LAYERED-LAVA, LAVA CHANNELS AND THE ORIGIN OF LAVA CAVES

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ABSTRACT

Two contrasting origins for lava caves have been suggested – crusting of an open lava channel, and sub-crustal drainage. The latter origin is associated by some workers with the presence of flow–units, and by others with that of layered–lava. Examination of the concept of layered–lava, and the study of field examples, shows that both flow–units and other layers may be present, and both apparently control cave development. Certain criteria may be used to distinguish cave systems formed from crusted–over lava channels which have later been buried, from those formed at depth by sub–crustal drainage.

THE FLOW OF BASALTIC LAVA

Many observations have been made this century of flowing lava, and film records have allowed more detailed study. Basaltic lava flow includes lobate flows which move rapidly and may spread laterally, moving with a "caterpillar-tread" motion, and cooling to a *pahoehoe* surface. Rapid flow may occur in channels formed as the lateral parts of the flow congeal. Slowly moving rubble–covered flows with a hot pasty interior are the *aa* type. An individual volcano may produce all these in succession over a period of time, or in the same eruption one type may give way to another with variation in terrain, slope and other factors such as lava temperature, gas content, and rate of discharge.

Lava channels and lava caves are almost always found in flows which were apparently of the more rapidly moving type.

FLOW IN CHANNELS

Within channels lava flow seems to differ from that of unconfined flows. Because it is confined, it retains more heat and more of its original gas content, and can move more freely. Although apparently sometimes flowing like water, with lava–falls, waves and overbank swash, it actually has a high measured viscosity. A variation in the rate of supply, or of channel width, depth or gradient, may lead to sudden changes in flow velocity as the apparent viscosity changes in response to applied shearing forces.

An increase in the flow rate may lead to swash over the channel walls and the building of levees, or to the crevassing of the bank and the development of new flow courses. A decrease in flow rate may cause the flow surface to subside rapidly within the channel; the flow may slow down, cool, and begin to solidify into discrete pieces which may become attached to the walls. The whole flow surface may crust over and attach itself to the walls, perhaps with flow continuing under this roof (Plate 1). The crusting of open channels has been discussed in detail by Peterson and Swanson (1974) and Greeley (1971b).

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Plate 1: Lava channel on flow four days old, near Sauna Ulu vent, Hawaii. Don Swanson walking upslope along margin of the channel, 3rd January 1970.

A further increase in lava supply may then lead to increased flow in the channel, and lava may break through and flow over the roof, strengthening it or destroying it.
The final flow through a lava channel will probably leave behind at least some roofed segments and on lava withdrawal these will form a cave and channel complex.

LAYERING WITHIN LAVA FLOWS

Commonly associated with lava channels and lava caves is the presence of layered lava. The layers (Plate 2) are generally horizontal, about half to one metre thick, and often show evidence of flow bases and original sub–aerial surfaces. Clearly successive thin lava flows may occur, and flows composed of such units have been termed "compound lava flows" by Walker (1971). Nichols (1936) described "flow–units" in New Mexico as being some "10 to 20 feet" thick but his illustrations also show further layering separated by horizontal partings within these units.

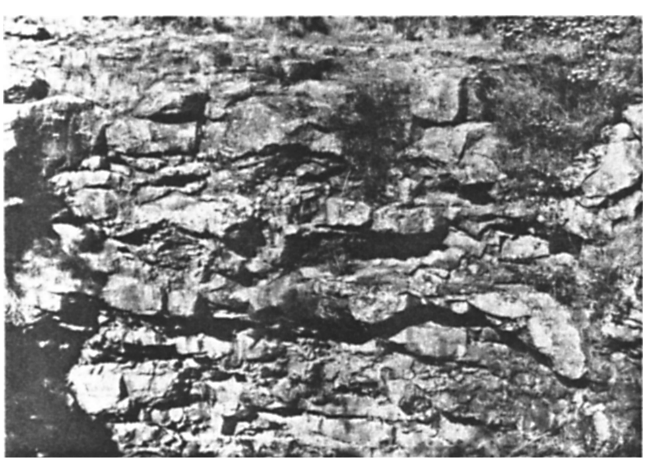

Plate 2: Layered lava exposed in south-west wall of the northern collapse at Church Cave, Byaduk, Victoria; three to four flow–units are present, each divided into several layered–lava units about one metre thick.

The presence of layers in lava flows in Victoria led Ollier and Brown (1965) to suggest that shearing within a flow mass could also produce layering. They described layered–lava as consisting of layers:

"varying from several feet to a few inches in thickness and parallel to the surface. The layers are of compact basalt separated by trains of vesicles or in some cases by definite partings" (p.220). "...we believe the layers are formed by differential movement within one thick lava flow" (p.221). "Movement of the lava in general is by laminar flow, and a layering is produced by partial congealing of the lava. Individual layers are separated by partings of vesicles and more liquid lava ... The rate of cooling of lava is usually too low for the laminae to be preserved. But in the regions where lava tunnels are present the flow layers invariably accompany them, and are well preserved" (p.228).

