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 isolated 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.

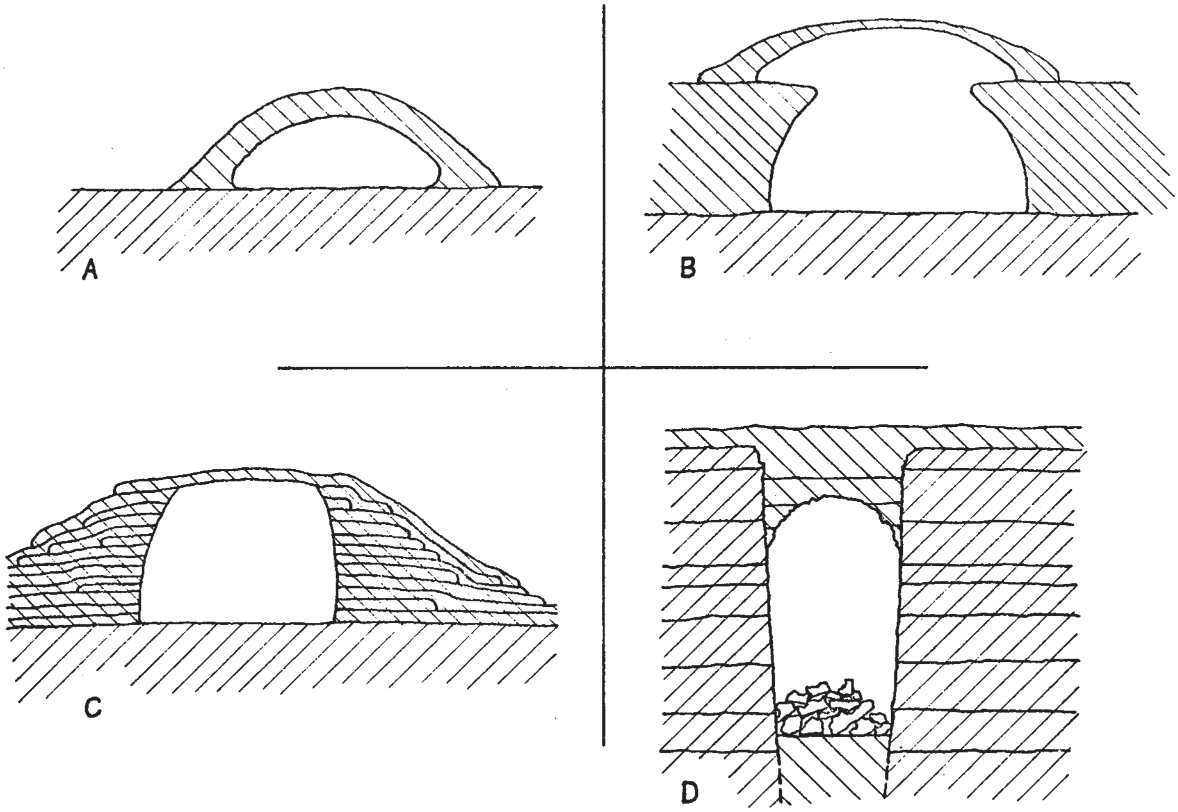

Figure 17-1: Cross-sections of various types of lava tubes.

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.

