

THE GEOLOGY OF LAVA TUBE CAVES

*Russell Harter, **J.W. Harter, III

ABSTRACT

Lava flowing across the ground surface tends to develop well-defined channels. Lavas of basaltic composition that are highly charged with dissolved gasses (termed 'pahoehoe') sometimes form crusts over the channels, making lava tubes. Lava tube caves are drained portions of roofed lava channels. Lava channels are primarily distributary in nature, serving to transfer lava from a volcanic vent to the advancing flow edge lower on the volcano.

Differing conditions, largely involving preflow topography and lava eruption rate, result in several distinct types of lava channels, and hence, of lava tubes. Rift tubes are formed where large open cracks are utilized as channels by the lava flow. Passages of rift tubes tend to be high and narrow; the shape of the rift. Walls of rift tubes consist of preflow country rock or soil. Leveed lava channels have walls built up by the lava streams they confine. Leveed channels are subdivided into true trenches which have walls consisting of only one flow unit, and semi-trenches that have walls built of numerous thin flow units. True trenches are usually of short length and are uncommon. Semitrenches are common, and a flow containing a semitrench generally makes a low, broad ridge with the tube on the ridge axis. A small lava stream can form a crust arching over the entire flow unit, making a surface tube that is perched on top of the ground.

Characteristic tube types tend to be found in specific parts of lava flows. Rift tubes tend to be found near the vent, and portions of the eruptive rift are the most likely to become rift tubes. Rift tubes are likely to feed ~~large~~ large semitrenches, which in turn feed smaller semitrenches and surface tubes.

Modifications of lava tubes occur as the eruption progresses. A temporary lessening of erupted lava allows tubes to cool, and rockfall occurs. Renewed flow may carry away the breakdown, and a lining will chill against the inner walls when a cool tube is refilled. Lava tubes are often buried by lava that overflows from the tube, or by lava from other sources. Hot gas and radiant heat remelt the inside of lava tubes, making small stalactites. Lava droplets accumulate on floors, making lava stalagmites.

INTRODUCTION

Lava channels of all types play an important role in the growth and development of volcanoes, because they transmit lava from the vent to the advancing flow front. Although open channels form in lava flows of various chemical composition, nearly all reported roofed lava tubes are in pahoehoe basalts. Lava tubes differ from other lava channels only in that they are roofed. Lava tube caves are portions of lava channels that have roofed and subsequently drained. The tube and open channel network of a lava flow is the plumbing system by which the lava flow was emplaced. By studying lava tubes, a more thorough understanding may be gained of the geologic structure of some volcanoes.

TYPES OF LAVA TUBES.

Based on the structure of the wall rock, there are five possible types of lava tubes. These are rift tubes, true trenches, semitrenches, surface tubes, and interior tubes (figure 1). Examples of lava tube caves can be identified for all of these types except the last one.

Rift Tubes

When lava comes to the surface in a volcanic eruption, it flows out of a large crack in the ground. Commonly some part of the crack, or rift, continues downhill from the point of eruption. Once erupted, lava flows downhill. Since the rift is a low place, the lava tends to follow the rift, using it as a channel. This channel may roof, and then drain. Because this is a lava tube in a rift, it is a rift tube. This type of tube makes cave passages that usually are high and narrow; the shape of the rift. The walls are made of country rock that was present before the eruption. Most rift tubes contain

*Geologist, 706 Venice Blvd., Apt. #1, Venice,
CA 90291
**Geologist, 2801 Sandborn Ave., Venice, CA 90291