They suggested that layered lava could act as a control for the separation and concentration of liquid lava within the semi–cooled mass, leading to the development of lava tube systems.

Direct evidence of shearing in flows is hard to find. An indication of horizontal shearing may be the cracks and vesicle concentrations sometimes seen in cross–sections of flow units (Figure 1).

Greeley (1971a) has pointed out that such layered–lava partings, as distinct from flow–unit contacts, are also discontinuous (see Plate 4).

Apart from shearing associated with laminar flow, layered–lava of the type described above could perhaps be formed under other conditions, e.g.

(a) arching and subsidence of a flow surface, as in the development of stony rise surfaces in Victoria (Plate 4);

(b) cooling and shrinking of a flow;

(c) settling following degassing of a flow.

Following the work of Ollier and Brown (1965) the concept of layered–lava as a factor in lava cave formation was used by many overseas workers e.g. Greeley (1971a), Hatheway (1976), but more recently, has been criticised by Wood (1974) and Peterson and Swanson (1974).

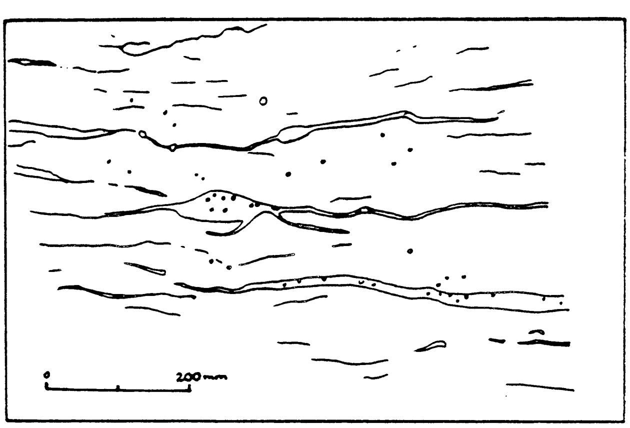

Figure 1: Horizontal cracks and vesicle concentrations, often discontinuous, in a cross-section of a flow unit exposed in the right bank of the Merri Creek, just upstream from the Coburg Lake Reserve. (Sketched from a photograph).

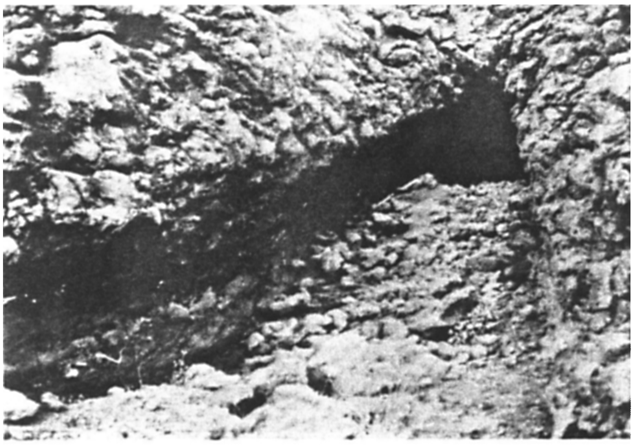

Plate 3: Lava channel on 1892 flow from Mt. Silvestri cone on southern flank of Mt. Etna, Sicily; levée layers are present, and the cave further upslope is roofed with thin material (compare with Gothic Cave at Mt. Eccles, Victoria).

Plate 4: Small cave formed by withdrawal below arched layered–lava in a stony rise lobe three kilometres south of Red Rock, Western Victoria; note dying–out of layered–lava parting in massive unit below right–hand post.

A third type of layering in flows is provided by the levée layers formed when successive thin swashes of lava along a channel edge build up a series of layers, each several centimetres thick, a metre or two across, and accumulating to a height of several metres in some cases (Plate 3).

To summarise, the first two types of lava layers discussed above are features of lava flows which commonly have an appreciable width and cover extensive areas. The third type, lava levées, are found along the margins of lava channels.

ORIGIN OF LAVA CAVES

Several methods of initiating a lava tube, which may later become a cave, are thus possible.

Type 1: *Crusting of an open channel* (Wood 1974 p.27) can occur as the flow rate decreases, and continued withdrawal of the lava below will provide a lava cave (Plate 1). Detailed accounts of lava channel formation are given by Peterson and Swanson (1974), and Greeley (1971b), and the concept has been applied to lava caves by Harter (1978).