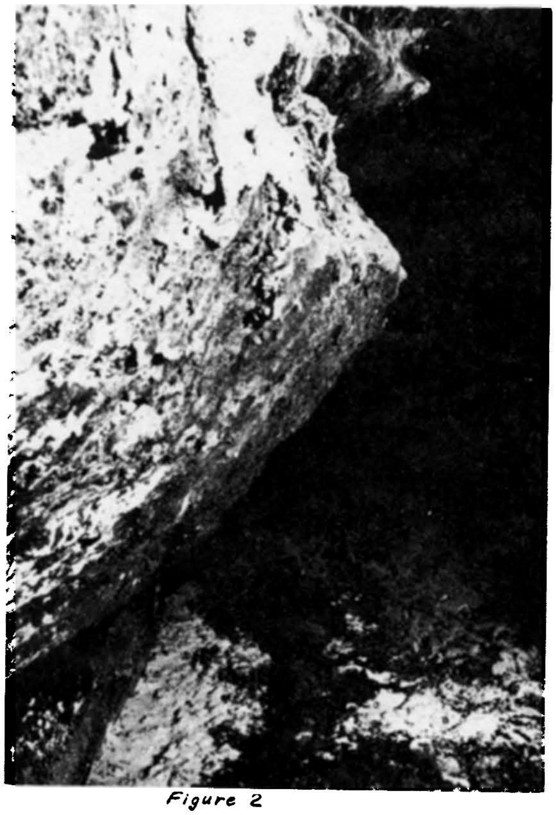

Figure 2

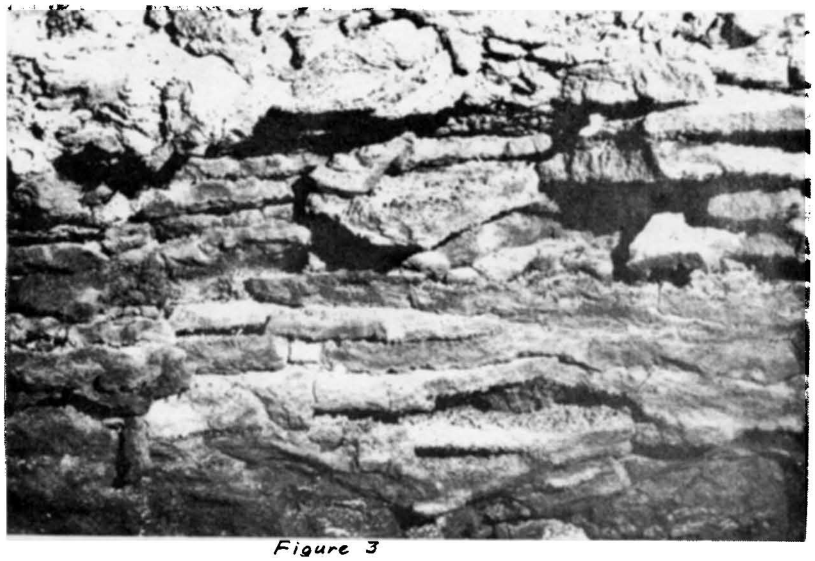

Figure 3

Figure 4

Figure 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.

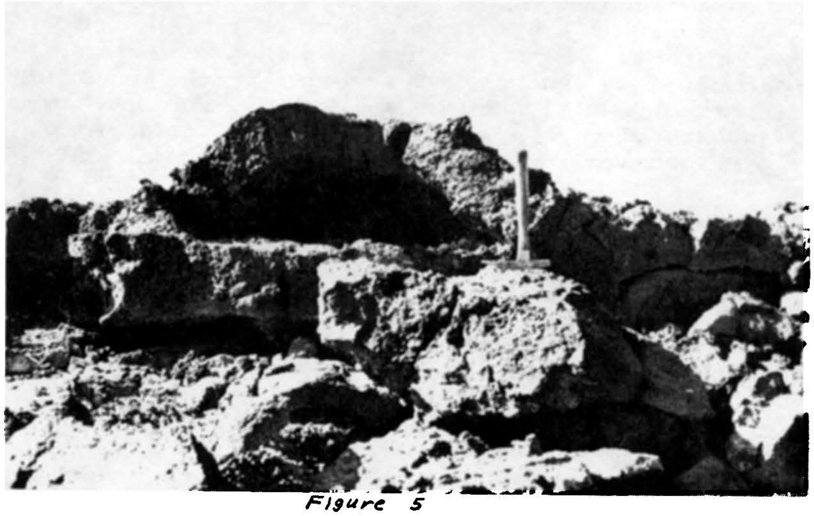

Figure 5

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.

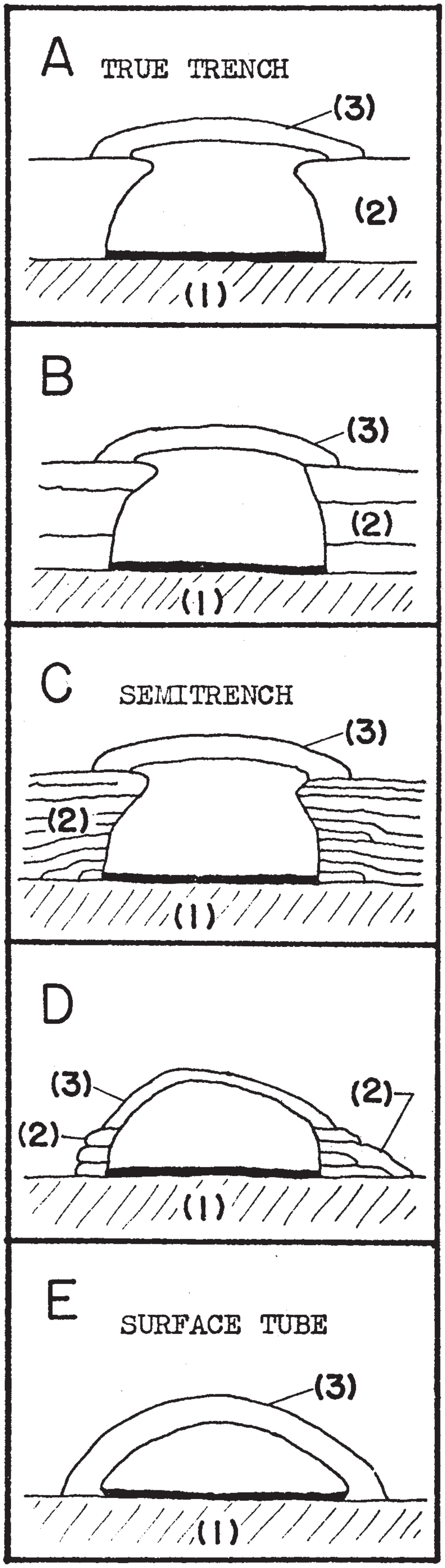

Figure 17-3: The Semi-Trench Spectrum.

