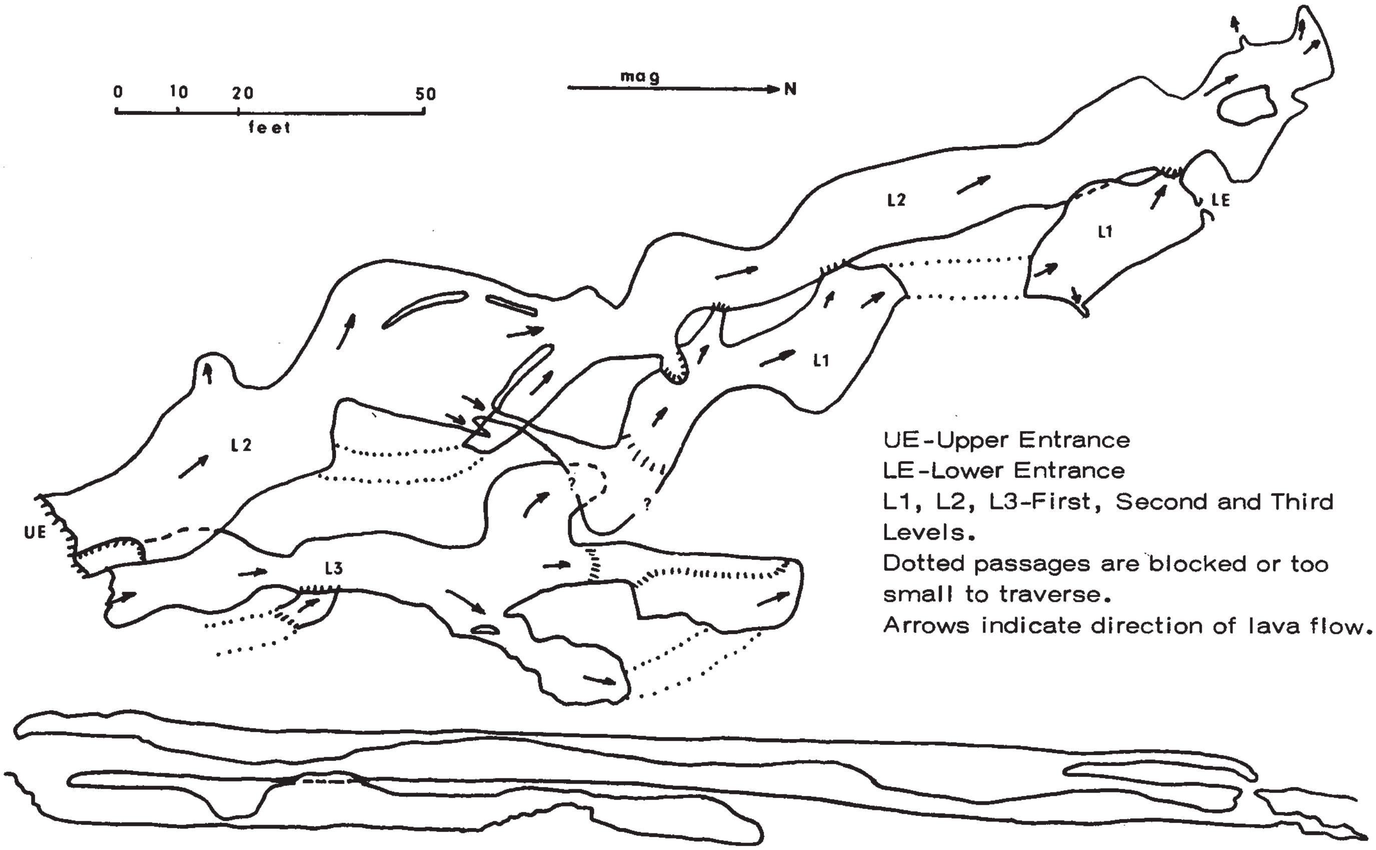


Figure 3-9: Plan and extended profile, B Cave, Pisgah Crater, California.

Another branch of the surface tube flowed on top of the east wall of the new semitrench. This is the first level. It ended in a chamber that emptied back into the second-level semitrench passage from above.

Near the upper entrance, the passage is higher than it is a few feet further into the cave. Lava flowed out through a hole in the roof at this point, building the total roof thickness. The overflow made a small pool that fed several solid streams and one surface tube (BT). The connection of the pool and tube below is now plugged. While lava still flowed through the larger tube, pieces of its initial roof crust cooled, shrank, and fell into the lava stream. The broken surfaces in the ceiling were remelted by hot gases. The result is the relatively high, but irregular ceiling near the upper entrance. The upper entrance of the cave was formed by the collapse of the part of the lava tube roof. The lower entrance is artificial. It was made by the removal of part of the surface tube wall, which is only about one foot thick.

RC3

RC3 is a tunnel. It has two entrances; the upper entrance plus a vertical shaft four feet in diameter and 25 feet deep at the lower end. The cave essentially consists of two chambers connected by a small crawlway. The upper chamber is heavily broken down and has a floor of huge boulders. A lead in talus heading uphill under the collapse extends at least 50 feet from the room. The breakdown in this chamber has such magnetic properties that it caused many difficulties in surveying.

From above, the lower end of the upper chamber appears closed by rubble, but a connection exists to a large lower chamber which contains little breakdown and presents no magnetic troubles. The ceiling is covered with remelt, but well developed stalactites are absent.

N HOLE

N Hole is a small surface tube which was fed from the vicinity of Station 7 A. It is above the general surface at its uphill end, and the entrance is in a low swale. The cave proceeds downhill from the entrance, continuing under a low hill which buries the tube. The lower end of the tube terminates in a low room with a dust-covered floor which is relatively level. Except for breakdown at the entrances, the cave is almost totally intact. The main entrance was enlarged by removing fallen rock from the floor. The uphill entrance was too small to enter when first found.

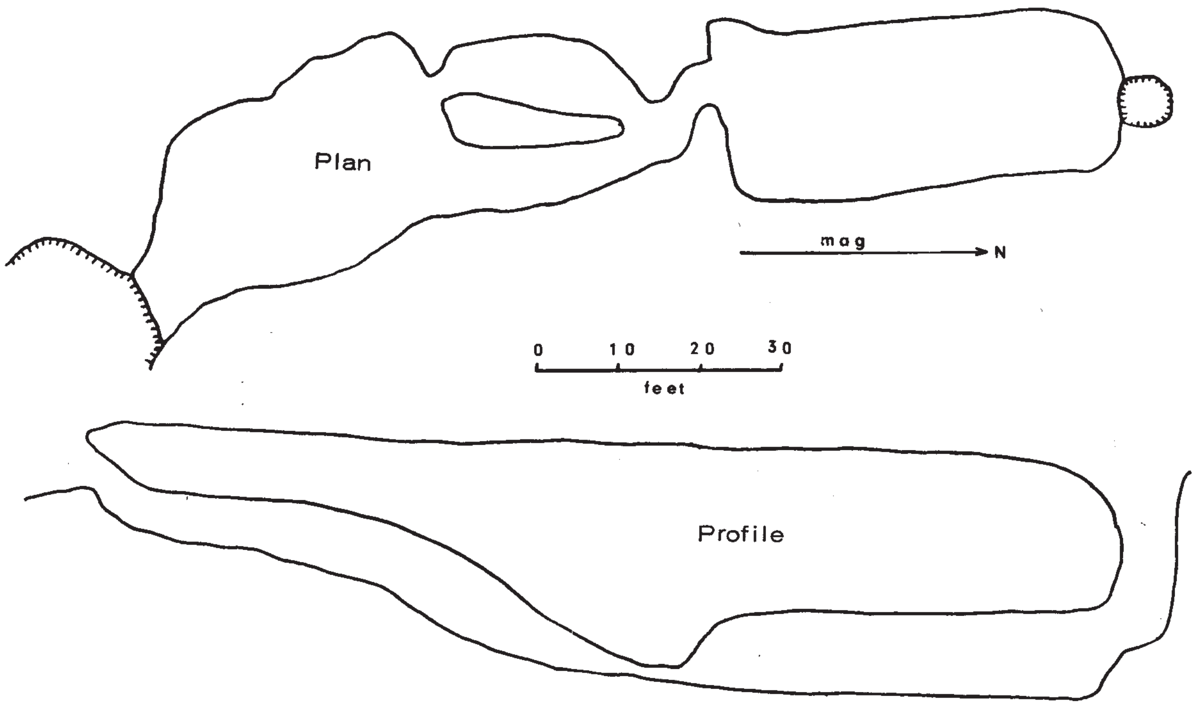


Figure 3-10: Plan and profile of Cave RC3, Pisgah Crater, California.

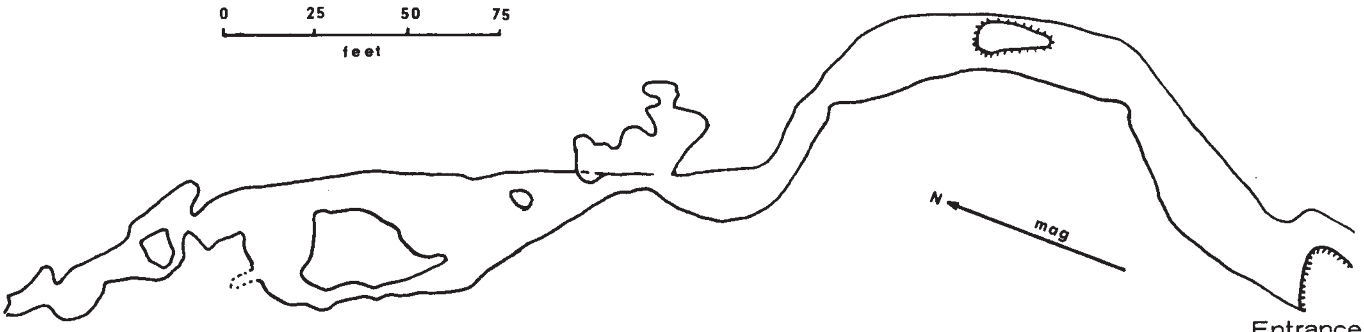


Figure 3-11: Plan of Cave C13N, Pisgah Crater, California

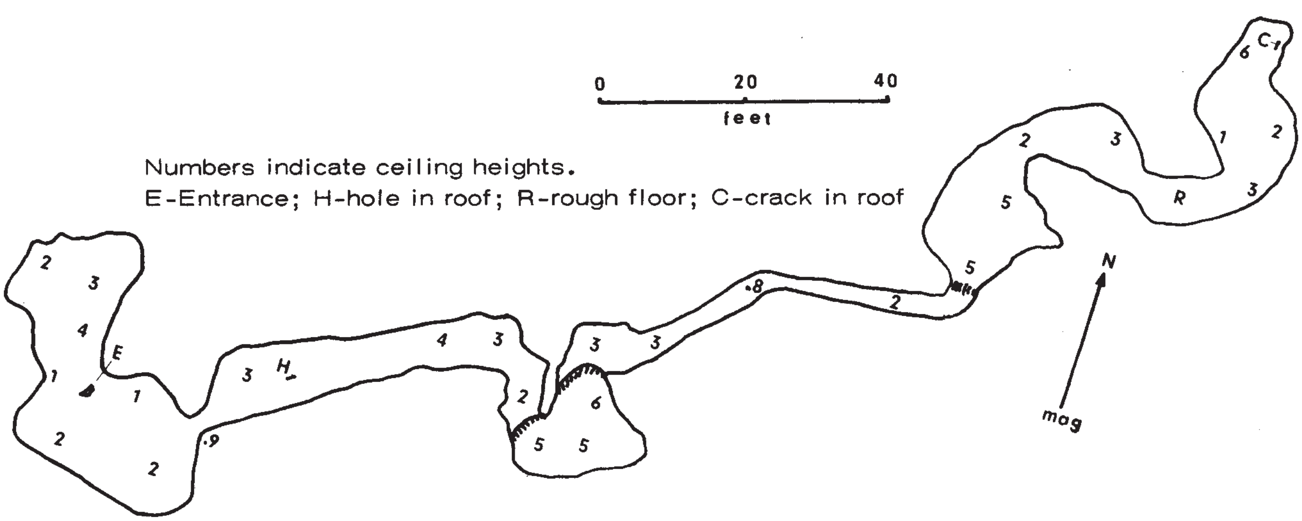
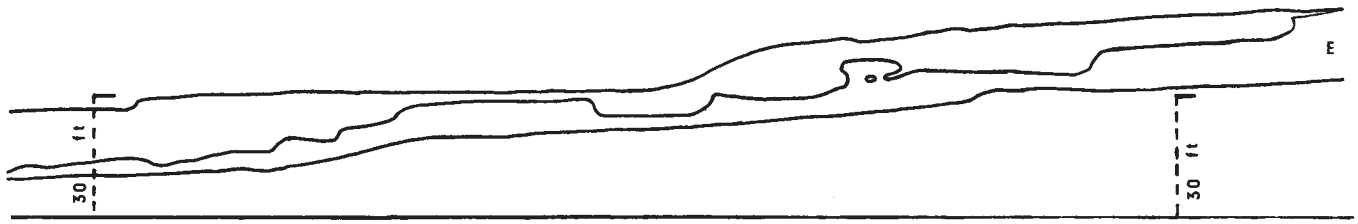


Figure 3-12: Plan of Tea Cave, Pisgah Crater, California.



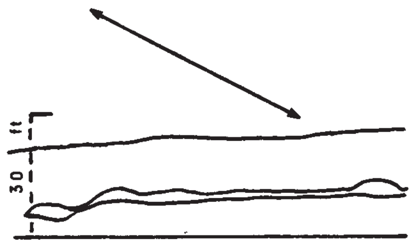


Figure 3-11: Profile of Cave C13N, Pisgah Crater, California

E-Entrance
Profile of short, nearly level side passage omitted.

N Hole is a unitary surface tube which has become buried by a flow over its lower end. Its size is typical for small surface tubes: about three to six feet in width, and 1 1/2 to four feet in height. The entire cave conforms closely to the original ground surface, and the overall slope is about nine degrees. The floor consists of small bits of loose rock, including some loose plates spalled from the walls and ceiling. Wind-or water-bourne dust has accumulated on the floor to a depth of an inch or two. The former mechanism is more likely here, although many of the caves in the same area show definite signs of seasonal rivulets. The passage cross-section is a low arch without distinct walls except in the passage uphill from the entrance. The ceiling is covered with remelt and drip pendants. Total length of the cave is about 89 feet.

C13N

C13N is the north branch at the C13 collapse (C13W is the west branch). It is a good example of trench converting to surface tube to distribute its lava onto the surface. The cave trends NNE from the entrance, but meanders and the general trend is NNW.

About 100 feet from the entrance, the trench overflowed though a hole in the roof. It made a small rise chamber in the passage roof, and the bulge can be seen on the surface outside. The lava coming from this overflow fed a small solid lava stream which continued downhill atop the C13N roof for about 60 feet: a demonstration of how tube roofs are frequently buried.

Forty feet further along the passage is a 20-foot crawl. Beyond is a well formed trench, with no breakdown. This portion of the passage meanders to the right, then left. About five feet above the floor, a shelf is prominent. A well developed lining curb is present at the floor level. The higher shelf is a structural trench shelf, and is much more prominent on the right wall (slipbank) than on the left (cutbank). The curb is present only on the outside of the curve.

Fifty feet from the crawlway along this intact meandering trench there is an overflow from the trench on the outside of a meander bend. The lava was unable to flow straight after the previous bend, and overflowed the trench here. The floor of this overflow is at the level of the trench top. The trench floor formed while the overflow was full, and the overflow then backdrained into the trench as the lava level fell. Subsequent flow in the trench put a lining over the entrance to this overflow, and the present entrance is through a partly freestanding lining which fills about half of the overflow entrance. The overflow is low surface tube chambers. At no point is it higher than 18 inches.

Just below this overflow is a spot of breakdown which marks the beginning of a transition zone from trench to surface tube. After 30 feet, the passage is split by the breakdown pile and the visitor enters a low, wide room about 25 feet in width and length. It is floored with aa clinker and is referred to as the 'clinker room.' Typical ceiling height is about three feet. At its downhill end the room has two exits. The one to the right is 7 to 10 feet wide, with a ceiling height of 2 1/2 to 3 feet. The lead to the left is smaller, 2 1/2 feet wide and 2 feet high. Their floors are clinker. Both connect to a second clinker room much like the first but with a ceiling one to three feet high. A low lead at the far right continues another 80 feet to the end of the cave, entirely clinker-floored crawlway, narrower and lower. A sharp kink is negotiable only on one's side. The terminal room is about four feet high. At its extremity a small hole permits view of another clinkery room beyond. This is the inside of the main stream of an emptying "toe."

TEA CAVE

Tea Cave has seen some metamorphosis from simple surface tube. The whole tube was apparently fed from a lead now plugged, at the west end of the cave and about ten feet from the entrance. The entrance is a small hole in the roof between two low surface tube rooms. The floor is coated with several inches of powdery dust in this area. It continues about 50 feet from the entrance. This length of passage is low and wide except at a point where its width shrinks to 2 1/2 feet. Little breakdown is present and crawling is fairly easy except for the dust. The dust floor contains loose bits of rock just before the first high room.

The first large room, 75 feet from the entrance, originally was bypassed but the surface tube formed a plug, developed a corner, and fell into what is now the room. The room drained through holes at its eastern end, now mostly plugged. A continuing passage begins as a large crawlway three feet off the floor, on the north side of the room. This lead rapidly shrinks to a small downhill channel, constricting to a width of 2 feet and width of 9 inches at a point where a 35 degree bend to the right and a lump on the left wall further constrain movement. 30 feet onward is a small room where the explorer can almost stand erect (quite a luxury by this point). Entering this room is negotiated feet-first, over a 5-foot drop. Lava also entered this room through a lower passage in the west wall. This inlet is now filled with a viscous plug. The floor here is bare lava with a rippled pattern. Breakdown is absent from these rooms and the connecting crawlway.

Continuing northward, the ceiling lowers. A clinker floor and a little breakdown are present. Here the passage is as much as ten feet wide, and 3 1/2 feet wide in the arched center. A curve meandering to the left brings the explorer to the end chamber. Here the floor drops about two feet and the ceiling rises to a maximum of 6.3 feet. Some breakdown is present, and a dim glow of sunlight enters through a narrow, crooked crack. A wire pushed to the surface through this crack showed the roof to be about 18 inches thick. Survey traverses closed within two feet.

My brother and I are continuing our studies of the caves and surface features of this fascinating area, and our findings will be published as time permits.

Figure 3-13: A 26" mud stalactite, Pisgah Crater, California. Harter & Harter photo.

LAVA TUBE FORMATION — THE MAKINGS OF A CONTROVERSY
Findings from Studies on the Bandera Lava Field, New Mexico

Allen W. Hatheway
Woodward-McNeill & Associates

(Much of the data mentioned in this paper can be reviewed at length in the author's thesis, available as mentioned in his list of references, and in: Hatheway, Allen W. and Herring, Alika K. 1970. Bandera Lava Tubes of New Mexico, and Lunar Implications. University of Arizona Lunar and Planetary Laboratory Communications #152, Vol. 8, part 4, pp. 298-327.)

Observations made on active (mainly Hawaiian) and older lava fields (such as the Bandera of New Mexico, Fig. s 4-1 through 4-4) have brought attention to the fact that there may be two primary modes of lava tube formation. Conjecture as to these modes of formation stems directly from the earliest description of lava tube formation (Wentworth and MacDonald, 1953) which is opposed by a theory of formation set forth by Ollier and Brown (1965). This second work also sets out the first succinct description of fluid lava as a habitat for forming lava tubes.

Since the only observations of lava tubes made while the process of formation is active are those supporting the Wentworth and MacDonald view, many investigators hold resistance to the concept of a "mobile cylinder" (Hatheway, 1971) as an extension of the Ollier-Brown work.

Wentworth and MacDonald, followed by several others, have actually seen lava tubes forming from open channels. The mode of formation is simply one of development of a solidified crust, while fluid flow continues beneath. Greeley has noted, in several publications, that his field observations tend to support this theory and that tubes so formed tend to migrate laterally and vertically, in sections over limited distances.

While the circumstances surrounding formation of tubes from open channels are fairly simple, those responsible for tube development through mobile cylinders are more complex. In 1936, R. L. Nichols proposed that lava flows move forward as a series of flow units. Ollier and Brown (1965) clarified this concept with the added observation that the flow units are separated into flow layers formed in shear, along planes of variable viscosity.

That differentiation by flow layering does exist has been noted by Lutton, Girucky, and Hunt (1967), in which the flow layers were actually observed to constitute a relict internal cylindrical flow structure within a single 61-m thick lava flow.

The crux of the problem of defining mode of lava tube formation lies in the question of the existance of an open channel for distances of up to 35km (the longest distance yet reported for a single lava tube; Undara Crater tube, Queensland, White, 1965, fig. 2, plate 2). Will the roof-forming process produce a buried tube of this length?

As proposed by Hatheway (1971), a modified Ollier-Brown theory seems to adequately explain the occurrence of the longer lava tubes (one km - plus). Although long lava tubes have not been observed while forming, this theory is proposed to encompass all of the natural pocesses necessary to produce the tubes; with all of their distinct features.

It is a well known fact that lava flows extend themselves by flow units, and from within these, by smaller tongues of lava issuing forth from ruptures at the toes of flow units. The ruptures occur when the hydrostatic head of the fluid interior exceeds the tensile strength of the cooling basalt at the toe. Since tensile strength decreases markedly with temperature (Hatheway, 1971), this level of hydrostatic stress is rather easily attained. As soon as the break forms, the configuration of fluid flow soon stabilizes into a circular cross-section of equal shear stress between the evacuating lava and the less-viscous host lava.

Now, with the development of a semi-stabilized supply source of more fluid lava just up-gradient from the toe, a mobile cylinder, or supply conduit, filled with fluid lava must be present to continue to supply the effluent tongue. The theory proposed here holds that this mobile cylinder naturally propagates in an up-hill direction, following the position of maximum gradient for the flow unit (actually observed from lava tube traces on the Bandera flows). This generation of fluid supply volume continues until the modile cylinder reaches the source area, or vent. At this time the cylinder ceases to grow in length and merely snakes its way down through its own conduit until, like a subway train, it has completely left the conduit (or enclosing sheath) and has spilled out at the toe of the flow.

The result is an evacuated conduit....a tube formerly occupied by the mobile cylinder of fluid lava.

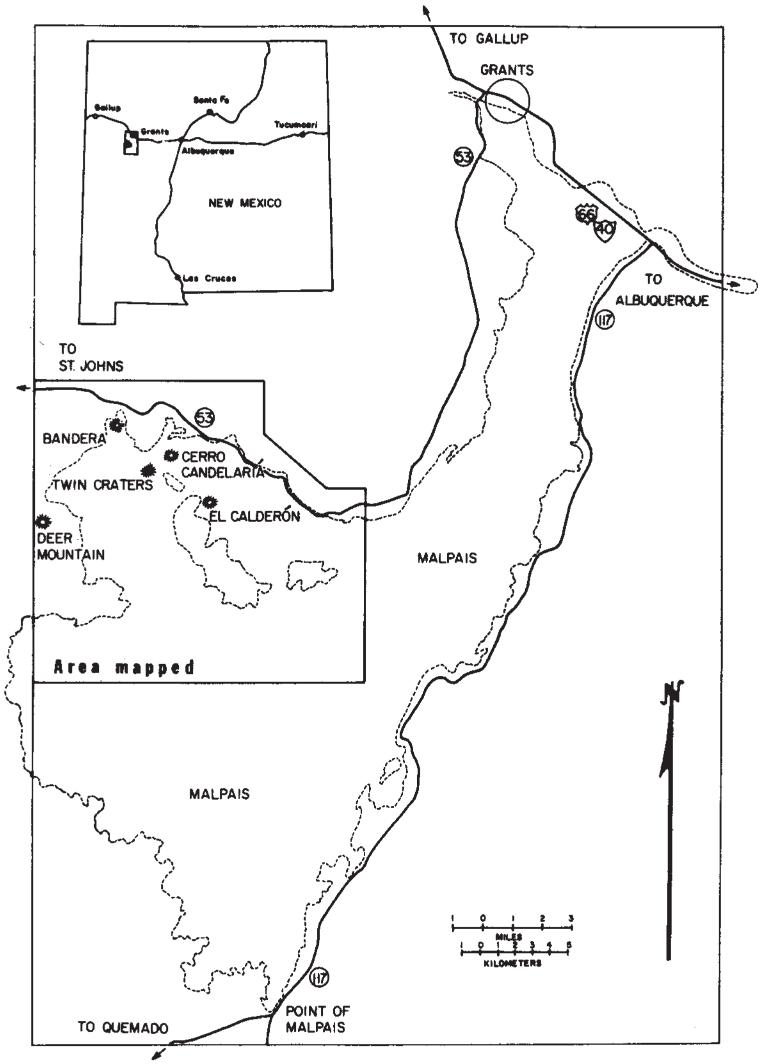


Figure 4-1: Index map to the Bandera lava field. Basalts of Pleistocene and Holocene age are outlined by the dashed line; they overlie in part older volcanics.(Ariz.fig.2)

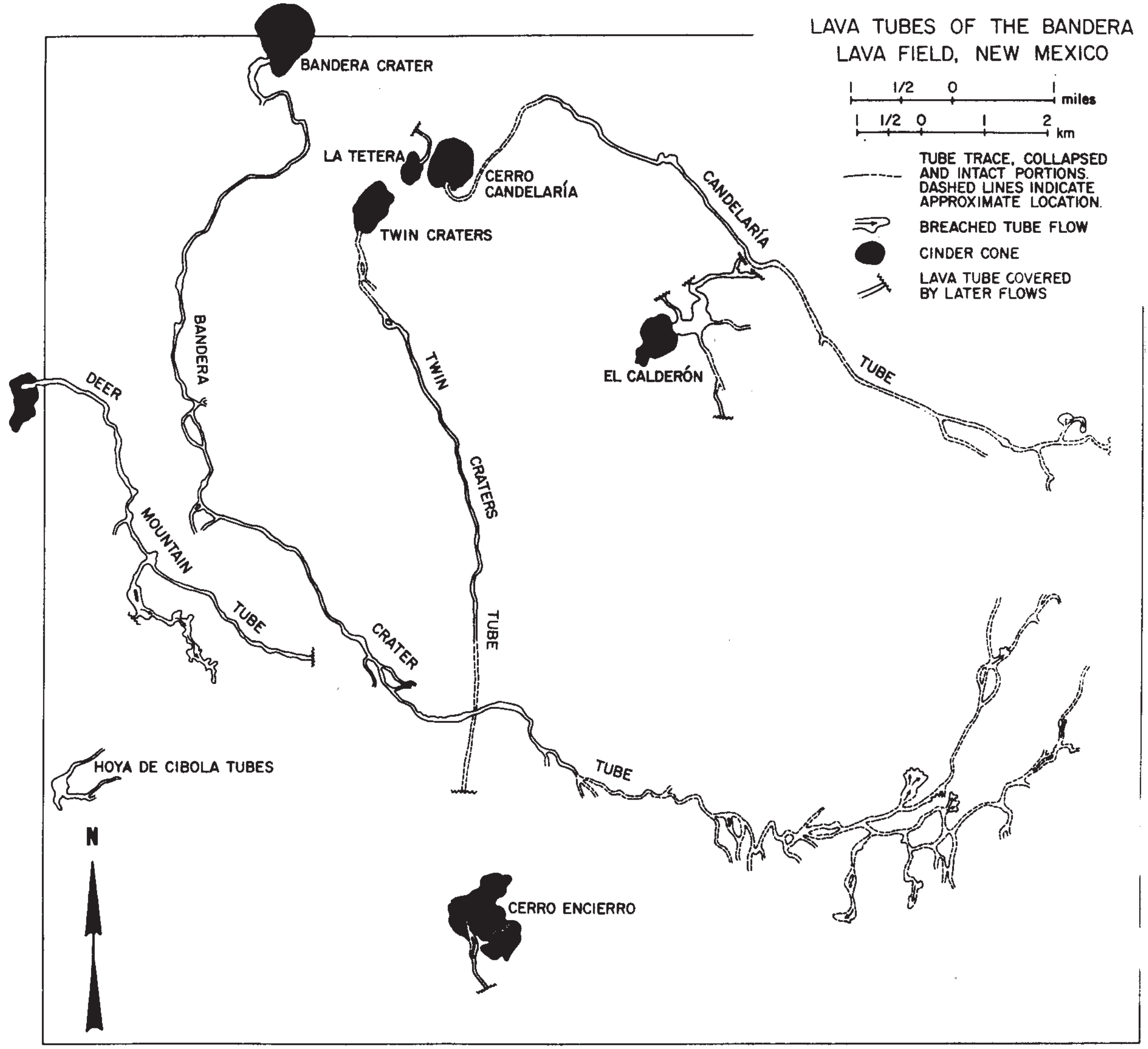
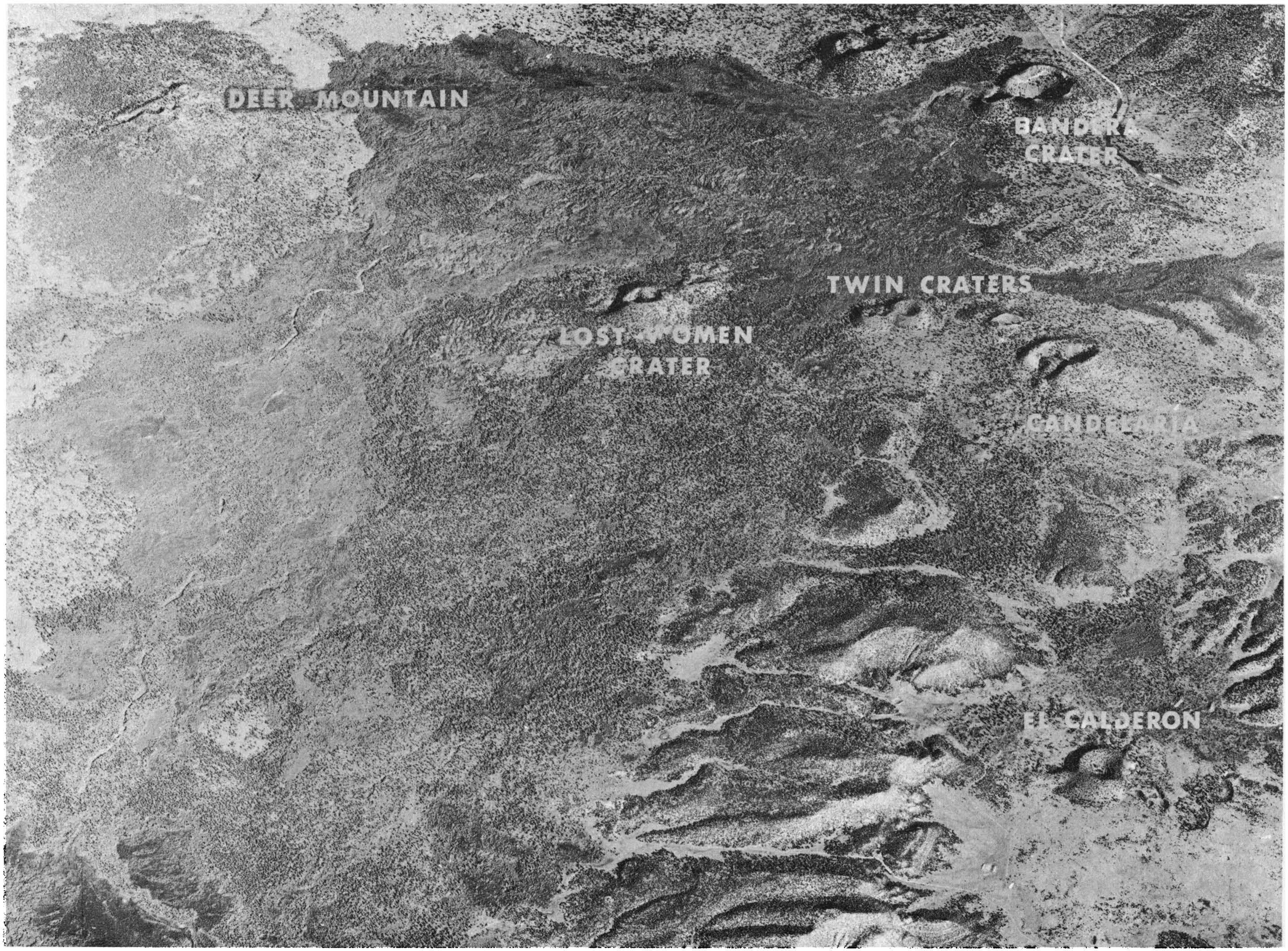


Figure 4-3: Lava tube systems of the Bandera lava field. (Ariz.fig.11)



Low oblique aerial photograph of the Bandera lava field showing principal craters and collapsed lava tubes. The view is to the NW with foreground about 8 km across. (U.S. Govt. Photo, 1965).

Figure 4-2

Measurements of Sinuous Bends

Lava Tube	D	λ	α	MRC	W
Bandera Crater					
site 1	0.0 — 1.7 km	1100 m	444 m	323 and 418 m	19 — 34 m
site 2	7.3 — 8.5	817	514	114 and 400	19 — 42
site 3	7.5 — 9.2	1480	42	247 and 418	27 — 49
site 4	12.5 — 13.0	475	104	171 and 323	57 — 60
site 5	13.0 — 14.4	1000	114	266 and 400	23 — 30
Deer Mountain					
site 1	1.0 — 1.4 km	684 m	228 m	76 and 532 m	19 — 49 m
site 2	1.7 — 2.9	874	133	360 and 400	15 — 60
El Calderón					
site 1	1.2 — 1.8 km	420 m	236 m	91 and 130 m	45 — 78 m

D = distance from source.
λ = mean length of bend.
α = amplitude of bend, as measured above and below the length line (Fig. 14).
MRC = mean radius of curvature.
W = channel width range for the bend.

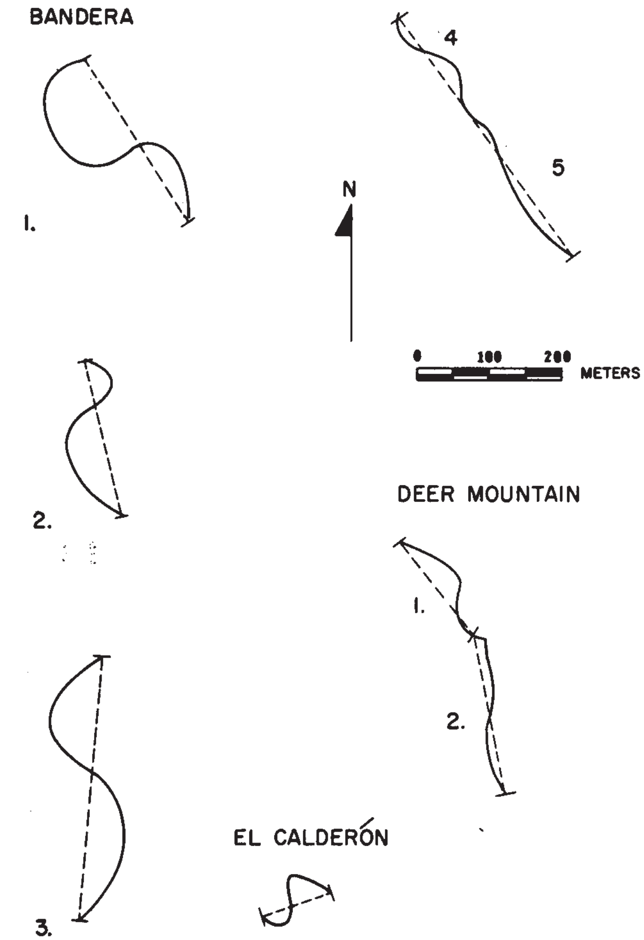


Figure 4-5: Traces of the more sinuous portions of several of the Bandera lava tubes. The bends are easily described by wave length and amplitude. The bends are analogous in many respects to lunar rilles. (Ariz.fig.14, incl.Table I)

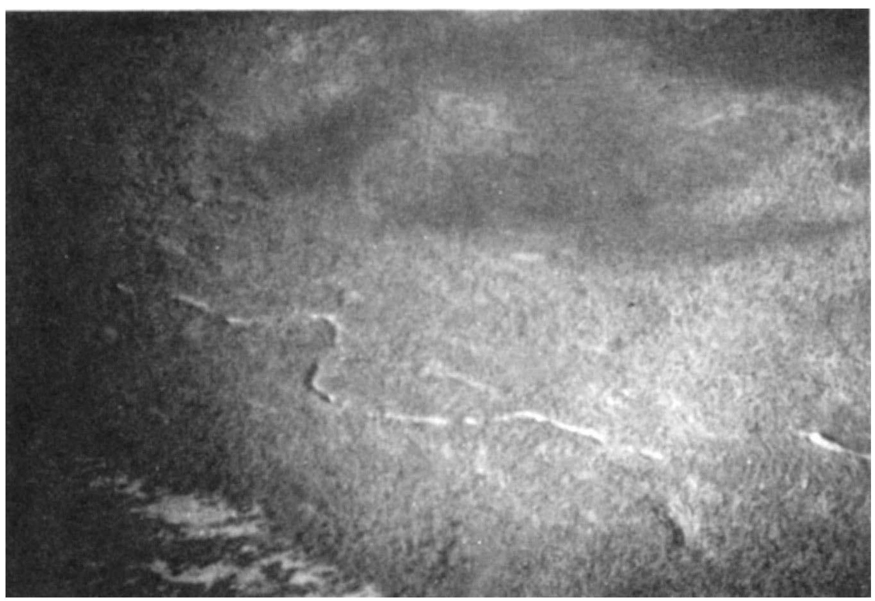


Figure 4-4: Aerial view of sinuous segment of Bandera Crater tube, showing segmental collapses. Halliday photo.