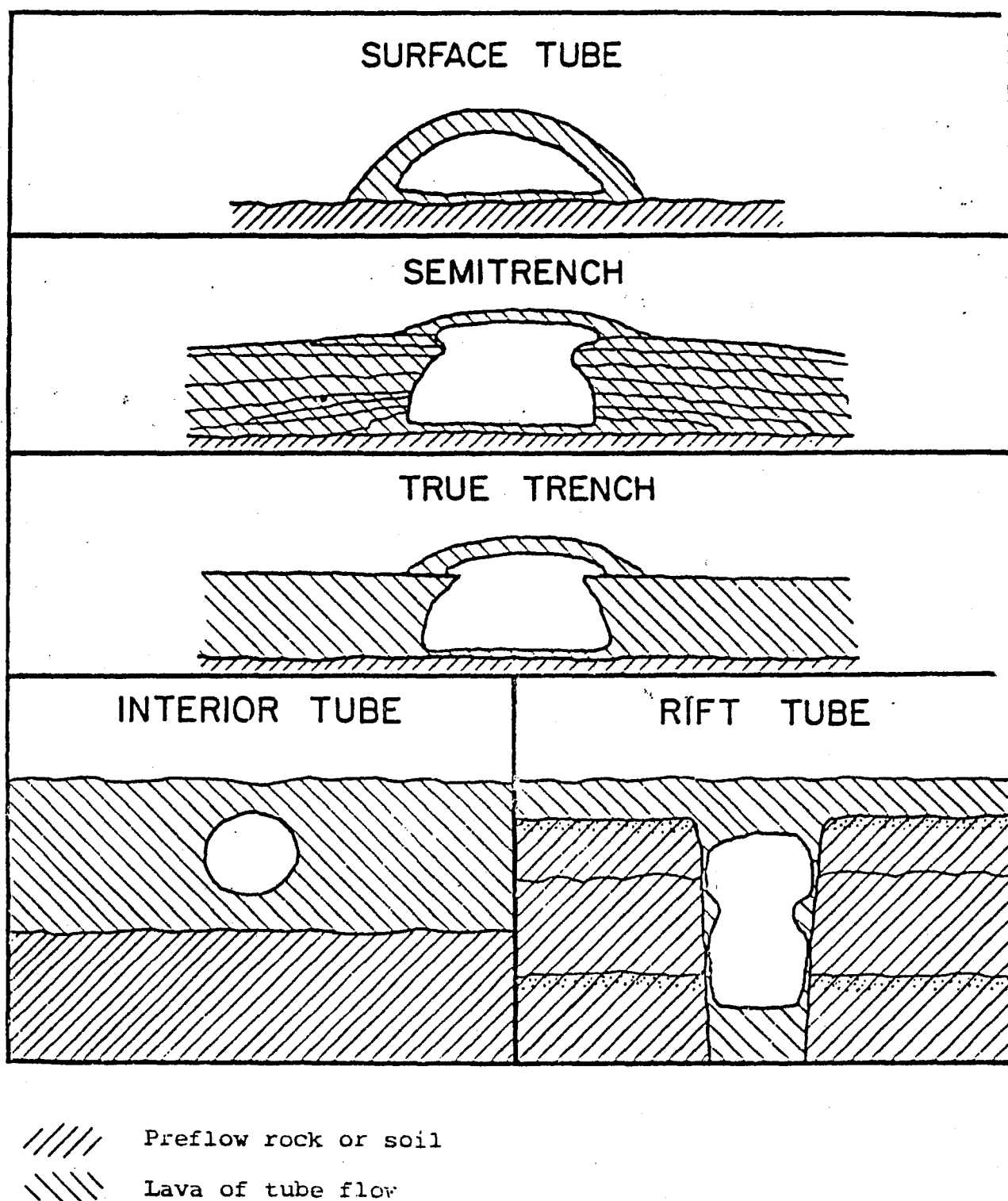


Figure 1. Idealized cross sections of different types of lava tubes. Surface tubes can be a variety of shapes, and usually form small passages. The roof and walls of a surface tube are a single layer of lava. Semitrenches have levee walls built up of overflows from the lava stream. A true trench has walls made of a single stratum. Rift tubes form in large fissures. Interior tubes lie entirely within a single layer of lava, and do not form caves.

linings on the walls that obscure the preflow rock. A rift cave is a drained tube in a fissure of a rift zone; it is a hollow, near surface, dike. The correct identification of rift tube caves can precisely locate volcanic rifts whose surface expression is otherwise obscured by lava flows.

True Trenches

True trenches are channels incised into a semi-solid flow unit by differential solidification. In areas of low ground slope, the lava can pond, making a single mass (a flow unit), with a channel through it. The channel geometry resembles that of a water stream channel incised into a silted-up lakebed. The cave wall consists of a single thick layer of lava.