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.

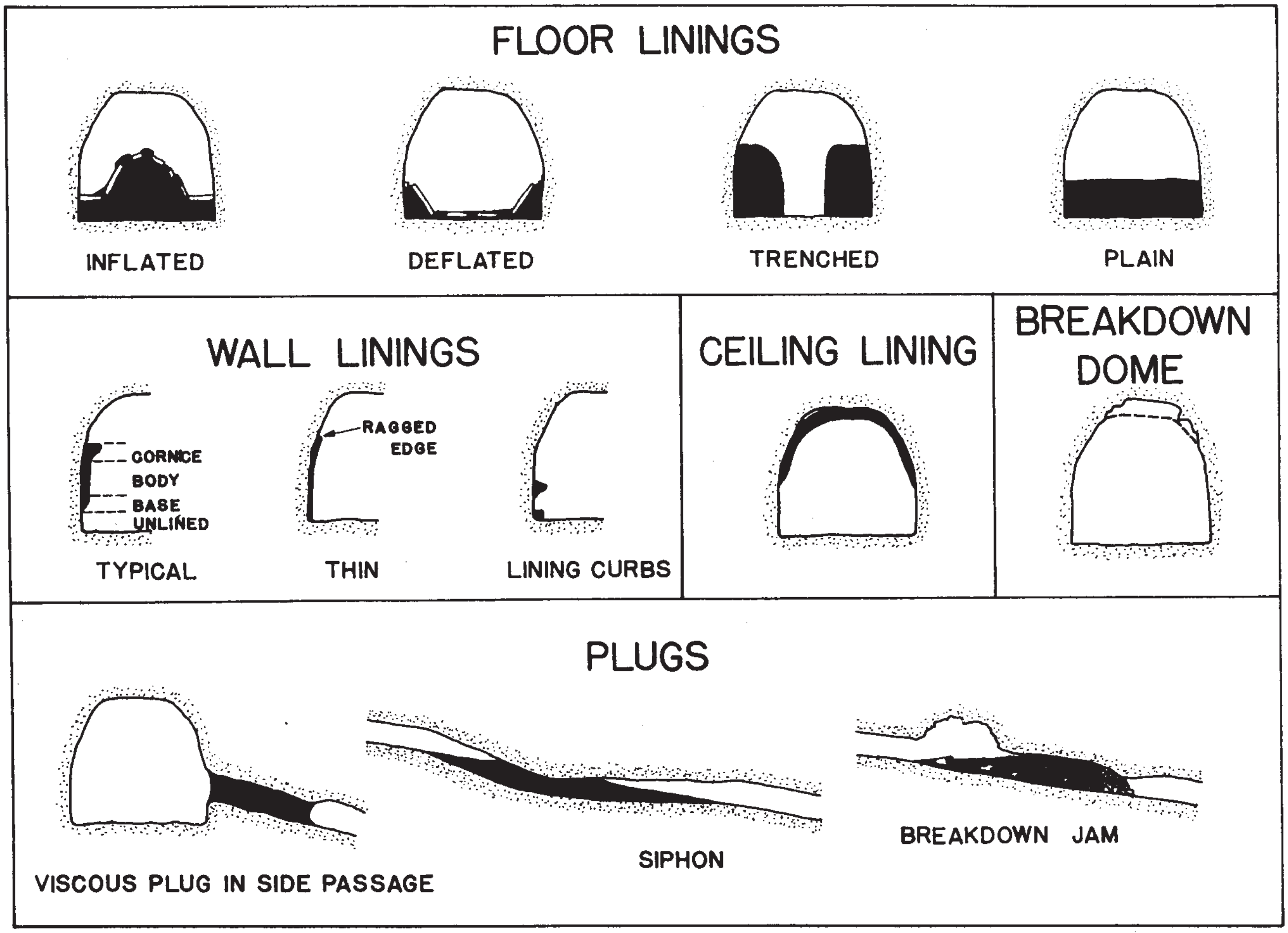

Figure 17-4: Forms of passage modifications in lava tubes

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 vesicles 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 sags 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.