Figure 4-6: Sinuous bends along the lava tube issuing from El Calderon Crater. Four distinct tubes (1 thru 4) branch from the subsidence pit (P). Collapse of tube number 4 is evidenced by S (straight-sided collapse pits) and T (tensile failure producing a hole in the roof of the tube). (Ariz.fig.7-R)

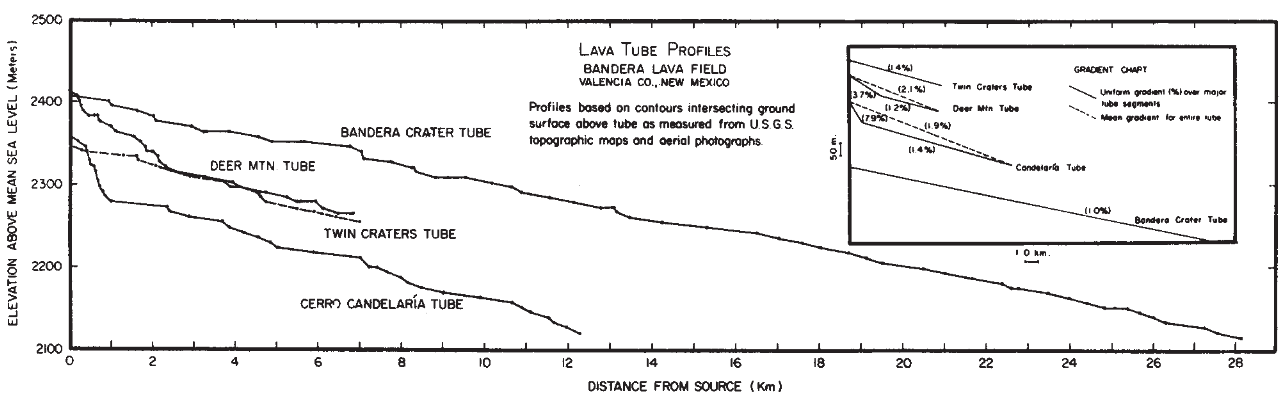
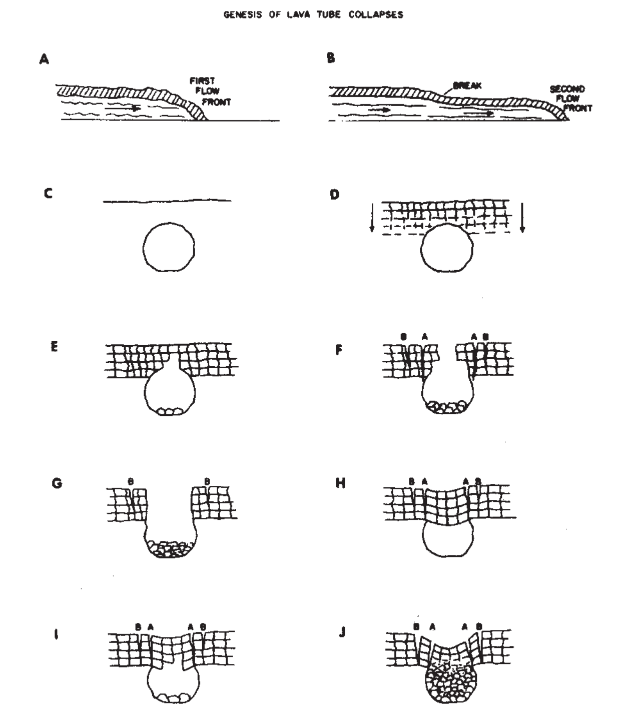


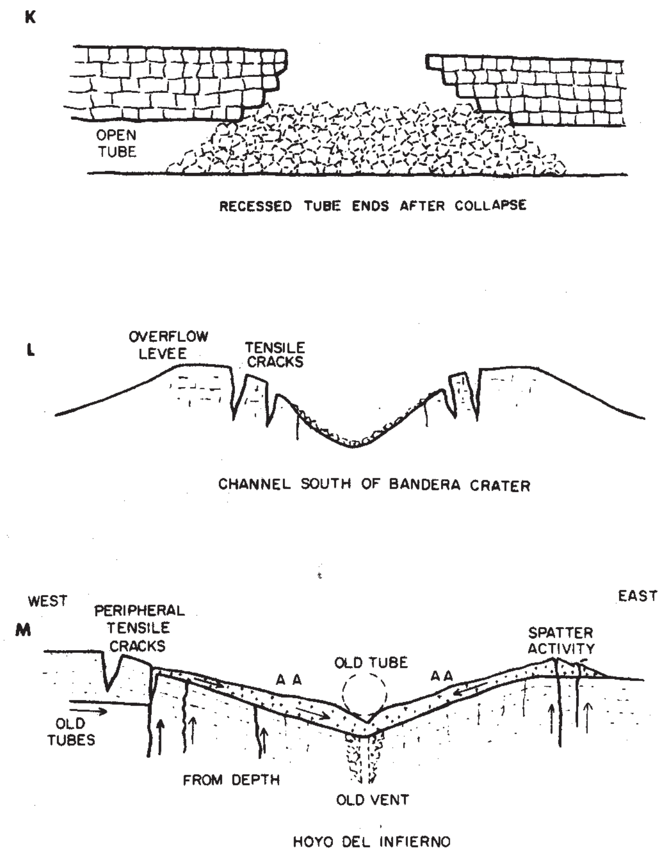
Figure 4-7: Gradient profiles of the Bandera lava tubes. (Ariz.fig.15)

Features observed on the Bandera and other basaltic lava fields of requisite chemistry and flow gradients, strongly suggest that most of the present-day collapse damage came about immediately after formation of the tubes (within a matter of weeks), before the host rocks cooled and became sufficiently strong to resist the shear and tensile components of gravity forces surrounding the lava tubes. Perhaps some of the damage was hastened by seismic tremors likely to have accompanied the eruptions.

At the present, data collected from numerous sites of lava tubes strongly suggest that these features occur only in alkali and high-alumina basalts and over flow gradients ranging upward from 4°31', but no less than 0°35' (Fig. 4-7). Characteristically the basalt associated with tubes and depressions is crystal-damaged and porphyritic; the barren host rock of nearby flow units devoid of depressions are finer grained and less damaged.

Velocity distribution in a newly formed lava tube (while occupied with full flow - or that of a mobile cylinder) equalizes shear forces around a circular section. Bends probably begin wher-





A. As the flow advances, the outer surface cools and solidifies, while the interior portions remain molten and fluid.

B. Hydrostatic pressure forces the molten interior against the immobile crust at the flow front, forming new flow units and draining lava from the interior.

C. Evacuation of lava creates a mobile cylinder of lava shearing a contact with the surrounding, more viscous lavas.

D. Differential cooling generates vertical joints which intersect the horizontal planes formed by laminar flow within the massive lava flow.

E. Joint cracks moving from the surface downward reach the upper surface of the tube and when contraction in the horizontal direction is sufficient, blocks begin to spall from the roof of the tube. Some plastic deformation may also occur along the upper interior surface of the tube. Shear planes may develop along the lower interior surface in areas in which heat dissipation has occurred to a lesser degree and where the rock may still be plastic.

F. Primary (A) and secondary (B) tensile fractures form in the roof arch and begin to outline a peripheral failure of the tube.

G. Final failure occurs along primary tensile fractures and the cycle is complete. The process may be assisted by seismic activity of a volcanic nature.

H. OR: Plastic deflection of the roof area results in deformation of the tube cross section.

I. Spalling then occurs.

J. The tube is filled with rubble and tilted slabs of basalt. In some instances this rubble fills the collapse pit to a point above the original roof line and the lava tube is made inaccessible.

K. Cave-like recesses found at the ends of many collapse pits along the lava tubes.

L. Diagrammatic cross-section of the channel on the Bandera Crater lava tube S of the crater. (See also Fig. 17.)

M. Diagrammatic cross-section of the Hoyo del Infierno subsidence pit. The interior of the pit is now largely covered with aa lava extruded through fissure vents and tensile cracks onto a surface of tilted pahoehoe slabs. (See also Figs. 25A and B.)

Figure 4-8: Genesis of lava tube collapse. Ariz.fig.16)

ever anomalously large pockets of equally viscous lava exist. As the pocket is mobilized in flow, continued flow erodes the section preferentially.

Young's modulus decreases radically with increasing temperature. The stability of a newly-formed lava tube depends upon its ability to resist the tensile and shear components of body forces surrounding the tube. Data were curve-fit and used in a thermoelastic stress analysis program.

Workers such as Murase have observed that lavas maintain an essentially linear structure elasticity for short periods of time at high temperatures. The thermoelastic stress analysis assumed linearity of elastic properties over the short time periods utilized in the analysis.

Typical shear surfaces formed by body stresses surrounding lava tubes were observed on the Amboy lava field of California and the McCartys flow of the Bandera lava field. There is a clear-cut transition between the tensile breaks of cooler origin near the surface, and shear at a depth of about one meter. Changes in surface character denote the temperature-dependent nature of tensile and shear failures in hot lava.

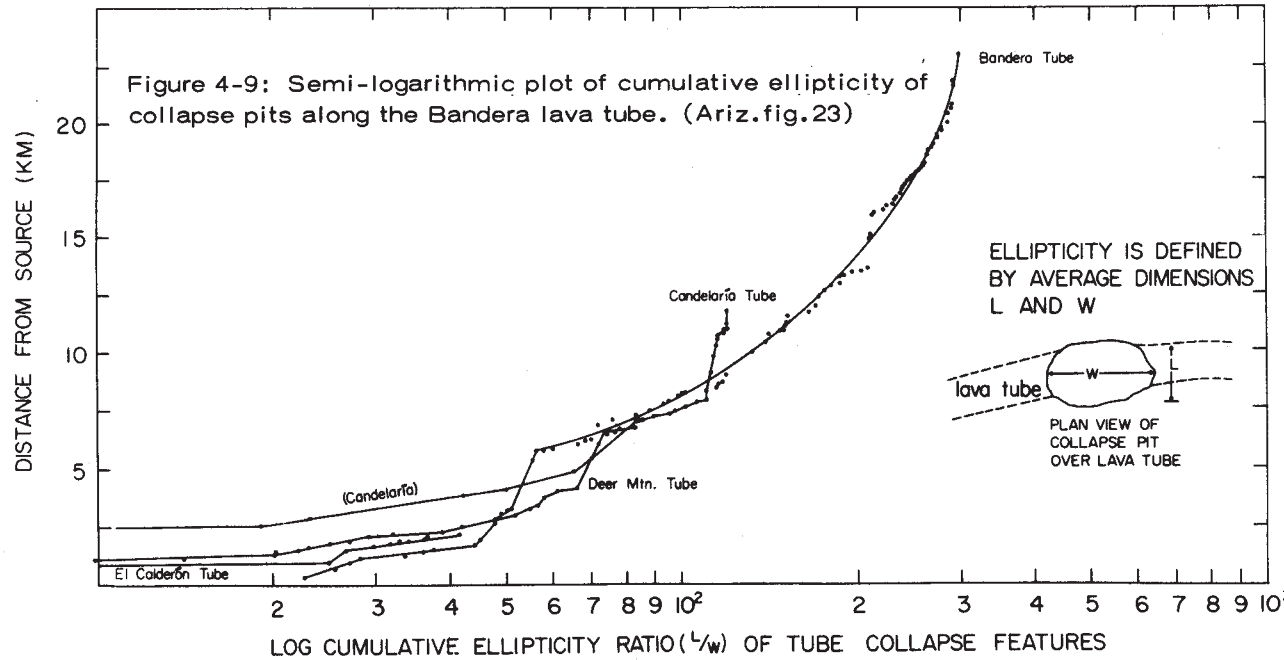


Figure 4-9: Semi-logarithmic plot of cumulative ellipticity of collapse pits along the Bandera lava tube. (Ariz.fig.23)

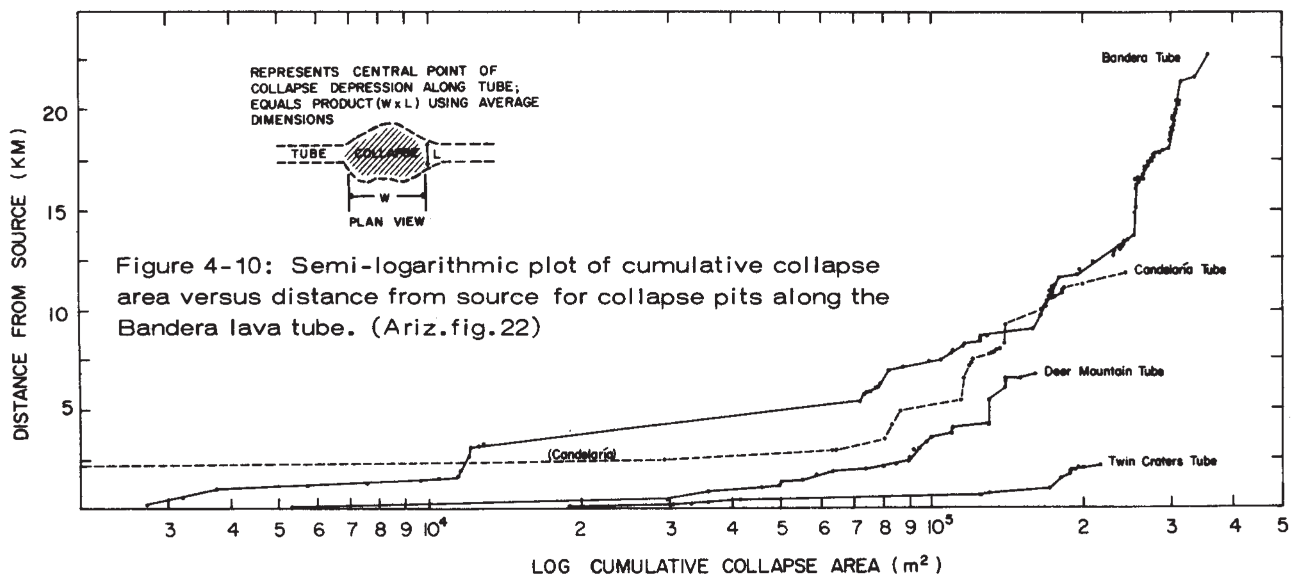


Figure 4-10: Semi-logarithmic plot of cumulative collapse area versus distance from source for collapse pits along the Bandera lava tube. (Ariz.fig.22)

Thermoelastic stress analysis showed that preferential shear and tensile failure occur just outside the periphery of the tube, from roughly the horizontal centerline upward into the lower half of the upper quadrants. Profiles vary considerably along short reaches of many lava tubes. Such variations attest to plastic deformation short of elastic failure, closely following formation of the lava tube.

Wide tensile fractures, extending three to five meters in depth, parallel the collapse features overlying many lava tubes (Fig. 4-8). One nearly continuous fracture circumscribes each collapse in the McCartys basalt, Bandera lava field. Concentrations of tensile and shear stress in the host basalt immediately surrounding the tube result in a failure of the basalt, which is weak by virtue of its temperature, and formation of collapse depressions aligned along the trace of individual lava tubes. Detailed topographic mapping of a single collapse depression formed over a lava tube in the McCartys basalt showed a complex arrangement of peripheral tensile fractures denoting that the basalt failed in tension at the surface. Regardless of length of tube, the ellipticity (or length to width ratio) of collapsed segments of lava tubes remains fairly similar (Fig. 4-9). The cumulative collapse area of pits along lava tubes shows the general effect of a thinning flow unit thickness as distance from source increases (Fig. 4-10).

Stratigraphic relationships and detailed lava-tube mapping at several locations in California and New Mexico have failed to substantiate that the longer tubes were formed in the alternative channel-and-fill mode.

Two theories thus have appeared which propose to account for the origin of lava tubes. The first of these, by Wentworth and MacDonald (1953) has been cited frequently in the past few years by several workers in lava tube research. The Wentworth-MacDonald theory is held by Hatheway (1971b) to constitute a valid explanation for formation of lava tubes less than about one kilometer in length. The theory calls for roofing by spatter and agglutination from lava flowing in open channels.

For the longer lava tubes, a compatible theory was developed by Ollier and Brown (1965) from basic observations of Nichols (1936). This concept has been modified to suit close field observations (Hatheway, 1971) and is herein proposed as a likely mode of formation for almost all lava tubes greater than about one kilometer in length.

The importance of a discussion of the two theories is that field observations of active basaltic eruptions, and those made on quiescent Holocene lava fields, suggest that the two theories are quite compatible; each explaining tube formation under a respective length criterion.

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GEOLOGY OF LAVA TUBES IN LAVA BEDS NATIONAL MONUMENT, CALIFORNIA

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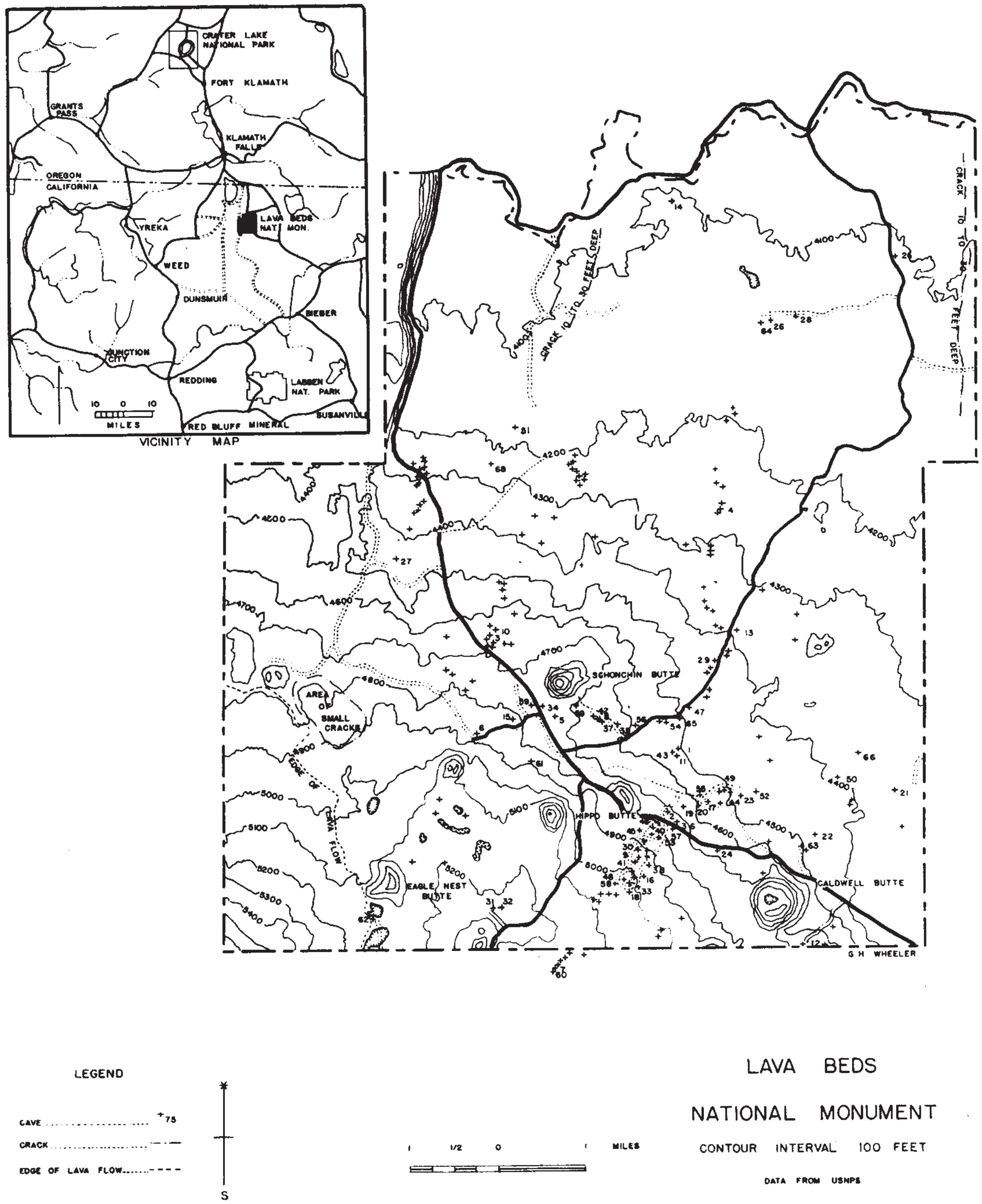
U.S. Geological Survey
Menlo Park, California 94025

READ IN ABSTRACT

Lava-tube systems in Lava Beds National Monument are among several that occur in young basalt flows which flank the Medicine Lake Highlands volcano. Mammoth Crater was the source for one tube system (including Heppe, Sentinel, and Dragonhead caves). This system includes both a major tributary and numerous distributary tubes. The large tributary (now collapsed) formed where lava ponded to one side of the main tube before draining it into subsurface . More typically the main channel fed numerous distributary conduits. Complexly branching distributary tubes at the monument headquarters are unusually well drained, evidently the result of a high gradient. The main channel in this area of high gradient (Crystal and Sentinel Caves) is narrow and deep and evidently carried a high rate of flow as suggested by evidence of high-velocity gas streaming above the lava river. Modoc Crater was the source of another lava large tube, whose uncollapsed segments include Bearpaw, Skull, Frozen River, Fossil, and Fern caves. This was a single channel throughout most of its 15-km length. Unusual features of this tube are a low gradient (less than 0.3^{o} at the downstream end), and a series of collapsed blisters that form non-explosive craters with high outward-toppled rims. Like the Mammoth Crater tube, this tube generally is deeper than wide, is multistoried, has a thick roof, and is enclosed in several flow units. These complexities, which are typical of large tubes, originated by such mechanisms as successive lava overflow and levee building before the roof completely formed, non-uniform accretion on the tube walls, and local erosion into underlying materials. Except for small features in the tube lining, most layering exposed by tube collapse is believed to represent superposed flow units and not shear layers within the flow.



Map of Lava Beds National Monument

Major caves of Lava Beds National Monument

1. Angleworm, 2. Arch, 3. Balcony, 4. Bat, 5. Beaconlight, 6. Bearpaw, 7. Berthas Cupboard, 8. Big Painted, 9. Blue Grotto, 10. Boulevard, 11. Bowers, 12. Caldwell Ice, 13. Captain Jacks Ice, 14. Captain Jacks, 15. Castle, 16. Catacombs, 17. Chest, 18. Compound Bridge, 19. Coopers, 20. Cox Ice, 21. Craig, 22. Crawfish, 23. Dragon Head, 24. Dynamite, 25. Fern, 26. Flat Arch, 27. Fleener Chimneys, 28. Fossil, 29. Frozen River, 30. Garden Bridge 31. Heppe, 32. Heppe Chimney, 33. Hercules Leg, 34. Igloo, 35. Incline Cavern, 36. Indian Well, 37. Irish Bridge, 38. Juniper, 39. Kirk White's, 40. Labyrinth no. 1, 41. Labyrinth no. 2, 42. Little Painted, 43. Lost Pinnacle, 44. Mahogany, 45. Maze, 46. Mushpot, 47. North Bend, 48. Ovis Bridge, 49. Post Office, 50. Rock, 51. Ross Chimneys, 52. Schonchin, 53. Sentinel, 54. Ship Cavern, 55. Silver, 56. Skull, 57. Stinking, 58. Sunshine, 59. Symbol Bridge, 60. Tecnor, 61. Trapper, 62. Upper Ice, 63. Valentine, 64. Wedding Cake, 65. White Lace, 66. Wild Cat, 67. Winemas Chimneys, 68. Wright Chimneys.

MAPPING THE CAVES OF THE HEADQUARTERS LAVA FLOW
LAVA BEDS NATIONAL MONUMENT, CALIFORNIA

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Knox and Gale (1959) have presented a summary of the geology and major cave features of Lava Beds National Monument, Siskiyou County, in northern California. Within the confines of the 75 square miles of the monument they reported the presence of 293 lava tube caves (of which 190 had been explored), with diameters up to 98 feet, lengths up to a mile, and a few with several levels, and/or year-round ice. Verification of this legendary number of 293 caves is needed. Most of this number probably represents segments of a comparatively few lava tube systems.

On a map of the monument (Knox and Gale, 1959) showing many cave locations (68 of which are named specifically), the greatest concentration is shown to occur on what is called the "cave loop road" at the Monument headquarters, in what I will call the "Headquarters Lava Flow." Here 16 named entrances occur on a part of the flow approximately one mile long and 1/2 mile broad.

Many of the caves along the cave loop road have been partially developed for visitors, with the installation of self-guiding trails, stairways, catwalks, ladders, and other unobtrusive constructions that minimally interfere with the natural state of the caves. Before 1963 the Monument supervisory personnel had neither maps nor sufficient knowledge of the extent of these caves that visitors were encouraged to explore. While a summer employee (student trainee, Park Naturalist) at the Monument in 1963 I presented a proposal to the administration to map these caves and it was accepted.

Approximately a month was spent making the surveys of the caves in the approximately 1/2 square mile cave loop road section of the Headquarters Flow. Notes on the methods of survey (using Brunton Pocket Transit and steel tape) are appropriate here. The survey of cave length began with the edge of the entrance, and did not include the collapse trench that preceded the entrance. However, when a cave was sectioned by a collapse at a point along its length, the length of the collapse trench was measured as the greatest distance parallel to the passage axis. The line of the survey axis was generally in the middle of the passage. Side passages and closures around pillars were tied into the nearest point on the survey axis, not to the nearest survey station. Thus, the following computed survey distances for the cave passages are minimal, and have not been inflated by any of the possible methods. The surveys are surprisingly accurate considering the legendary difficulty of making magnetic compass surveys in lava regions. One calculated error of closure was 2% (64 feet of error in 3,191 feet of surveyed loop in the Labyrinth section).

The following is an account of the name of the major segments of the system in the Headquarters Flow, followed by the surveyed length of underground and collapse trench passage, followed by the length of collapse trench passage in parenthesis, and then any existing auxiliary named entrances for the parts of the segments. <u>Labyrinth Cave Section</u>, 12,845 feet (1,310 feet). Indian Well, Devil's Mushpot, Lava Brook, Labyrinth, Thunderbolt, Golden Dome, Hopkins Chocolate Cup, Garden Bridges, and Blue Grotto. Most of the large amount of collapse trench reported above lies concentrated at one end of the system, in the Garden Bridges area. <u>Hercules Leg - Juniper Caves Section</u>, 4,419 feet. <u>Catacombs Cave Section</u>, 6,562 feet. It is interesting to note that an inscription at the entrance of this cave states that J.D. Howard and J.F.G. Cone surveyed 6,800 feet in 1920 and 1,495 feet in 1925 with instument and chain. Their map is presumably lost. <u>Sentinel Cave Section</u>, 1,082 feet (70 feet). This cave contains an unsurveyed lower level in which I have seen at least 400 feet of additional passage. <u>Paradise Alley- Ovis Caves Section</u>, 1,920 feet (390 feet). <u>Sunshine Cave Section</u>, 466 feet.

Another cave, Crystal Cave, named because of the ice crystals it contains, lies in the Headquarters Flow. It was surveyed in 1961 by D. Smith, D. Tomer, R. Curl, W. Halliday, E. Hedlund, R. Wilt, J. McLean, M. Smith and A.I. Smith, to a total length of about 1,120 feet.

In summary, under only approximately 1/2 square mile of land surface of the Headquarters Lava Flow, there are 27,414 feet (5 1/4 miles) of surveyed lava tube caves and minor collapse trenches (a total of 1,770 feet of trench). Of this, five miles is open for human visitation. This system was probably continuous over the time span of its formation (less than 60,000 years ago), but now is broken into the seven above-named components through lava plugs, or extensive collapse trenches. The greatest length of tube not intersected or broken by a collapse has not been determined, but probably would be Catacombs Cave with 6,562 feet of passage.

The entire cave system of the Headquarters Flow is more extensive than here indicated. Several collapse trenches are visible in the flow on the topographic map upslope from the known caves. More caves could exist here. Downslope in the flow some ten additional caves are known but these are not generally open to the public, and have not been surveyed. Hence, when the Headquarters Flow is wholly explored and surveyed, it may rank as one of the world's largest concentrations of lava tubes, and most cavernous lava flows.

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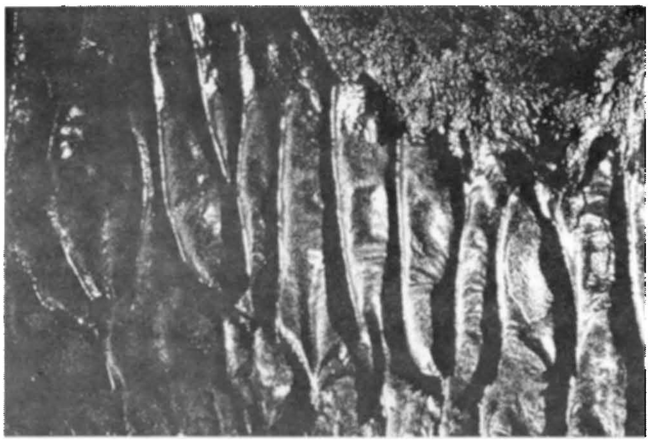


Figure 6-4: Ribbed wall in Golden Dome Cave.

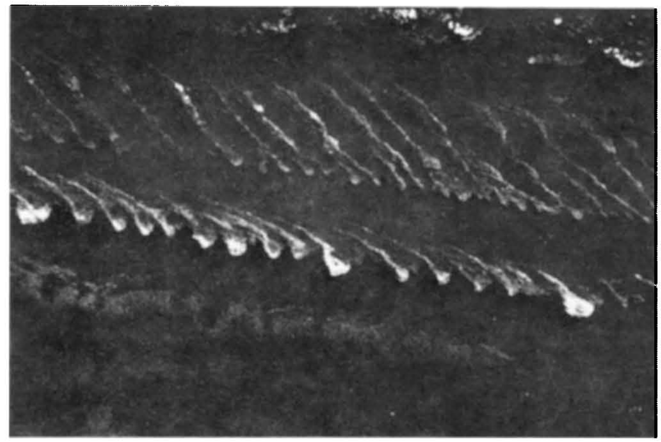


Figure 6-5: Features in Crystal Cave.

Figure 6-6: Ice speleothems on Crystal Cave.

Figure 6-7: Pictographs in Fern Cave.

Figure 6-1: LABYRINTH LAVA TUBE CAVE SYSTEM

LAVA BEDS NATIONAL MONUMENT

SISKIYOU COUNTY, CALIFORNIA

MAPPED BY THE NATIONAL PARK SERVICE JULY 22 – AUGUST 23, 1963

BRUNTON COMPASS & STEEL TAPE SURVEY BY:

STEWART PECK, STUDENT TRAINEE (PARK NATURALIST)

G. GILBERT SOPER, PARK RANGER (GENERAL)

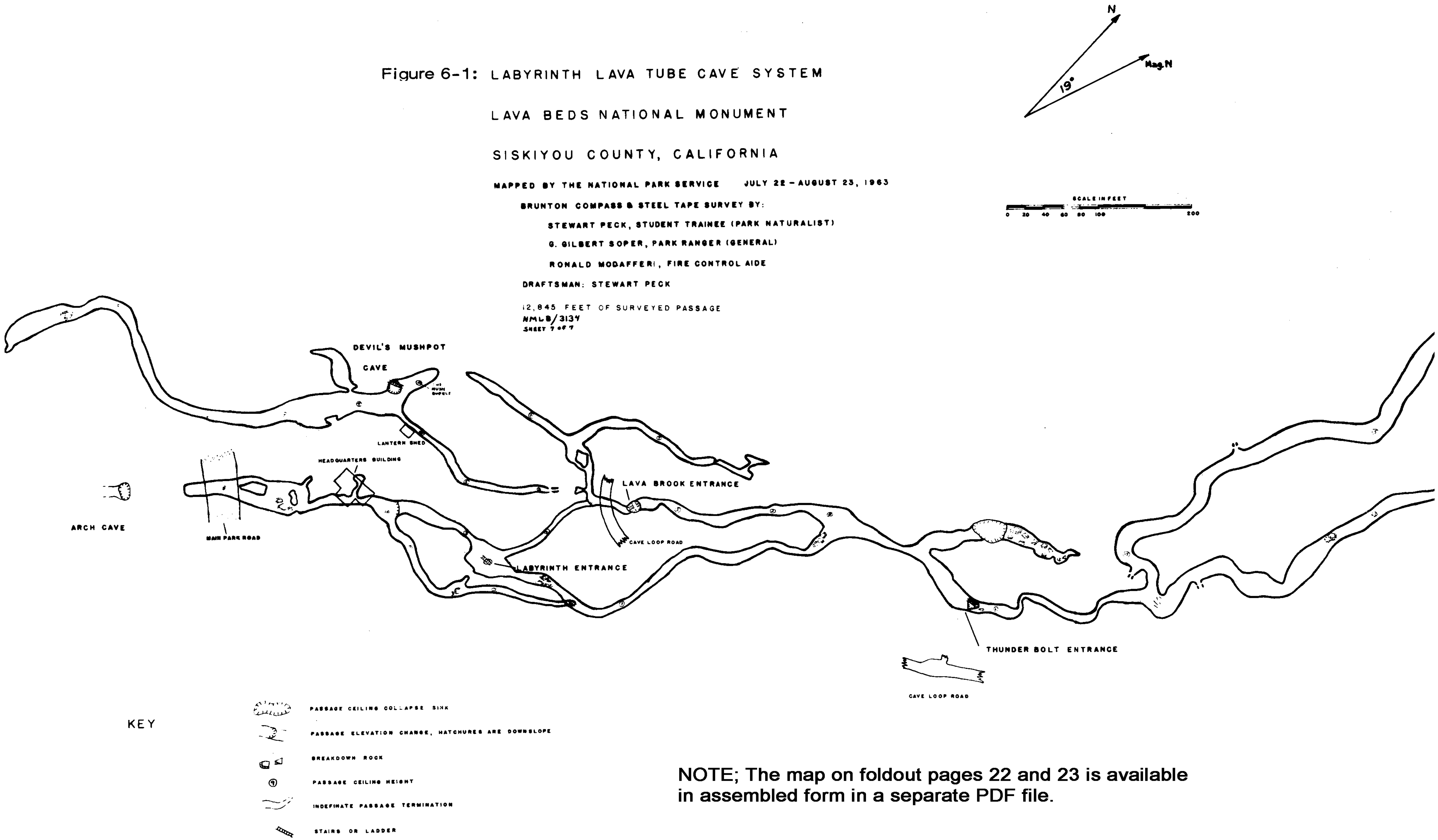
RONALD MODAFFERI, FIRE CONTROL AIDE

DRAFTSMAN: STEWART PECK

12,845 FEET OF SURVEYED PASSAGE

NMLB/3134

SHEET 7 OF 7



NOTE; The map on foldout pages 22 and 23 is available in assembled form in a separate PDF file.

BLUE GROTTO ENTRANCE
CAVE LOOP ROAD
CAVE LOOP ROAD
GARDEN BRIDGES AREA
HOPKINS' CHOCOLATE
CUP ENTRANCE
DISCOVERED BY
E L HOPKINS, OCT 2, 1892
CAVE LOOP ROAD
GOLDEN DOME ENTRANCE
OPENED BY CIVILIAN CONSERVATION
CORPS
FIRE ROAD
CAVE LOOP ROAD
GOLDEN DOME ROOM

NOTE: The map on foldout page 24 and page 25 is available in assembled form in a separate PDF file.

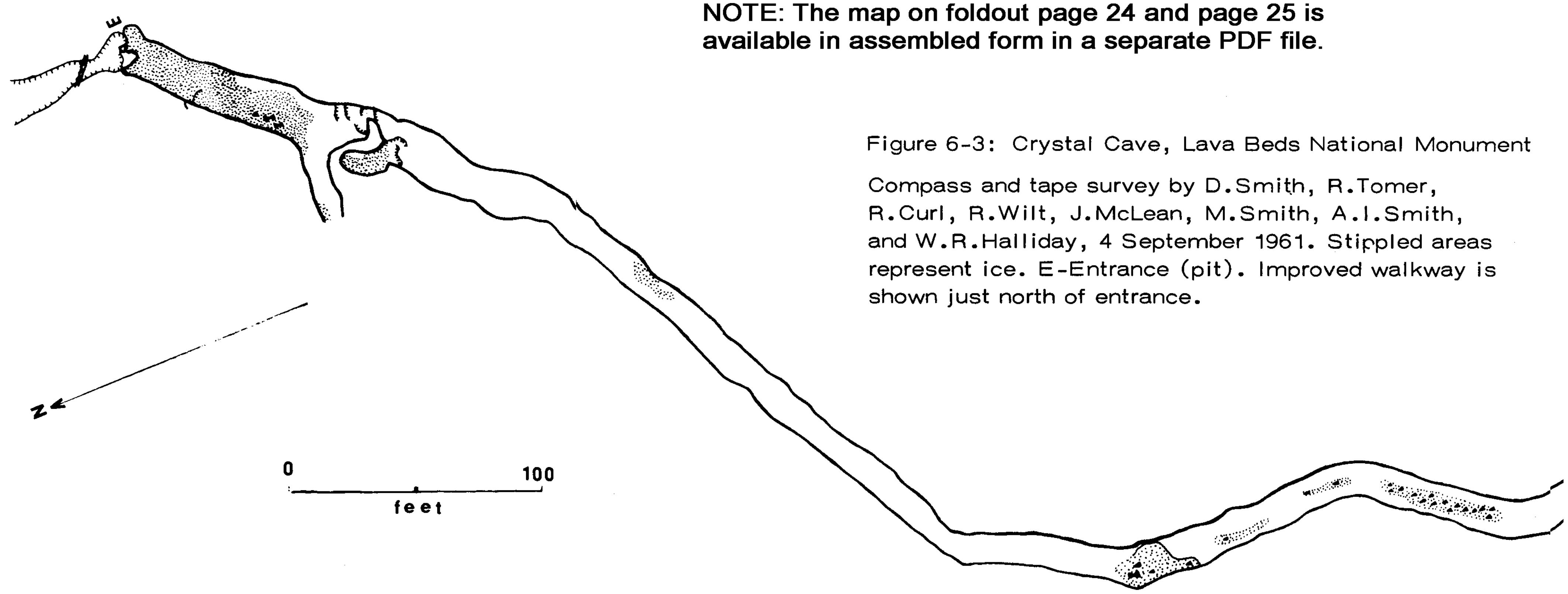


Figure 6-3: Crystal Cave, Lava Beds National Monument

Compass and tape survey by D.Smith, R.Tomer, R.Curl, R.Wilt, J.McLean, M.Smith, A.I.Smith, and W.R.Halliday, 4 September 1961. Stippled areas represent ice. E-Entrance (pit). Improved walkway is shown just north of entrance.