Type 2: *Chilling of a shell* around flow units or *pahoehoe* toes (Wood 1974 p.27) can occur when a lobe of flow cools on the outside; if the still-liquid interior breaks out a cave may be formed (Plate 4). Such caves would only be of short extent, and are probably not of major importance by themselves. Shallow Cave at Byaduk, Victoria, (Ollier and Joyce 1968, Plate 1) is an example, and the recently discovered small caves at Warrion Hill, Victoria are probably of this type (Webb, Joyce and Stevens, in press).
Type 3: Liquid segregation in layered–lava (Ollier and Brown 1965; Ollier 1967; 1969) is believed to occur when liquid elements in an otherwise largely cooled flow can select a path related to layered–lava and then by erosion and melting develop a tube system (Plate 5). Ollier and Brown (1965 p.225) describe a "two–stage theory" in which the first stage refers to the separation of the liquid lava into tubes, and the second stage to partial or complete drainage to leave caves. This would require the liquid lava to emerge down flow; in most cases it probably also required an adequate supply of lava at the upper end of the system to allow the erosion and melting necessary to develop an integrated and therefore drainable tube system.

Plate 5: Largely–filled lava tube about one metre in diameter developed in layered–lava, exposed in a road cutting about two miles north–east of Haalehu, Hawaii.

DISCUSSION

Interest in the origin of lava caves has rapidly increased in recent years because of their use as terrestrial analogs for lunar and planetary features (e.g. Joyce 1976). Attempts to explain the origin of lava caves has led to controversy, and in particular the third type of origin suggested above is in dispute (see reviews by Wood 1974, 1976, 1977a, 1977b). The argument hinges on whether layered–lava exists, and whether such layers can concentrate flow and allow cave systems to form.
Wood's "chilling of a shell" (Type 2) is an elaboration of the original concept of lava cave formation (see for example Nichols 1936). In his study of caves in Iceland, Wood (1971) suggested that individual flow–units in a lava pile may form tubes by withdrawal of their interiors, leading to the development of a complex cave system.
The controversy does not seem to concern the possibility of lava withdrawal at depth in a lava pile, but whether the withdrawal is related to flow–units or layered–lava.

If we accept that layered–lava exists (as does Greeley (1971a), Hatheway (1976), and other workers) then how does movement of liquid lava take place in relation to the layers? Ollier has not explored this problem in detail. He says (Ollier and Brown, 1965 p.228):

> "When layered–lava is formed, the more congealed lava goes into the layers, and the more liquid lava (accompanied by many volatiles) is concentrated *between* the laminae. At this point something very unusual and unexpected happens. The liquid lava becomes further segregated, and comes to occupy tubes running *through* the layered–lava" (my emphasis).

Does the movement take place between the layers as he seems to be suggesting? It is hard to see substantial movement of large amounts of liquid lava occurring in partings only a few centimetres across. Or does it take place within the layered–lava units?
Greeley (1971a p.9) following Ollier and Brown, has suggested that in layered–lava "flow apparently is confined to fluid conduits between shear planes". This statement is ambiguous but his general discussion suggests he means that the flow takes place within the layered–lava units which are bounded by the shear planes or partings.
To summarize, if flow occurs between layered–lava units then it might be expected to take place equally–well between flow–units. If it takes place within the layered–lava units then it is very similar to, and perhaps in practice indistinguishable from, Wood's concept of withdrawal from the interior of flow units.
Ollier (1977) has recently reviewed his earlier ideas, and suggested the term "sub–crustal lava caves" for those formed in layered–lava in the way originally suggested by Ollier and Brown (1965). He further comments:

> "...since 1965 ... Victorian lava caves have revealed both shearing layered–lava and flow units, and the circular caves cut across both" (p.151; his emphasis).
>
> "Whether layered–lava is made by laminar flow and shearing, or is made largely of flow units, is not sure. However, the general contention that the layers are eroded by continued flow of hot lava through tubes is not affected by details of earlier formed structures" (p.156).

Thus it appears the origins suggested for type 2 and type 3 lava caves have now converged, and can be considered as aspects of the same process, for which the term "sub–crustal drainage" seems appropriate.
More detailed studies of the features of cave systems within lava piles (i.e. the sub–crustal drainage type) are needed. Most studies have been made only where lava is exposed in the collapses associated with caves. These generally show sections along the flow direction. It is rare to find natural cross–sections across the direction of lava flow, showing details of tubes and their surrounding lava; this is probably due to the young age of most flows which contain lava caves. Suitable road cuttings can be valuable sources of information (Plates 4 and 5).
The feature in Plate 5 shows no indication of being related to an earlier lava channel. But is it an example of withdrawal from a flow unit, or is it the result of lava movement related in some way to the layered–lava which surrounds it?

FEATURES OF LAVA CAVES DEVELOPED IN DIFFERENT WAYS

Caves at depth within flows which have layered lava are common in Victoria, for example Byaduk, Porndon, Skipton. Some workers might explain these caves as lava tubes of type 1 (crusted–over channels) which have been buried under later flow units. Criteria for distinguishing cave systems formed in each of the two main ways suggested (i.e. type 1 in contrast to types 2 and 3) would be useful.