Semitrenches

If the walls of a tube are composed of a number of thin layers rather than a single lava layer, the tube is a semitrench. Semitrench walls are formed by repeated overflows to the sides of the channel, and make levees that slope gradually away from the channel. The overflows are small flow units and sheets of lava, that cool in place. Inside a cooled lava tube of this type the edges of the sheet overflows are horizontal layers in the walls, while the flow units appear as interlocking but discrete blobs of rock. Thickness of the layers is typically about seven to eighty centimeters.

Surface Tubes

A small lava stream can form a crust over its entire outer surface. This makes a tube with roof and walls consisting of a single arched stratum. The tube is formed entirely above the adjacent ground surface, so is called a surface tube. Surface tubes are typically small in size, and are fed from larger tubes (trenches and rifts).

Interior Tubes

Within a single thick lava flow unit, channels can form within the interior of the lava mass. The tubes lie entirely within a single flow unit, with a fairly flat top on the flow surface, so are termed interior tubes. The cross sectional shape is elliptical, with the width about 10% greater than the height. The interior tube is the thermal equilibrium shape, so other types of tube tend to modify toward this shape. Although plugged interior tubes have been identified, no such open lava caves are known to the writers. Lava tube caves that have been identified as interior tubes by Ollier & Brown, Hatheway & Herring, and Greeley (1971b) are readily identifiable by other workers as either semitrenches or rift caves. Furthermore, a theoretical relationship between interior tubes and hypothetical shearing within the lava flow has yet to be demonstrated in any manner.

Identifying Tube Type

The structure of the walls of a lava tube can be identified at points within the tube where the lining is missing, exposing the wall strata. Since rift caves have walls made of preflow country rock, these often are much older lava flows with fossil soil horizons. In semitrenches the strata may be

very thin flow units, that are readily identifiable as such because they were deposited separately and successively, allowing at least the surface of one to cool before the next flowed over it. The underside of each flow unit makes a cast of the flow unit below. Open gas pockets near the middle of the thin flow units often occur, due to degassing of the lava as it cools.

Surface tubes, semitrenches, and true trenches are actually distinct configurations of a continuous series. Hybrids between true trenches and semitrenches may have only a few thick flow units in the walls, or a few thin flow units at the base, and has a typical surface tube roof. The largest lava tubes are semitrenches and rift tubes.

LAVA TUBE MORPHOLOGY

Since a semitrench is a leveed channel, the main tube is located at the axis of a very wide, low, ridge. A flow width of a kilometer is typical for a tube height of ten meters. The advancing toe of a flow that is building a semitrench ridge extends itself as numerous thin flow units and toes, forming braided channels at first. Later, many of the small branches are plugged or cut off as the main tube develops. The levees of a moderate to large size semitrench generally contain numerous small surface tubes, and these sometimes make an elaborate complex of crawlway side passages.

Any type of tube may overflow through a hole in the roof. Such overflows frequently bury the lower tube completely, adding significantly to the roof thickness (Anderson 1910, p. 630; Wentworth & MacDonald 1953, p. 45). When a roof overflow drains only partially, it leaves a cupola in the passage ceiling. More complete drainage often yields a complex of surface tubes radiating outward from the cupola. Overflows to the side of any open lava channel may make tubes that become side passages when the main channel roofs and then drains. This occurs most commonly in semitrenches.

Rift tubes tend to overflow on a grand scale. The entire complex of flows and channels produced by an eruption is merely the overflow from the eruptive rift. Repeated minor overflows of a rift being utilized as an open channel can construct a semitrench atop the rift, increasing its capacity. Such structures are difficult to distinguish from semitrenches that have deeply eroded floors and usually can be identified only by careful consideration of several geometric factors.

Rift tubes take on the geometry of the fissures they follow, with the primary modifications being linings and filling of adjoining parts of the fissure system. Because tension cracks are irregular and not straight, the plan view of a rift cave may appear to show meanders. The lava stream may actually have had the tendency to meander, but was restricted by the rift walls. A rift tube cannot curve or branch unless the fissure does. Restriction by the rift walls also means that rift tubes often have a characteristic high and narrow passage shape that other types of tube cannot obtain. Vertically superposed passages can form by roofing over the rift at different levels within the confining walls. Stacked lava tubes of other types will not be exactly superposed, because a tube

roof is a small ridge and the upper tube will flow away from it.