Figure 6-2: CATACOMBS LAVA TUBE CAVE

LAVA BEDS NATIONAL MONUMENT, SISKIYOU CO., CALIFORNIA

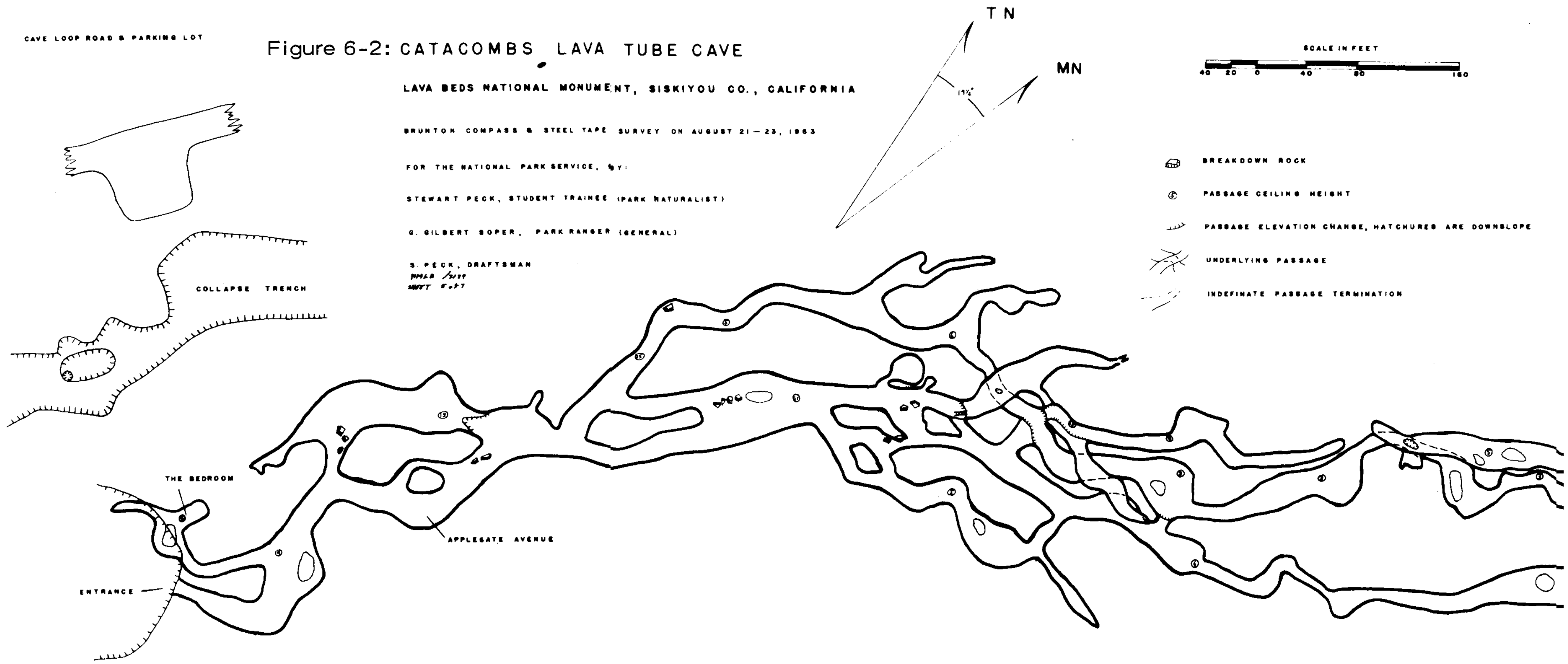
BRUNTON COMPASS & STEEL TAPE SURVEY ON AUGUST 21 – 23, 1963

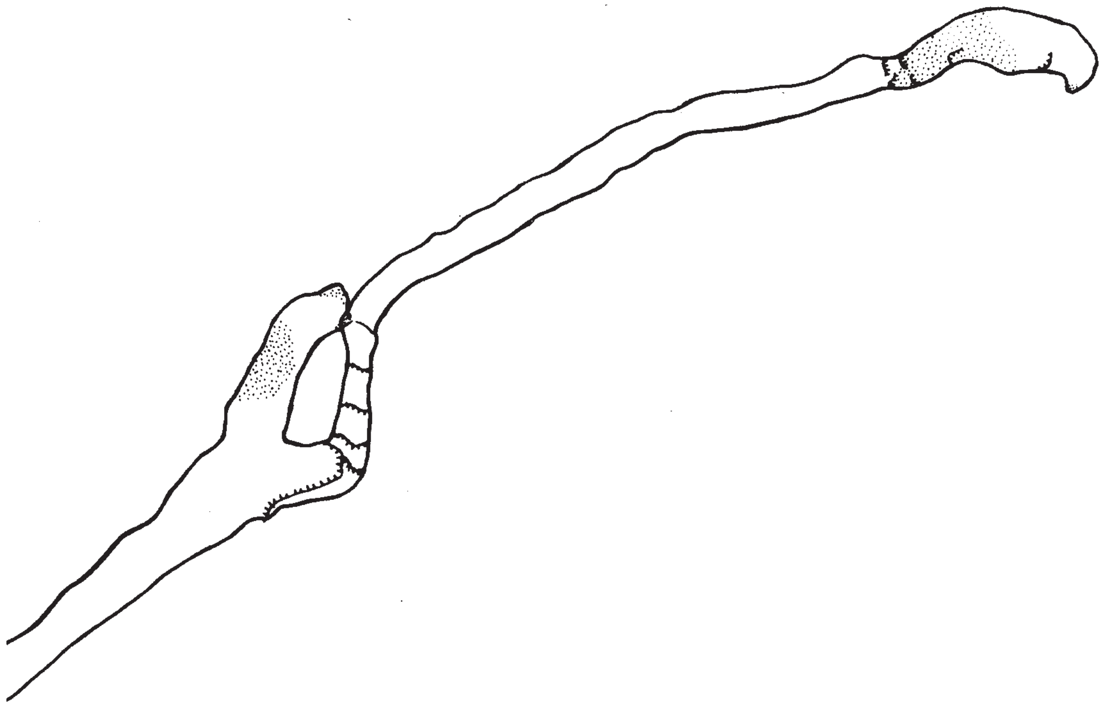
FOR THE NATIONAL PARK SERVICE, BY:

STEWART PECK, STUDENT TRAINEE (PARK NATURALIST)

G. GILBERT SOPER, PARK RANGER (GENERAL)

S. PECK, DRAFTSMAN

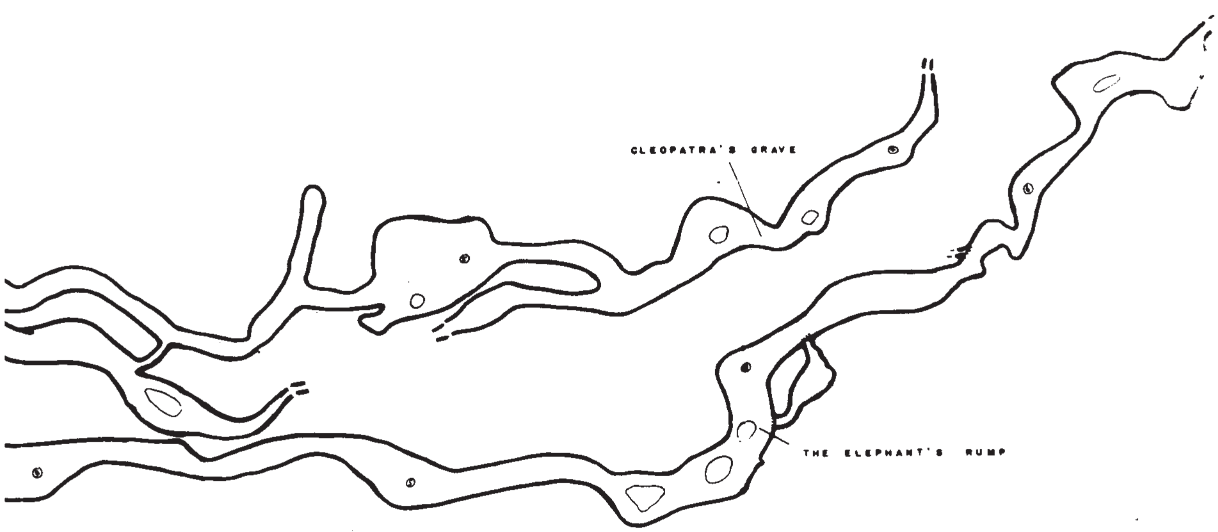




6862 FEET SURVEYED PASSAGE

DISCOVERED MARCH 2, 1918 BY J.D. HOWARD

J.D. HOWARD — J.F.G. CONE SURVEY : 6800' IN 1920 & 1495' IN 1926 : MAP LOST



MAJOR LAVA CAVE SYSTEMS OF OREGON

R. S. Knutson
Oregon Grotto of the National Speleological Society

INTRODUCTION

In recent years there has been a significant increase in attention given to the genesis of lava tube caves and the features they contain. This has in part been due to NASA funding of projects designed to investigate lava caves as potential terrestrial analogs to certain lunar features (Greeley, 1971a). This report will look at the three major lava tube systems in Oregon and attempt to relate certain flow parameters to the overall character of these system.

The systems in question are the Arnold (Knutson, 1969, Greeley 1971b) and Horse (Greeley 1971b) Lava Tube Systems near Bend in Deschutes County, and the BLM (Ciesiel and Wagner, 1969, Knutson, 1970) Lava Tube System northwest of Burns Junction in Malheur County. In describing the Arnold and Horse Systems this report will rely heavily on the study by Ronald Greeley and for the BLM System the article by Ciesiel and Wagner will be utilized.

ARNOLD LAVA TUBE SYSTEM

The Arnold Lava Tube System is located about 12 miles Southeast of Bend, Oregon, in Deschutes County. It is traceable for a distance of about 7 km (4.5 miles) and consists of tube segments alternating with collapsed tube portions or collapsed lava ponds. The original limits of the system are not known. Beyond the upper and lower extremities, the Arnold flow is covered by younger basalts.

The character of the intact cavernous portions is that of unitary tubes of large diameter, up to 15 m high and 12 m wide. Roof sections are quite thick, up to 25 m and the deepest portion is some 40 m below the surface. This character is most evident in the long caves of the lower portion including Wind Cave (1170 m) and Pictograph Cave (about 500 m).

The upper portion of the system has several large collapse depressions, which can be interpreted as reflecting original tube sections as described for the lower portion of the system. Arnold Ice Cave is short but has a roof thickness of some 25 m.

In the middle portion are found the only shallow caves with relatively small diameter. Here the Arnold system flow was covered by a younger flow originating near Lava Top Butte. It can be presumed that this flow entered collapse-trench or tube portions of the Arnold system and created these shallower caves (Deg and Bat Caves). The latter is also the only cave in the system exhibiting 2 levels.

The lava ponds shown on the Arnold System map are interpreted as structures resulting from a halting in the flow of lava. Upon rupture of the downslope side, the pond drains (into a lava tube) lowering the thinly developed crust to the pond floor. The deepest part of the resulting depression is near the downslope end and the edges often dip in toward the center, reflecting deformation of the thin roof crust of the pond. It is possible that lava ponds result from irregularities in the pre-flow topography, where the lava flow is halted by a topographic rise.

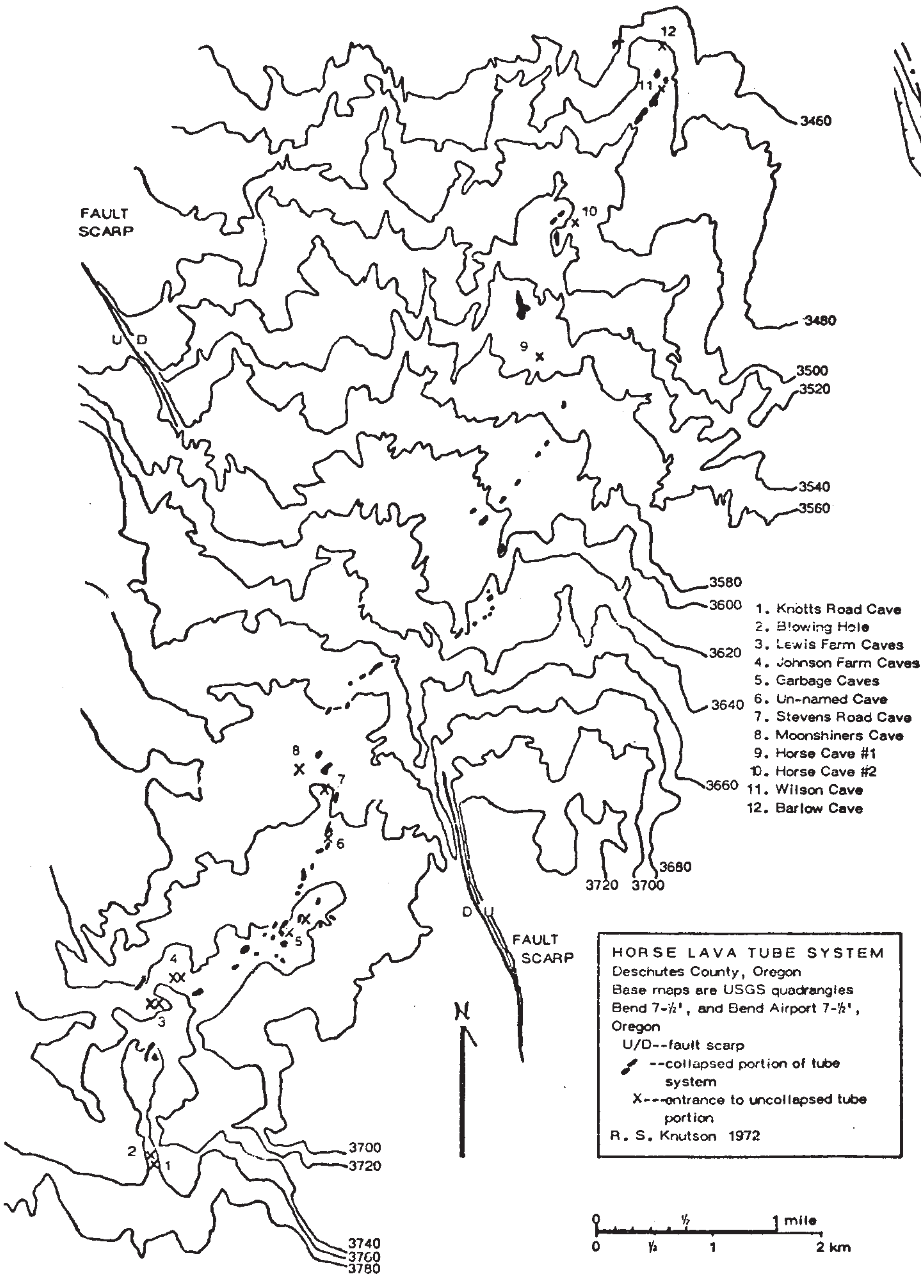
HORSE LAVA TUBE SYSTEM

The Horse Lava Tube System, about 2 miles east of Bend, is traceable for a distance of about 11 km (6.2 miles). As with the Arnold system, the source and terminus are covered by younger basalt flows. The character of the system, however, presents a marked contrast. Collapsed tube portions and short, intact cave segments represent a system of branching, braided, parallel, and sometimes disconnected lava tubes, all apparently combined as units in a single flow. No intact tube portion is deeper than 10 m below the surface and no collapse depression indicates a greater depth. Roof thickness varies from 3 to 8 meters. The longest intact tube portion is only about 150 m but this is not a good indication of tube length since intact segments often end in sand or dirt fill.

As with Arnold System, the Horse System appears to have generated a broad, low ridge along its axis.

BLM LAVA TUBE SYSTEM

The BLM Lava Tube System is situated in a lava flow south of Saddle Butte and northeast of Burns Junction, in Malheur County. The system has been traced for about 13.6 km (8.5 miles) and consists of tube segments and long, unroofed trench or collapsed tube portions. Two adjacent,


FAULT SCARP
U D
3460
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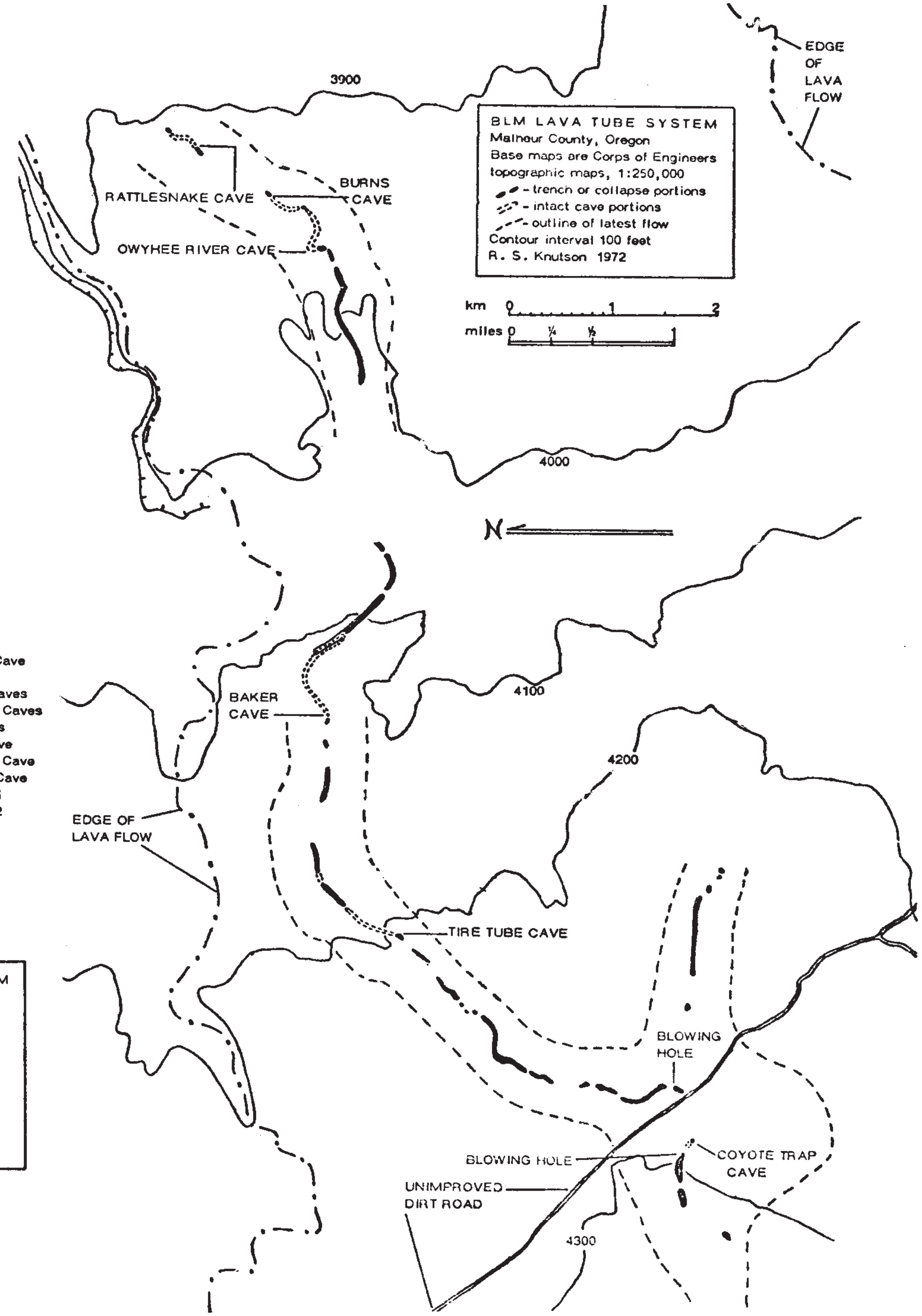
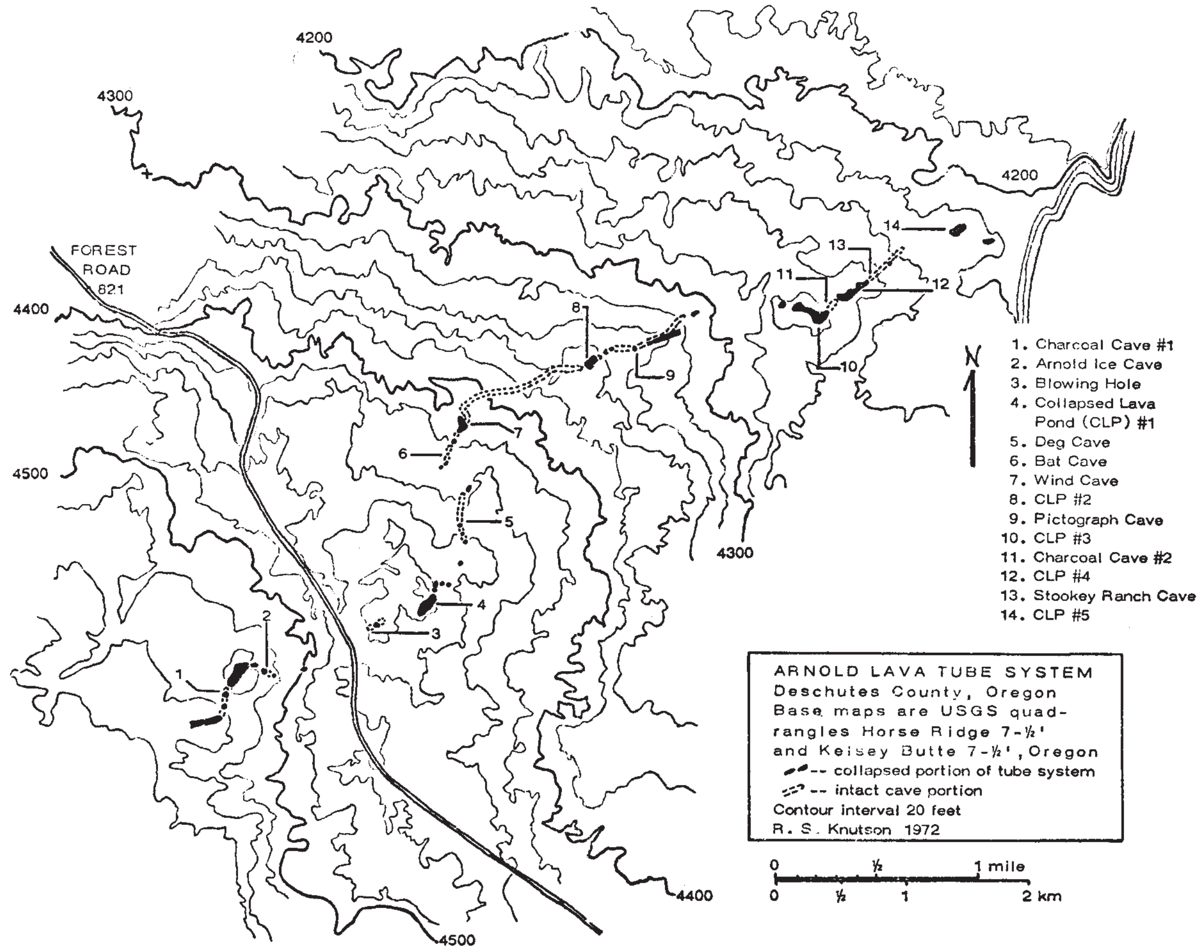
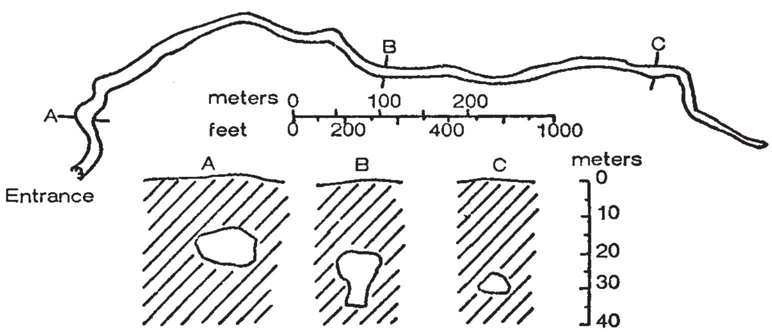
1. Knotts Road Cave
2. Blowing Hole
3. Lewis Farm Caves
4. Johnson Farm Caves
5. Garbage Caves
6. Un-named Cave
7. Stevens Road Cave
8. Moonshiners Cave
9. Horse Cave #1
10. Horse Cave #2
11. Wilson Cave
12. Barlow Cave
D U
FAULT SCARP
N
HORSE LAVA TUBE SYSTEM
Deschutes County, Oregon
Base maps are USGS quadrangles Bend 7-½', and Bend Airport 7-½', Oregon
U/D--fault scarp
--collapsed portion of tube system
X--entrance to uncollapsed tube portion
R. S. Knutson 1972
0 ½ 1 mile
0 ½ 1 2 km

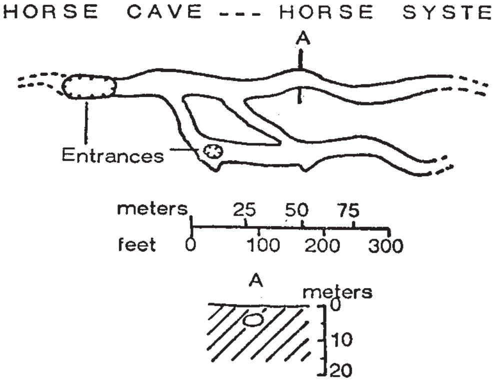

3900
EDGE OF LAVA FLOW
BLM LAVA TUBE SYSTEM
Malheur County, Oregon
Base maps are Corps of Engineers topographic maps, 1:250,000
- trench or collapse portions
- intact cave portions
- outline of latest flow
Contour interval 100 feet
R. S. Knutson 1972
km 0 1 2
miles 0 ¼ ½ 1
RATTLESNAKE CAVE
BURNS CAVE
OWYHEE RIVER CAVE
4000
N
4100
BAKER CAVE
4200
EDGE OF LAVA FLOW
TIRE TUBE CAVE
BLOWING HOLE
BLOWING HOLE
COYOTE TRAP CAVE
UNIMPROVED DIRT ROAD
4300



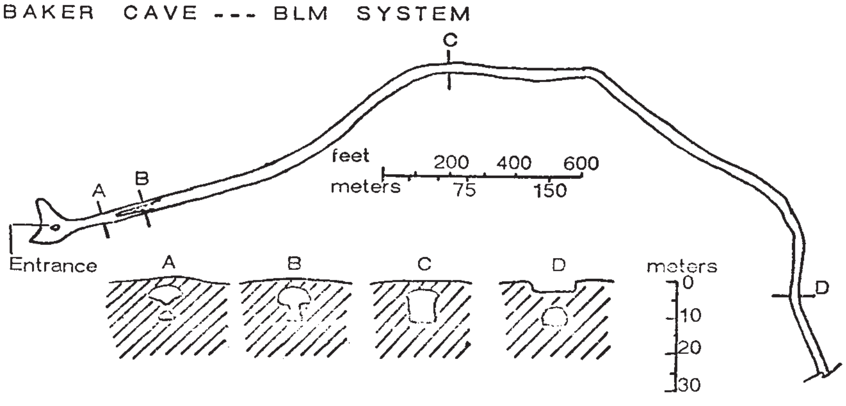
WIND CAVE --- ARNOLD SYSTEM



HORSE CAVE --- HORSE SYSTEM



BAKER CAVE --- BLM SYSTEM



SLOPE GRADIENTS FOR THE ARNOLD, HORSE AND BLM LAVA TUBE SYSTEMS

SYSTEM	TOTAL LENGTH	VERTICAL EXTENT	GRADIENT
Arnold	4.2 miles	320 feet	77 ft/mile
Horse	6.2 miles	260 feet	42 ft/mile
BLM	8.5 miles	370 feet*	43.5 ft/mile

*corrected for a steep section above the 4000 contour with a drop of 35 feet.

collapse depressions near the head of the system are of larger dimensions and may represent collapsed lava ponds or possibly the lava source, although short, uncollapsed cave portions are to be found about one-half mile upslope. These latter may not be part of the system. In general the trench portions are no deeper than 5 m, often have vertical walls, and there are long sections with a quite level dirt floor. It may be that these uniform trench sections represent unroofed channels. Such a trench is superimposed over the last 1000 feet of Baker Cave.

The tube segments are of medium to large dimensions. The longest is Baker Cave at about 1100 meters. This cave has sustained width and height of 15 m and 10 m, respectively. Owyhee River Cave achieves a cross-section of 20 m wide by 12 m high. At no point in the system is a cave floor more than 20 m below the surface. Only in Baker Cave is there separation into two levels, and there only in a short portion near the entrance. All known caves are unitary tubes.

Topographic indication of the tube system is minimal, but some trench and collapse structures represent local topographic highs. About 1-1/4 miles east (downslope) of Baker Cave the slope of the flow steepens for about 400 feet achieving a vertical drop of about 40 feet. It is assumed that this represents a steep portion in the pre-flow topography. A rim-rock scarp is adjacent to the flow at this point. No caves or collapse depressions are present in this steep section.

DISCUSSION

The three lava tube systems, from 7 to 14 km in length, are all situated on relatively flat lava plains, or relatively constant, gentle, gradient. It may be assumed that pre-flow topography was of similar nature--lava plains with no abrupt ridges or valley walls to channel the tube--containing flows.

Yet the three systems present a wide variance in size and nature. The ranking in depth of tube floors from the surface is: Arnold--40m, BLM--20m, and Horse--10m. The Horse System is apparently a braided network of channels while the Arnold and BLM Systems are unitary in nature.

It must be assumed that lava tube formation in terms of the size of tube formed in an unconfined flow will be determined by the viscosity of the flow and the gradient of the system.

The ranking in system gradient is as follows: Arnold--77, BLM--43.5, and Horse--42 ft/mile. This presents a rough correlation, especially if it is assumed that a braided system is shallower than the same flow operating through a unitary channel. That is, the Horse System may have been deeper if it had developed via a single flow channel.

Flow viscosity is a complex parameter and is dependent on several factors, including chemical composition, gaseous content and temperature of the lava. Since variance in only one of these factors is sufficient to control flow viscosity, determination of the eruptive viscosity of a flow is difficult.

The Arnold and Horse Systems are contained in the same basalt unit (Greeley, 1971b) presumably indicating a similar composition and gas content. Yet they are quite different, both in size (depth) and nature. The main factor here appears to be gradient, with the Arnold System on a much steeper slope. Yet it would seem that for lavas of similar viscosity, the flow on the steeper slope would be the thinner, not the thicker one. Perhaps the Arnold flow was lower in temperature, more viscous, and this resulted in a thicker flow.

The Horse and BLM Systems are of similar gradient but are in widely separated basalt flows. The difference in depth and character might, therefore, broadly be explained by a difference in flow viscosity. Indeed, the BLM flow lava appears to be much less vesicular and some cave breakdown blocks are composed of completely non-vesicular basalt. The lower gas content presumably resulted in a more viscous lava creating a thicker flow and a deeper cave. The low gradient and relatively higher fluidity of the Horse System lava presumably allowed for a broad, relatively thin flow resulting in more than one major channel.

The above analysis is probably over-simplified. For instance, the Arnold System may be formed in a narrow valley or rift which is now completely obscured. Detailed chemical analysis of the various lavas would be desirable.

CONCLUSIONS

The Arnold, Horse, and BLM lava tube systems present an interesting contrast in character, relative cross-section, size and depth. These systems are contained in flows of similar, non-channeled, situation. It is tentatively concluded that the differences are due to the controlling factors of lava viscosity and flow gradient.

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LAVA TUBES OF THE SOUTH MEDICINE LAKE HIGHLAND, CALIFORNIA

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Space Science Division, Ames Research Center
National Aeronautics and Space Administration

Roger Baer
Department of Geology, University of New Mexico

ABSTRACT

The Medicine Lake Highland is an eastern extension of the Cascade volcanic province in northern California. Situated on the Modoc Plateau, the Highland is composed of a basaltic and andesitic shield volcano about 13 miles in diameter. It has a prominent summit caldera 6 miles long and 4 miles wide; postcaldera lavas include andesites, dacites and rhyolites. Holocene basalt flows, which erupted predominately from pit craters on the flanks of the shield volcano, contain numerous well-developed lava tubes in the northern region (Lava Beds National Monument) and in the southern region (Siskiyou County). In the southern region an unnamed series of basalts flowed south down a fault valley and merged with similar flows erupted from the Timbered Crater vent. Extensive lava tubes, many of which are partly collapsed, characterize the flows. One partly collapsed tube (possibly originating from Giant Crater) can be traced for about 14 miles. Some sections of the tube divide into four distinct levels that are stacked vertically for a total height exceeding 120 feet. Collapsed wall sections display preflow country rock and reveal the lower surface of the lava flow. Well-preserved sections of the lava tube linings, and subsequent flows along the floor. Details of these and other lava tube structures provide additional information on the mechanisms of lava tube formation and geomorphology.

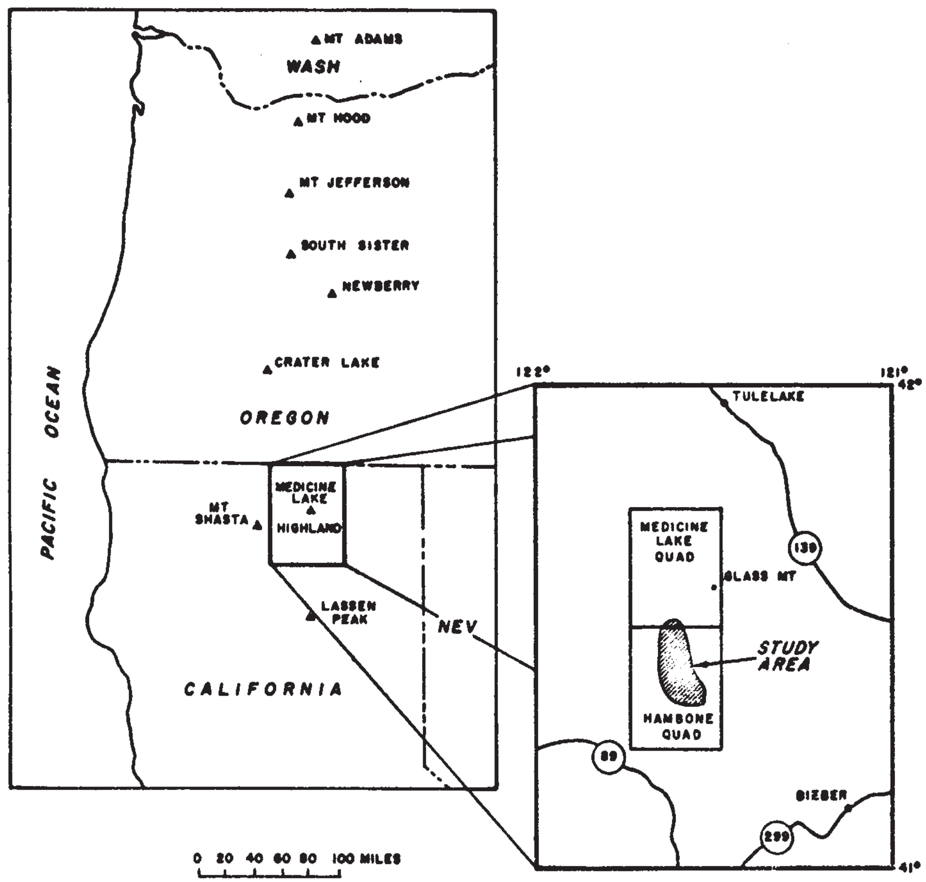

Figure 8-1: Map of northern California, western Oregon and southern Washington with a blowup of the one degree quadrangle containing the Medicine Lake Highland. Selected peaks of the Cascade Range and the location of the study area are shown.

Fig. 2 Map of northern California, western Oregon and southern Washington with a blowup of the one degree quadrangle containing the Medicine Lake highland. Selected peaks of the Cascade Range and the location of the study area are shown. Maps after Macdonald (1966).

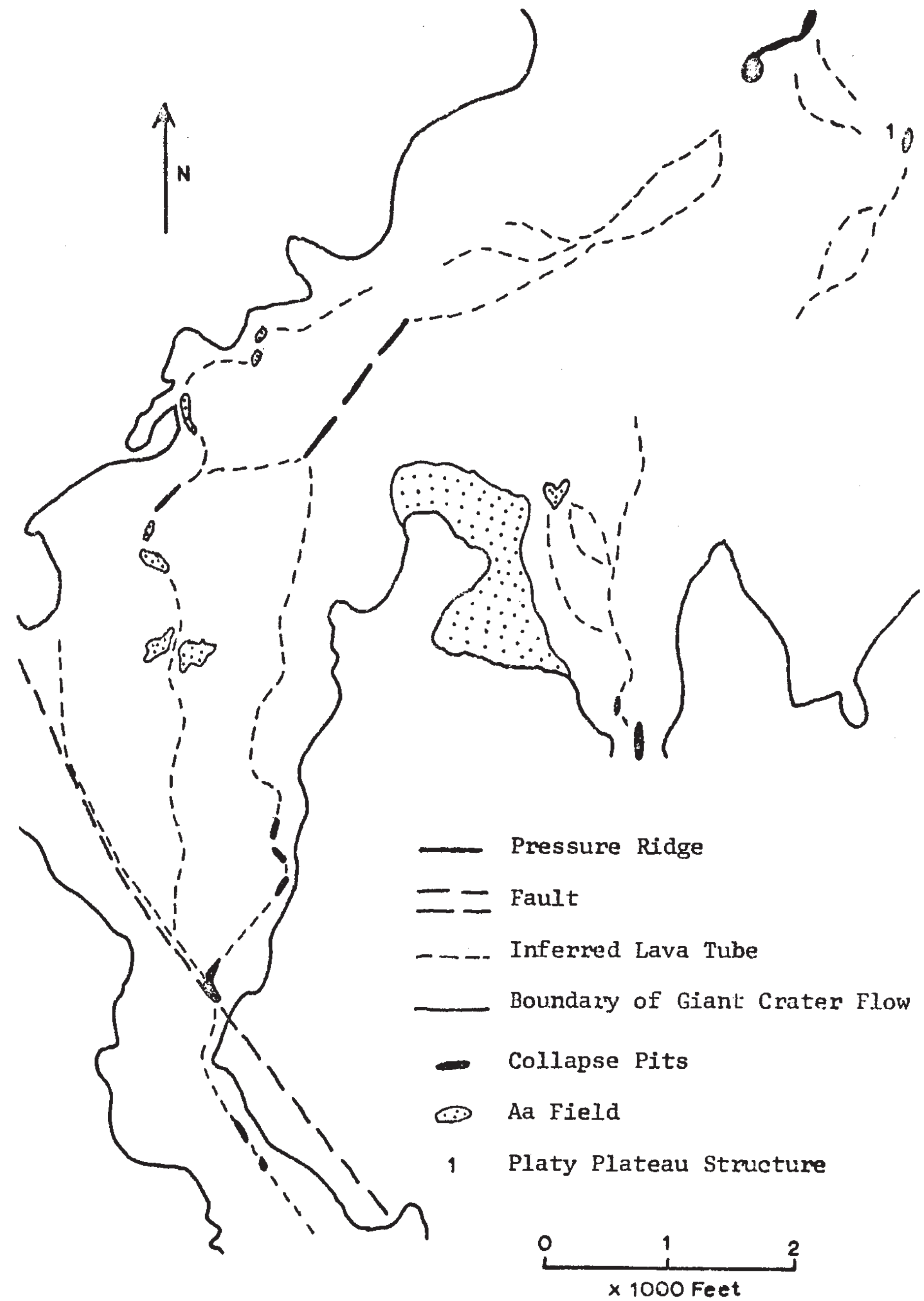

Figure 8-2: Map of a section of the Giant Crater flow.

HAWAIIAN LAVA TUBES -- A PRELIMINARY REPORT [1]

Francis G. Howarth
B.P. Bishop Museum
Honolulu, Hawaii

The easternmost islands of the Hawaiian Archipelago are high volcanic islands built up primarily by relatively thin fluid flows of vesicular basalts. These flows occur either as smooth pahoehoe or rough aa depending on gas content and temperature. Lava tubes usually form in pahoehoe basalt and are a common feature in the Hawaiian Islands. Although sea caves and a limestone cave occur in the Hawaiian Islands, the purpose of this report is to briefly describe the significant lava tubes on each island and give their geological history.

BIOLOGY

The biota of Hawaiian lava tubes, especially the arthropods, are my primary research interest (Howarth, 1973). However, to understand lava tube ecosystems a detailed account of their geology and history is needed. In Hawaii there are troglobites (obligatory cave animals) living in lava tubes that have existed for a shorter period than is necessary for the evolution of the animals themselves. The vesicular and highly fractured nature of most basaltic lava, including pahoehoe, allows numerous avenues for subterranean dispersal by cave organisms. Thus, where vulcanism is nearly continuous over a prolonged period and the environmental conditions allow colonization of lava tubes by animals, then cave organisms can progressively move from remnants of older lava tubes into younger lava tubes as they become colonizable. The recognition of this dispersal mechanism is very significant for it now allows us to predict the existence of a specialized cave fauna in lava tubes elsewhere in the world. Significant faunas in lava tubes are also known from Japan (Ueno, 1971) and the Galapagos (Leleup, 1968).

LAVA TUBE REMNANTS

The oldest lava tubes in the Hawaiian Islands are exposed remnants on cliff faces and on the sides of river valleys. Some of these entrances are shelter caves formed by erosion, but many are the exposed termini of lava tube segments. Most of these are only shelter caves, the lava tube having been either partially or completely filled by subsequent lava flows, siltation, or collapse not far from the cliff face entrance. A few of these visited on the island of Oahu, however, have been true cave segments, with lengths of 50 m. These entrances are common in the drier cliff faces on all the main islands, but many are of difficult access and most remain unexplored. These caves were often used by the early Hawaiians for burials.

KAUAI

The primary vulcanism which built the shield volcano on the island of Kauai ceased 5-6 million years ago. However, there was extensive post-erosional volcanic activity on Kauai, known as the Koloa volcanic series, which now covers much of the eastern half of the island and lasted approximately 1.5 million years. The most recent dated flow is 600,000 years old (Macdonald and Abbott, 1970). Many of these post-erosional flows fill deeply eroded valleys and are very thick.

There are several lava tube sections extant on Kauai in the Koloa volcanic series which, judging from the degree of preservation, are most likely younger than 600,000 years. However, since sand dunes formed during the Waipio stand of the sea are found on the surface of the lava flow, the lava tubes must be at least 120,000 years old (Ku et al., 1974).

OAHU

Oahu has few lava tubes of much interest to the vulcanospeleologist. The latest substantial post-erosional flows on Oahu are the Tantalus and Sugarloaf flows which now underlie part of the city of Honolulu, smaller flows in Niu and other valleys on Southwestern Oahu, and a number of littoral tuff cones, the most famous being Diamond Head and Punchbowl. A number of large caves were accidently discovered in Honolulu during the past several decades by collapse from urban construction. These caves were water filled and have now been covered over by urbanization and are no longer accessible.

1. Contribution no. 40, Island Ecosystems IRP/IBP Hawaii. NSF Grant no. GB 23075.

Halliday (1958), described some of the caves on Oahu. Makua Cave is a large sea cave, as confirmed by the presence of dikes in the cliff above the entrance. Judd Street Cave is a remnant lava tube section in a steep slope at the entrance to Nuuanu Valley, Honolulu. The cave is a low braided stream passage typical of distributary systems near the edge or end of a flow.

MAUI

The island of Maui is actually two islands joined by a sandy isthmus. West Maui is much older and highly eroded. Only remnants of lava tubes in cliff faces are currently known from West Maui.