Most lava caves, as former conduits for flowing lava, have some features in common e.g. wall linings, flow level marks, stalactites and a floor representing the surface of the final flow through the system.

However, broader scale features of the entire cave system may give some indication of its mode of origin. Such features would relate to the initial formation of the system, either as a lava channel, or a sub–crustal drainage system. Figure 2 summarises some of these features, and indicates some possible local examples.

The criteria given in Figure 2 have been deduced by a general consideration of the origin of these two contrasting types of lava cave, and the figure incorporates observations made on active lava channels in recent years (Greeley 1971b; Peterson and Swanson 1974) and details of published descriptions of lava caves.

Wood (1974 p.27) has distinguished simple or unitary lava tube caves as "unbranched, sinuous, elongated and uni–level in character"; they form in single, thick, rapidly emplaced and cooled lava flows. His complex lava tube caves have "predominantly ingressive tubes or more complicated anastamosing tube patterns", may be multi–level, and are found considerable distances from the vent. This distinction bears some resemblance to the division suggested in Figure 2.

As a cave system develops with time, it evolves by wall erosion and melting, so that it may no longer show diagnostic features of the type suggested.

CONCLUSION

The origin of lava caves is still under discussion. Two contrasting origins are generally proposed — the crusting of an open channel, and the development of a tube system within a pre–existing, partly–cooled layered mass (the sub–crustal drainage cave).

When first formed, each of these two types can be distinguished. A cave formed from a lava channel may on burial by a further flow begin to look like a tube formed at depth in layered–lava. It is suggested that certain features of cave systems may be useful in distinguishing their origin (Figure 1).

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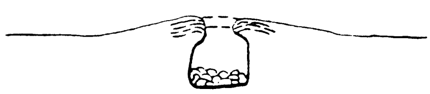
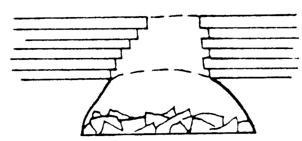
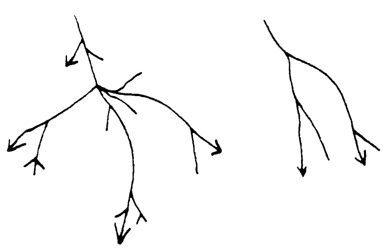
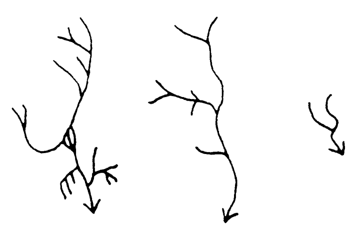
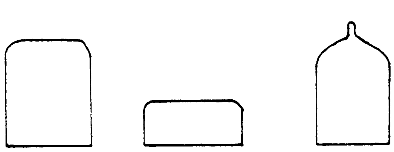
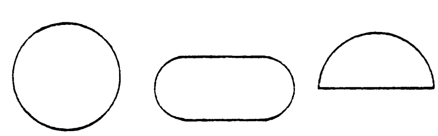
Dr Carmelo Sturiale of the University of Catania, Sicily demonstrated the young flows on the southern flank of Mt. Etna in October 1969 (Plate 3). Don Swanson of the Hawaiian Volcano Observatory took me over the still–hot flows of the active Mauna Ulu vent of Hawaii on 3 January 1970.

Figure 2 Features of lava cave systems initiated by :

(a) CRUSTING OF AN OPEN CHANNEL	(b) SUB-CRUSTAL DRAINAGE
surface form initially a channel on a ridge	surface expression limited to collapse e.g. Byaduk
roof composed of flow surface and levees	roof composed of layered-lava e.g. Byaduk
thin roof initially	thick roof, i.e. cave initially at depth e.g. Byaduk
roof collapse common and extensive, re-forming channel e.g. Gothic Cave at Mt Eccles, Mt Napier caves	roof collapse limited in extent, often sub-circular; may not reach to surface e.g. Arch Cave, Porndon
	
walls behind lining show levee layers and spatter, possibly distorted e.g. Gothic Cave	walls behind lining show layered-lava e.g. Byaduk
channel straight or meandering, possibly braided	channel straight or anastomosing, e.g. Mt Hamilton
drainage pattern distributary - down-slope branching e.g. Mt Napier	drainage pattern dendritic - down-slope joining e.g. Panmure
	
cross-section vertical-sided slot, roof flat to "gothic"	cross-section tube or half-tube
	
simple long profile	may be multi-level e.g. Mt Hamilton, Church Cave at Byaduk
generally near vent	generally far from vent e.g. Byaduk
total length less than 1 km	total length greater than 1 km

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