The mechanics of flow unit advance (Nichols, 1936) often produce chambers along a lava tube. In surface tubes, the chambers are individual flow units. In a cave, the boundary between two flow units is a short, small, connection between two much larger rooms. The connection is a hole that burst through the skin of an inflating flow unit.

Individual caves are generally just segments of a much larger lava distributary system. If one lava tube cave is found, others are very likely to be found in the same flow. Since the basic function of lava tubes is to transfer and distribute lava in a downhill direction, the overall pattern is that channels diverge downhill, and cave passages that converge in the direction of flow are nearly always branches of a braided stream, rather than streams coming from separate vents.

PASSAGE MODIFICATIONS

Because the interior tube shape represents thermodynamic equilibrium, as a lava tube develops it slowly evolves toward the passage shape of an interior tube. A lava tube often has a complex history wherein rock is repeatedly added within the tube as linings, while other rock is removed by rockfall during cooling episodes. Rock may also be removed through the erosive action of flowing lava. Modifications that occur after the initial tube formation generally have little relation to the remainder of the lava flow.

Breakdown

When lava cools, it shrinks and breaks. Over a lava tube, unless the pieces key together to form an arch, the roof will fall in. This may happen due to temporary cooling during periods of slack flow, as well as during final cooling. Fragments that fall while the tube is still active are often carried away by the flowing lava, although a large block or breakdown pile may jam between the floor and ceiling, making a pillar. When rockfall occurs upon final cooling, portions of the ceiling stope out, and breakdown piles up on the floor. Most entrances of lava tube caves are formed by collapse of a portion of the roof. Nearly all breakdown in lava tubes occurs during or shortly after formation, as a result of cooling. Once a lava tube has withstood the stress of cooling shrinkage, it is ordinarily very stable.

Linings

A floor lining is present in every lava cave, because lava chills against the cold ground below it and drainage of the tube is not complete. The floor lining can be considered a small lava flow. It can be either pahoehoe or aa, and can form channels or tubes. If the lava withdraws from beneath a crust, it may leave a deflated floor lining. A passage with a deflated floor lining may be near round in cross section, even though additional drainage would have left a flat floor. If additional lava is injected beneath a crust, the floor lining can be inflated. In both cases, the edge of the crust is anchored to the wall, while the center deflects (figure 2).

^{and} Wall/ceiling linings are deposited when renewed flow within a temporarily drained tube partially or completely refills it. If a rigid crust forms on the lava stream when the tube flows at less than full capacity, the crust may bridge across the tube. This makes a lining partition or false floor, resulting in two vertically superposed passages. False floors tend to form near skylights where outside air chills the crust.

Plugs

The end of a lava tube cave often is a spot where the passage simply pinches out. This usually is a plug, and the actual tube continues even though the cave does not. In the lower portions of a lava tube network, the tubes often plug from a simple failure to drain. Where a lava stream is choked by breakdown, the tube tends to plug. The individual blocks may remain visible, or they can be completely hidden within a mass of lava that they chilled. Upper ends of major caves often are breakdown plugs.

Viscous plugs are closely related to linings. As a cool tube refills, it may produce enough chilled lava to completely fill the passage, resulting in a viscous plug. An upper level above a lining partition is especially prone to plug if refilled, while the somewhat warmer lower level tends to remain open. Since even thin linings reduce the passage size, repeated lining eventually leads to plugging - with the final viscous plug being produced in the same manner as the linings that surround it.