East Maui, or Haleakala Volcano, is much younger and a number of extensive lava tubes are known. The youngest lava on East Maui is Kalua-o-lapa flow on the south coast which occurred between 1785 and 1790 A.D. It has a small lava tube approximately 100 m long near the vent. Larger lava tubes have been known for some time in Haleakala Canyon near the summit of the mountain. These are Long Cave and Crystal Cave. A few large tubes are known above the town of Hana on the eastern slopes and a partially submerged lava tube nearby in Waianapanapa Caves State Park was well known in early Hawaiian legends.

HAWAII

The island of Hawaii holds the most interest for vulcanospeleologists, for it is here that one can watch lava tubes forming and study both young, well preserved lava tubes and older lava tubes in all stages of degradation. Lava tubes can be found here of all types and some have been described in the literature: Thurston Lava Tube by Powers in 1920 and Kaumana Cave by Von Seggern in 1968. Lava flows containing caves vary from short bursts of only small amounts of lava to the 1859 Mauna Loa flow which flowed 50 km to the sea and added nearly 0.7 km^3 of lava (Macdonald & Abbott, 1971).

The longest currently known lava tube in the State is Kazumura Lava Tube, located on the Southeast Rift of Kilauea Volcano at approximately 400 m elevation. The total mapped passage length (1972) is 3435 m. An additional 900 m of passage is known. The cave is young and well preserved. It is in an undated prehistoric flow which covers the 20,000 year old Pahala ash. The cave displays many of the phenomena found in lava tubes and is of great significance biologically. Several endemic cave arthropods are known from this cave (Howarth, 1972, 1973).

Passage shapes in the cave vary from high narrow meandering "canyons" to large elongate rooms which are nearly circular or key-hole shaped in cross-section. There also are sections of the cave with up to 4 well defined levels. These different passage types alternate with one another and each must have a common origin. The multi-level passages most commonly indicate the existence of a skylight in the upper-most level. Such correlation suggests that secondary roofs form over the molten lava under skylights. Other passage shapes may be formed or influenced by the slope and landforms before the flow, the amount of erosion and levee building by the flowing lava, the thickness of the roof, spalling during and after the flow, and also the amount of draining of the molten lava at the cessation of the eruption. Since not all the lava drains from such cave passages and there is currently no way of measuring the thickness of the floor, these caves may display less than 10% or more than 90% of the size of the active flow channel. Below lava falls in the cave well preserved plunge pool surfaces in the form of sine waves are "frozen" in the floor. Such kinetic energy, especially at a lava fall, most likely erodes the substrate.

In most of Kazumura Lava Tube the walls and ceiling are glazed. The floor here and there has a smooth, typical pahoehoe surface, commonly also with a "stepping stone" pattern of plate-like crusts frozen in the surface. In places it has a clinkery pahoehoe surface. Occasionally the passage is nearly filled by large treacherous spalling block mountains. There are a few areas well decorated with speleothems, mainly lavacicles and driblet spires.

The cave passage has 7 known skylights in the 4335 m of passage. All of these skylights appear to have been formed while the lava was flowing in the tube. In most cases a secondary roof had time to form beneath the skylight. At the other skylights most of the spalling blocks from the skylight fell into molten lava and were carried away by the flow.

The upslope cave begins at an entrance from a sinkhole 15 m long, 7 m wide, by 4 m deep. An unexplored cave passage continues on the upper end of the sinkhole. Four of the skylights are small holes in the ceiling at high narrow canyon passages and since the diameter of the largest is less than 1/4 of the width and 1/4 - 1/16 of the height of the cave passage, they are not considered to interrupt the continuity of the cave. The other 2 entrances are offset on upper levels. These entrances also do not interrupt the continuity of the cave passage.

POSTSCRIPT

Since this lecture was given the final terminus breakdown in Kazumura Lava Tube has been bypassed. The present (1974) surveyed main passage length is 8.1 km with an additional 2 km of main passge and side passages known.

ACKNOWLEDGEMENTS

I thank W.C. Gagné, N.C. Howarth, J. Jacobi, J. & S. Juvik, S.L. Montgomery, W. Ruffin, and F.D. Stone for assistance during field work. I am especially indebted to W.C. Gagné, N.C. Howarth and F.D. Stone for reviewing the manuscript and assisting in its preparation.

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FORMATION AND GROWTH OF LAVA TUBES DURING 1970-71 AT KILAUEA VOLCANO, HAWAII

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U.S. Geological Survey
Menlo Park, California

READ IN ABSTRACT

An expansion of this paper with additional content by Donald W. Peterson has been published in Studies in Speleology (Vol. 2, part 6, 1974, for 1973, pp. 209-222), under the title: Observed Formation of Lava Tubes during 1970-71 at Kilauea Volcano, Hawaii.

A complex braided and distributary system of lava tubes developed by roofing of lava rivers and coalescence of pahoehoe toes during 1970-71 at Kilauea. Lava was eventually transported as far as 12 km underground through these tubes, at average rates of 2-3 km/hour. Skylights formed at various times during development of the tube system, allowing observations into the active tubes. Initially the tubes were small--generally only 1-3 m deep--but they enlarged to at least as deep as 15 m, probably by erosion while lava continued to flow through them. The tubes were excellent heat insulators, so that lava cooled very little during its flowage in the system. Underground lava falls, multi-storied tubes, lava stalactites, and many other features common in prehistoric lava tubes were observed in various stages of formation.

INTERNATIONALLY SIGNIFICANT LAVA TUBE CAVES OF THE CANARY ISLANDS

William R. Halliday, Director
Western Speleological Survey

INTRODUCTION

The Canary Islands are a group of seven large and innumerable tiny volcanic islands off the northwestern coast of Africa. Major lava tube caves are known on at least three of the main islands: Tenerife, Lanzarote, and Hierro.

In recent years, the title of world's largest lava tube cave has been claimed successively for two of these caves: the Cueva de Los Verdes system on the island of Lanzarote (von Fritsch, cited by Stone, 1889, Montoriol, 1969), and the Cueva del Viento system (Fig. 11-1) on the island of Tenerife ("Anombro", 1970, Teigell, 1970, "Troglobio", 1970). Almost a century earlier, a British visitor casually mentioned local estimates of a length of 11,000 feet for La Cueva de San Marcos at the seaward end of the flow in which Cueva del Viento is located (Stone, 1889), a figure far exceeding the mapped length of any lava tube cave until 1958 (Halliday, 1972).

In November, 1971, my wife and I conducted a vulcanospeleological reconnaissance of the archipelago, with special reference to Lanzarote. This report is based on that expediton, plus study of some of the pertinent literature.

CUEVA DE LOS VERDES SYSTEM AND THE MONTE CORONA FLOWS

The Cueva de Los Verdes system takes its name from a particularly spectacular now-commercial segment of this moderately extensive lava tube system, bearing that name. The origin of the term "Los Verdes" (Spanish for "The Greens" or "The Greenery") seems lost in antiquity. Several modern explanations have been advanced. My own conjecture is that it derives from the relative abundance of small plants living on this part of the Monte Corona flows. Seasonally they color much of the lava, contrasting vividly with the brown, red, grey, and black face of most of the remainder of this near-desert island.

Monte Corona is a large cinder cone or small volcano located near the northeast end of Lanzarote, with the appearance of being of early Recent or late Pleistocene age. Nearly all the Monte Corona flows coursed east, fanning out over about 50 km^2 and extending the coastline as much as 3 km (Macau, 1965). Aside from short surface tubes which are widely distributed and have no apparent relationship to the main caves, lava tubes and sinks are known in only one narrow, sinuous zone of the flows. Probably the flows predated human habitation of the island; the main cave figured prominently as a shelter from Moorish raiders in pre-conquest days (prior to 1400 A.D.).

Speleological features of this area divide naturally into three groups: (1) a group of small sinks and very short segments of lava tube located close to the east side of Monte Corona and separated from the Cueva de Los Verdes system by a steep slope about 100 feet high, perhaps a flow front; (2) the Cueva de Los Verdes system, described in some detail below; (3) a group of small tubes and sinks near the ocean, the most important and largest of which is the Jameo del Agua, site of a delightful underground nightclub, marine nature reserve, and cultural center (Fig. 11-3). This is probably a segmentally isolated continuation of the Cueva de Los Verdes thoughway. The position of some smaller sinks and short branches of tube nearby suggests that a small amount of distributary branching may be present. However these instead may be features of independent flow units. The most seaward jameo (the local word for collapse sink) shows invasion by two small solid surface tongues (Fig. 11-4).

The Cueva de Los Verdes system occupies the central half of the cavernous zone, and is entered through the following orifices listed from west to east, progressively down-flow: Jameo de Prendes; Jameo de la Gente; Jameo Cumplida; Puerta Falsa or Jameo de los Almacenes; Cueva de Los Verdes (commercial entrance) or Jameo de la Puerta Mora.

A considerable literature describes and discusses this system in several languages. I have been unable to find the source of the description Stone (1889) attributed to a Herr von Fritsch, but the now-commercial cave was discussed and one section rather amusingly depicted by Hartung (n.d., ca. 1860). Earlier Spanish-language citations were tabulated by Puig (1894). In modern times it has been studied especially by Macau (1965) and Montoriol (1969).

The system is comprised of five cavernous segments separated by jameos. Two of these collapse sinks - Jameo de la Gente (Fig. 11-6) and Puerta Falsa (Fig. 11-7) - are awesomely enormous. The overall pattern of the system is unitary, with multiple superposed levels variously interconnected. The dominant impression is vast spaciousness. A splendid variety of flow

features is profuse in some areas; other sections consist largely of breakdown-demarcated tube. Considerable minutely crystalline gypsum is present in some areas, and some lateral breakdown is due to elongation of gypsum crystals in cracks.

EXTREMITY SEGMENTS

At each end of the system are short caves of such little importance that they can be dismissed for the purposes of this account. The lowest segment houses the electrical generator for the commercial section, and a resulting fume problem precluded study at the time of our visit. Montoriol (1969) recorded a length of 130 m and depth of 20 m. This segment consists of a spacious corridor descending, ascending and finally redescending. The floor is composed of breakdown slopes. Uptube from Jameo de Prendes is a tube segment about half as long as that at the lower end of the system. We did not visit it, and no investigator seems to have described it in detail. Jameo de Prendes is the smallest of the orifices of the system, measuring about 12 m in diameter.

THREE MAJOR CAVERNOUS SEGMENTS

The three main caves of the system are (from west to east): (1) The upper cave or Jameo de Prendes - Jameo de la Gente segment, 1,170 meters long (Montoriol, 1969); (2) the middle cave or Jameo de la Gente - Puerta Falsa segment, with about 1,650 meters of single-level and stacked passages over a distance of about 1,165 meters; (3) the Cueva de Los Verdes proper, with about 1,900 meters of single-level and stacked passages over a distance of about 1.350 meters.

As the system is most conveniently traversed upslope from the lowest point of the Cueva de Los Verdes proper, each will be described here in that direction and order.

CUEVA DE LOS VERDES AND PUERTA FALSA

The Cueva de Los Verdes proper was well mapped and described by Macau in 1965. Its downslope (commercial) entrance (Fig. 11-9) is the more convenient, but quite confusing and the speleologist will probably prefer to obtain special permission to approach by way of the Puerta Falsa, located about 4 km downslope from Monte Corona. This is a spectacular collapse sink, slightly sinuous, and 92 by 18 m in length and width (Montoriol, 1969) and five to fifteen m deep. Its deeper downslope end opens into the undeveloped up-tube segment of the Cueva de Los Verdes. This is an impressively spacious but comparatively featureless breakdown passage about 800 m long and averaging about 12 m in diameter. One short length of superposed passage is present. Considerable powdery gypsum occurs on the floor and walls.

The commercialized 1/2 km length of this cave is radically different. Comparatively linear, it consists of a stacked sequence of two major and several rudimentary levels. The lower (commercial) entrance opens directly only into the upper level, hence that level is about 50 meters shorter than the lower.

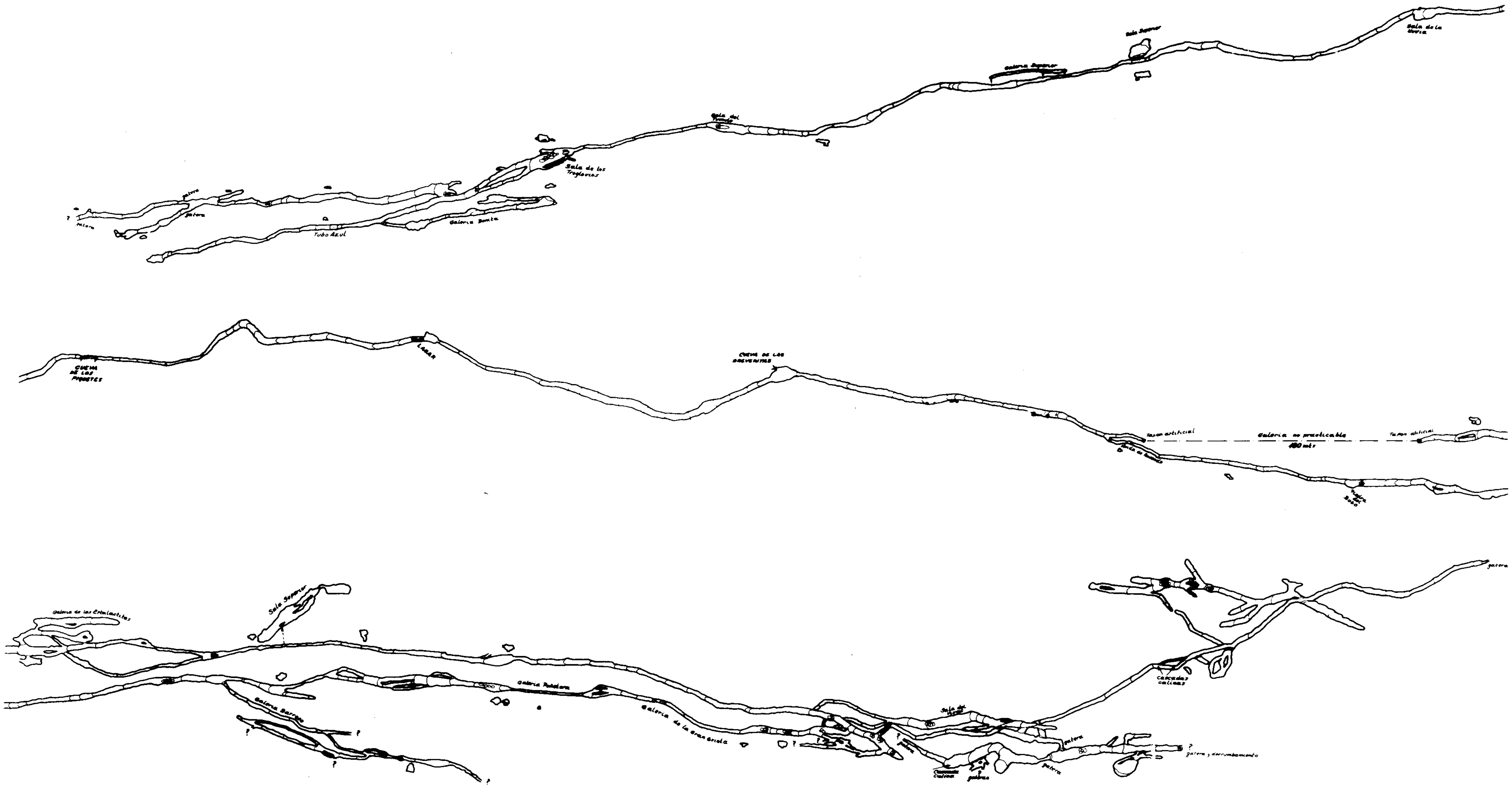
Throughout this section of the cave breakdown is comparatively scant. Well developed flow features include lateral ridges and gutters, lava balls, slumped glaze, tapered stalactites, and some unusual forms meriting special study beyond the scope of this report. Lateral coatings vary from pellicular to thick multiples. Large, spacious chambers are demarcated by flow-determined narrows. The principal characteristic of this section is complexity so marked as to merit even more intensive study than it has received to date. For example, not all the rudimentary levels are of similar genesis. "La Crypta" is a short length of rudimentary level consisting mostly of a tube-in-tube within a short sub-tube. An upward-sloping crawlway above "El Refugio" in the upper level leads to a small tumulus chamber not shown on Macau's map.

The commercial entrance is a collapse sink terminating the upper level. By proceding seaward a few dozen meters in the jameo, a small hole permits descent into the lower level near its lower end, at a point where it is as much as 20 m below the surface of the flow.

Total length of all the passages in this lowest of the three caves including rudimentary levels, is about 1,900 m.

MIDDLE CAVE
(Jameo de la Gente - Puerta Falsa segment)

This cave posesses other vertical complexities. Proceding west (up-slope) from the Puerta Falsa jameo, the twilight zone consists of a single spacious corridor containing remnants of multi-level development in the form of partially collapsed flow ledges about halfway up the 10-m walls. After a few dozen meters, the visitor encounters a short segment where the multilevel structure is intact, forming a short natural bridge. Beyond is a short gap in the interlevel partition, thence the remainder of this cave is stacked as far as the termination of the upper level at the Jameo



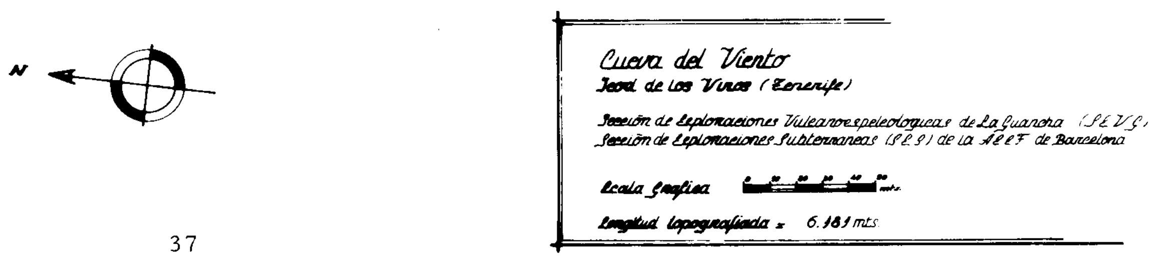
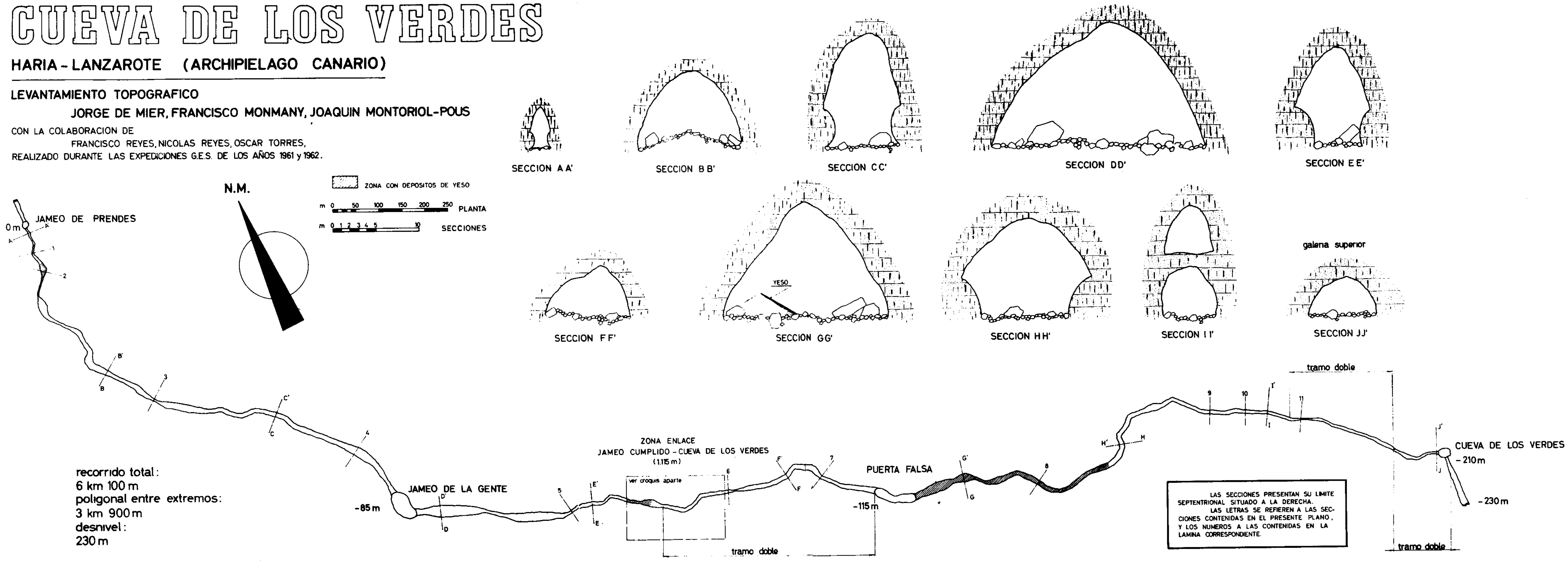


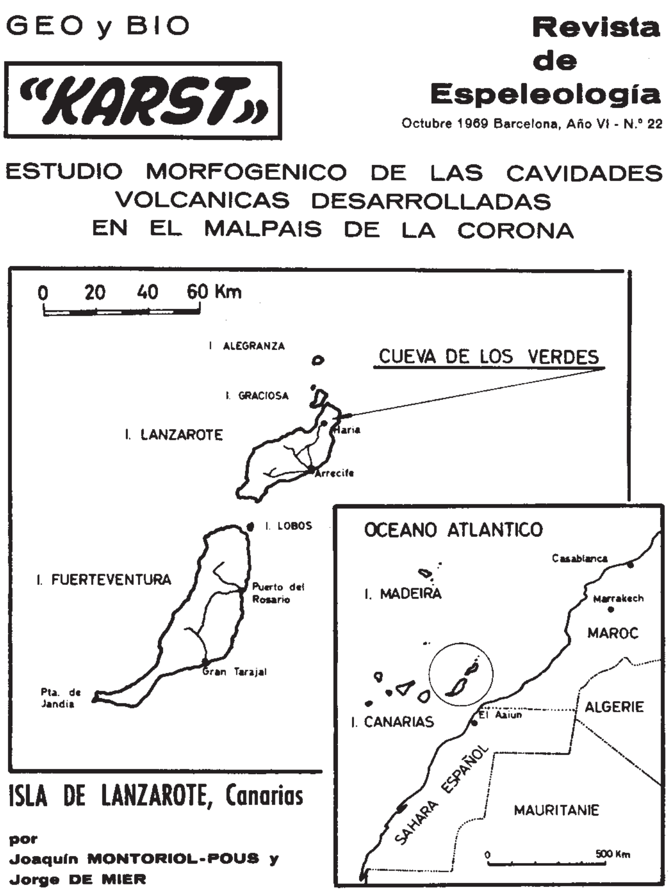
Figure 11-1: Map of Cueva del Viento, Tenerife, courtesy of G.A.M.



CUEVA DE LOS VERDES
HARIA - LANZAROTE (ARCHIPIELAGO CANARIO)
LEVANTAMIENTO TOPOGRAFICO
JORGE DE MIER, FRANCISCO MONMANY, JOAQUIN MONTORIOL-POUS
CON LA COLABORACION DE
FRANCISCO REYES, NICOLAS REYES, OSCAR TORRES,
REALIZADO DURANTE LAS EXPEDICIONES G.E.S. DE LOS AÑOS 1961 y 1962.
N.M.
ZONA CON DEPOSITOS DE YESO
m 0 50 100 150 200 250 PLANTA
m 0 1 2 3 4 5 10 SECCIONES
SECCION A A'
SECCION B B'
SECCION C C'
SECCION D D'
SECCION E E'
SECCION F F'
YESO
SECCION G G'
SECCION H H'
SECCION I I'
galeria superior
SECCION J J'
0 m
JAMEO DE PRENDES
JAMEO DE LA GENTE
-85 m
ZONA ENLACE
JAMEO CUMPLIDO - CUEVA DE LOS VERDES
(1.115 m)
ver croquis aparte
tramo doble
PUERTA FALSA
-115 m
tramo doble
CUEVA DE LOS VERDES
-210 m
-230 m
tramo doble
recorrido total:
6 km 100 m
poligonal entre extremos:
3 km 900 m
desnivel:
230 m
LAS SECCIONES PRESENTAN SU LIMITE SEPTENTRIONAL SITUADO A LA DERECHA.
LAS LETRAS SE REFIEREN A LAS SECCIONES CONTENIDAS EN EL PRESENTE PLANO, Y LOS NUMEROS A LAS CONTENIDAS EN LA LAMINA CORRESPONDIENTE.

Figure 11-3: Jameo del Agua. Photo by Gabriel, photo courtesy Cabildo Insular de Lanzarote.

Figure 11-4: Lava Tongue invading Jameo del Tresoro.



GEO y BIO

"KARST"

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Octubre 1969 Barcelona, Año VI - N.° 22

ESTUDIO MORFOGENICO DE LAS CAVIDADES VOLCANICAS DESARROLLADAS EN EL MALPAIS DE LA CORONA

ISLA DE LANZAROTE, Canarias

por
Joaquín MONTORIOL-POUS y
Jorge DE MIER

Figure 11-5: Cover of Montoriol's study showing Lanzarote and its relationship to Africa and adjoining islands.

Figure 11-6: Down-tube end of Jameo de la Gente.

Figure 11-7: Down-tube end of Puerta Falsa.

Cumplida. Both upper and lower levels are major throughway tubes. An intermediate small tube is seen at the lower end of the stacked levels but this is rudimentary and is not seen at a small collapse pit connecting the levels some meters up-tube.

UPPER LEVEL OF MIDDLE CAVE

Much of the 450 meter length of the upper level of this segment of the system is floored with a soft mixture of gypsum and earth material. At first this passage is about 5 meters in diameter. At a point about 100 meters up-tube from the natural bridge, it is almost blocked by a lava plug, but a tight ascending crawl leads to a continuation several meters higher. Initially this is small, but enlarges markedly up-tube toward the Jameo Cumplida where it terminates with an orifice about 10 meters in diameter. This part of the cave is only slightly sinuous.

JAMEO CUMPLIDA AND UP-SLOPE CAVES AND SINKS

The Jameo Cumplida is a sinuous collapse trench about 300 meters long, terminating the upper level of the middle cave. Its midpoint is spanned by a short natural bridge. Its portion up-slope from the bridge is about 5 meters deep, but the down-slope section is about twice as deep, suggesting single- and multi-level collapse respectively.

A shallower sink is present about 100 meters further up-slope. No penetrable openings connect it and the Jameo Cumplida although a small cave about 30 meters long extends toward Jameo Cumplida from the jameo up-slope. It is almost entirely walled by breakdown but terminates with two short superposed tube segments, each about one meter in diameter. These appear to be local rudimentary tubes.

LOWER LEVEL OF MIDDLE CAVE

The lower level of this segment of the system is comparatively featureless but considerably longer than the upper level. A few hundred meters up-tube from the natural bridge in the Puerta Falsa twilight zone, it appears to end in a huge talus pile which fills the passage to the ceiling. However, a small opening high on the north wall permits the explorer to continue into a section with fine flow patterns and some siliceous dripstone, virtually free of breakdown. The mass of breakdown seemed to be located beneath or near the lower end of the Jameo Cumplida but I was unable to perform the mapping necessary to evaluate this.

Up-tube from the point where the passage is almost plugged by breakdown, the lower level enlarges to a diameter of about 15 meters. This section is slightly sinuous. It contains much amorphous and some finely acicular gypsum. A few tiny oulopholites are present. A few short, rudimentary ceiling channels were observed. This corridor terminates at the lower end of the Jameo de la Gente.

Montoriol (1969) found the length of this level to be about 1,165 meters, so the total length of the middle cave is about 1,650 meters. It descends 29 meters (Montoriol, 1969).

JAMEO DE LA GENTE

Montoriol (1969) recorded the length of this jameo (Fig.s 11-10 and 11-11) as 70 meters, and its width as 35 meters. Deeper and more sheer-walled than the Puerta Falsa, it is indeed a spectacular sink. The down-tube end is about 20 meters deep, but the up-tube section (Fig. 11-12) is considerably shallower. Here a lower level extends partway under the breakdown pile, producing an overhang about five meters high.

UPPER CAVE
(Jameo de Prendes - Jameo de la Gente segment)

I was able to study only the lower end of this cave. There, multiple lateral coatings and flow ledges were especially well developed. Montoriol (1969) found it to be a unitary tube 1,170 meters long, with a descent of 86 meters. Near the upper end are gypsum deposits. Height and width are more variable than in other parts of the system but except at the lower end, as mentioned, no stacked multilevel sections were recorded.

* * *

THE CUEVA DEL VIENTO SYSTEM

The Cueva del Viento system differs radically from that just described. It is in the steep Pico Viejo flows near the west end of the north side of the island of Tenerife. These flows descend about 3 km in a slope distance of about 15 km; the steepest speleoliferous flows I have observed

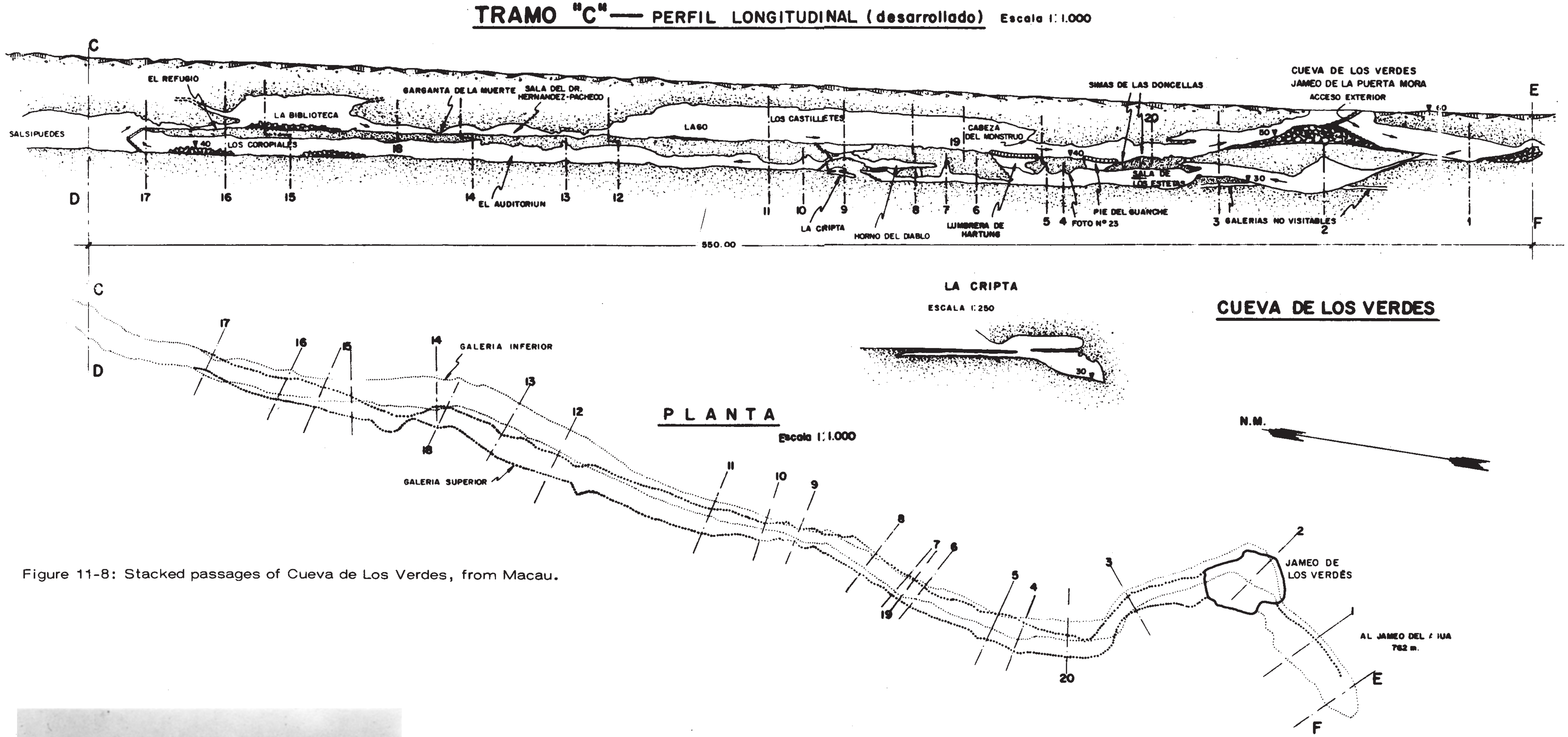

Figure 11-8: Stacked passages of Cueva de Los Verdes, from Macau.

Figure 11-9: Commercial entrance to Cueva de Los Verdes, looking up-tube on a hazy day.

Figure 11-10: Surface of the lava flow downslope from Jameo de la Gente (left edge). Jameo Cumplida is barely visible on the horizon.

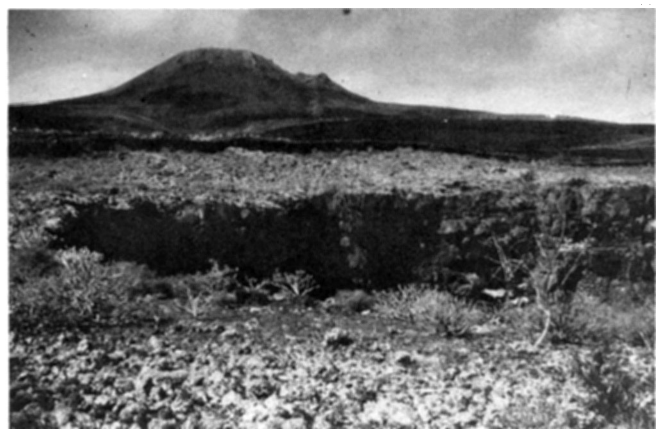

Figure 11-11: Looking across part of Jameo de la Gente to Monte Corona.

Figure 11-16: Siliceous microgours in Cuevo del Viento.

(Fig. 11-13). They terminate in a sea cliff containing the lower entrance of Cueva de San Marcos, mentioned above. The descent of the then-mapped portion of the system is about 580 meters (Montoriol, written communication, 28 October 1971).

This system consists of an elongated, braided complex of superficial, small- to medium-sized passages (Fig.11-15), interrupted by a single 10-meter collapse sink (Fig. 11-16) which divides it into upper and lower caves (some artificial barriers also are present). These caves are being mapped by the Grupo Vulcanoespeleologico de La Guancha of the Grupo Montanero de Tenerife, with 4,632 and 1,578 meters completed in the upper and lower caves, respectively, as of November 1971. Exploration is continuing at both extremities, and also at the upper end of Cueva de San Marcos where about 2,000 meters of passage have been penetrated (Teigell, oral communication, November 1971).

Parallel to the Cueva del Viento system but at a higher elevation are at least two more lava tube caves, one unitary, one braided (Teigell, oral communication, November, 1971). It seems likely that all these caves are integral parts of a "super-system" of a type not previously delineated. For this the term "megasystem" may be appropriate.

With the exception of recent press reports ("Anambro", 1970; Teigell, 1970; "Troglobio", 1970) the literature on this system is almost entirely limited to Cueva de San Marcos. Under a variety of names (Cave of Icod, Cave of Guanches, etc.) it was an object of considerable celebrity in the late 19th Century because of the discovery of mummified remains of Guanches, aboriginal inhabitants of the island. Its relationship to the lower cave of the Cueva del Viento system is not yet clear.

While the diameters of these caves are much smaller than those of the Cueva de Los Verdes system (mostly being one to two meters in size), they are of exceptional scientific interest, and contain numerous features meriting detailed study. Closed white siliceous microgours are dramatic locally (Fig.). The variety of lava features is exceptional. In some areas, flow patterns are extremely sharp and clear-cut; elsewhere they are unusually rounded and smoothed. In a few locations are thread-like speleothems somewhat resembling Pele's Hair, and bizarre spider-like helictites. Unique in my experience is a succession of hollow lava tongues which enlarge downslope and take on throughway characteristics.

SUMMARY and CONCLUSIONS

Both the Cueva de Los Verdes and Cueva del Viento systems are of international significance because of their size and scientific interests. Together with Manjang Cave, Korea, Ape Cave, Washington state, U.S.A. (Halliday, 1972) and Kazumura Cave, Hawaii, U.S.A., the upper cave of the Cueva del Viento system is one of the four longest lava tube caves in the world. Although possessing no single cavernous segment of near-record length, the Cueva de Los Verdes system is of additional significance because of its awesome spaciousness.

ACKNOWLEDGMENTS

D. Carlos Teigell assisted greatly in field work on Tenerife, and Dr. Joaquin Montoriol Pous, in many ways. Our field studies on Lanzarote were made possible by authorization by the Direccion General de Seguridad de Espana (Ministerio de la Governacion), obtained with the assistance of D. Rafael Ferrer Sagreras, Consul-General of Spain in San Francisco, California. Addi-

Figure 11-12: Up-tube end of Jameo de la Gente.

Figure 11-15: Up-tube end of collapse sink which segments the Cuevo del Viento.

Figure 11-13: Silhouette of the Pico Viejo flows with El Teide visible above and beyond Pico Viejo. Photo courtesy Spanish Tourist Bureau.

tional authorizations and assistance on Lanzarote were kindly provided by D. Jose Ramirez Cerda and D. Antonio Alvarez Rodriguez, president and vice-president of the Cabildo Insular, and by D. Serafin Martin Rodriguez of Arrecife and D. Aquilino Rodriguez of Haria.

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ORIGINAL CONTRIBUTIONS TO VULCANO-SPELEOLOGY FROM ICELAND

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C. Wood

Great Britain

The study of Icelandic lava caves by members of the Shepton Mallet Caving Club began in 1969 in preparation for the club's 21st anniversary expedition to Raufarhólshellir, the famous lava tube cave in the south-west of the island. As a result of the preparatory bibliographic work and the experience gained in the field during the 1970 project, research has continued in the compilation of a comprehensive bibliography of Icelandic lava caves, in the improvement of the accuracy of cave surveying in basalt terrains, and in the improvement of geological field techniques. This paper traces the lines of research which this group has followed in the study of Icelandic lava caves, and discusses future plans of research which are based tentatively upon a new model of lava tube evolution.

ICELANDIC CAVES AND CAVE EXPLORATION

In order that considerations might be given to the area in which the group would cave in the summer of 1970, a bibliography was compiled by one of us (M.T.M) and this now much expanded has allowed a map to be compiled of the location of cave sites in Iceland. It must be remembered that the cave sites mentioned here are those recorded in the literature and as such do not represent a complete picture. The majority lie in post-glacial basaltic lava flows and it is in some of these enormous expanses of unexplored lava that future discoveries would seem inevit able.

Examination of the literature of known caves provides an interesting study concerning their age and the history of cave exploration. Some references to Icelandic caves may be traced to the saga period of the twelfth to the fourteenth centuries. The sagas are also of great importance to the vulcanospeleologist in that they contain records of volcanic eruptions which help to date lava flows. The Völuspá, a Sibylline poem descriptive of Scandinavian mythology, and the Daemi-

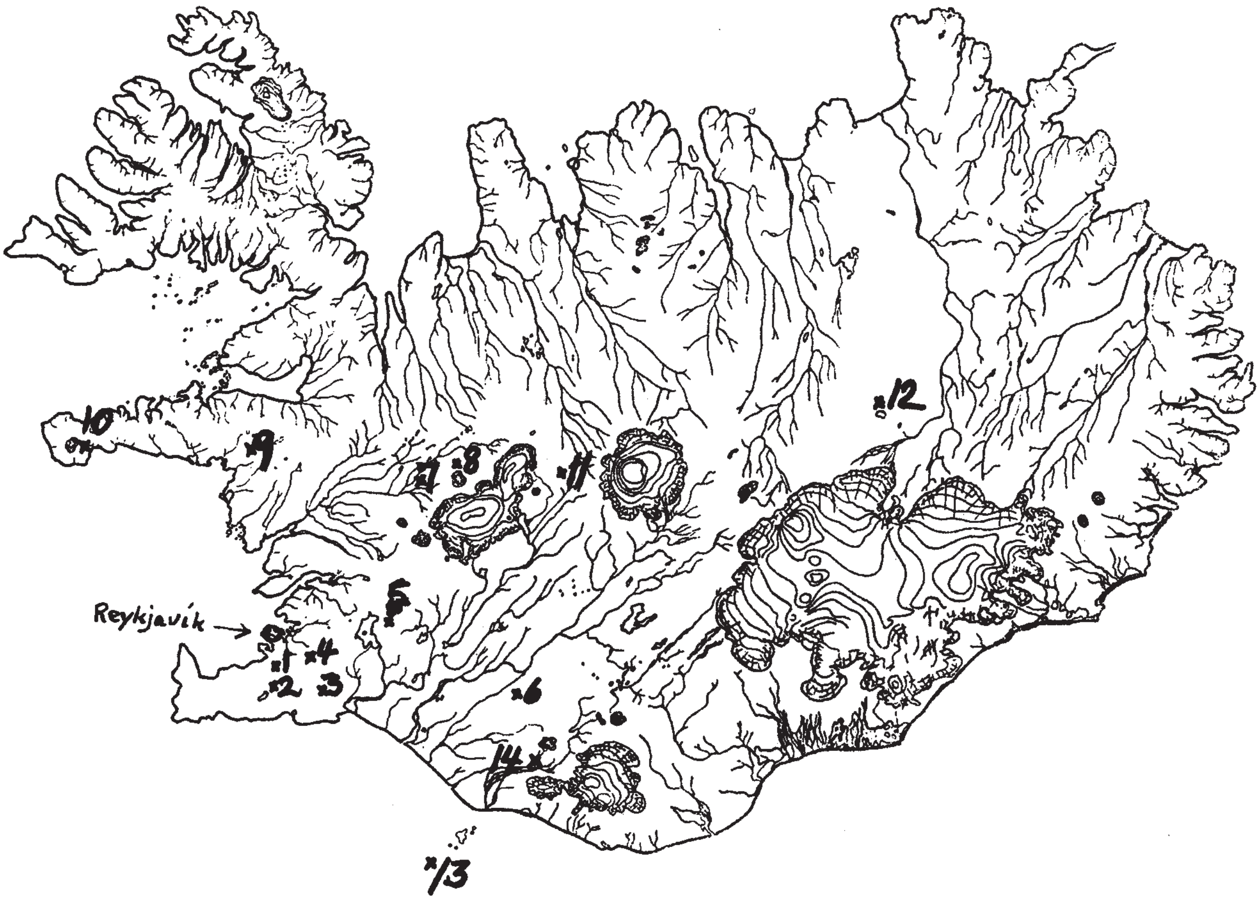

Figure 12-1: Location of well known lava tube caves of Iceland, courtesy Dr. Gudmundur Kjartansson.

1. Several small caverns south of Hafnarfjordur.
2. Daudalier, a group of closely spaced small caverns.
3. Raufarholshellir.
4. Narrow tube under the main road.
5. Gjabakkahellir.
6. Karelshellir, a 133-meter tube in a lava flow formed by the Hekja eruption of 1947-'48.
7. Group of three large lava tubes, Surtshellir, Stefanshellir and Vidgelmir, and some smaller ones.
8. Halmundarhellir.
9. Several tubes found in 1957 in the lava flow Gullborgar hraum.
10. Vegamannahellir, found in 1963.
11. Grettishellir.
12. Small tubes in the Askja lava, formed 1961.
13. Several tubes in the new lava of Surtsey.
14. Mogugilshellir, not a real lava tube, formed in an intrusive vein.

saga mention Ragnaröckr in Snorro's Edda in connection with Surtur, the black prince of fire after whom Surtshellir was named, and the Sturlunga Saga recalls the bandits of Surtshellir. Surtur and Surtshellir are also recorded in the Holmverja and Landnama sagas. The underground dwellings of Surtur was part only of the cave of the Fire Giant, which was said to stretch across the whole of Iceland. An outlaw is thought to have found his way into the cave and to have walked through it for a long time in pitch darkness, and when he came out at the other end his shoes were full of gold with which he purchased his freedom. Such enchanting stories are associated with more than one Icelandic lava cave.

In more recent times the caves were most written about following visits by European Victorian explorers and travellers. Hooker's records, for example, are typical: 'Journal of a tour in Iceland in the summer of 1809'. Some were women who crossed hundreds of miles of Icelandic country on horseback, and one can almost imagine their determination to visit those wonderfully inaccessible places of the Icelandic interior: 'Journey to Iceland: and travels in Sweden and Norway' by Ida Pfeiffer was written in 1852. 'Iceland: Its scenes and sagas' was written by Sabine Baring-Gould in 1863. Although many of these works are beautifully written and produced, they

Figure 12-2: 1860 representation of the entrance of Surtshellir, from Forbes' Iceland: Its Volcanoes, Geysers and Glaciers.

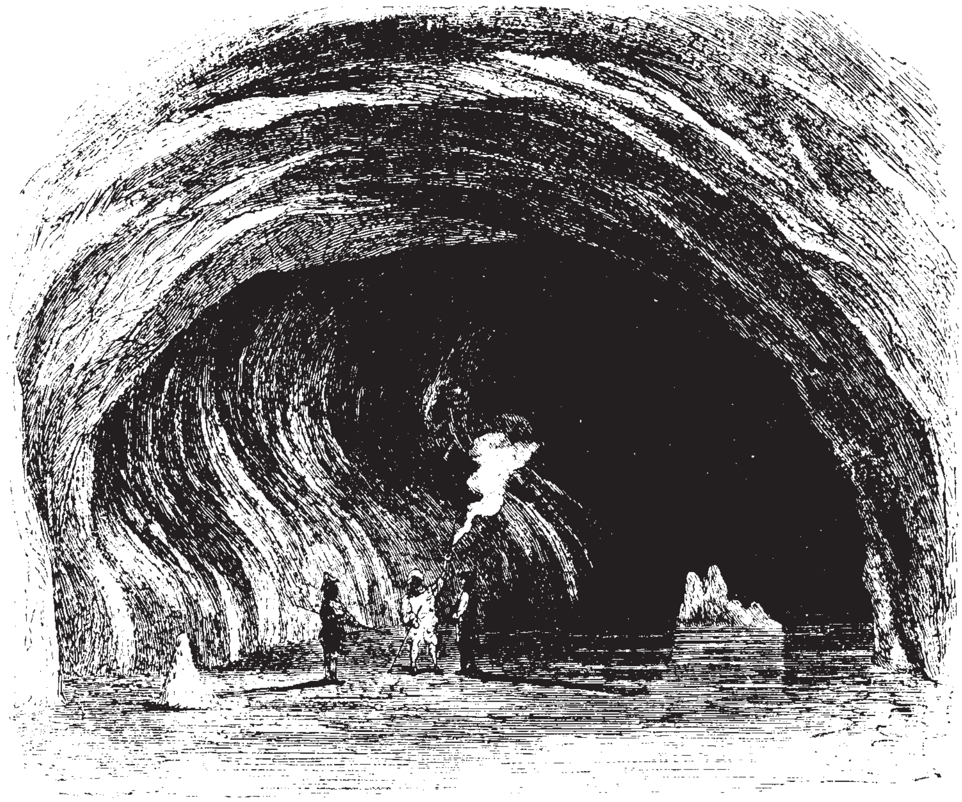

Figure 12-3: Sketch of main passage of Surtshellir from Forbes' Iceland, Its Volcanoes, Geysers and Glaciers.

Figure 12-4: Cross-section of wall of lava tube ("The Church") at Myratn, north Iceland; a postcard view from the Halliday collection.

generally lack details of the location of speleological features mentioned in the text. Exploration of the lava caves was usually by candle light and Icelandic guide, the women in skirts, and it is difficult to envisage how such beautiful and accurate engravings of the caves could have been produced under these conditions, particularly as many Icelandic caves are covered with ice and snow.

Generally, the maps of the Geodetic Institute of Copenhagen have been found most useful in locating cave sites, though many await confirmation and detailed description. Most recently there are a few caves which have been described by modern Icelandic vulcanologists such as Einarsson and Thorarinsson. One lava tube cave was actually observed forming during the eruption of Hekla in 1948.

To describe the caves as lava caves is a generalization and several different forms may be readily identified. The famous fissure Grjotagjá, for example, is noted for its 260m of cave passage, much of which holds water at a temperature of 105.5°C, and provides a swimming place for visitors to the Lake Myvatn area. Caving under such conditions has been found to be extremely strenuous and dangerous. Sea caves in columnar basalt are mentioned in the literature at Stappen and Cape Dyrholar, while a variety of smaller cavitites associated with pahoehoe lava flows have been described from numerous localities. In many caves evidence has been found that suggests that they were used for human habitation.

The large and more important lava tube caves are numerous and it would not be unreasonable to say that most Icelandic pahoehoe lava flows possess larger or smaller spelean features. It would be tedious to record the geographical distribution of these features here. Suffice it to say that one of us (M.T.M.) has found references to locations of over 30 lava tube caves, none of which have been explored in any great detail. As one would expect, many of these features are located in the more densely peopled regions such as the Snaefells peninsula, mid-west Iceland, south-west Iceland and the Reykjanes peninsula. There are, however, vast areas of basalt in Iceland which are completely unexplored by the speleologist, such as the enormous expanse of the Odádahraun and the region around Lake Myvatn in the north-east of the country.

THE GROWTH OF SCIENTIFIC THOUGHT ON THE EVOLUTION OF LAVA CAVES

It is interesting to trace historically from the references the lines along which scientific thought developed on the origin of Icelandic lava caves. The earliest reference so far traced with any suggestion of a possible mechanism to explain the origin of lava caves is that provided by Kant who, in his 'Physische Geographie' of 1803 recorded of Surtshellir that 'one can almost not quite believe it, that this cave is made from a river of molten lava, which has built a way through the mountain'. The inference that the molten lava had melted its way through the hillside was greatly expanded by Olafsen & Povelsen who visited Iceland in 1755 and 1801. In their discussion concerning the origin of Surtshellir, they have much to say of lava stalactites and the glaze lining the cave, and they held these as 'certain proof of subterranean fires, and that the lava, in a state of fusion, has passed like a rivulet through this channel, while it began to cool on the sides and the top of the cavern'. They noted additional proof that 'the whole of these caves had formed by the melting or dissolution of stones', but that constrictions in the cave passage were the result of more resistant rock.

In 1810 Mackenzie's visit to Iceland resulted in his 'Travels in the Island of Iceland', in which he introduced the term 'cavernous lava'. He had noticed during his travels through south-west Iceland that there were two distinct formations of lava. One of these gave the appearance of not having flowed, it having been heaved up into large bubbles or blisters, round to oval in shape, and from a few meters to 10 or 15 meters in diameter. He termed this lava 'cavernous' due to the fact that a great many of the bubbles had burst to reveal caves of considerable depth. Mackenzie concluded that this lava may have been formed by heat at depth melting the rocks in situ, or that the lava had been erupted beneath water, causing it to blister. He noted that near Mt. Hekla the lava was covered by sand and gravel, affording evidence of the sea having once been upon it, though today such deposits may be regarded as pyroclastic and glacial. Indeed, Mackenzie's descriptions of seas of lava which consisted of waves and domes is a description of a typical pahoehoe surface, many of the waves being pressure ridges and many of the domes being tumuli.

Extension of the blister hypothesis persisted in the literature even until 1902. Both Bisiker and Baring-Gould postulated the origin of Surtshellir as a chain of gas bubbles. Bisiker suggested that such a formation was helped partly 'by a crust of lava being forced upward in the form of an arch by pressure acting from the sides '. Furthermore, he was certain that the cavern had been deepened and enlarged by the eroding action of flowing water, for along the sides of the caves were found numerous water-worn lines, indicating different levels of the old river.

Henderson was one of the first to suggest in 1818 that lava cave formation was the result of the conge lation of a crust upon the lava flow: 'the sides of the cave, run into vitrified horizon-

tal stripes, that appear to have been formed by the flowing of the stream of melted stones, while its exterior parts have been cooled by their exposure to the atmosphere'. Dufferin in 1857, Burton in 1875 and Chapman as late as 1930, suggested that this mechanism of cavern formation, followed by roof collapse, resulting in the formation of the huge tectonic rifts which disect Iceland, such as the Almannagjá at Thíngvellir. Paijkull in 1868 noted that the large dimensions and complex forms of lava caves could not be explained by blistering of the flow, and if this had been the case the roof of the cave would have been arched above the surface of the flow. Instead, he favoured the congelation of the surface and the draining of the underlying mass of fluid lava. With the exception of Lloyd Morgan all other references to lava cave evolution followed this traditional concept.

Lloyd Morgan proposed in 1919 an hypothesis which involved the entrapment of snow in a ravine, which subsequently became buried by lava, as an explanation of lava cave evolution. The ice and snow was not melted, but during the following warmer climate (i.e. post-glacial) the loss of the snow and ice from the ravine left a cave beneath the lava. That the cave had been cut by a stream was indicated by 'all the familiar evidence of water action on the sides', and it is clear that Lloyd Morgan* was mistaking lava flow features for water worn features. The probable reason for the ice remaining beneath the hot lava, he suggested, was that a layer of volcanic dust, whose ulterstices were filled with steam, was formed on the upper surface of the ice.

Corbel modified the traditional hypothesis of lava cave evolution after visits to Icelandic lava caves in 1955. He was the first to attempt to account for tributary passages: 'The flow of the lava cooled more rapidly on the surface, solidifying higher up while those parts below remained fluid and continued to flow. The lava which is fluid, being no longer fed from upstream continues to flow under the solid crust of the surface, thus producing a void. This is the origin of the central tunnel. The void is in turn a point of discharge for pockets of lava which are still fluid on the sides. These flow into the tunnel. The emptied pockets are the origin of side galleries'. Apart from several cave studies by Icelandic geologists, which are in the process of being translated, and apart from the work of a Spanish team which reputedly examined thirteen Icelandic lava caves in 1968, but whose report is still awaited, no other modern work had been completed in Iceland prior to the Raufarhólshellir study of 1970.

TECHNIQUES USED IN THE MEASUREMENT OF ICELANDIC LAVA TUBE CAVES

It is astonishing that geological thought on the evolution of lava tube caves has advanced very little since 1818, not only in Iceland, but through-out the world. The traditional model has been modified somewhat to include the formation of small tubes in pahoehoe toes, and an internal feeding system in pahoehoe flows is envisaged by Hawaiian geologists to consist of a complex of minor distributary tubes which branch from one or more larger feeder tubes. Yet, although this seems to be a sound hypothesis, based upon observations on the surface and at the advancing front of active pahoehoe flows, and observations of cross-sectional structures of ancient flows, workers have found difficulty in reconciling the model with forms of lava tube caves they have met with in the field. Halliday has pointed out in 'Caves of Washington', for example, that 'As a group, these tubes do not seem entirely in accord with the traditional concept of these caves as simple lava conduits with distal ramifications'. In a similar fashion Ollier & Brown in their survey of the lava caves of Victoria, Australia, have noted that the traditional model of lava tube evolution 'does not account for all the observed shapes and structural features encountered in lava tubes'. They proposed a more elaborate explanation of laminar flow, which was based upon recognizable structures within the flow and the caves. Although a stimulating hypothesis, however, there are several difficulties with the concept of laminar flow and layered lava as a prerequisite to lava tube cave evolution: a) it has been argued elsewhere that the detailed description of layered lava given by Ollier & Brown would also well describe the structure of a flow composed of superimposed flow units which were observed at an exposure which was longitudinal to the direction of flow (i.e. , not cross-section); b) it has also been argued that the liquid lava which is confined between laminae must have lost much of its original heat and therefore its capacity to erode solid lava; c) it is difficult to envisage a horizontal arrangement of laminae and shear planes in a lava flow, rather than a concentric arrangement of these features. Poli, in his description of the lava caves of Mt. Etna, Sicily, envisaged a lava flow to constitute many successively enclosed cylinders of lava whose viscosity increased outward, thus retaining a central liquid core.

It is our contention here that it has been difficult to reconcile the traditional model with the wide diversity of lava tube cave morphologies met in the field, because inadequate care has been taken in establishing the flow structure, the cave morphology, and the topographical environs in which cave formation is induced. Ollier & Brown have pointed the way to more detailed examination of lava tube caves, and the study can be recommended for its detail in scientific method. It was primarily due to the fact that no model could satifactorily explain the evolution of complex lava caves, that a determined effort was made in the study of Raufarhólshellir to establish a

* and E.-A. Martel (W.R.H.).

standard in methodology upon which other such studies by us could be based, in the hope that a new model would be constructed. Of greatest interest was the upgrading of cave surveying in basalt terrains. The surveying programme is regarded by us as the most important single contribution to cave research, for it is not only essential to establish the form of the cave which is undergoing study, but also to understand the morphology of the flow surface so that some relationship between the two may be ascertained. The survey of lava tube caves can therefore be divided into two units--surface surveying and cave surveying, the two being linked at primary survey points at collapse holes.

Study of geological literature prior to our visit to Iceland suggested a strong possibility of there being magnetic anomalies in areas of basaltic lava, but in all previous accounts of surveying lava caves this had been ignored, and corresponce with persons from the U.S.A. and Spain who had carried out such surveys produced the information that, although this interference was appreciated, it had not been investigated, and magnetic surveys had been used because of time considerations.

A preliminary closed traverse was therefore made from the entrance of Raufarhólshellir, along the first 100m of cave passage, out through the last collapse hole and back over the surface to the entrance. Both magnetic and theodolite bearings were taken, and on calculating the results it was found that the theodolite traverse had a 0.84% misclosure, and the magnetic traverse failed to close by 6.24% (as compared with less than 0.5% which would have been expected in a limestone cave). Forward and backward compass bearings had been taken along each survey leg and were found to differ by up to 16.5' (as compared with less than 2' which would have been expected in a limestone cave). Three subsequent magnetic and theodolite closed traverses confirmed that the above results were typical, and provided data for further research. In view of our findings it was decided that the survey of Raufarhólshellir would have to be based upon a theodolite traverse to obtain maximum accuracy.

The survey comprised a simple (i.e., not polygon) traverse made with a tripod mounted simple cave theodolite, comprising an abney level read to the nearest 0.5' and a 15cm diameter horizontal circle that was graduated to 0.5', but read to the nearest 0.25' by estimation. The distances were measured with a 30m 'Fibron' tape to the nearest 1.5cm, and never did the distance between stations exceed the length of the tape. At every survey station distances left and right to the passage walls, to the instrument and roof heights, and where possible the height of the highest point of the original tube glazing, were also recorded. Sufficient measurements were taken to enable representative cross-sections to be drawn of the cave passage; the location of approximately half of these were chosen to illustrate geomorphological features which were measured in much greater detail.

The survey was plotted roughly in the field and a copy of this plot was taken into the cave to check for gross errors and the plotting of passage detail between stations. The measurement of the height of tunnel glazing meant that'an estimated line of the original tube roof' could be plotted on the extended section of the cave. This gave a good indication of the amount of breakdown that had occurred in the cave. From the survey measurements, the rectangular co-ordinates of each survey station was calculated and the survey plotted from these. No closed traverses were surveyed entirely within the cave and estimations of the accuracy of the resultant survey are based on the results of the four experimental closed traverses, but it was expected that the error in the position of any point in the cave as shown on the survey would be less than 2% horizontally, and 0.2% vertically, of the traverse distance from the cave entrance to that point.

The bearings between survey stations and the horizontal equivalent of the slope distance between each were repeated using the cave theodolite on the surface of the lava flow, commencing from the same cave survey station at the entrance. Thus the line of the cave below ground was traced upon the surface, and with a theodolite and staff the relative levels of the cave survey station positions on the surface were found, from which, by plotting these on the extended section, the position of the cave in relation to the flow surface could be ascertained, and also the thickness of the roof. This was the principal project of the surface surveying programme, but the measurement of a profile down the lava flow for 3km from the cave, and also the determination of the magnetic declination at the cave entrance, were also carried out.

It was found by us that the position the lava tube cave occupied within the flow, and relative to the vent, was of great significance. The cave was found to be situated 10km below the fissure from which the flow was extruded, in a part of the flow which was constricted in a narrow valley, and was located immediately above a part of the flow which had a rapidly steepening gradient.

TOWARDS A NEW MODEL OF LAVA TUBE EVOLUTION

As we have noted above, any model of lava tube evolution must be based soundly upon the relationship of the cave morphology and the structure of the lava flow. It was found at Raufarhólshellir, that there was a direct relationship between the confluent form of the cave and the flow unit structure of the parent flow, for the smallest tributary tubes were discovered to be the drained

cores of single flow units. Working then upon the basis that each flow unit represented a potential small lava tube, evidence was found to suggest that the larger tube forms had originated by the coalescence of the drainage channels of adjacent and superimposed units. The consequent elimination of the crusts of the flow units was thought to be the result of erosion and remelting by the lava stream, which at that time was still in direct contact with the vent. Although the origin of the main tube was not as fully established as that of the tributary tubes due to the considerable amount of breakdown, it was believed that this too had a similar mode of formation, and loop tubes were flow unit meanders which had been truncated by the lava stream of the main tube.

Although only a single, isolated study which needs confirmation, this model of the origin of Raufarhólshellir can be reconciled with the traditional concept of lava tube evolution. Let us speculate with the information that is available.

Lava tube caves may be sub-divided on the basis of morphology into simple and complex varieties. The simple or 'unitary' form, as Dr. Halliday has termed it, is unbranching, sinuous, elongated and generally uni-level in character. It is frequently of considerable length. Some may extend for over 10km. The Cueva de los Verdes, for example, is considered by Bravo to be 10.8km long if its collapsed portions are also considered, while a greatly collapsed cave of unitary form stretches through the length of the youngest lava flow of the Saddle Butte area, Oregon, and has been noted by Ciesiel and Wagner to be 13km in length. Furthermore, it is a general characteristic that caves of unitary form are more likely to have a source actually at the vent than caves of more complex morphology. The lava tube caves of more complex form range from confluent to anastomosing varieties, and some are particularly noted for their multi-level developments. The majority of these caves have a source which is situated a considerable distance from the vent. Our studies at Raufarhólshellir have shown that the cave is located 10km below the fissure from which the lava was extruded, and at Surtshellir/Stephanshellir, one large lava cave system of complex anastomosing form, a similar situation was found by us, with the cave located 26km below the vent.

Lava tube caves of unitary form are explained by the traditional hypothesis and appear to be the product of single unit flow. Nichols has suggested that flows emplaced as single units are the product of fluid lava, a steep gradient and rapid outpouring of magma from the vent. These factors inhibit the formation of flow units, and a high fluidity in particular will account for the extreme lengths of some unitary lava tube caves. Viscous lava, a flatter gradient and slower outwelling of lava from its source, Nichols suggested, gives a low velocity and favours the development of flow units and, if we tentatively accept the model of Raufarhólshellir, more complex lava tube caves.

It is apparent that the greater the distance the lava has travelled from the vent, the greater will become its viscosity, due to cooling and loss of volatiles. Thus it may be that single unit flow is characteristic of the initial emplacement of the lava, while multiple flow is more common in the distal regions of the flow. The most common form of lava tube cave to be developed under such conditions would therefore be similar to that envisaged by workers in Hawaii. Indeed, one collapsed lava tube cave near Butte Crater, Idaho, which is over 5km in length, does show a unitary form with distal anastomoses. These complete forms may be rare in the field, and difficulty may have been experience in reconciling diverse tube forms to the traditional concept, due to the fact that only parts of tube may have emptied of liquid lava. The study of Raufarhólshellir has shown that the cave emptied of liquid lava due to a rapid steepening of the gradient immediately downslope of the cave. Similar evidence may be found at Surtshellir/Stephanshellir, which also formed in a flow of multiple structure. In both cases lava tube development must obviously have occurred through the whole length of the parent flow, but subsequent draining of the tube was localized, occurring some 10km and 26km respectively from the vent. If drainage of these tubes had occurred in the higher parts of the flow, there would have been a greater likelihood, perhaps, of finding a cave of unitary form.

CONCLUSION

These conjectures are important because they illustrate the need for detailed examination of individual lava tube caves or individual lava flows. In general, one must conclude that research by speleologists on the evolution of lava tube caves has only just begun, and there is little evidence as yet with which to assess the importance of the models mentioned here. It must be emphasised that it is only on the basis of a large number of studies of diverse features that firm conclusions can be made. The study of each individual cave in our opinion must take place under the points outlined below:

1. It is imperative that an accurate survey of the cave by non-magnetic means must be executed, so that the true form of the cave in plan, long profile and cross-section, may be established, and the relationship of the various cave segments ascertained.
2. Details of the flow surface maut be plotted and must include measurements of the thickness of the cave roof so that the long profile may be competed, the plotting of the plan on the surface so that its position and location may be noted, the levelling of the surface of the

flow both above and below the cave entrance so that gradients may be noted.
3. The age, composition and, in particular, the structure of the flow must be determined.
4. Details of flow features must be noted so that the form of the cave, the age of various segments, and the history of the draining of the tube may be discovered.
5. The extent to which the morphology of the cave is related to the flow structure is of the utmost importance.

For our part, during our stay in Iceland this summer, we intend to make a detailed study of the lava tube caves of the Gullborganhraun and Snaefells peninsula, and to journey into the uninhabited interior of the island in order to examine and draw up a preliminary report on the vast Odadahraun flow of north-central Iceland.

LAVA CHANNELS AND ASSOCIATED CAVES IN VICTORIA, AUSTRALIA

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INTRODUCTION

Basaltic volcanoes of late Pliocene and Quaternary age are found over an extensive area of southeastern Australia (Fig. 13-1 , 13-2) as well as in several areas in the northeastern state of Queensland. Caves (Fig. 13-3) have been described from each area (Matthews, 1968). The caves of Victoria were described by Ollier and Brown in 1964. Until recently only minor new caves have been found (see Ollier and Joyce, 1968), but in the last few years caves have been found at Warrion Hill volcano (pers. comm., J. Taylor) and at Mt. Napier (pers. comm. L.K. Elmore), and further caves have been found at Mt. Eccles. The caves at Mt. Napier and Mt. Eccles are associated with the only lava channels known in Victoria. This paper discusses the channels and associated caves at Mt. Napier and Mt. Eccles, and describes their relationships. The features at Mt. Napier were discovered by Elmore and will be described elsewhere by him. Details of the lava channels and the newly-discovered caves at Mt. Eccles are given here for the first time.

THE MT. NAPIER AREA

The main area of lava flows around Mt. Napier (Fig. s 13-4 , 13-5) is about six miles across. An associated radiocarbon date suggests an early Holocene eruption. A lava channel and associated caves are found about 1 1/2 mile west of Mt. Napier, among the irregular flow ridges and depressions of the type known locally as "stony rises". A channel 2 to 3 m deep and 6 to 8 m wide leaves a lava depression at the foot of a small scoria cone with a crater, and runs for about 1/4 mile. Two caves open into the channel and a natural bridge across the channel is the remnant of a formerly more extensive cave. A number of other small cones and ridges are found up to two miles or more from the main volcano. Such a distribution is not known from any other local volcano. One spatter ridge contains a small cave about three or four meters long on its flank, possibly due to sagging.

The Byaduk Caves are about four miles southwest of the main volcano, where the lava began to flow down the Harman Valley for a further ten miles or more. Collapses in the flow surface (Fig. 13-7) give access to a number of caves here (Ollier and Brown, 1964). Mt. Napier itself (Fig. 13-4) is a multiple scoria and spatter cone which rests on a broad lava shield built up by the flows. On its northern flank are two small, irregular caves which were probably formed by later erosion beneath a small flow. On the western flank two small lava caves are associated with indistinct lava channels which lead out into the surrounding "stony rises". One cave here is in line with a channel which runs down the flank below a low point in the crater wall. It is within a small dome of lava built up of many thin layers (Fig. 13-9). Its cross-section has the form of a pointed arch, suggesting distortion of the upper walls and roof (Fig. 13-10). The floor and roof are parallel, and slope steeply down the flank of the volcano. Lava stalactites are inclined down-flow. Near the upper entrance the cave's lining has fallen away to expose thin layers of lava which make up the upper part of the cave wall. In the other cave nearby, are found groups of needle-like stalactites with individual diameters of 1 m or less. Some bunched and helictitic forms are present (Fig. 13-11).

THE MT. ECCLES AREA

Mt. Eccles volcano lies about 14 miles southwest of Mt. Napier and is probably about the same age. It is surrounded by an area of "stony rises" about six miles wide. Thence a valley flow ran west and south 19 miles to the coast, with a further nine miles now submerged. The main volcano

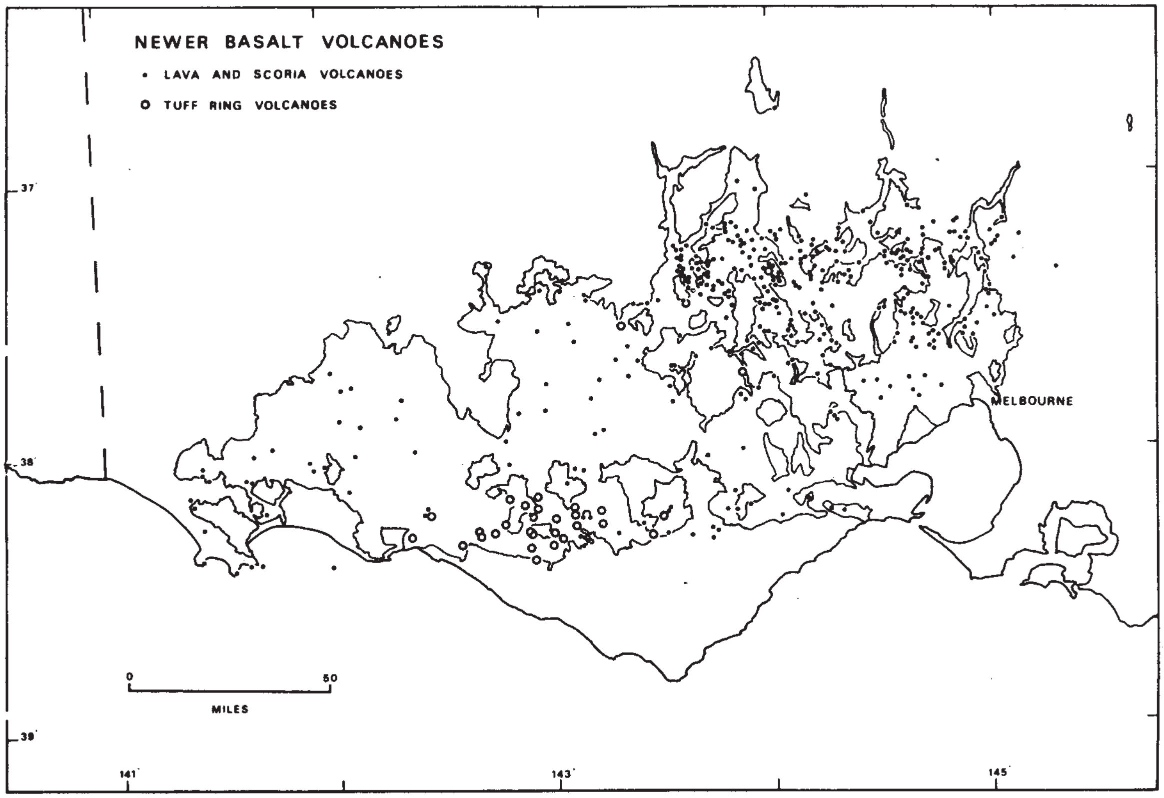


Figure 13-1: Distribution of holocene volcanoes in southeastern Australia.

Younger lava flows of Victoria, Australia:

N-Mt.Napier and its flows
E-Mt.Eccles and its flows
R-Mt.Rouse and its flows
P-Portland
PB-submarine extension of Mt.Eccles flows
into Portland Bay
F-Port Fairy

For scale compare with Fig. 13-14.

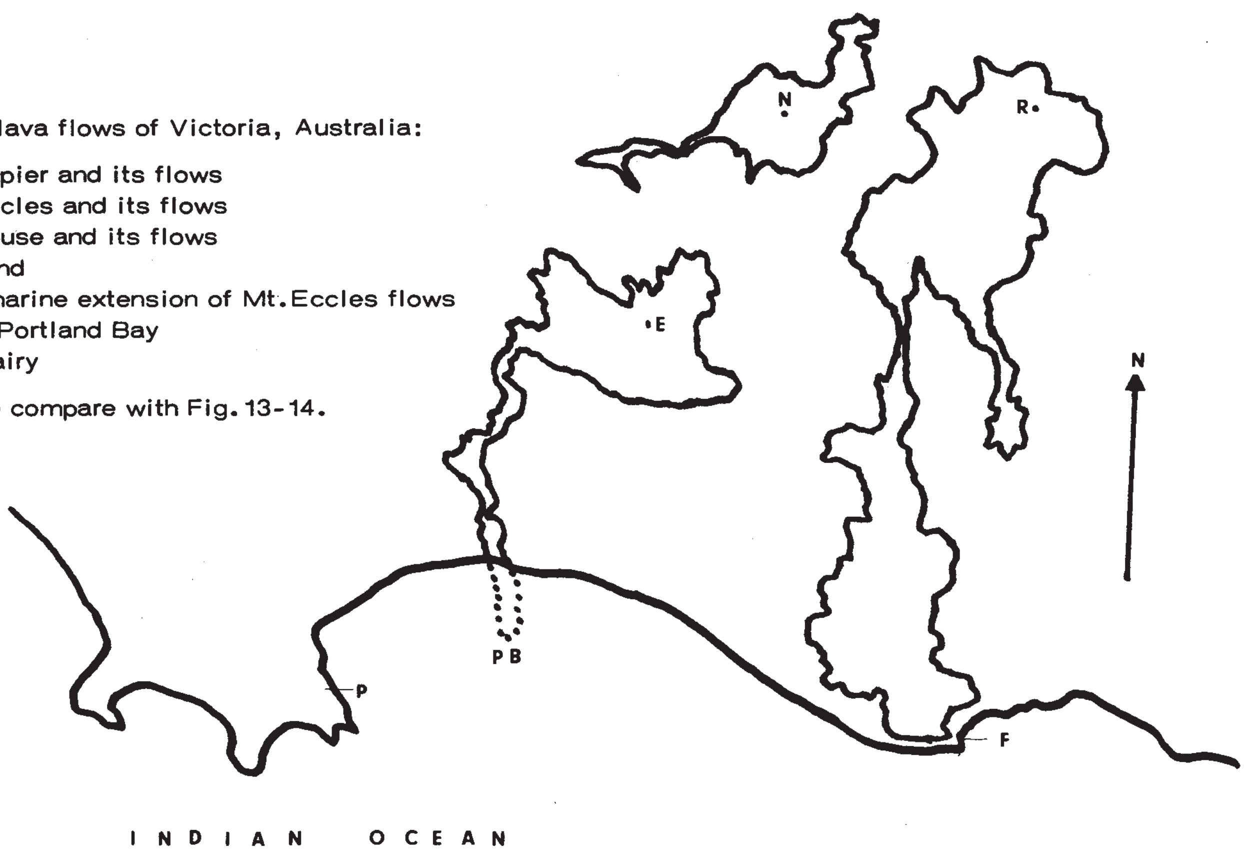


Figure 13-2: Lava flows of Mount Eccles, Mount Napier and Mount Rouse.

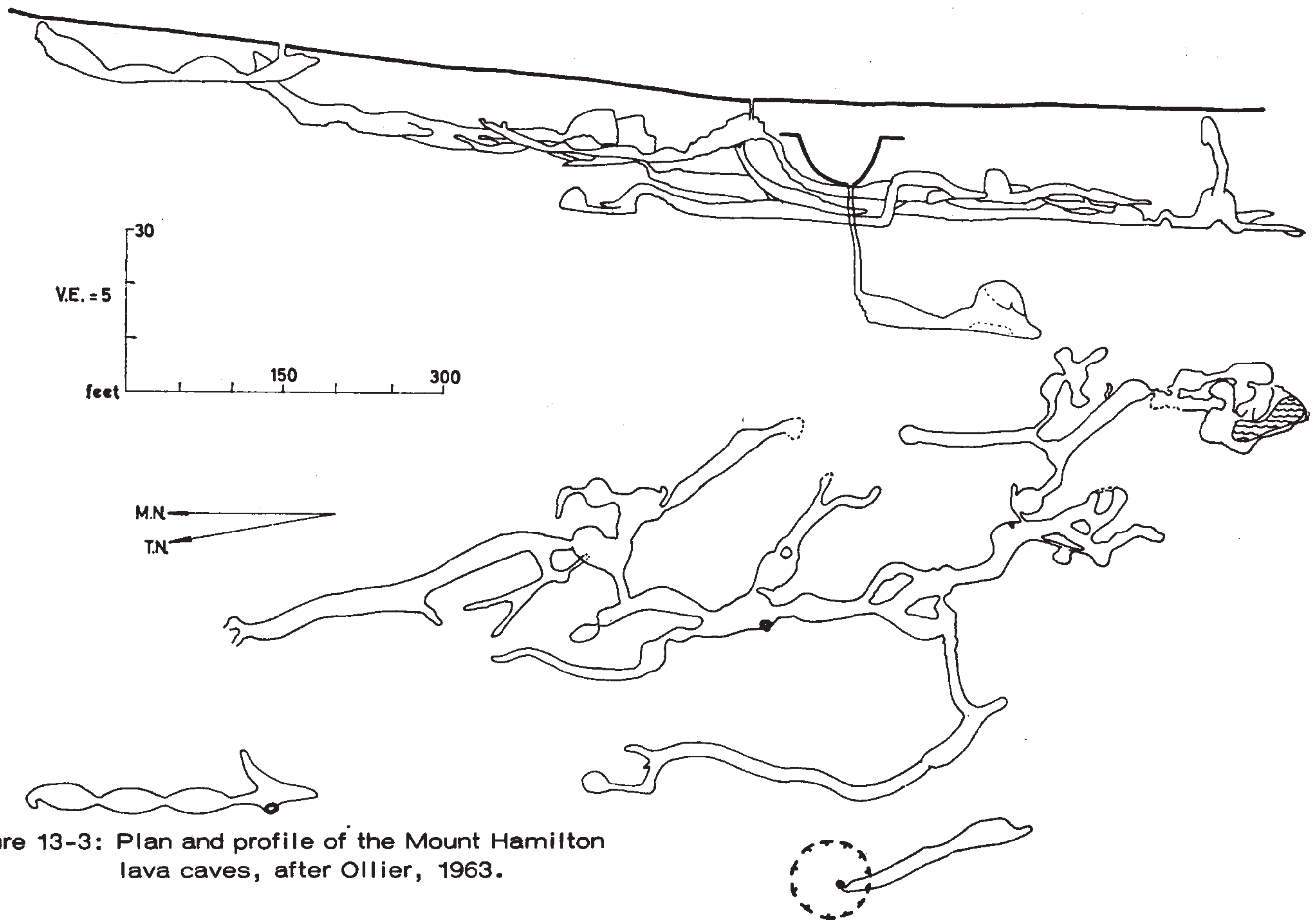


Figure 13-3: Plan and profile of the Mount Hamilton lava caves, after Ollier, 1963.

Figure 13-5: Map of Mt.Napier and vicinity.

C-lava channel
F-edge of flow
x-cave in spatter ridge
N-Mt.Napier cone

is a steep-walled elongate crater containing Lake Surprise (Fig.s 13-12, 13-13). From the north end of the crater a lava channel runs out into the "rises" where it splits into two branches (Fig. 13 14). These features are jointly known as the Lake Surprise Lava Channels. The west branch extends over two miles from the crater, and the southwest branch, 2.4 miles. The average gradient is 25 feet/mile. Beyond these channels the gradient increases to about twice that figure.

Southward along the line of the main crater is a series of spatter cones. From one cone a narrow lava channel (Fig. 13-15) runs about one mile westward, with a roofed section known as Gothic Cave.

The known caves and other features of Mt. Eccles were described by Ollier in 1964. The area is not yet fully explored. Caves and side-channelsknownalong the main channels are indicated on the accompanying map (Fig. 13-14). From the air, the channels closely resemble a type of lunar rille (Fig. 13-16). In some places the channel runs along a ridge-like area but elsewhere its walls are at the general level of the lava field around it. The western channel ends by the walls decreasing in height and the channel widening, but the southwestern channel appears to end in a depression, wider than the channel itself.