Erosion

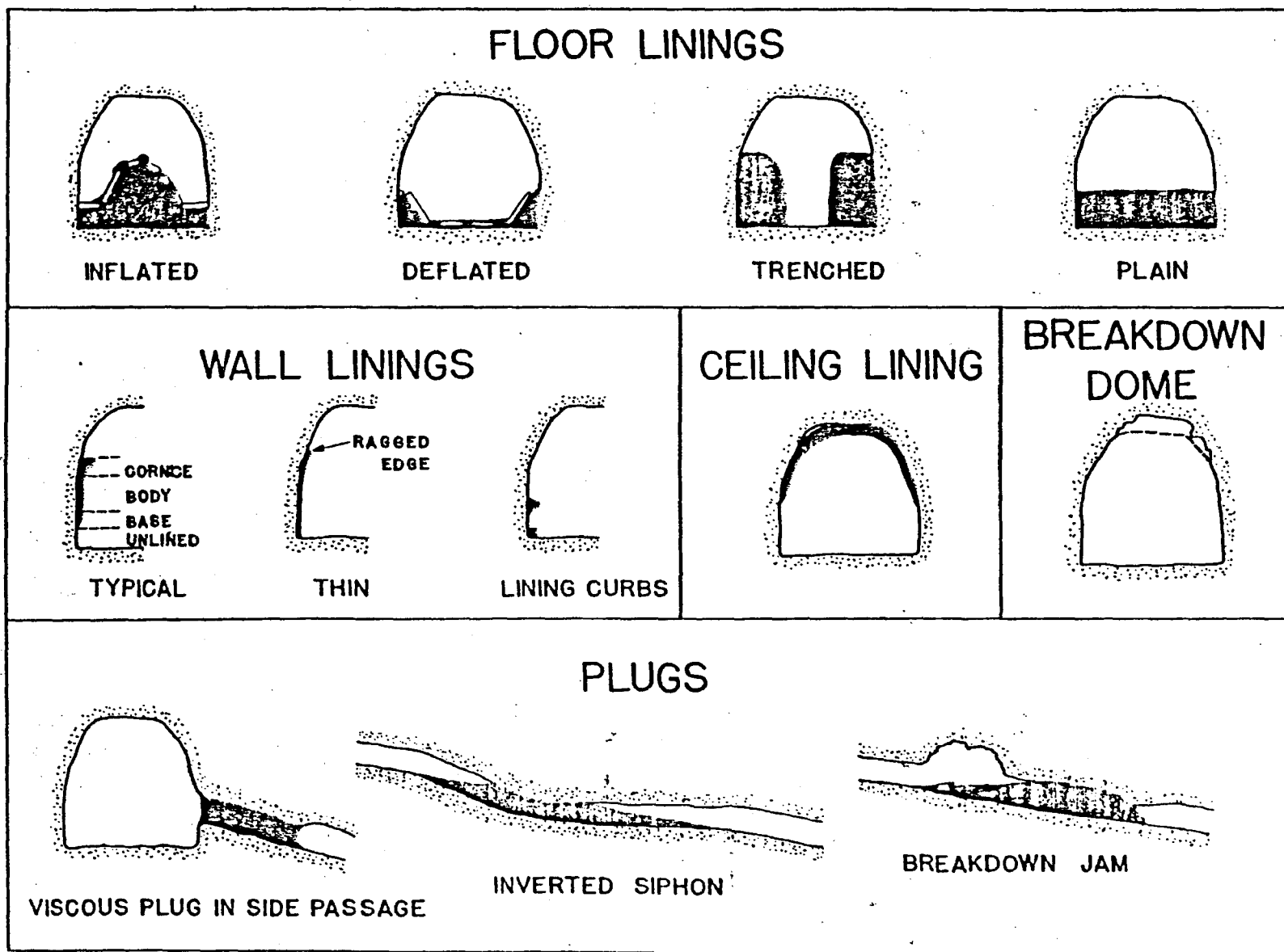
Lava flows usually have insufficient heat to melt the underlying rock. However, a lava stream can sometimes erode its walls and bed by scouring and plucking. Eroded material initially is cold, but if it is carried far by the flowing lava it must be at or near the temperature of the lava stream. If too much material requires heating, erosion will cease and a lining will deposit. In extreme cases the chilling produces a plug, which will completely block the lava tube. Thus, the erosional processes of scouring and plucking (as well as melting) are limited by the available heat. If any type of erosion is to be extensive (such as cutting of a channel into preflow rock or soil) great quantities of heat must be present. If the eruption is of a long enough duration, sufficient excess heat may be available to erode the bed of a lava stream on a large scale. In the case of a lava tube of Mauna Ulu (Kilauea Volcano, Hawaii), the floor reportedly eroded downward a maximum of 15 meters between early September 1970 and mid-May 1971 (Swanson, 1973, p. 621).