The known caves and side-channels are in the upper part of the main channel walls. The caves generally run away at right angles to the main channel for 50 to 60 m. Ollier (1964) used the name Tunnel Cave for the first such cave discovered, because of its perfect tunnel-shape.

The depth of the channels varies, and lava mounds and ridges are found along the floors. The west channel is from 140 to 220 m wide and 4 1/2 to 6 m deep. The southwest channel is 80 to 100 m wide and 6 to 12 m deep. In places the walls are steep and even overhanging, and inward collapse is occurring. Nearer Lake Surprise the channel is only 40 to 70 m wide and 4 1/2 to 6 m deep. The walls of the channels may be of lava layers one to two m thick, but in places at least the upper part of the wall is in thin layers, 5 to 10 cm thick. These appear to be successive thin flows over the levee edge of the channel.

The area of "stony rises" through which the channels run is covered with scrub and eucalyptus trees. Immediately around the crater an ash deposit has left a small area of land suitable for farming.

The Gothic Cave Lava Channel runs out of a small cone south of Mt. Eccles (Fig. 13-15). Where it leaves the cone the channel has built levees of thin lava layers. Further downflow the channel is rather narrow (10 to 18 m) and steep-sided, and is floored by loose boulders 4 to 6 meters below the general ground level.

Gothic Cave was named for its shape in cross-section. It was described by Ollier (1964) who noted "contortions (which) indicate intense deformation after the formation of the layers but before complete solidification." In the entrance the layers appear as flaps which hang down. Within the cave the floor is seen to be well below the level of the floor of the channel outside. The ceiling height is about 7 1/2 m, and the cave is strikingly elongated vertically. Above the main cave is the remains of a small high-level cave (Fig. 13-18). Contorted layers can be seen in the figure. The layers appear to come horizontally from the walls and hang vertically into the cave. Ollier (1964) suggested that "a squashing in of the sides" gave the present shape, but the attitude of the layers suggests that the roof parted along a central axis, breaking originally continuous layers and allowing them to hang vertically. This parting did not extend to the surface which is continuous across the cave area, but the downward movement left behind a space which became the small upper cave (Fig. 13-18). The slumped layers originally were levee layers which formed the upper part of the cave and channel. Often more than one lining covers parts of the cave wall, indicating successive flows through the cave. In one location a lining is cracked into polygonal blocks. In another part of the cave the lining is marked with ridges and grooves which represent bands of differing vesicularity. Only behind this lining are found the true lava layers.

Apart from the section which now is Gothic Cave, the lava channel has been partly filled by collapse after flow ceased. Much of the channel thus was roofed originally.

CONCLUSIONS

1. Thin lava layers due to successive flows over the levees of lava channels can be important elements in the walls of lava channels and caves. Such thin layers will readily slump and contort and should be distinguished from the layered lava of generally greater thickness described by Ollier and Brown (1965) and apparently formed by differential movement within a flow.

2. In Victoria lava caves and channels are associated in two main ways. The lava channel may be the collapsed portion of a formerly more extensive cave, as is the Gothic Cave channel at Mt. Eccles, and the channels at Mt. Napier. Along the large Lake Surprise channels at Mt. Eccles overflow and break-through along the walls has given smaller channels and caves which

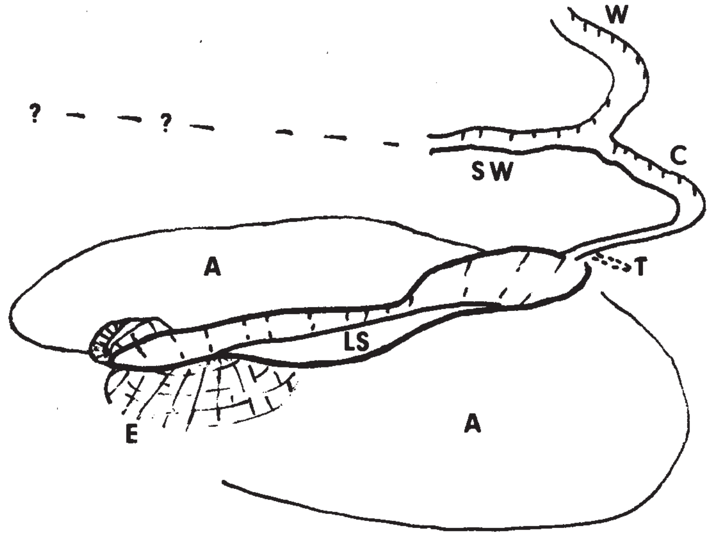


Figure 13-13: Diagram of aerial view of Mt.Eccles.

E-Mt.Eccles
LS-Lake Surprise
A-Ash fall areas, cleared for agriculture
T-Position of Tunnel Cave
C-Lava channel up-flow from bifurcation
W-West branch of lava channel
SW-Southwest branch of lava channel, extending into forested areas and "stony rises" flows.

Figure 13-12: Oblique aerial view of Mt.Eccles.

Figure 13-4: Vertical air photo of Mt.Napier

Figure 13-16: Aerial view of flow channels.

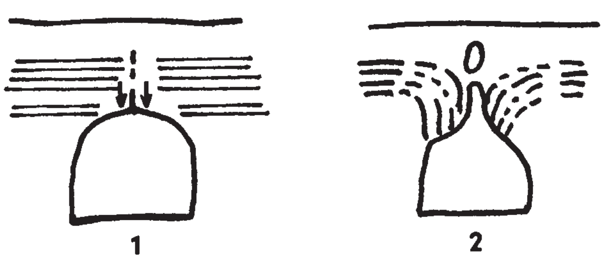
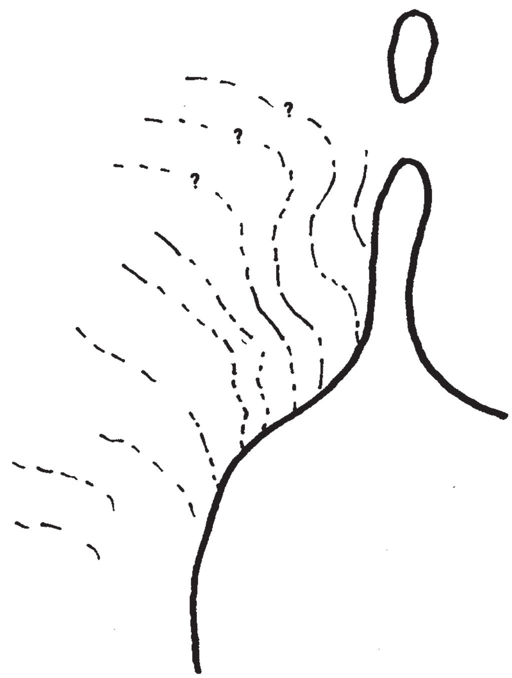


Figure 13-18: Cross-section of upper part of Gothic Cave, showing deformation and small upper cave.



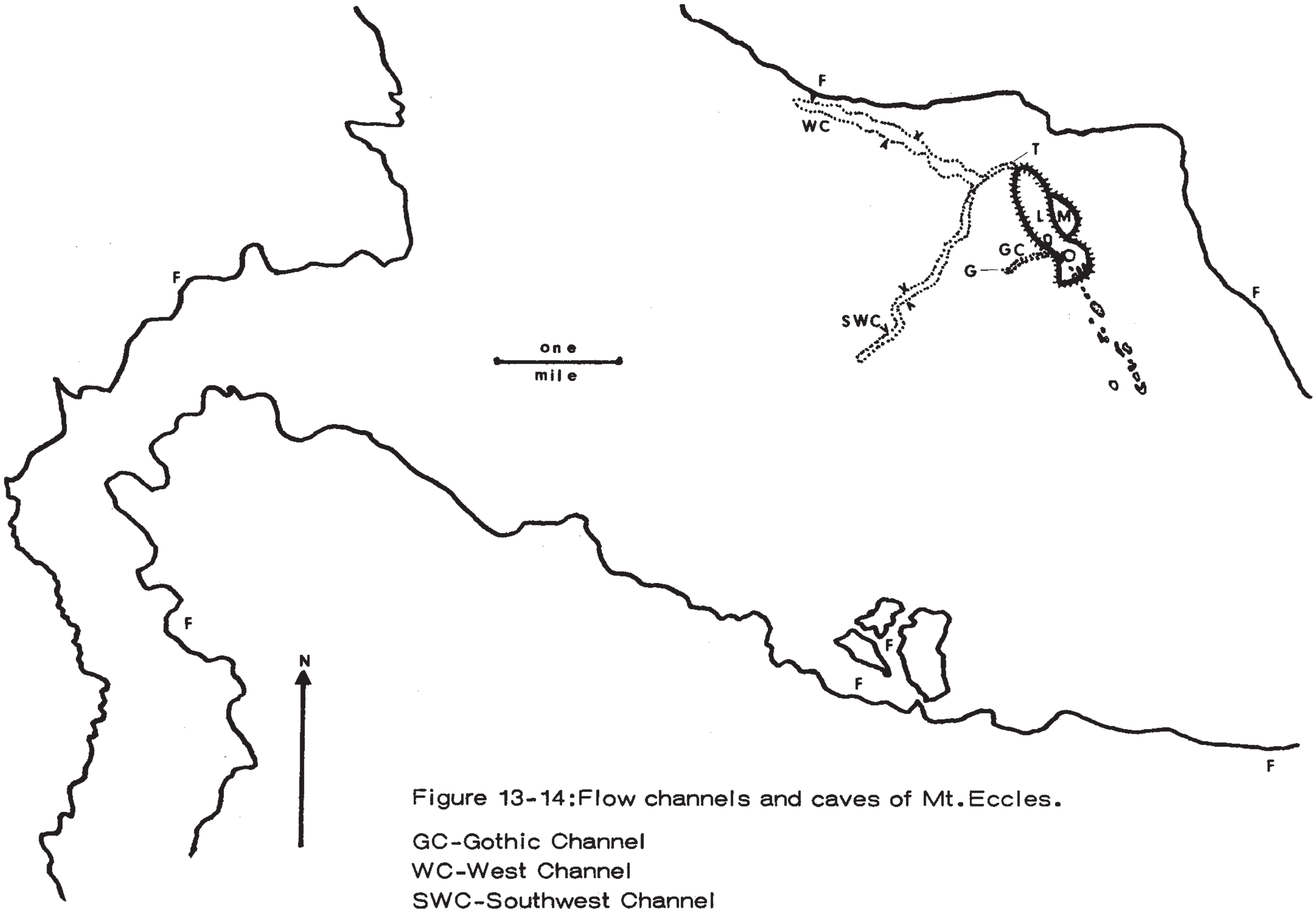


Figure 13-14:Flow channels and caves of Mt.Eccles.

GC-Gothic Channel
WC-West Channel
SWC-Southwest Channel
v-side channel or minor cave
T-Tunnel Cave
G-Gothic Cave
F-margin of flow
LM-Lake Surprise-Mt.Eccles complex.

Figure 13-15: Segmental collapse and flow channel near Gothic Cave.

Figure 13-7: Sequential collapses in the Mt.Napier area.

Figure 13-9: Entrance of cave in small lava dome.

Figure 13-10: Interior view of same cave.

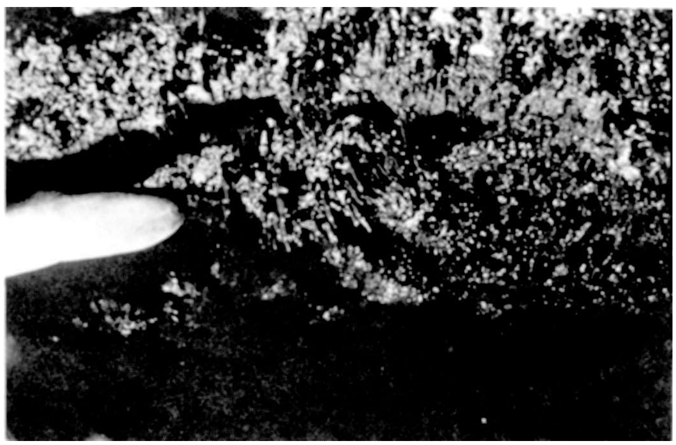


Figure 13-11: Needle-like speleothems in same cave.

lead away from the main channels. This second type of association suggests that lunar rilles may have small caves developed at reular intervals along their upper walls.

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THE UNDARA LAVA TUBES, NORTH QUEENSLAND, AUSTRALIA

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In northern Queensland, within 200 km of the east coast there are several large areas of Pliocene to Pleistocene basalt flows (Fig. 14-1). One of these, the McBride Province, (Twidale, 1956) is about 5,000 km^2 in area, and forms a plateau with an altitude mostly from 600 to 900 m above sea level (Best, Stevens, and Tweedale, 1960). It is broadly domed due to accretion of basalt flows. These appear to have been derived from comparatively few of the many vents present. Small shield volcanoes, pit craters, and scoria cones are present; a total of 109 centres have been located on aerial photographs (Best, 1960) but few have been investigated on the ground. The vents are aligned northeast-southwest, and this is an important structure trend in northern Queensland.

The Undara lava tubes are in the northwest quadrant of the basalt province, close to the largest granite inlier. Two tubes have been recognized, called the Undara West and Undara North Tunnels (Best, 1960). They begin as one tube, close to Undara Crater, then bifurcate and extend westward and northward respectively. Their location is shown on Fig. 14-2 of this paper and on the Einasleigh 1:250,000 geological map (Commonwealth of Australia Bureau of Mineral Resources, 1963) as a series of black dots and irregular areas, representing collapsed parts of the lava tubes. These are easily distinguished on aerial photographs (Fig. 14-3) since the luxuriant vegetation which grows in the depressions is of the "rain forest" or closed forest type usually associated with the coast and nearby ranges, and is quite different from the open forest of the surrounding country (Fig. 14-4).

The linear arrangement of the collapsed areas indicates that there are two continuous tubes. These are not necessarily open tubes where the roof has not fallen in; some parts may be partly

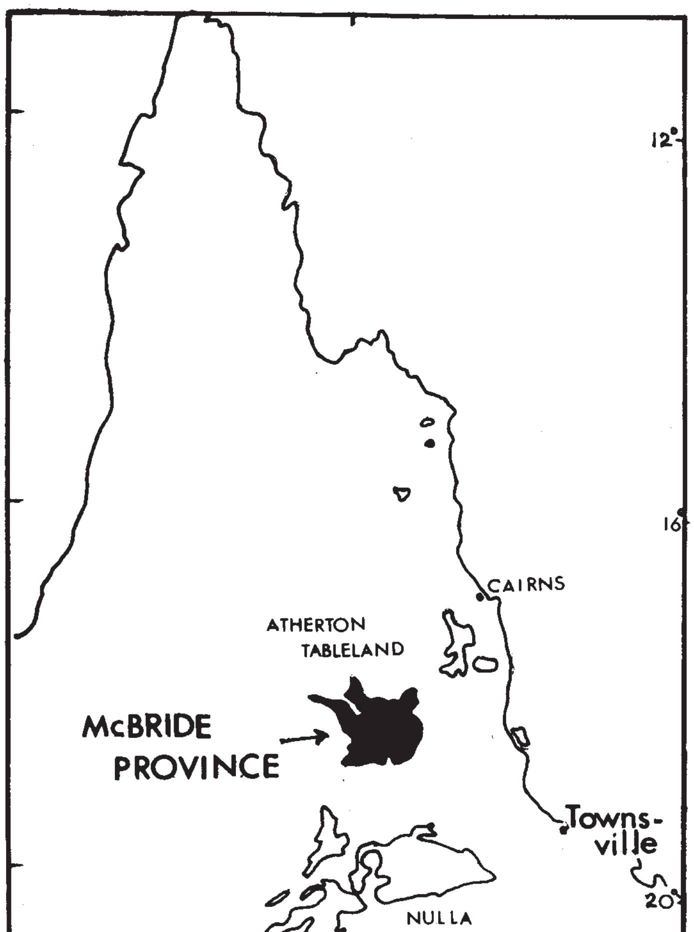

Figure 14-1: Major basalt flows of northern Queensland.

Figure 14-3: Vertical aerial photo of segmental collapse in Undara System.

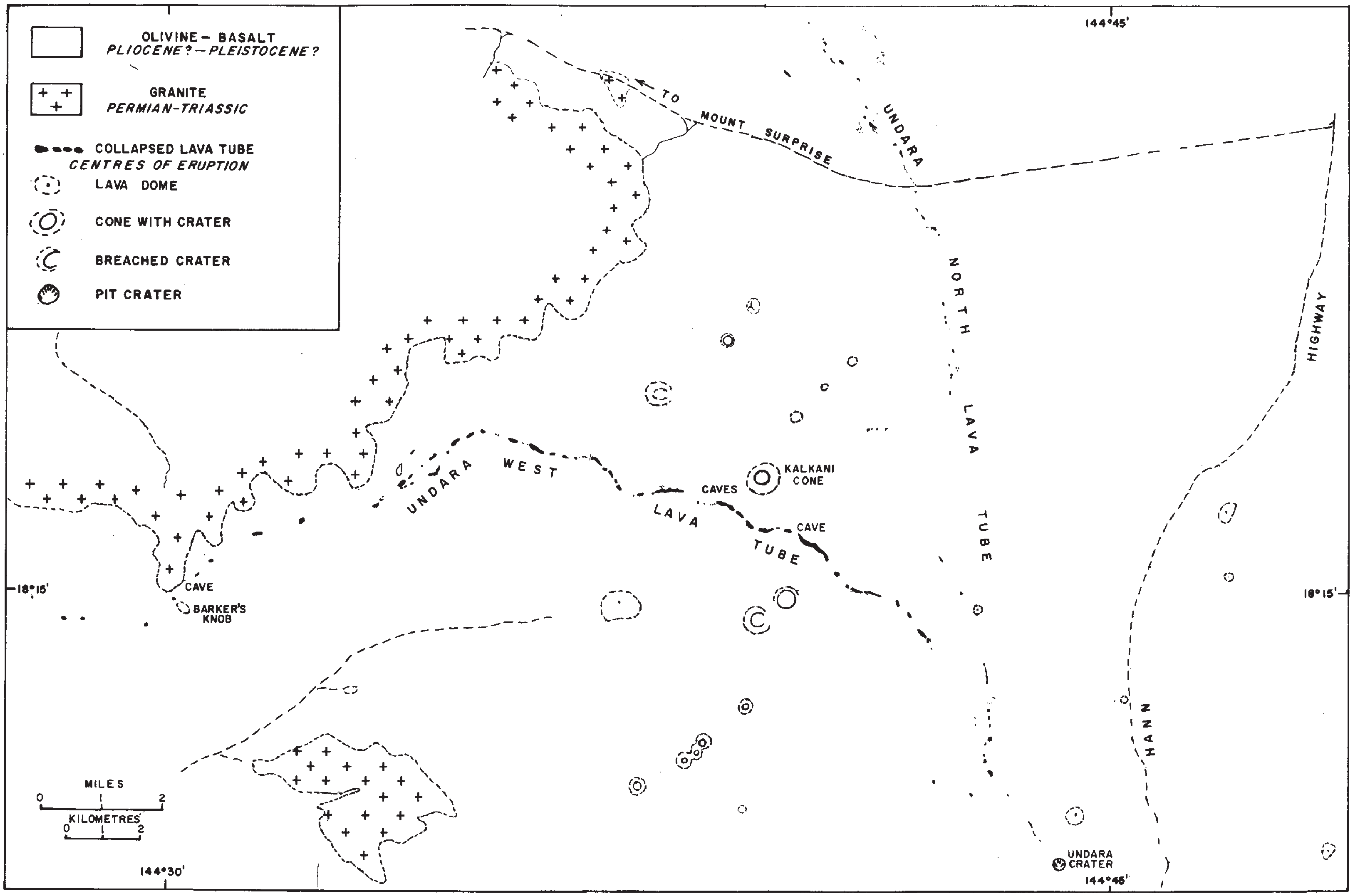

Figure 14-2: Map of Undara Lava Tubes System.

or entirely filled with solidified lava. The total length of the Undara West tube (assuming it emanates from Undara Crater) is over 35 km, that of Undara North Tube is 19 km (from the junction) plus 4 km in common with the Undara West Tube. Near the western end of the Undara West Tube, the tube approaches and is diverted southwesterly by a large area of hilly granite country, and passes between the granite of Barker's Knob and the main granitic inlier (Fig. 14-5).

THE BASALT AND ITS AGE

Best (1960) distinguished four basalt formations and ages: the Older and Newer McBride Basalt, overlain by the Undara Basalt, overlain in turn by the Kinrara Basalt. He considered the latter to be recent, because of the perfect preservation of the cone, crater, and lava structures. The Undara Basalt, in which the tubes occur, was thought to be Pleistocene. No age determinations have yet been made on the basalt of the McBride Province, but the basalts of the Nulla Province, to the south, have been dated at 4.0 - 4.5 m.y., 2.3 m.y., 1.3 m.y., 1.1 m.y., and 0.04 - 0.08 m.y. (Wyatt and Webb, 1970). The youngest of these, the Toomba Basalt, is similar in geomorphological and surface features to the Kinrara Basalt, and is probably of similar age. The Undara Basalt is probably similar in age to the next youngest flows, slightly more than 1 m.y., and thus Pleistocene. All of these basalts are alkali olivine basalts (Morgan, 1968; Wyatt and Webb, 1970).

UNDARA CRATER

When approached from any direction, only a slight rise indicates the proximity of the crater, but once the rim is reached a most impressive, almost vertical-sided unbreached pit crater is found. Although the wall appears to be almost entirely of rough, angular blocks of basalt, varying in size up to 0.6m^3, there is sufficient soil to support closed forest vegetation.

Descending into the crater, several indistinct levels are noticed which may have been former levels of a lava lake. However they are not nearly as distinct as the high-lava mark of Kinrara Crater, a younger crater of the same province. The floor of the crater, approximately 100 m below the rim, is covered with fine red soil, with fragments of scoriaceous basalt, some with the characteristic twist of volcanic bombs. Gravity measurements (Langron, 1969) indicate a high density lava plug beneath this site. It is probable that the lava which drained out through the tubes came from Undara Crater, but no sign of a tunnel entrance is visible. Perhaps lava fragments from a final explosive eruption cover any which may have been present.

LAVA CAVES

To date, five lava caves (non-collapsed parts of the Undara West Tube) have been entered by one of us (F.A.A.) but only two have been mapped. The entrances to all of these are marked only by slight depressions and entry is made over blocks from the collapsed roof.

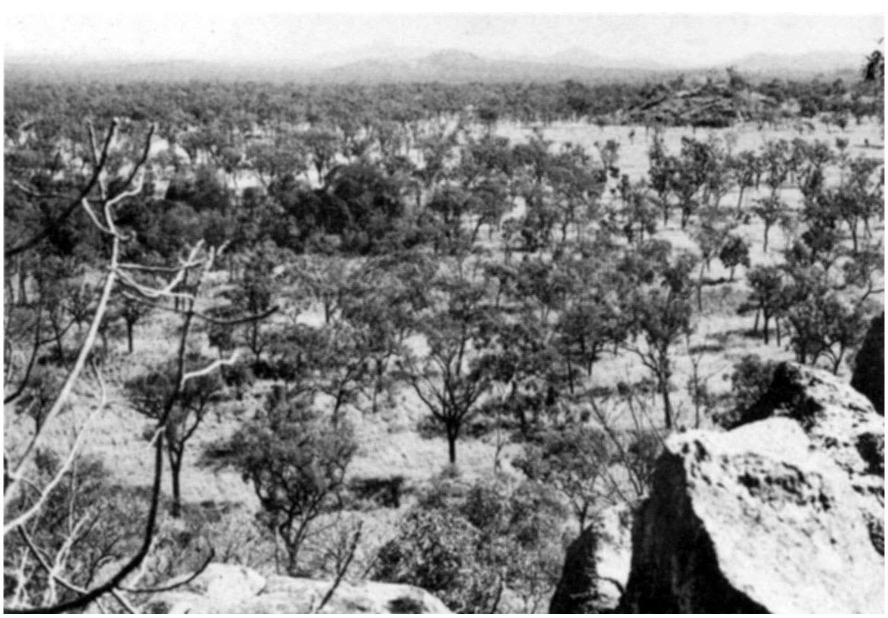

Figure 14-4: Surface of flow near Barker's Cave. Darker vegetation at left center is in collapse sink.

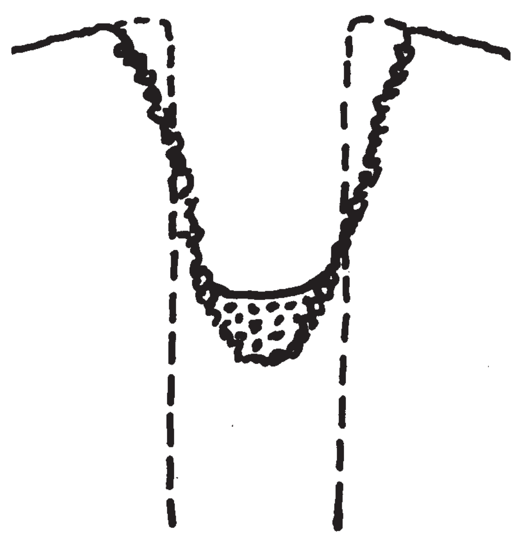

Figure 14-5: Theoretical vertical section of Undara Crater.

Pinwill's Cave. The location of Pinwill's Cave is about half-way between Kalkani Cone and an unnamed crater to the south (Fig.). Its length is 50 m; average height: 6 m, maximum width 21 m. The western end is blocked by a rock fall; here the width is 5 m. The basalt varies from massive to highly vesicular. The vesicles vary from almost microscopic to several cm in length. Elongation of vesicles gives evidence of flow; a flow line on the north wall has a dip of about one-half degree westward. The floor is covered by soil and bat guano, but approximately 30 m from the entrance is a good example of ropy lava. Lava drips are seen on blocks fallen from the walls and roof.

The most unusual feature of this cave is a table-like structure near the entrance. It consists of a curved layer of lava, fairly uniform in thickness (15 cm) which extends 6 m along the wall at a height of 2.4 m above the floor. It is 1.7 m wide for most of its length (Fig. 14-7). The structure is presumed to be a remnant of a former flow level.

Traves' Cave. This cave is approximately 2.4 km west of Pinwill's Cave (Fig. 14-9). It is 67 m long, has an average height of 6 m, maximum height of 10.6 m, and average width of 10.6 m. Rockfall prevents further penetration. Interior surface features of the basalt include lava drips and "runs", (lava dribble).

Atkinson's Cave. This cave adjoins Traves' Cave to the west. The collapsed entrance is similarly marked by dense vegetation of "rain forest" trees and vines. Its length is 100 m, the

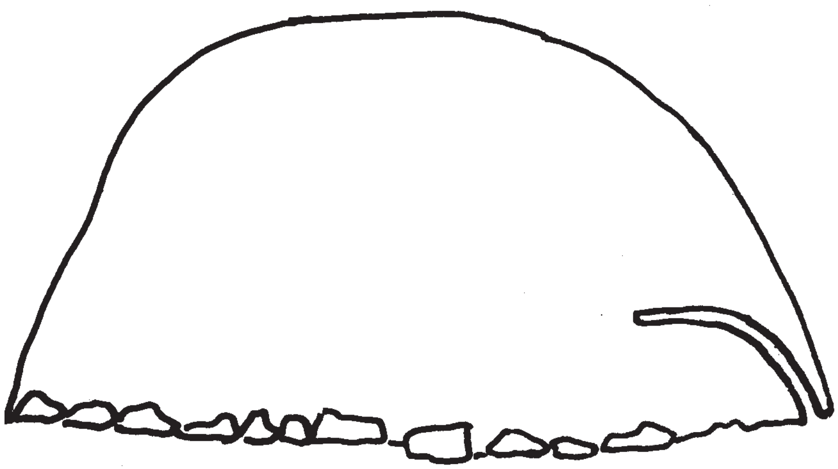

Figure 14-6: Cross section of Pinwill's Cave.

Figure 14-7: "Pancake" lava stalagmite in Atkinson's Cave.

Figure 14-9: Lava "runs" (drips) near entrance of Barker's Cave.

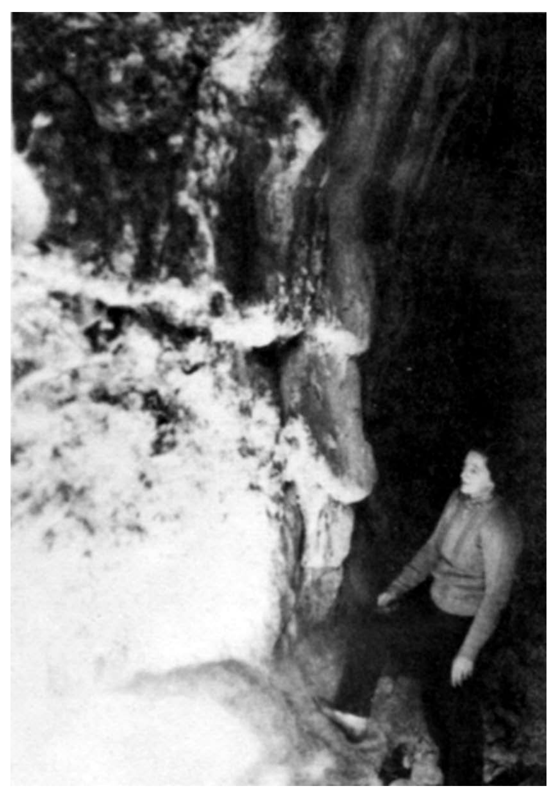

Figure 14-10: Wall of Barker's Cave near entrance.

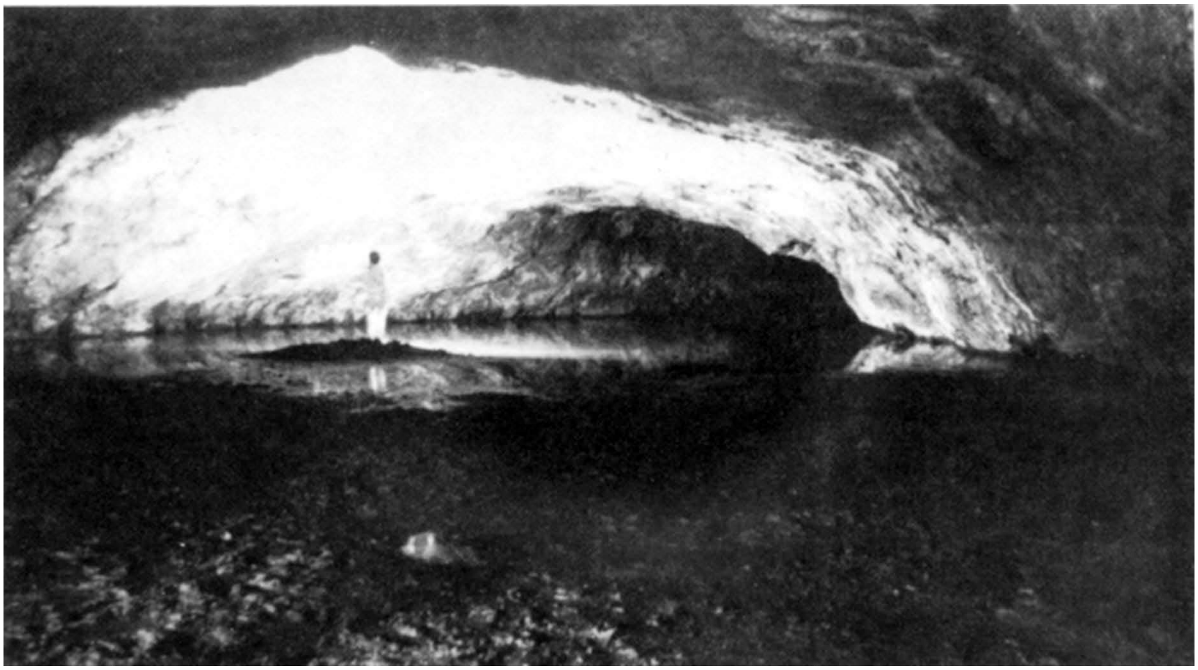

Figure 14-11: Terminal lake, Barker's Cave.

average height is 6 m, and the width is 7 m, expending to 21 m near the entrance. The entrance arch appears unstable. Near the entrance and also well within the cave, "runs" from the roof are visible, and also flow structures on the walls. Small lava stalactites and stalagmites were seen in a cavity on the north wall (Fig. 14-9). An interesting "pancake" structure was present in the stalagmites.

Barker's Cave. Barker's Cave is the only cave of this province described previously (Shannon, 1969; Watt, 1972). It is between Barker's Knob (a small granite hill) and the main granite inlier. Measured to the margin of an underground lake at the far end of the cave, its length is 518 m. This is less than previously measured; probably this was due to a record wet season in 1972 causing a greater amount of water in the lake. The lake extends at least a further 60 m. 60 m from the entrance, the width is 6.7 m (the minimum); 396 m from the entrance, it is 20 m (the maximum). The maximum height is 11.6 m. The floor slopes from east to west at approximately 3 degrees (Fig. 14-10). The entrance is in a small depression. It is unspectacular but the entrance arch is interesting in that it shows the curve of the tunnel roof. The lava at the center of the arch is only 48 cm thick. However the arch gives an impression of stability because of the height to width ratio, which is greater than that of other cave entrances. This ratio decreases with distance from the entrance (Fig. 14-11). Near the entrance is an area of recent rock fall.

A small cavity in the south wall close to the entrance shows fragments in the lava with twisted flow structure. The higher parts of the walls show "runs" (Fig. 14-12) with numerous small lava drips, forming a pattern of small triangles. Much of the lava is vesicular. At the base of the wall are very well developed flow structures which extend a long distance into the cave. Ropy lava forms a central raised section on the floor approximately 4.7 m wide, with trenches about 1.2 m wide at the entrance and increasingly wide down-flow. At the base of the walls, at approximately the level of the central raised section is a very distinct horizontal ledge or flow mark. Additional less distinct flow marks are seen at irregular intervals up to a height of 2.5 m (Fig. 14 13).

SPELEOGENESIS

The lava which flows in or around the tunnel probably followed a main river bed of a pre-basalt surface and became constricted between the granite of Barker's Knob and the main inlier. Many vesicular layers are present. Today, water flows in this part of the tunnel and forms a terminal lake already mentioned (Fig. 14-14). The slight curves in the tube may be in accord with the curves in the pre-basalt river valley.

It appears that the lava in the tube initially flowed at full capacity, filling the tube. The flow then diminished abruptly to half its volume or less, producing a fairly even cover of lava drips in the upper half of the cave. Later, when cooling had advanced sufficiently for a crust to form on the lava "river", this was forced to arch upward when it came to a constriction 60 m from the entrance, (Fig. 14-15), producing a raised "rope" formation.

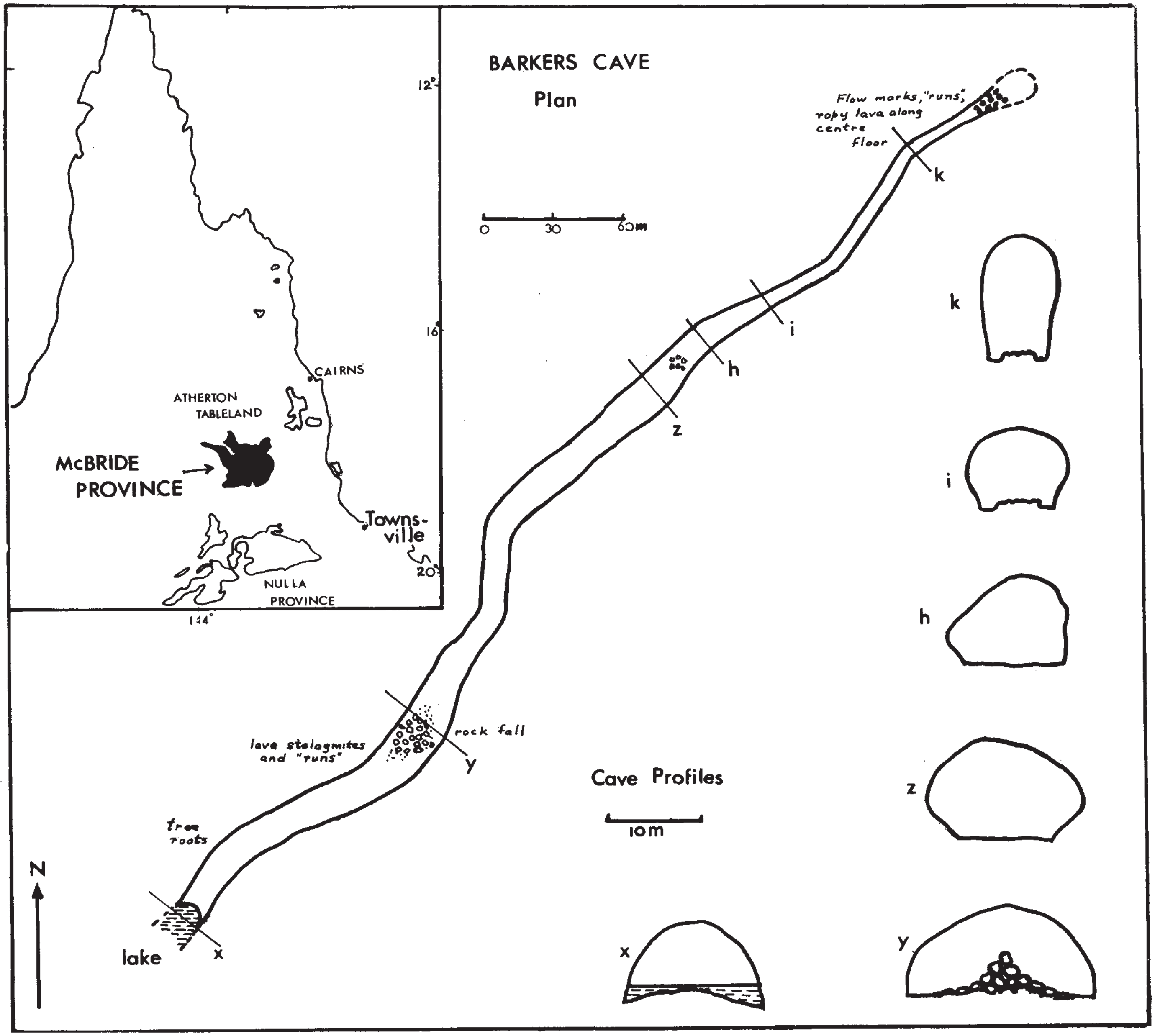

Figure 14-8: Map of Barker's Cave.

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SOUTHERN HALF OF THE GREAT RIFT, IDAHO

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(Editor's note: This multimedia presentation was not well adapted to adequate presentation in published proceedings such as this. For additional data and some alternate interpretations, the reader may wish to consult "Geologic Field Guide to the Quaternary Volcanics of the South-central Snake River Plains, Idaho," by Ronald Greeley and John S. King, Idaho Bureau of Mines and Geology Pamphlet no. 160, published in 1975.)

The Great Rift is located in southeastern Idaho on the 20,000 square mile Snake River Plain (Fig. 15-1). It consists of a zone of fissures from which volcanic products have erupted. Because of its uniqueness, it has been designated a national landmark. Its northern end is in the Pioneer Mountains, north of Craters of the Moon National Monument. It cuts across the monument from northwest to southeast, then curves southward and ends south of the Crystal Ice Cave area where its trend is about north 10° west. The rift zone is approximately 48 miles long. This presentation will be confined to the southern half of the rift, beginning at the point where it intersects the Craters of the Moon Lava Field (Fig. 15-2).

No lava flowed from the rift between the north end of the Crystal Ice Cave Field and the south edge of the Craters of the Moon Lava Field, a distance of 15 miles. In this section the rift appears as large earth cracks cutting through sagebrush-covered desert. The Crystal Ice Cave Field segment of the rift is about 3 1/2 miles long and covers an area of about 1 1/2 square mile. Just south of this is the Wapi Field which has an area of about 160 square miles (Fig. 15-3). Although not proven, it is suspected that the Great Rift was the source of lava for the Wapi Field. Apparently all of its lava came from Pillar Butte which is perforated with craters and small vents. The Wapi is relatively unkown but is a young volcano very similar to hundreds of somewhat older volcanoes on the Snake River Plain. Many lava channels and tubes radiate from Pillar Butte. Some can be followed for more than a mile. Away from Pillar Butte, most of the rest of the Wapi Field looks as if it was the product of a single eruption.

The series of volcanic events leading to the origin of caves within the Great Rift at the Crystal Ice Cave Lava Field (Fig.s 15-4 thru 15-6) is complex. The dominant structure here is a major fissure from which flowed two sequences of lava (the King's Bowl Rift). When this rift first opened, surface soils either cracked, forming two vertical faces, or caved off into the rift. Along an excavated trail, the soil zone is at least nine feet thick; caving into the rift occurred at this particular location. Ash blown by a west wind was deposited in stratified layers on the east side of the rift before the first eruption.

In the Hades area, at the north end of the field, the lava dike filling parts of this rift is exposed in Abyssal Pit (Fig. 15-7). Reddish soil is sandwiched between the older lava below and young rift flows above.

Lateral baking of the soil extends about 12 feet from the King's Bowl Rift. Vertical baking extends only about three inches below the lava. In unbaked soil, sagebrush roots have yielded a radiocarbon date of 2,130 plus or minus 130 B.P. This is comparable to one of the youngest dates obtained by Fred Bullard of the University of Texas at Craters of the Moon National Monument (2,085 plus or minus 85 B.P.).

Secondary fissures opened parallel to and about 1,500 feet distant from the main (King's Bowl) rift during the eruptions. These erupted no lava, and lava from the main rift flowed into them.

After initial flows, draining of lava occurred along the King's Bowl Rift to a point below the water table. Steam explosions resulted, followed by a spatter phase. A row of spatter cones called the Kilns formed at the extreme south end of the field (Fig. 15-3).

A second period of lava flows followed. Numerous minor vents became plugged and this rift began to develop specific centers of eruption. From north to south, these centers are: Hades area, Centicone area, King's Bowl area (the largest), and the South Grotto area. The South Grotto spatter cone is the largest on the Crystal Ice Cave Field. A natural bridge spans the rift inside the South Grotto. Here the rift has been explored to a depth of about 800 feet. Lava channels formed when lava drained back into the rift for the second time. Especially fine examples are located about 1,000 feet south of the King's Bowl. In other areas, the lava crust over the rift subsided as draining occurred.

Subsequently a major steam eruption occurred. In the Hades area, several large pits were blasted out. Tephra (explosion debris) was widely scattered in this area. In the King's Bowl area where vents were numerous, much of the lava capping was ripped off the previously capped

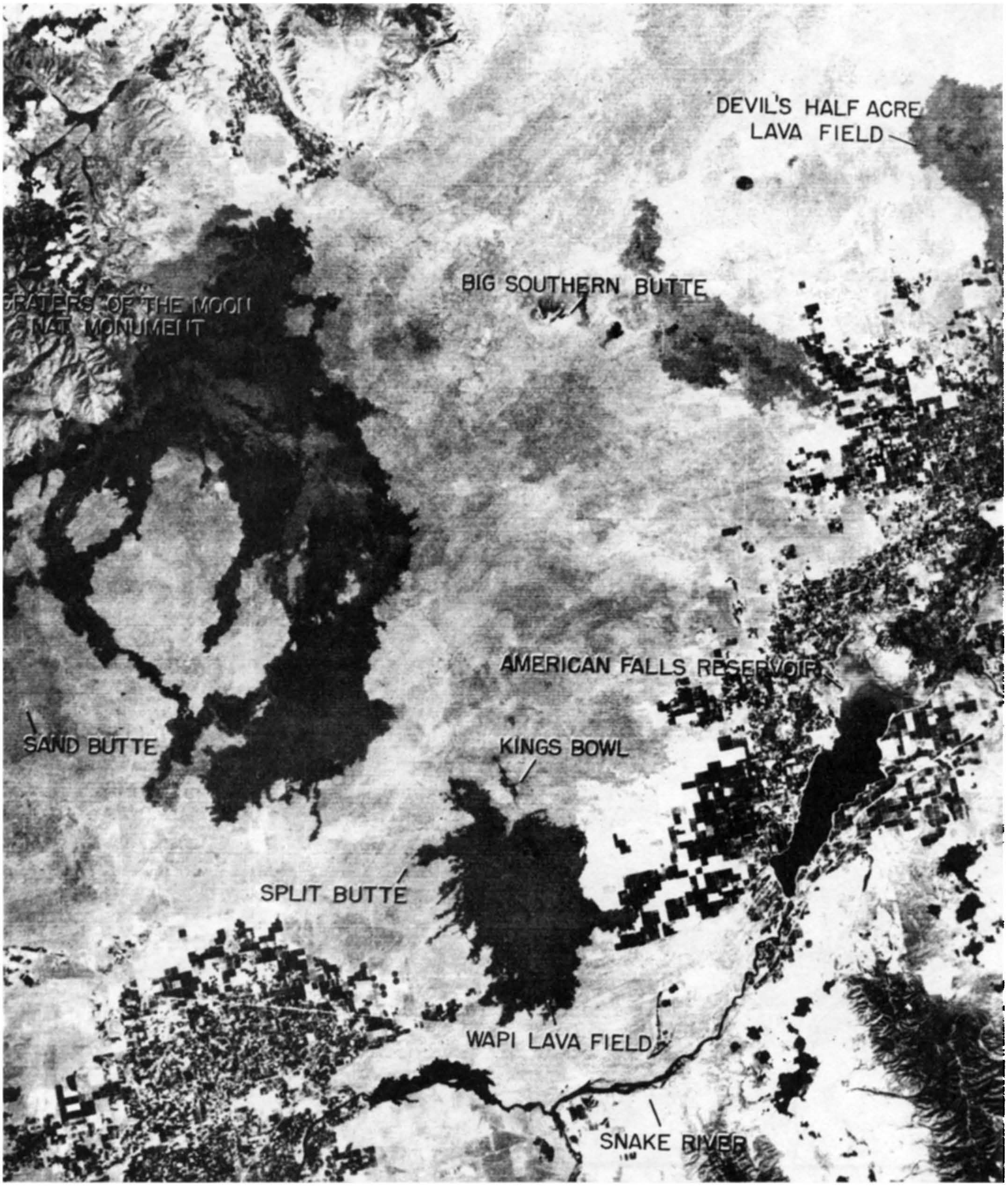


Figure 15-1: ERTS view of the Great Rift area, from Greeley and King, p.4.

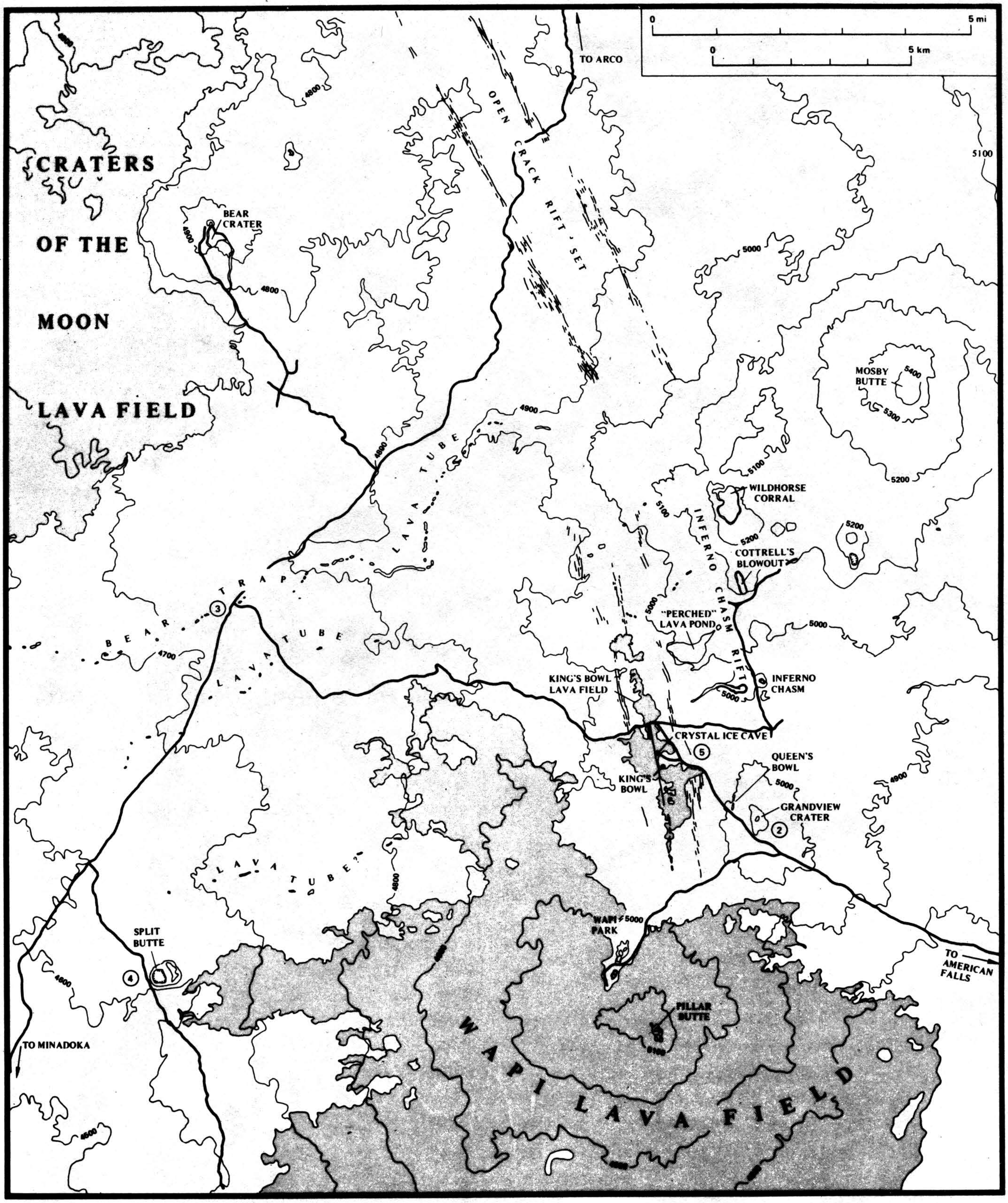
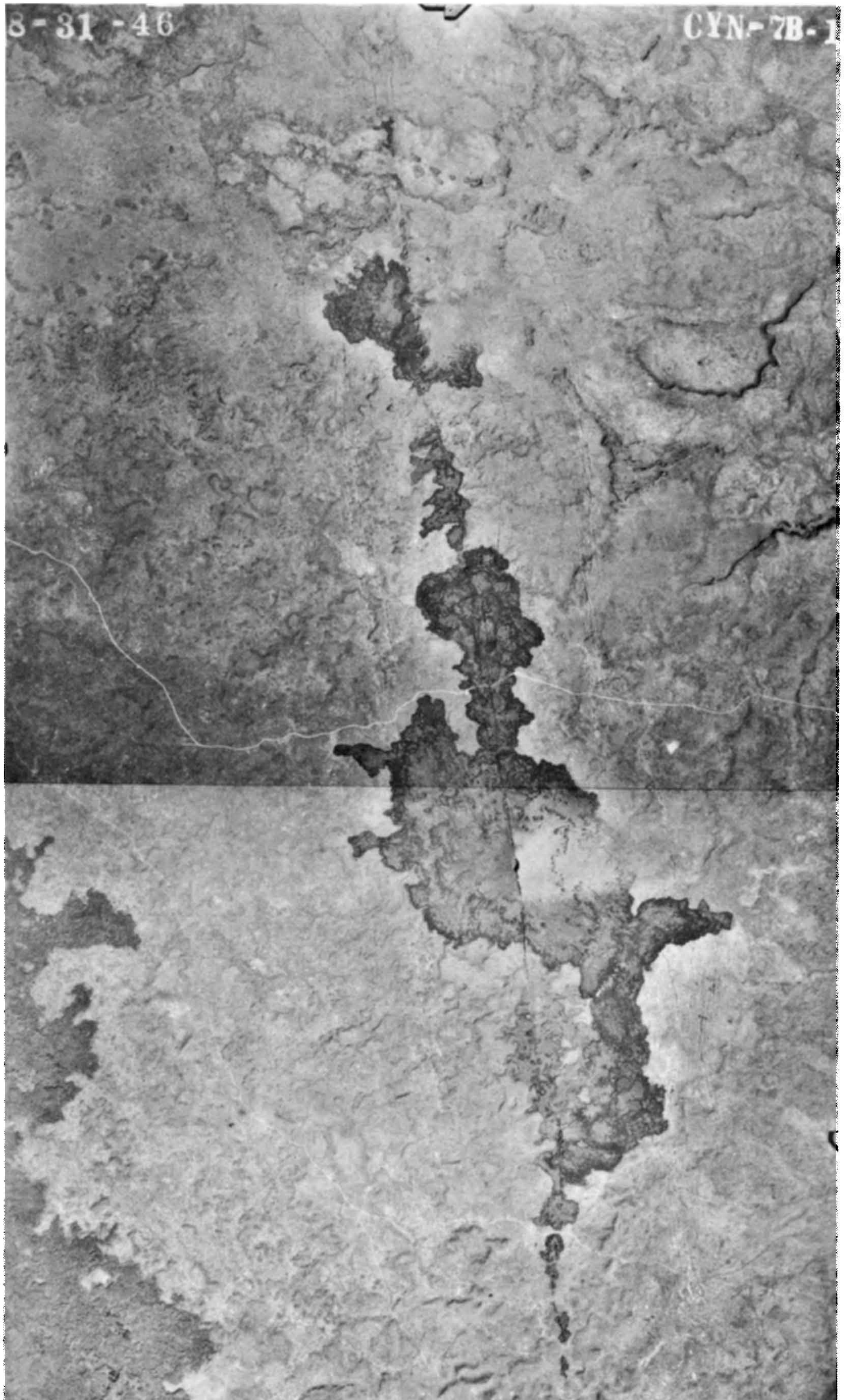


Figure 15-2: Map of southern half of the Great Rift, from Greeley and King, p.6.



Figures 4 & 5: Mosaic aerial view of Crystal Ice Caves Lava Field.

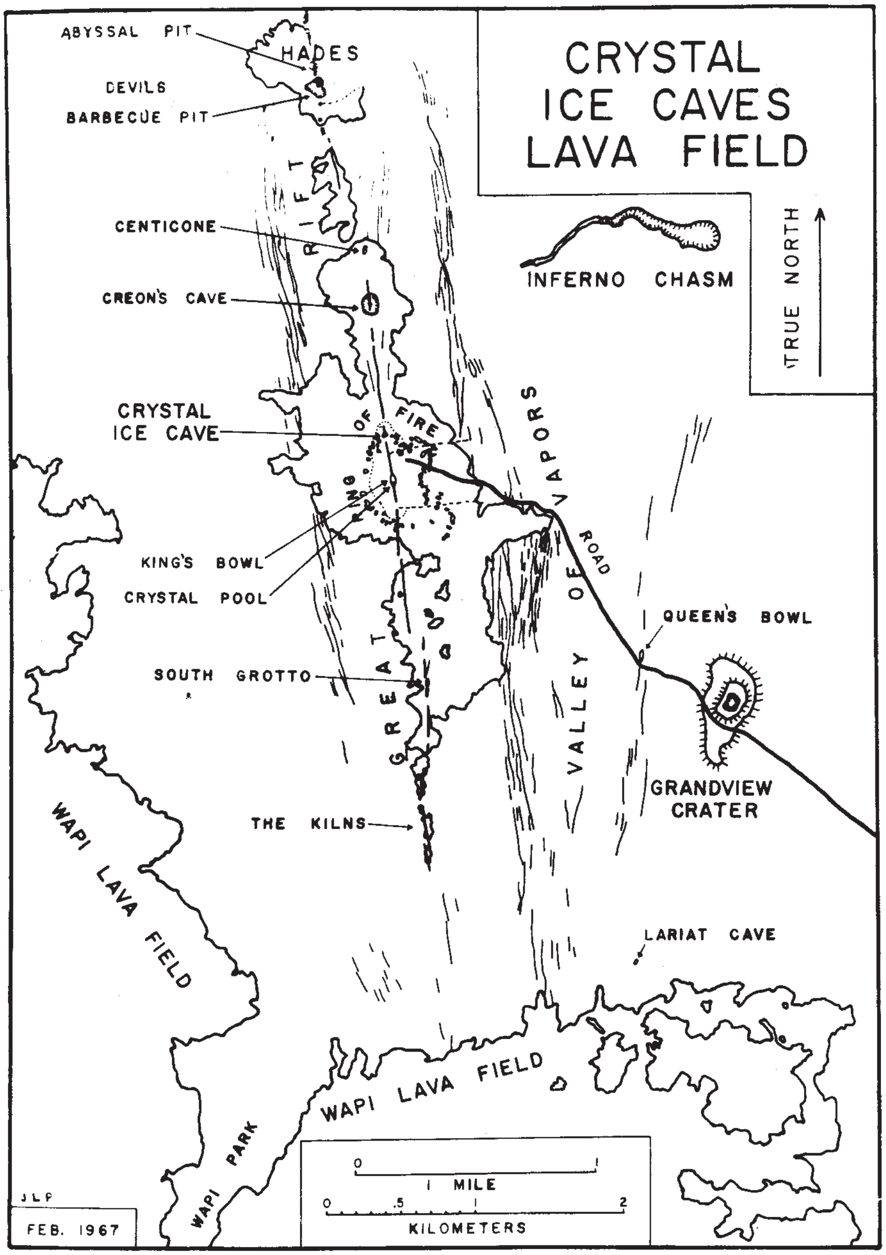


Figure 15-3: Map of Crystal Ice Caves Lava Field.

Figure 15-8: Ground level view looking toward South Grotto.

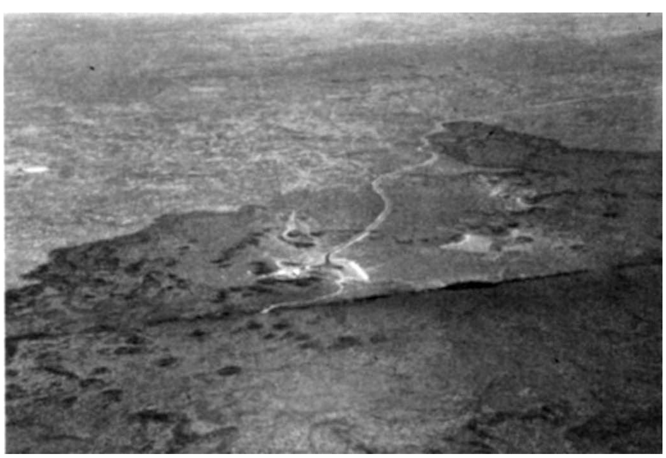


Figure 15-6: Oblique aerial view of King's Bowl area, showing ash drifted by west wind.

Figure 15-9; Soil horizon and dike in Abyssal Pit.

Figure 15-7: Low level view of Crystal Ice Cave section of the Great Rift.

Figure 15-10: King's Bowl and Great Rift, looking toward South Grotto.

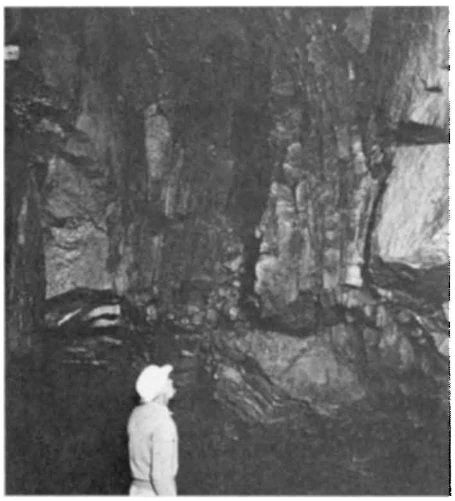


Figure 15-12: Selvages. Halliday photo.

Figure 15-13: Giant ice column, Crystal Ice Cave.

Figure 15-14: Ice crystals and dripstone, Crystal Ice Cave.

Figure 15-11: Cavernous segment of the Great Rift. Halliday photo.

portions of the rift. The King's Bowl explosion pit (Fig. 15-8) was the center of greatest violence. Lava drained to unknown depths below the water table, leaving the rift momentarily empty. Flooding ground water then resulted in steam explosions. A well recently drilled near the King's Bowl has encountered the present water table at a depth of 775 feet.

Fine ejecta was swept eastward by a west wind, obscuring the east edge of the lava field immediately down wind from the King's Bowl (Fig. 15-4). Nearby are small mounds which are believed to be rootless vents and erupted lava which flowed under the surface crust of flows from the King's Bowl vent. This surface originally was level with or higher than the tops of these rootless vents. Evidently much lava flowed out from these vents, enlarging the field, but great quantities must have drained back into the rift. The present surface slopes toward the rift and King's Bowl.

To view part of the King's Bowl Rift underground, visitors walk on a trail blasted out of solid rock (Fig. 15-10). Exposed on the walls of the rift are vertical layers, called selvages. These were coated on the walls of the rift by chilling of the molten lava. Each layer represents one eruption followed by a draining of lava. In the vicinity of the King's Bowl, the rift is about six feet wide.

Crystal Ice Cave is a commercialized segment of the rift. It has a continuous ice floor and is 370 feet long. The clearness of many of the ice speleothems is breathtaking (Fig. 15-11). In some areas, ice crystals grow on the cave walls at certain levels (Fig. 15-12). Another cave south of Crystal Ice Cave and north of the King's Bowl contains a room 500 feet long, 40 feet wide, and 70 feet high. I know of no other cavern chamber approaching such dimensions. Fissure caves of this sort are uncommon, and I would appreciate information on any others known or discovered throughout the world.

MATHEMATICAL ANALYSIS OF SOME LAVA TUBE MECHANICS

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PART I — BETA FORMULA

The simplest form of tube-bearing flow occurs when a mass of lava spreads from a small source, coolings as it advances. Consider a differential element of length dy, width dx, and height z. Heat radiation from the top surface is $\frac{dU}{dT} = E\sigma T^4 dx\,dy$. Change in heat content is $dU = pcz\,dx\,dy\,dT$. Combining: $E\sigma T^4 dx\,dy\,dT = pcz\,dx\,dy\,dT$.
Or, taking $v = \frac{dy}{dt}$, which defines the coordinate system: $dx\,dy = zv\,dx\,\frac{pc}{E\sigma}\,\frac{dT}{T^4}$, and integrating: $\iint dx\,dy = \int zv\,dx \int \frac{pc}{E\sigma}\frac{dT}{T^4}$, where the integrals on the right separate because T becomes independent of x in this coordinate system.

The double integral is surface area of the lava flow, while the first integral on the right is flow rate, Q. Defining beta as the temperature integral: 1) $A = \beta Q$, which is the desired result.

For a pahoehoe flow with constant, but not necessarily known, temperature profile, and neglecting heat of fusion: $\beta = \frac{pc}{E\sigma}\left(\frac{1}{T_1^3} - \frac{1}{T_0^3}\right)$. Using lack-of-movement freezing point for T_1 and eruption temperature for T_0, this describes a flow unit. Inserting Wentworth's temperature figures, beta is 5×10^3 sec/meter, which should be accurate to better than 30%.

Aa basalts have much lower surface temperatures than pahoehoes, so they should have significantly higher betas. Acidic lavas, on the other hand, have large T_1 and should have correspondingly small beta.

If flow rate is constant, equation (1) can be substituted into the volume equality $Ah = V = QT$, giving: (2) $\beta h = T$, which relates mean thickness of the flow unit to time of formation. For this relation it is convenient to use the reciprocal of beta, 70cm/hour.

It should be noted that a large number of fluid properties would intuitively be expected to affect size of a flow unit, but these properties all vanish with proper selection of coordinates and regions of integration. These properties affect shape, but not <u>size</u>.

It also should be noted that the T are surface temperatures, and that E can be eliminated by using pyrometer temperatures. This means that experimental error should be essentially the error in measuring Q. Equation (2) actually may be accurate enough that experimental beta could be used to obtain heat of fusion of the lava.

Formula (1) represents the conservation of energy, as applied to heat. The integral that gives beta is much less general. We might want to add terms for convection cooling, for heat lost from the bottom of the lava flow, or for heat of fusion, and we might want to assume temperature profiles that vary with surface temperature, depending on type of lava flow. If we are trying to predict size of flow units, fancy corrections don't mean much. We have a number for beta, and the corrections merely specify how the number was obtained. If we are observing sizes, then calculating properties, the corrections are what we are trying to calculate so fancier forms are necessary. My studies are not in that area.

PART II — GROWTH EQUATIONS OF THE SEMI-TRENCH RIDGE

(Introductory Note on the Formation of Lava Tubes, by Russell G. Harter)

A common conception of lava tube formation is generally stated approximately as follows: the upper surface of a lava flow hardens, and the still-liquid lava below drains out, leaving a lava tube. The tubes are cylindrical, and make a network of capillaries that can permeate the entire flow.

Many lava caves in the northwestern United States are quite complex, but this is readily accounted for by the common notion. It permits one to explain all arrangements of passages. Indeed, this concept enables one to explain any lava tube structure -- whether it is physically possible or not. My brother and I have abandoned this concept.

When lava flows across a surface, it tends to move in well defined channels. There are several types of lava channels, and lava tubes are roofed lava channels. Each is built in a definite way. Lava tubes do not happen suddenly nor miraculously, and are not impossibly complex.

When lava erupts, it flows out of a large crack in the ground. The crack (rift) often trends downhill from the point of the eruption, so the lava may follow it. A current develops in the rift, making it a lava channel. The top surface of the lava chills, making a thick, mushy scum. The scum is separated from the molten lava by the accumulation of a layer of hot gas rising from the lava. The hot gas supports the crust until it cools enough to stand by itself. Now the lava may drain away, leaving a cave. Since this produces a cave in a rift, it is a rift cave. This type of lava tube cave is almost always high and narrow--the shape of the rift. False roofs may form at low stages of flow, separating the rift into levels that are perfectly superimposed, one above another. Rift caves are hollow dikes.

If a lava flow is not in a rift, the lava streams must form their own walls. Thin sheets of lava flow out to the sides and cool, building walls along the channel. Or, in areas of low ground slope where the lava is temporarily ponded, the stream channel continues through it. This latter case we call a true trench, and the case of the lava stream forming a broad ridge through building its own levees we call a semitrench. True trenches leave a flat surface because they are incised into a flow unit by differential solidification.

Most large lava tubes are rift caves or semitrenches. They are able to transport hot lava for long distances, because comparatively little heat is lost from the roofed channels.

Large lava tubes feed small streams of hot lava. A single arched crust forms over the stream, making a smaller lava tube. This kind of tube is entirely above the adjacent ground surface, so we call it a surface tube. It is described by the beta formula just discussed. Most small lava tubes are surface tubes or a hybrid of surface tube and semitrench.

Semitrenches often flow in braided lava streams, much like the braided channels of a water stream. The individual channels over-flow requently, sometimes making surface tubes. In the resulting cave, the surface tube is a small lead off of a large passage. Overflows through the roof make surface tubes on an upper level. If the overflow plugs, it will leave a cupola in the ceiling of the lower passage.

After lava tubes form initially, rock is often added or removed, changing the passage shape. The lava is added as layers of linings. Rock is removed primarily by rockfalls. The many passage combinations, and extreme modifications, result in caves that are sometimes very complicated. They are possible to explain, however, without resort to illusion.

Lambda Relations of Semi-trench Growth

A lava flow advances slowly, pushing out small lobes and thin sheets of lava. Farther uphill, we find that the great bulk of the lava flow is solid. There is molten lava only at the tip and in a narrow longitudinal channel.

Later, after the lava flow has cooled, we find that the uphill ends of the sheets and lobes lie less than five centimeters behind the surface of the channel wall. This is quite remarkable: the structure of the growth region appears random, but both channel and lava flow have uniform

shape and size, for extensive distances.

Clearly, growth of the lava flow must be a process that is uniform in the large but not in the small, and it must be inherently stable. The stability requirement can be written as a differential equation:

$$1) \quad \frac{\partial^2 y}{\partial x \partial T} \cdot \frac{\partial y}{\partial x} + \frac{\partial^2 y}{\partial z \partial T} \tan\theta = 0,$$

where y is thickness, x is width, z is length, and θ is ground slope. This equation states that deposition rate is a function of position along the flowline.

The uniformity requirement is a change of variable: $\mathfrak{z} = (vT - z)\cot\theta$, where v is rate of advance of the lava. 1) becomes: $\frac{\partial^2 y}{\partial x \partial \mathfrak{z}} \cdot \frac{\partial y}{\partial x} = \frac{\partial^2 y_x}{\partial \mathfrak{z}}$

This equation will integrate directly, once: $(\frac{\partial y}{\partial x})^2 = 2\frac{\partial y}{\partial \mathfrak{z}} + F(x)$ The arbitrary function F must be evaluated by use of boundary conditions. This is a somewhat tedious process, because the bounds concern lack of roots of derivatives, but the result is $F(x)$ is a constant. This implies that y has the form $y = y^* + C$. We work with y^*, and define p : $\frac{\partial y^*}{\partial x} = p$, $\frac{\partial y^*}{\partial x} = \frac{1}{2}p^2$

Inverting variables: $\frac{\partial x}{\partial \mathfrak{z}} / = -p$, $x = 6' - p\mathfrak{z}$

$$y^* = \int p \frac{\partial x}{\partial p} dp, \quad y^* = p6' - 6 - \frac{1}{2}p^2\mathfrak{z}$$

where 6 is any function in p of class C_2, and the primes are derivatives with respect to p .

Again, boundary conditions must be appled. This time, we find that a suitable choice of origin gives $6 \equiv 0$: $x = -p\mathfrak{z}$, $y = C\mathfrak{z} - \frac{p^2\mathfrak{z}}{2}$

$$y = C\mathfrak{z} - \frac{x^2}{2\mathfrak{z}}$$

Since we are dealing with a ridge, and not a trench, C must be positive. Let $C = \frac{2}{\lambda^2}$. Also define $x_0 = \lambda y_0$ and $\mathfrak{z}_0 = \frac{\lambda}{2}x_0$. Then:

$$2) \quad y = y_0 \frac{\mathfrak{z}}{\mathfrak{z}_0} - \frac{x^2}{\lambda^2 y_0} \frac{\mathfrak{z}_0}{\mathfrak{z}}$$

This function is a parabolic cone with vertex at the origin. It has two features that we can be quite sure that the actual lava flow does not have : it is smooth, and the leading end has a definite corner. Both of these were introduced in the boundary conditions, as a requirement that we are dealing with a mean surface and ignoring individual flow lobes. Less restrictive F would give full detail of the flowfront, but the second integration would have to be performed numerically, on a computer. Exact solution would be impossible.

Lambda now must be evaluated. We begin by specifying that the point $(x_0, 0, z_0)$ is the end of the growth region. For this z : 3) $y = y_0 - \frac{x^2}{\lambda^2 y_0}$ and the flowline through the point is $x = x_0 e^{-\frac{\mathfrak{z}}{\mathfrak{z}_0}}$, which gives the growth region an area: $A_G = 3x_0\mathfrak{z}_0\tan\theta = \frac{3}{2}\lambda^3 y_0^2 \tan\theta$.

For a channel with liquid depth h, area A_1, and shape factor N , flow is: $Q = \frac{\rho g}{3\mu}A_1 h^2 N \tan\theta$ (For constant width w , $N = 1/(1 + (2h/w)^2)$.) Substituting A_G and Q into the beta formula gives:

$$4) \quad \lambda^3 = \frac{A_1}{A_0} N\left(\frac{h}{y_0}\right)^2$$

where A_0 is a collected constant with dimensions of area: $A_0 = \frac{9\mu}{2\rho g}\beta$.

Since A_0 depends on viscosity of the lava, care must be taken in using any fixed value. However, 7.2 mm^2 should be accurate enough for finding lambda from dimensions of a lava tube. In other work, such as predicting how width of a lava flow is going to vary at a change of slope, one of the A_G forms might be preferable.

To this point, all calculations have concerned the initial-growth portion of the lava flow. However, the form of 2) shows that equations 3) and 4) will still apply at later stages of development. The term h/y_0 is the key factor. For an open channel, it equals 1. For a lava tube, $y_0 - h$ is the roof thickness, and the term may make an appreciable correction.

V has been ignored. Since it is rate of advance of the lava flow, someone may want to calculate it: $V = \frac{3\lambda^2}{2\beta}\tan\theta$.

This development is not quite complete. One additional equation is needed, before application to active lava flows will be feasable. This equation would relate one of the other parameters to theta. It probably can be obtained from energy considerations, but the proper energy function definitely is not obvious.

Without the additional equation, 3) and 4) can be used to find obscured flow edges, to determine whether all major tubes of a lava flow have been found, and to locate any missing ones. For this work, $A_0 = 7.2 mm^2$ probably is not accurate enough, and an experimental value probably should be found by measuring actual lava-tube flows.

I found equation 1) about the beginning of July, so I haven't had time to check the value of A. This would make a good project for someone who is feeling frustrated because our magnetic caves are making his Brunton point east. The surveying is all tape and verticals, and you can omit the verticals if you pick something like the Red Cave system to measure. Chain off the width of the lava flow to get X_0 and the depth of the collapse to get Y_0--remember that you have to go to the bottom of the breakdown. Then lambda is X_0 over Y_0. Measure passage size and shape, and that gives h, A_1 and N. We have a graph (Fig.). These curves are made for shape of a semitrench passage, rather than for a rectangular one, which is what the essence of N_s is all about.

The most immediate application of this development is tracing lava tubes in stretches where cave is not known. We know that a semitrench lava tube is going to lie on the axis of a ridge. Equation 3 describes the shape of the ridge, and equation 4 gives its width. This is sufficient to allow one to begin at a cave and proceed along the ridge until he reaches the next cave perhaps a half-mile distant.

We do not have a good way to state what parts of a system will be found to be collapsed, what parts are going to form caves, and what parts are going to be plugged with solid lava. But a little practice allows us to follow plugged or obscured segments almost as easily and accurately as we follow collapsed segments.

Ridge-walking is, of course, an old technique. What the mathematics do for us is to relate the ridge and the cave. Included is warning that the ridge shape may lead one astray, and provision to get back on line when we do stray.

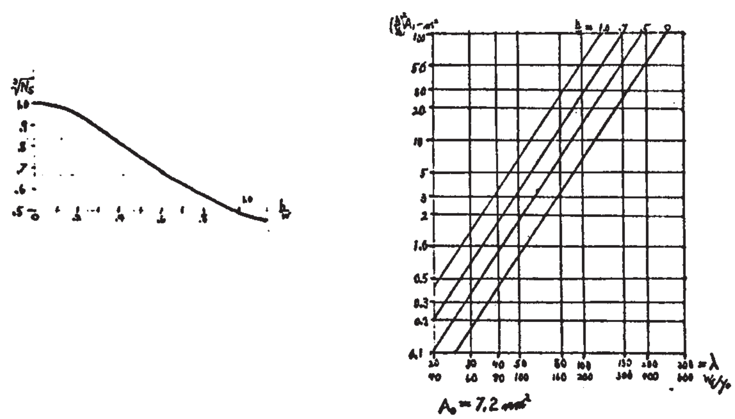

Figure 16-1: Graph for Lambda relations of Semi-Trench Growth.

MORPHOLOGICAL CLASSIFICATION OF LAVA TUBES

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Lava caves exist in seemingly bewildering variety. There are tiny caves six feet long and barely four inches in diameter, and there are large caves over a mile long and sixty feet high. They can be isol ated chambers, unbranched passages, or complex networks. There may be one level of passage, or many. A way to sort the many types of lava caves is required.

The most obvious features of a cave are size, amount of branching, presence or absence of chambers, and number of passage levels. These features, included in almost every cave description, provide a rough sorting of types, but serious classification problems arise.

At least one basic factor is missing from the description. As many as six different processes can produce caves in the same lava flow. This suggests that the missing factor is the process that formed the cave, and field study verifies this conclusion.

Thermodynamics gives an 'absolute' classification, consisting of mathematical cases. The theory cannot be used directly to classify caves, but indirect application is quite practical. A characteristic cross section for each formation process exists, and can be used. This is not the simple cross section of the cave--it is a cross section of the lava flow. It contains both the cave outline and the stratification of the surrounding rock. (Since study of rock statification is a basic tool of physical geology, this should not be surprising.) The important strata can be observed at cave entrances and at rockfalls within caves. The statification patterns suggest obvious names for the basic classes, which are: surface tube, true trench, semitrench, rift cave, and interior tube.

Surface Tube (Figure 17-1a). There are two strata: a flat floor stratum which extends well to both sides of the tube, and a roof stratum that forms an arch. Inner and outer surfaces of the roof stratum are nearly parallel, except near the floor, where stratum thickness may double or treble. The passage usually has a width greater than twice its height. Shape of the arch may vary greatly along the length of the passage, and wall contour near the floor is especially variable. The walls and roof are a single thin shell of rock; this characteristic permits identification of surface tubes even when deeply buried by later flows.

Trench. The walls join the floor at right angles and curve to overhang the passage. The roof is a separate stratum. There is at least a corner where the wall and ceiling meet, and the roof may be set back from the top of the wall to leave a shelf (Figure 17-2). Passage height and width are nearly equal and seldom have a ratio greater than 3:2. There are two distinct stratifications of trench:

True Trench (Figure 17-1b). There is one wall stratum. The lower surface of the roof is arched but the upper surface is flatter. A few feet outside the passage, the roof terminates in a rounded edge. In a straight passage, each wall overhangs by about two fifths of its height. In a curved passage, the overhangs are unequal, and the sum of their widths becomes less. The walltop shelf is usually present, and the shelf width may be greater than the wall overhang. If several cross sections are taken, wall height and overhang are found to vary less than passage size and shape. True trenches lie in a single flow unit, and their walls are massive, with little or no internal structure.

Semitrench (Figure 17-1c). The wall of a semitrench has a complex internal structure which, unfortunately, usually is hidden behind a smooth surface. There is a definite wall, and the roof is a separate layer of rock. One can almost always find the corner between wall and roof if he knows where to look. The wall overhangs the passage, and often is about 45° from vertical where it joins the ceiling. The floor stratum is identical to that of the true trench. The wall consists of the edges of laminae of roughly equal thickness (Figure 17-3). These laminae often merge or abruptly terminate a few feet outside of the passage. The roof is the top lamina. Wall overhang tends to be less than in the true trench, and the walls can be vertical. The shelf is often completely absent, leaving only a sudden change of slope between wall and ceiling.

Rift Cave (Figure 17-1d). Rift caves form in volcanic rifts, and in some lesser fissures. The structural walls are the sides of the fracture; they are usually parallel but may form a truncated 'V'. They are often covered by a lining whose surface resembles that of a stucco wall. The roof strata are nearly flat, but they usually stope out to form an arched ceiling. The observable floor commonly consists of loose rock from the stoping. The passage normally has a height more than twice its floor level width, and thrice is common.