Erosion normally occurs only on a small scale, where its overall effect is to round off sharp corners and projections, leaving smooth curves.

MINOR MODIFICATIONS

As pahoehoe lava flows, it loses dissolved gas. When a lava stream has a crust over it, the gas accumulates as a frothy layer beneath the crust. The froth soon begins to break down, forming a continuous layer of gas. As the gas layer accumulates, the crust becomes a roof that is separate

Figure 2. Common passage modifications.



from the stream. At the time of separation, the under surface of the roof is still molten, held in place only by surface tension of the gas bubbles which have not yet broken. As the ceiling froth continues to break down, the remaining molten material migrates toward low points (peaks of froth) and drips off. The result is a small, blunt, pyramidal stalactite. Such stalactites are known as common stalactites.

Remelt

Heat transfer through solid lava is less efficient than radiation across open space. Therefore, the ceiling and walls of an active lava tube have almost the same temperature as the lava flowing through the tube. While this temperature seldom is high enough to remelt bulk lava, it often is able to surficially remelt some components of the lava. This produces a variety of thin glazes that often are much different in color (black, reddish brown, or silver) from the underlying rock.

More extensive remelting allows flowage of the glaze. Since the more refractory components of the lava can be transported as a suspension of crystals in the remelt, the migrating material may be almost indistinguishable from that associated with common stalactites. Both produce small ribs, gours, slumps, and similar lava flowstone structures on walls.

When the migrating material drips from a ceiling or an overhang, it can produce a variety of stalactite known as a drip pendant. Drip pendants vary in shape: small beads, conical shafts, short cylinders, and shafts with delicate narrow waists. A drip pendant actually is a single hanging drop, so the various shapes represent stages of the drip cycle. Drip pendants formed by remelting of smooth or dense surfaces tend to be small. Those associated with common stalactites hang from the tips of the pyramids, and consist of a large pyramidal base with a drip pendant tip.

Lavacicles

A third type of lava stalactite is the lavacicle. Lavacicles are cylindrical or only slightly tapered, with little or no base. Some lavacicles have been reported (for example, Dana, 1889, p. 452) that were soda straws at least 75 cm long, but most are even shorter than drip pendants (less than 3 cm). Linear striations and concentric rings indicate that lavacicles are extruded from the ceiling, but the mechanism is not well understood. Lavacicles often are helictitic, having several sudden changes of size and direction within a short length. This appears to result from irregularities of the extrusion process.

Lava Stalagmites

Stalagmites form when many droplets of lava fall onto the same spot on the floor. If the floor is a moving lava stream, the droplets are lost and no stalagmite can accumulate. Small stalagmites occasionally are found below drip pendants, and consist of solid droplets of lava. Most lava stalagmites that are more than a few centimeters in height are found below lavacicle stalactites, and consist of bubbles of lava.

Blowout Pockets

Blowout pockets form when a flat gas pocket behind a remelt layer or thin lining blows the lava covering it into the lava tube. The pressure appears to come from superheating the pocket of steam or air as the lava surface inside the tube is remelted. The most common form of blowout is a final, removal, step in the degeneration of a stand of common stalactites. In this case, it is related to the roof-separation mechanism, and the gas pressure involved may be quite small.

ROOF STRATA

Lava tubes are distinguished from open lava channels by the presence of a roof. Roof strata of lava tube caves may be observed in section at breakdown entrances and at areas of roof breakdown within caves. Three general types of strata occur in lava tube roofs: initial roof strata, overlying lava, and linings. The various strata can be identified in cooled lava tubes by their surfaces and geometric interrelationships. The presence of either overlying lava or of ceiling linings in a cave roof is evidence that the initial lava tube roof has been modified. Detailed sequences in the formation of lava tube roofs can be determined through examination of roof strata in cooled lava tube caves.

Lava channels can form roofs in at least six ways:

1. Wholesale crusting of the lava stream (Peterson & Swanson, 1974 p. 211).
2. Agglutination of lava splash and spatter in arched levees (Greeley, 1971; p. 222-223).
3. Jamming and fusion of floating crustal plates (Wentworth & MacDonald, 1953, p. 45).
4. Crusting of whole lava toes (Wentworth & MacDonald, 1953, p. 43).
5. Underriding of cooled lobes by the lava stream (Baldwin, 1953, p. 3).
6. Lining shut of the upper walls of a deep lava channel.

The mechanism of roofing (that is, formation of the initial roof stratum) can be established for cooled lava tubes if sufficient exposures are present. Indications of the mode of initial roof stratum formation include: single crusts with no internal complexities, lumpy or clotted outer surfaces, plates with sutures at distinct boundaries, lobes connected to a continuous lava layer below, or roof consisting of vertical linings.

Cooling rates of lava tube roofs (with lava flowing below) should be somewhat similar to measured cooling rates of crusts on ponded lava (which has internal convection). In addition, flow units that cool outside should have cooling rates generally similar to those of lava lakes. Figure 3 gives a first approximation of lava crust thickness as a function of time.

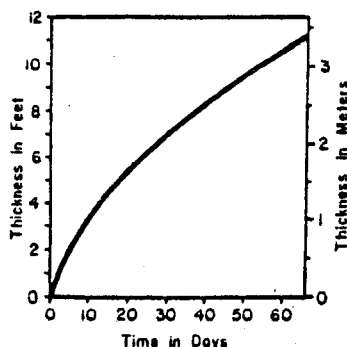


Figure 3. Graph of lava crust thickness versus time. The curve represents the approximate mean values of the extremes of the experimental data. Data from Peck, Moore, and Kohima, 1966.

AFTER THE FLOW HAS COOLED

Whereas limestone caves form during time spans on the order of thousands to hundreds of thousands of years, a lava cave forms during a time span that may range from a few hours to perhaps a year and a half. Differential cooling of lava leaves caves that are essentially complete before the entire lava flow has cooled.

After cooling, processes of weathering and erosion begin immediately to obliterate the lava cave. Depending on the climate, especially the quantity of rainfall, a lava cave may last only a few years, or be nearly as long lived as a limestone cave. Since the cave is topographically a low spot, sediment tends to accumulate and fill it. Portions of a tube roof that are only marginally stable will fall when weakened by weathering.

Various soluble salts are leached from the lava by rain and redeposited in cooling cracks and cave passages below. These secondary minerals include thenardite, mirabilite, gypsum, and calcite. Various types of silicates have been identified, usually reported as "opal".

FINDING CAVES

One of the simplest ways to locate lava tubes is by linearity. If several collapse sinks lie roughly along a line, it can be assumed that there is (or was) a connecting lava tube. The uncollapsed portions would be the first places to check for caves.

Surface tubes lie in small abrupt ridges. Semi-trenches lie in low, broad, ridges. Lava streams that follow rifts frequently overflow the rift and build semitrench - type walls, making a low, broad, ridge over a rift cave. Any of these ridges may be level areas if they are buried by later lava flows.

The ridges show where the lava tubes were at the time the flow was emplaced. Unfortunately, this

is not necessarily where present caves are. The ridge includes plugged tubes and segments of open tubes that do not have entrances. Digging may be futile, since more than half of the tube segments without entrances are probably plugged. So, finding caves becomes a matter of finding entrances to known lava tubes.

Some entrances remain open from the initial formation of the tubes. These include gas vents, overflows, or other places where the tube failed to roof. Although this type of entrance is common on the island of Hawaii, in the western continental United States most lava tube entrances were formed by collapse during cooling. Weathering seems to fill lava caves with soil rather than make their roofs fall in.

Entrance collapses tend to occur at points that were flaws during formation. These points include roof overflows, passage junctions, joints between roof crustal plates, sharp changes in slope along the tube axis, and any thin spot in the roof. Inconveniently, these relationships are in most instances noted only after the cave entrance is found by accident. Such is the present state of the art.

MANAGEMENT PROBLEMS OF LAVA CAVES

The problems of managing lava caves, as with other types of caves, can be reduced to two. These consist of protecting the cave from people (preservation), and protecting people from the cave (safety).