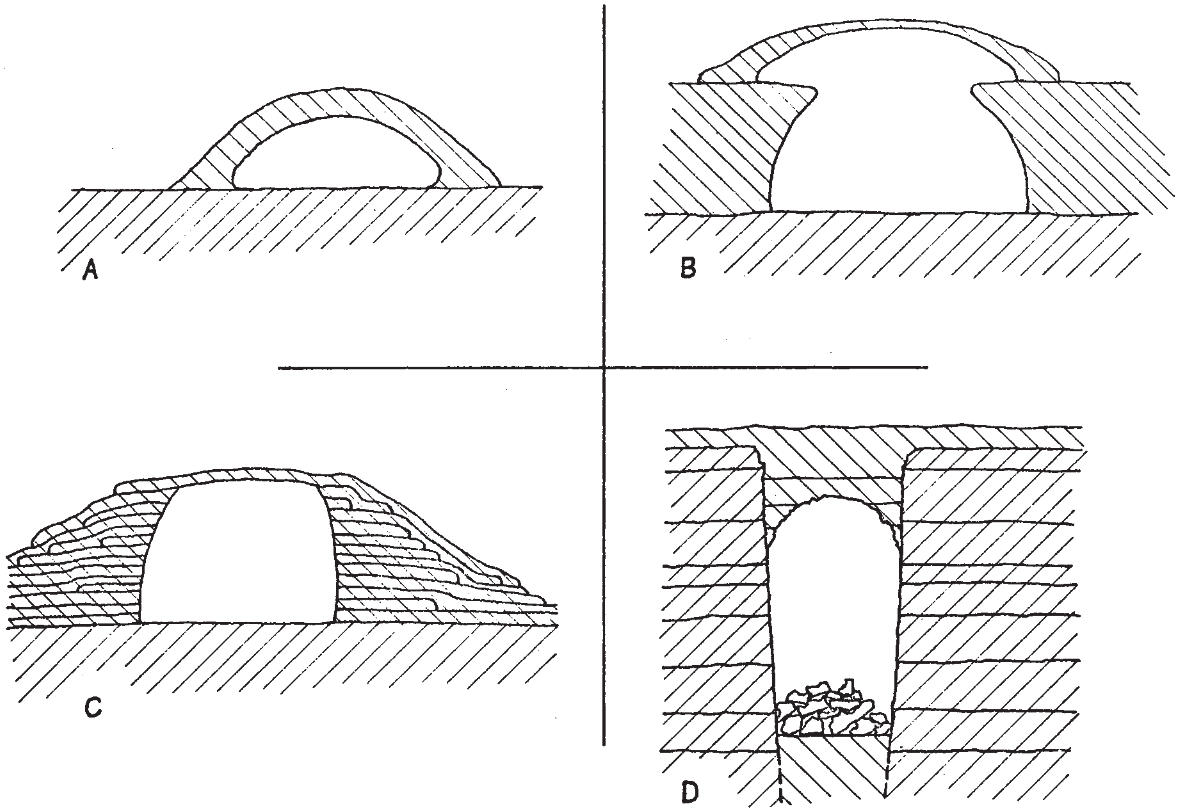


Figure 17-1: Cross-sections of various types of lava tubes.

Interior Tube (Figure 17-4). In straight passages, the interior tube cross section is elliptical, with its width about ten percent greater than its height. In curved passages, the shape becomes a regular hexagon with rounded corners. The theoretical interior tube would lie entirely within a single stratum of lava, but in practice no such caves are found. The actual interior cave is obtained by extensive modification of the other shapes and shows a jumble of fragmentary strata that is characteristic of extensive modification.

Classification of chambers is similar to that of passages. But, the chamber must be related to its associated passages as well as having its cross section classified. The only special difficulty that arises with any frequency is the occurrence of a chamber whose floor rises to meet a flat roof. This chamber is a variant of one whose roof descends to meet its floor, so it is a surface chamber.

Variation from the basic shapes is of three distinct types. First, the surface tube, semitrench, and true trench are phases of a continuous spectrum, so the base of a surface tube wall may consist of a few strata of semitrench wall, and a trench wall may consist of two or three massive strata. Second, erosion (by molten lava) and stoping can remove portions of the structural strata. This can make a buried surface tube appear to be a semitrench. Third, additional strata may be deposited both over and within a lava tube. In particular, semitrenches may contain linings that strongly resemble surface tube roofs. And, it is common to find a false roof dividing a rift into vertically separated passages that resemble semitrenches.

Lining and erosion generally proceed toward the interior shape. This shape occurs because it is stable for both mechanical and thermodynamic processes, while the others are not. However, lining and erosion in a partially filled tube provide exceptions. A partial lining may form a shelf, which can be mistaken for the structural shelf of a trench. Erosion may convert the passage shape to a triangle, with the floor as one side. Lining, erosion, and stoping occur together more often than separately, with the result that classifying a modified tube may require reconstructing much of its history.

Tube type sometimes changes within a cave. For example, a transition from trench to surface tube, followed by extensive branching of the surface tube, is the standard pattern in areas where a tube flow empties onto the surface. These changes are significant in terms of lava flow mechanics. Practice is required to locate these transitions precisely, but when found they are usually abrupt. Where its flow units became thick enough, C13 North at Pisgah Crater, California, dropped into it and changed from semitrench to true trench. At the bottom of a slope, the trench ends, but the cave continues as surface tube, buried under about four meters of lava.

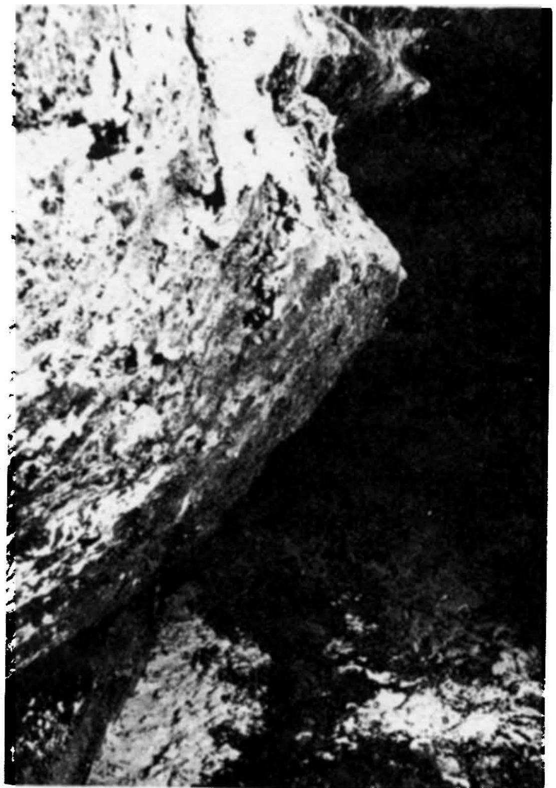


Figure 2

Figure 3

Figure 4

Figure 5

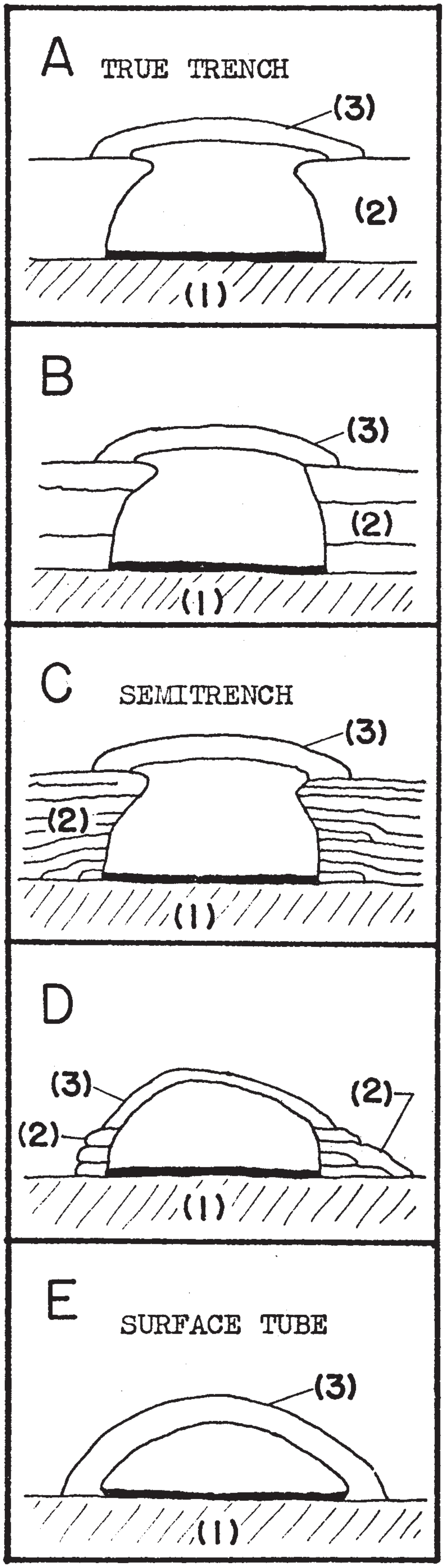
Figure 17-2:

Figure 2, trench shelf.

Figure 3, wall inside a semitrench.

Figure 4, Skeleton Cave - hexagonal shape of a curved passage, modified to interior.

Figure 5, small surface tube.



This is the continuous series of true lava tubes that form caves. We have named the end points and mid-point of the series in "Classification of Lava Tubes." The cross sections at left illustrate these and two intermediate hybrids. (Rift caves are considered to be a special case which is not included in this series.)

In the drawings, (1) is the pre-existing surface over which the lava flowed. (2) is wall built by the lava stream. (3) is the roof stratum. A floor lining (a common modification) is shown in each case.

A is a 'true trench'. The walls (2) are a single flow unit. A channel in (2) had sufficient current that it did not solidify, and the channel has become the lava tube. The walls overhang as a result of the flow surface being chilled by the air. The roof forms separately from the walls as a crust on the lava channel.

C is a 'semitrench'. It commonly produces moderately large caves. The walls are low, wide, levees that were built by numerous small overflows from the lava channel.

E is a 'surface tube'. A small stream of lava formed a crust on its outer surface. The wall and roof are the same stratum.

Both D and E typically form small caves, and occur in a variety of shapes. The surface tube/semitrench hybrid D often has accretionary walls only a few inches thick, with a nearly flat roof several feet wide.

Figure 17-3: The Semi-Trench Spectrum.

Almost every lava cave that consists of crawlways is either a small surface tube or an intermediate between surface tube and semitrench. Both types are best classed as surface tube. This is the most common type of lava tube, but where there has been enough weathering to produce a layer of soil on the lava flow, the soil and plant growth obscure these small surface tubes.

Since some confusion has occurred in previously published literature, a note on stratum thickness is needed. The structural roof stratum of a large surface tube is usually between eight and eighteen inches thick; the roof of a small tube may be only one inch thick. Where the thickness of a tube roof is over six inches, it is not related to tube size. Trench roofs tend to be thicker than those of surface tubes, but the thickness is never more than three feet. Rifts usually have roof strata that are between two and four feet thick. Linings usually are about as thick as surface tube roofs but can be much thinner. If a roof stratum extends much farther to the side, or is much thicker than called for by the tube type, it is almost certainly an overlying lava flow.

It should also be mentioned that there are a number of structures in lava flows which are closely related to lava tubes but which are not, in themselves, lava tubes. On study of flow mechanics, the relationship of these phenomena to the lava tubes is usually found to be relatively complex, so the classification system should not be extended to consider them. This includes such features as speleothems, "pressure" ridges, and lava blisters.

Since the classification system is derived from theory, examples of the pure types are relatively rare. Also, most caves which provide good examples are not well known. Since the following examples are selected from better known lava caves, they are more complex than the archtypes.

Subway Cave, a few miles north of Lassen National Park, is one of the best-known lava tubes in California. It consists of semitrench passages and chambers. But, in terms of strata it approaches true trench, while the passage and chamber shapes are more typical of surface tubes. The trench shelf is completely absent, and parts of the roof have eroded into overlying lava flows. Also, most of the cave is coated with a thin lining which hides the statification and modifications.

Lava Beds National Monument, in California, contains many well known lava tubes. Mammoth Cave, a few miles southeast of the monument, superficially resembles Subway Cave but is actually a large surface tube. Valentine Cave, within Lava Beds, is a better known example of surface tube.

Valentine Cave is known best for well formed lining curbs, seen near the entrance. Curbs like these can be found in any type of lava tube, but they are seldom as well formed as those in Valentine. The floor in Valentine has been heavily eroded and partially built up, but the wall above the curbs is essentially unmodified. Variation in shape of the ceiling arch is readily seen. The small side passages and the low, wide chambers are typical of surface tubes.

Catacombs Cave is another large surface tube at Lava Beds. It is more complex than Valentine and has three passage levels. Except for a segment of small semitrench on the lowest level, it is all typical surface tube. The niches in the walls, which give the cave its name, are plugged surface tubes which branch from the main passage. Their appearance is typical of plugged surface tubes.

Mushpot Cave, at Lava Beds, is electrically lighted and has its entrance in the parking lot of the monument headquarters. Near the entrance, Mushpot is true trench with a narrow, sloping shelf. Near the lower end of the path, the trench converts to surface tube which emptied onto the surface of the lava flow. Mushpot was later buried by other lava, so the pattern of a tube emptying onto the surface cannot be observed from outside. Mushpot contains several 'rise chambers', in which the trench overflowed to make an upper level of surface tube junction pools. Each pool, characteristically, fed several surface tubes which radiate from its perimeter. These surface tubes supplied some of the lava that buried the main level of the cave.

The "Thunderbolt" section of Labyrinth Cave, at Lava Beds, is a heavily modified lava tube. It formed as semitrench, but stoping and erosion have generally removed the structural strata. Several linings were also extensively broken out and eroded. Such modifications prohibit accurate classification, and the best way to classify such passages is 'modified toward interior'.

There are some small surface tubes in the Fleener Chimney area. There are also a couple in the cave loop, to the left of the road as one goes from the Hercules Leg turnout toward the Juniper Cave turnout. Undoubtedly, there are many more in the monument, although they are usually not noticed. Small surface tubes may be any of a variety of shapes. The roof may be very wide and nearly flat, with low semitrench walls. The walls may merge at the ceiling in a sharp peak. The height may be significantly greater than the maximum width, but this has not been found in any surface tube more than two feet wide. When found as part of a larger cave, rather than as separate caves on the surface, small surface tubes often occur as little overflows from the ceiling or from high on the walls.

At Lava Beds, the rift zone that produced Mammoth Crater bisects the cave loop and continues east to Craig Caves. The major flow through the area followed the rift to make Compound (Natural) Bridge, Ovis, Crystal, and Sentinel. The main rift began to overflow significantly at Compound Bridge. This overflow split. The southern stream fed Hercules Leg; the northern stream crossed over the rift and made Sunshine. Several small overflows went to the south side of the rift in the vicinity of Ovis, making Paradise Alleys, which then fed Catacombs. Some of Catacombs, possibly much of it, emptied back into the rift in small surface-tube streams (which are now plugged). These apparently fell back into the rift uphill from the upper Sentinel entrance. Sentinel's top (meandering) level is a surface tube which rode the roofed rift. It was later connected to the lower levels of Sentinel by extensive breakdown. It is unclear whether this top level of Sentinel is a lower section of Catacombs, a local overflow from the rift, or a lower section of the Labyrinth Confusion.

Upper portions of Blue Grotto (Labyrinth) probably lie in minor parallel fissures of the rift, but this is hard to prove. Golden Dome, Hopkin's Chocolate, and Labyrinth were fed from a single overflow of the rift. It can be found by following the collapse uphill from the Garden Bridges to the big collapse of the rift. Mushpot (and apparently Arch) are lower portions of Labyrinth. Stinking Well, Indian Well, and a couple of other caves are lower portions of the Sentinel tube. The flow seems to leave the rift about 100 feet uphill of the main road. Some of the lava continued straight, rather than turn through Stinking toward Indian Well, and made the large flat area where the maintenance yard and employee s residences are.

The vent for the whole 'cave loop flow' was almost certainly in the rift, probably less than half a mile east of Mammoth Crater. The specific vent structure has not been found. The area of the vent is covered with dense brush. Even if the brush was not there, the vent might not be distinguishable.

The whole cave loop tube complex emptied out toward the maintence yard and the campground, flowing down the hill until there was no more lava. The Craig Caves are evidently the last open tubes the flow made.

There are many interesting lava tubes near Bend, Oregon. One of the best known is Lava River Cave, which is a state park. It is an excellent example of an intact rift cave. The passage height is two to three times its width, but these proportions are obscured by deep deposits of sand on most of the floor. The lower half of the wall is covered by a lining which extends across the passage in one area to make a false roof. At this place, this type of level splitting can be examined in detail.

Wind Cave is another rift cave near Bend. Its size and shape are similar to those of Lava River, but its appearance is entirely different due to extensive stoping. The floor consists entirely of large blocks of loose rock which fell from the ceiling. The lower half of this cave contained a lining, which is intact in several places. High piles of breakdown provide easy access to examine the lining.

Skeleton Cave, also near Bend, is a semitrench with an unobtrusive wall shelf. The main passage has been modified by a small amount of erosion and breakdown. One section, shown in Figure , has been modified to the hexagonal interior shape. The trench-shelf level can still be seen as a discontinuity midway up the walls, making two opposite corners of the hexagon.

Skeleton Cave has one minor side passage, of semitrench. It has an upper level, consisting of surface tube. The shelf level of the side passage is identical to that of the main passage, and lies slightly below the floor of the surface tube. This level relationship is common among closely associated passages which form simultaneously. While the relationship has some use in classification, it is more useful in compiling the history of lava caves.

At Craters of the Moon National Monument, Idaho, there are many lava tubes. The more accessable ones are those associated with Indian Tunnel. Except for Arco Tunnel, they are all rather poor examples of true trench. Arco Tunnel contains both true trench and surface tube. The cave forms a pattern of trench converting to surface tube, followed by much branching. The surface tubes are not buried, and their characteristic of forming on the surface is easily seen. The tube roofs form distinct ridges running across the lava flow. Unfortunately, this complex of caves formed abnormally, and other observations cannot be generalized. The caves formed in a bluish basalt whose composition and properties are radically different from those of basalts normally associated with lava tubes.

The examples above are not meant to act as full descriptions of the caves. A complete cave description must be more detailed and must include features other than the basic tube type. The type description is merely the framework for a more complete description.

A more important use of lava tube classification is to clarify the relationship between associated caves. Since it is based on formation mechanics, classification can help to predict size and location of lava caves. While most prediction involves many factors other than classification, such advanced speleology requires some classification system at least comparable to the above. Classification is a powerful basic tool for study of lava tubes.

PASSAGE MODIFICATION IN LAVA TUBES

The sketches of cross sections represent idealized situations. Ordinarily, some modifications occur. A common modification is a floor lining. The cross section is usually determined by visual inspection. Stratification of the surrounding rock is determined by whatever exposures are available.

Linings

Floor linings. Any lava that deposits within a lava tube is a lining. Linings can form on walls, ceilings or floors. Floor linings are the most common and conceptually the simplest: A lava tube is the bed of a stream of lava. At the end of the active life of the tube, the stream drains from its bed, leaving a cave. Drainage seldom is complete, and some lava remains in the cave, as a floor lining.

This final portion of the lava stream can be considered a small lava flow. It can be either pahoehoe or aa, and it can form channels and tubes, just as in a larger lava flow. But, the flow lies within a lava tube, so its structures are somewhat modified. The clinkers of aa linings are much smaller than those of other aa flows, and the distinction between pahoehoe and aa is not great. Transitional surfaces, such as clinkery pahoehoe ripple, are common.

Where a floor lining contains a channel, the channel usually is unroofed. Even a surface tube channel is more likely to form a "railroad track" than a completed lava tube. If the channel is a true trench, the overhanging lip usually is lost from the trench wall. Such trenches resemble wall linings or the true-trench-with-shelf of the basic classification system, but they are identifiable by the absence of the overhang.

"Inflated" and "deflated" floor linings are relatively common. The inflated lining is produced by injection of additional lava after the lining has developed a solid crust. The lining splits near the centerline, hinges upward along cracks at the side of the passage, and forms a pressure ridge within the lava tube. The deflated lining is produced by withdrawing lava from beneath a crust. If the crust is reasonably rigid, it breaks loose at the sides and settles as a sheet. If it is less rigid, it bends downward without breaking free, giving the passage a dished floor.

If the cross section of a lava tube appears round, the lava tube probably is either a semi-trench with a deflated floor lining or a surface tube with an eroded floor. Most processes produce floors that are nearly flat.

Floor linings may be extremely massive. A common passage termination is a region that is completely filled by a floor lining. Such a blockage is similar in nature to the inverted siphon of limestone caves; the passage resumes on the other side of the siphon, when it rises above "lava level". In considering this type of plug, it should be remembered that the reference surface is the hydraulic grade, and not a true horizontal. The lava tube need not contain a reverse slope to contain an inverted siphon.

Wall linings. A typical wall lining consists of three parts. The body of the lining extends for most of the height, and has uniform thickness. The base tapers in a compound curve that terminates the lining significantly above floor level. The top forms a cornice, whose upper surface resembles a fragment of floor lining, and whose under surface is another compound curve.

The lining may be separated from the wall at some points. The resulting pockets can contain air, aa clinkers, or other lava. Molten lava may have drained into the lava tube from some of these pockets.

If a lining is twenty or thirty centimeters thick, all of the features, including air pockets usually are present. Thinner linings may consist entirely of body, continuing downward to the floor, and terminating with a ragged upper edge. A squat lining, a lining curb, omits the body and combines the tapers of cornice and base. Other variations also occur but are less common.

Formation of the typical lining begins with a reduced stream flow, possibly filling only the bottom tenth of the lava tube. Such a shallow stream is unable to maintain heat in the lava tube, so the upper walls cool by several hundred degrees. The lava stream also cools, becomes highly viscous, and slows. If the stream were to remain shallow, it would continue to cool. Eventually, it would freeze, forming a floor lining. A flow increase, before the surface solidifies, will produce a wall lining.

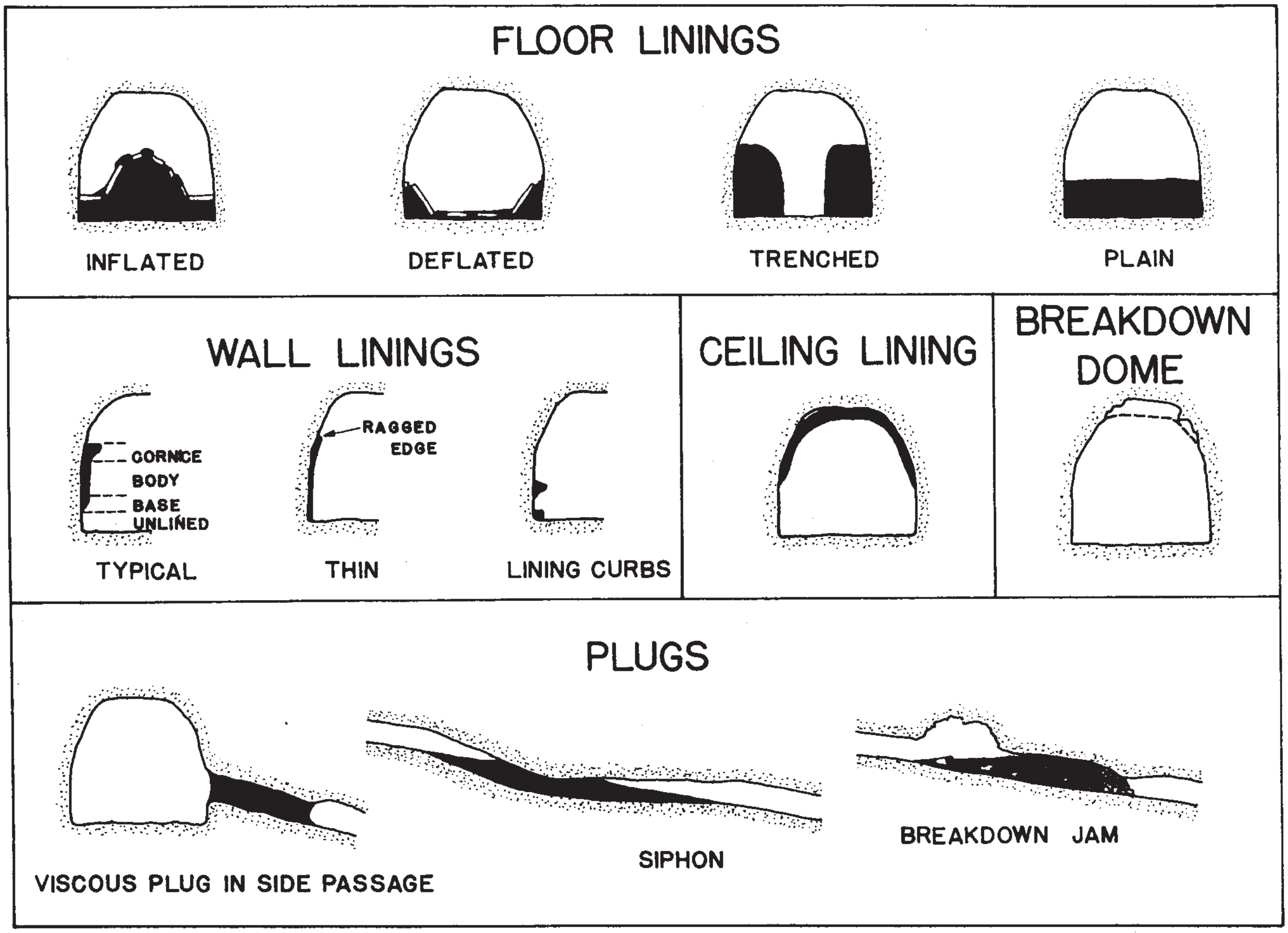


Figure 17-4: Forms of passage modifications in lava tubes

When flow increases greatly, and when motion stabilizes, the lava stream will be hot, deep and fast flowing. However, the leading edge of the hot lava overtakes the older, cooler material. This produces an incipient, moving hydraulic jump. The axis of the jump lies within the hot lava, so the transition contains a definite flood crest and has definite leading edge.

As in most hydraulic jumps, the upstream material attaches itself to the bottom of the channel and underrides the downstream material. The stream surface stretches, moving upward and outward, until it collides with the walls of the lava tube. Since this is the cool lava, it immediately begins to freeze. The crest of the jump passes, and the stream drops to a stable level. The top of the solidifying material drops with it, shearing free of the sides. The sides are bonded to the wall, so they remain in place and become the lining.

This entire process is quite rapid. From stable stream to stable stream, the transition region will pass any given point in less than four minutes. Since the lining forms so rapidly, it is in radical disequilibrium with gravity. The outside of the lining, the surface against the old wall, is a stratum top, while the new wall surface is an underside. The pockets of air, clinker and hot lava lie "above" the lining and are mere accidents of steam inflation.

Both the cornice and the basal taper represent patterns of heat flow during the stream transition. After motion stabilizes, the lava stream is too hot to deposit more lava and too cool to erode lava that has already deposited. The base records the temperature near the old stream surface, while the cornice is a region that lost heat both to the wall and to the space above the new stream surface

Since the bottom edge of the lining is a stream surface, a lining that continues to the floor represents a complete cessation of flow in the lava tube. These linings are derived from hotter lava, and are thinner than ones that have base tapers. They also lose relatively little heat to the air above the stream, so the cornice is small or absent.

Ceiling linings. Ceiling linings are wall linings in which the stream crest completely filled the lava tube. Their deposition involves no special features, but their separation from the lava stream is of interest.

When the lava stream drops to its stable level, a lining is still hot enough to be flexible. If the stream were to fall away from a ceiling lining a vacuum would be drawn. The roof of the lava tube would have to support both air pressure and the weight of the lining. This load is roughly equal to the weight of four meters of lava, and it is adequate to collapse most roofs. "Shearing free" occurs only in large passages that have thick roofs and complex histories.

Linings usually separate by the same mechanism as initial roof strata. Gas bubbles in the flowing lava rise until they reach the underside of the lining, where they collect. When a sufficiently frothy layer has formed, it suddenly collapses into a layer of gas. The froth is a good heat insulator and is mechanically strong enough to support the lining. When it coalesces no vacuum is drawn, so the roof need only support the weight of the lining, and the lining probably is cool enough to support itself at this time.

When the froth collapses, it leaves an irregular ceiling, with a coating of molten lava. The coating runs to low points, where it drips off, forming "common stalactites", the speleogenic variety of drip pendant. Common stalactites are identifiable by their large pyramidal bases, which form more than half of the length of the stalactite (Harter, 1971).

Common stalactites, cast surfaces, and remelt glazes are the major indicators for identifying roof strata. (Remelt glazes should not be confused with thin flash glazes, such as are found in large vesicles). A remelt glaze shows that a surface was exposed to the heat of the lava stream; that it was a ceiling at some stage of development. Common stalactites show that the surface was a ceiling when it formed. A cast of underlying rock shows that the surface was not a ceiling when it formed, although a glaze may show that it later became one. Casts of rippled pahoehoe are quite common and are especially easy to identify.

Once former ceilings are known, most ceiling linings are easily identified. Identification of the initial roof stratum is more difficult. Many roofs lose their initial strata to rockfalls, so the outermost ceiling may belong to a lining, or to overlying rock.

Rockfalls

If a roof stratum is not strong enough to support itself when hot, it cannot separate from the lava stream. As it cools, it becomes still stronger. When cold, the roof of a lava tube is a very strong arch, and it can support amazingly large loads. However, like most materials, lava expands when heated and contracts when cooled. In cooling from its freezing point, lava shrinks almost one percent, producing very large stresses; and lava flows shatter as they cool. Almost all rockfalls in lava tubes are part of this shattering.

If a stream stratum is thicker than sixty centimeters, its surface will cool much more rapidly than its interior. Thermal stresses will crack the lava into roughly cubical blocks, and the effective tensile strength of the stratum will be negative. Such thick roof strata remain intact only in rift caves, where they carry large compression loads, and in overlying strata of roofs, which carry no load at all.

When a ceiling lining is deposited, the older roof strata already have partially cooled. If the lining is tightly bonded into the roof, it will be stressed in tension when it cools, so it will be likely to lose structual integrity and collapse. If the lining is more loosely bonded, it may separate from the rest of the roof, shrink freely, and remain intact.

A rockfall usually occurs where several roof strata with significantly different temperatures are bonded together. The stresses appear in all of the strata, and the break faces tend to ignore the joints between strata. If upward propagation of the breakage is not halted by a weak joint, the roof stopes out to a high arch that has the irregular surfaces that characterize breakdown domes. If a weak joint halts stoping, only two or three strata may fall, leaving a ceiling with less arch.

Many rockfalls occur during final cooling of the lava tube. Regions of breakdown are as common as regions of intact passage, and some caves contain enormous quantities of fallen rock. Many other rockfalls occur during the reduced flow that precedes deposition of a wall lining. These early rockfalls tend to be overlooked, because the break faces are later covered by linings, and the fallen rock is removed by the lava stream. However, early rockfalls probably are even more common than rockfalls during final cooling.

To some extent, rockfalls are desirable. They provide cave entrances and exposures for geological study of roofs. They also block lava streams, allowing lava tubes to drain and form caves. But rockfall complicates the structure of lava tubes. Many passage terminations and most of the more irregular passage shapes were produced by sequences of rockfalls.

If a rockfall occurs after the lava stream stops flowing, there usually is a traversable space above the debris, so the rockfall causes little trouble. An earlier rockfall is likely to dam the

lava stream, and the dam may produce an inverted siphon. Or, if the dam washes out, the loose rock can jam at the next constriction, plugging the passage with a mass of sintered breakdown.

Erosion

When molten lava freezes, it changes from a reasonably homogeneous liquid to a mixture of several kinds of microscopic crystals. Since energy is required to separate the crystals, the freezing point of molten lava is much lower than the melting point of any of the crystals. This produces a temperature range where solid lava will not melt and molten lava will not freeze. The temperatures of lava streams usually lie within this range.

Since erosion does not remelt lava, most erosion in lava tubes is by scour or by plucking. At the temperature of a lava stream, solid lava is quite soft, while molten lava is somewhat abrasive. Where a stream splits, as at a column or at a passage junction, scour can heavily erode the column. Elsewhere, the wall develops a smooth surface that is nearly immune to scouring.

Where the wall of a lava tube is extremely rough, in a newly formed rift cave or where a lining has fragmented, large pieces of rock may be torn from the wall. This is plucking. While scour forms a smooth surface that is protected from further scouring, plucking produces holes that are suitable "grip points" for further plucking. It ceases only when accidents of fracturing produce a surface that is smooth enough for scour to replace plucking. In some rift caves, this does not occur until plucking has tripled passage width.

Small quantities of loose rock, produced either by rockfalls or by plucking, often appear in the lava stream. This rock is torn to pieces by a combination of further plucking, scour, and simple fracturing. The pieces, in turn, are torn to still smaller pieces. When the pieces become small enough, they dissolve in the molten lava. The process is solution rather than remelting, but the final effect is the same.

Solid lava would be slightly denser than molten lava, except that the lava contains vesicles (small gas bubbles). The ves icles reduce the density, so many solid pieces will float on molten lava. When a fallen block is this light, it will float away, and it will be lost even faster than one that is removed by redissolving.

Variants

Viscous plugs. The most significant variant of the lining process is formation of a viscous plug. Viscous plugs usually are found in side passages, where they may constitute extensions of linings of the main passage.

After solid lava has cooled sufficiently, molten lava no longer will wet it. If the walls of a passage cool to this extent, renewed flow will not deposit a conventional wall lining. Contact with the walls will chill a certain amount of lava, but this will be stirred back into the leading edge of the stream. A large, well stirred mass of materials cools slowly, finally solidifying into the viscous plug.

The lava of the viscous plug cease to move when its changing character finally allows it to wet the passage wall. At this time, the lava of the plug is mushy, rather than completely molten. Its surface tension is extremely large, and the lava tube functions as a capillary tube. The ends of the plug are nearly flat, with a slight dishing, and the plug can be considered to be a gigantic droplet of liquid tha is "stuck" in the capillary.

Where a viscous plug develops in a side passage, its upstream face often is almost flush with the wall of the main passage. The only obvious evidence that there once was a side passage at this location is the color of the plug face. Viscous plugs usually have slightly darker color, and a smoother surface, than walls.

Overflow chambers. Many lava tubes, especially semitrenches, have small upper-level chambers where the lava tube overflowed through flaws in its roof and formed surface tubes. The connecting passage between the parent tube and one of these chambers often develops a special lining. On the upper surface, this lining is part of the floor lining of the chamber. On the lower surface, the lining is a cross between a ceiling lining and a viscous plug. Structure and appearance of these linings are not particularly interesting; their importance lies in the fact that the chamber and the lava tube once were connected.

These linings also have a special type of rockfall. Level of the lava in the main tube drops at a time when the lining has not yet separated from the lava stream. The lining tears loose along one edge and sag s against the wall of the shaft, where it remains as a tongue of lining. This usually is at a time when the entire floor of the chamber has a semi-molten surface, so lava runs back into the shaft, and the floor lining records flow from the chamber into the underlying lava tube. This direction may be completely opposite to primary motion of lava in the chamber.

Lining partitions. One type of lining is characteristically found near entrances of lava tubes. This is the lining partition. During an interval of steady flow, air enters the lava tube and chills the surface of the lava stream. A floor lining begins to develop, but it develops over an active lava stream, as a ceiling lining. The lava tube now has been divided into two passages. The upper passage has a floor lining and is cool enough for renewed flow to produce viscous plugs. The lower passage is still hot since it contains the lava stream.

Supposedly, lining partitions could also develop at great distances from entrances, and the upper passages could be hot enough to have extensive active lives. However, the prevalence of viscous plugs in upper levels and the relation of partitions to entrances indicate that the chilling effect of outside air is the usual driving force that produces lining partitions.

Exfoliation chips. When the roof of a lava tube cools and cracks, loose chips of rock often spall from the break faces. These chips are a normal consequence of fracturing, and their presence on the floor of a lava tube shows only that the cracks opened during final cooling. In any given area, chips of this type usually are present only in small numbers.

A second type of chip spalls from a ceiling. When a remelt glaze forms, it often is much hotter than the bulk rock. As temperatures equalize, the glaze may break into chips and fall. A relatively small patch of ceiling can produce large numbers of chips, and the chips can significantly affect the character of a lava stream. In several cases, the clinkers of aa floor linings formed around exfoliation-chip cores.

Spalling of a ceiling leaves a surface that is completely nondescript. Such surfaces present the major difficulty in identifying former ceilings of lava tubes.

Blowout pockets. Blowout pockets actually are a stage in the development of common stalactites, so they are not really modifications. A wall or ceiling evolves past the drip-pendant stage of the stalactite, and a very thick remelt layer develops. Gas from collapsing vesicles collects behind the remelt layer. Rising gas pressure eventually blows a patch of remelt free from the wall, leaving a characteristic surface that is covered with beads and threads of lava.

The most important characteristic of blowout pockets is the fact that the gas is derived from collapsing vesicles and not from external sources. Venting of external sources, such as flashing of groundwater to steam, is rare. Most "examples" are really blowout pockets or the accidental pockets of wall linings.

Comment

The most important characteristics of passage modification may be the restrictions. Floor linings do not solidify until the end of the active life of the lava tube. Wall linings are associated with flow increases. Excessive cooling before lining deposition results in a viscous plug, rather than a lining. Rockfalls are associated with large temperature changes, and very little rock is lost either during steady flow or after final cooling. Stream erosion is effective only when it is removing an irregularity. In general, a modification process acts only when well defined conditions exist and then only for a very limited time. During most of its active life, a lava tube has a relatively static structure.

Any given short segment of lava tube is unlikely to be heavily modified. A floor lining, two or three wall linings, and one or two rockfalls are all that usually need be considered. This does not, of course, imply that a cave must be simple. The modification histories of two portions of the same cave may be entirely different. The implication is that a complex cave has simple components.

SUMMARY

A cave may consist of one tube type, or several. An open stream or collapsed tube can also be classified, since the classification system is for lava channels rather than for caves.

In oversimplified terms, the formation of the types of lava tubes are as follows.

Surface tube: The top and sides of a lava stream cool into a single continuous arched stratum.

True trench: A channel forms through a puddle of lava, and then roofs. Usually, if true trench is present, it is a transition zone between other types, such as semitrench and surface tube.

Semitrench: As a stream of lava flows, it pulsates and overflows to the sides, building up comfining walls.

Rift cave: For lava to get out onto the surface, there must be a hole in the ground. It is effectively impossible to make such a hole without cracking the ground. Rifts form. Lava (usually) flows downhill. A crack is a low spot, so the lava will run down the crack. A lava channel forms, using the rift as a bed. It may roof, and there is then a lava tube roof on a rift. (Rift Cave.) This type of rift cave is actually quite common. Lava tube caves that are predominatly in rifts include: Sentinel, Crystal Ice, Ovis, Merril, and Skull at Lava Beds National Monument; Lava River, Wind, "40-Mile", and others in Oregon; Ape, Lake, Dynamited, Cheese, and others in the Mount Saint Helens-Mount Adams area in Washington. Nearly all superposed multilevel lava caves are in rifts. Rift caves are hollow dikes. The direction of flow within a rift is independent of the fact that a 'rift cave' has formed.

Interior tube: In a single lava flow-unit, channels form within the mass of the stream. The channels are slightly elliptical in cross section. Interior tubes exist, but do not make caves. They invariably collapse or plug. The 'interior' shape is the equilibrium shape, so modifications (stoping, lining, erosion) tend to develop other shapes toward it.

TERRESTRIAL ANALOGS TO LUNAR SINUOUS RILLES

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Lunar sinous rilles are meandrous channel-like depressions restricted mostly to mare areas. Several diverse models have been proposed to explain their origin; these include erosion by either volcanic ash or running water, surface collapse resulting from intrusive stoping, fluidization of surface regolith by outgassing through fractures, or that the rilles are lava channels, collapsed lava tubes, or both. Considerations of the composition of lunar mare lavas and geomorphic evidence support an origin by lava tubes and channels for at least some sinuous rilles. Lava tubes and channels on earth commonly (and nearly exclusively) form in basaltic flows; and since lunar mare lavas are predominatly basalts it is reasonable to assume that these features would be present in the maria. Lunar sinuous rilles generally flow around topographic highs, and are often composed of discontinuous segments, have pronounced lateral levees or a broad topographic high along the rille axis, originate in irregular craters, and may have distributary structures (rather than tributaries). Nearly all aspects of rille morphology are analogous to terrestrial lava tubes and channels except that of size: sinuous rilles are considerably larger than the terrestrial structures. However, considerations of the lunar environment may account for the difference in size. Laboratory determinations obtained independently for Apollo 11 samples indicate that at least some lunar lavas have a much lower viscosity and thermal conductivity than terrestrial lavas; thus, the lunar lava flows could be longer. Lava tubes and channels, therefore, could be correspondingly larger on the Moon. Although these interpretations may explain certain lunar sinuous rilles (e.g. Hadley Rille, rilles near Herigonius), it is possible that other rilles were formed by other mechanisms.