Matters of safety in lava caves are largely like those of other caves. Within a lava tube cave there may be unsteady breakdown, vertical drops, and slippery slopes of mud or ice. In cool climates lava tubes tend to be especially cold, so hypothermia may be a constant problem for cave visitors. As with other caves, it is occasionally possible for inexperienced people to become lost or trapped.

Lava caves are often thought to be featureless and indestructable. In spite of this viewpoint, lava formations exist and are highly vulnerable to both accidental and malicious breakage. The potential for damage has greater significance when we realize that lava stalagmites, soda straws, and helictites are rarer than similar formations in limestone caves. Spray paint is nearly impossible to remove from lava. Litter can cause serious lasting damage (carbide dumps, batteries) and may be especially difficult to remove from caves (broken glass).

Lava caves are no more expendable than are any other type of cave. Once a cave is lost by quarrying, flooding, road building, or land development, it is gone. Even the constructive efforts of volcanoes cannot keep ahead of the unrestricted destructive habits of man.

REFERENCES

Anderson, Tempest 1910 "The Volcano of Matavanu in Savaii" Geological Society of London Quarterly Journal v 66, p. 621-639.

Baldwin, E.D. 1953 "Notes on the 1880-1881 Lava

Flow from Mauna Loa" The Volcano Letter #520 April-June, p. 1-3.

Dana, Edward S. 1889 "Contributions to the Petrography of the Sandwich Islands" American Journal of Science v 137, p. 441-467.

Greeley, Ronald 1971a "Observations of Actively Forming Lava Tubes and Associated Structures, Hawaii" Modern Geology v2, p. 207-223.

Greeley, Ronald 1971b "Geology of Selected Lava Tubes in the Bend Area, Oregon" Bulletin 71, Oregon Dept. of Geology & Mineral Industries 47p.

Harter, J.W., w/ R.G. Harter 1970 "Classification of Lava Tubes" May, 10p.

Harter, J.W. 1972 "Passage Modification in Lava Tubes" Oregon Speleograph v 8 #4 April, p. 41-45.

Harter, Russell 1971 "Lava Stalagmites in Government Cave" Plateau v 44 #1 Summer p. 14-17.

Harter, Russell 1971 "Bibliography on Lava Tube Caves" Western Speleological Survey Bulletin #44 June, 52p.

Harter, Russell 1972 "Basic Morphology of Lava Tubes" Oregon Speleograph v 8 #3 March, p. 29-31.

Harter, Russell 1973 "Secondary Chemical Deposits in Lava Tubes" Oregon Speleograph v 9 #7 July, p. 114-116.

Harter, Russell 1978 "Strata of Lava Tube Roofs" National Speleological Society Bulletin v 40 #4 October, p. 118-122.

Hatheway, Allen W. w/ A.K. Herring 1970 "Bandera Lava Tubes of New Mexico, and Lunar Implications" University of Arizona Planetary Laboratory Communications v 8 part 4 #152, p. 298-327.

Nichols, Robert L. 1936 "Flow-Units in Basalt" Journal of Geology v 44 #5 July-August, p. 617-630.

Ollier, C.D. w/ M.C. Brown 1965 "Lava Caves of Victoria" Bulletin Volcanologique v 28, p. 215-229.

Peck, Dallas L. w/ J.G. Moore & G. Kojima 1966 "Temperatures in the Crust and Melt of Aa Lava Lake, Hawaii, After the August 1963 Eruption of Kilauea Volcano - a Preliminary Report" United States Geological Survey Professional Paper 501-D, p. 1-7.

Peterson, Donald W. w/ D.A. Swanson 1974 "Observed Formation of Lava Tubes during 1970-71 at Kilauea Volcano, Hawaii" Studies in Speleology v 2 part 6 January, p. 209-222.

Swanson, Donald A. 1973 "Pahoehoe Flows from the 1969-1971 Mauna Ulu Eruption, Kilauea Volcano, Hawaii" Geological Society of America Bulletin v 84 February, p. 615-626.

Wentworth, Chester K. w/ G.A. MacDonald 1953 "Structures and Forms of Basaltic Rocks in Hawaii" United States Geological Survey Bulletin 994, 98p.