VULCANOSPELEOLOGY - EXTRA TERRESTRIAL APPLICATIONS AND THE CONTROVERSY: MODE OF FORMATION OF LAVA TUBES.

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ABSTRACT

Basaltic composition of rock samples from the MOON stimulated great interest in terrestrial volcanic features, particularly lava tubes, as analogues to lunar and planetary surface features (Figures 1a to 1e). With this stimulus, their mode of formation was re-examined.

Features of active and Recent lavas and stages in the development of actively forming lava tubes have been studied in Hawaii (Fig. 2). It was noted that, in some lava channels that had crusted over, tubes formed when flow diminished. These observations provide an explanation, the "Hawaiian" theory, of many features of older tubes and also their mode of formation in general and, in particular, that of the Undara Lava Tube System, North Queensland.

Alternative hypotheses for the formation of tubes are examined. One worker claims that the "Hawaiian" theory is applicable only to tubes less than 1 km long, but the length of the Undara System refutes such a distinction. To explain the formation of some more complex lava tubes, alternative hypotheses may be necessary.

Figure 1a: A meandering channel which may represent a collapsed lava tube in a lunar mare area near Apollo 15 landing site. (National Geographic Magazine, U.S.A.) Photo: Astronaut A.M. Worden, NASA Apollo 15 Mission.

Figure 1b: ?Partially collapsed lava tube, lunar mare area. (National Geographic Magazine, U.S.A.). Photo: Astronaut A.M. Worden, NASA Apollo 15 Mission.

INTRODUCTION

Pictographs in some American lava tubes evidence their pre- historic use and in Europe they have been visited since at least as early as the eighteenth century. However, they do not contain decorations to compare with those of limestone caves so it was not until the first LUNAR SAMPLES proved to be basaltic, megascopically (Fig. 3, at end) and microscopically (MacKenzie, 1982) similar to terrestrial basalts, with only minor geochemical differences, that a real interest was awakened in their nature and mode of formation. (The minor geochemical differences of lunar basalts are believed by some to be due to their age of 3.6 billion years.)

The shape of channels on the lunar surface (Fig. 1a) had suggested fluvial origin but such an hypothesis could not be supported in the absence of atmosphere. It was therefore proposed (Kuiper, Strom and LePoole, 1966; Oberbeck, Quaide and Greeley, 1969; Greeley, 1970, 1971a) that sinuous lunar rills (Fig. 1a) may be collapsed lava tubes (Fig. 1c). From Mariner 9 photographs Greeley (1972b) identified similar features in three regions on Mars.

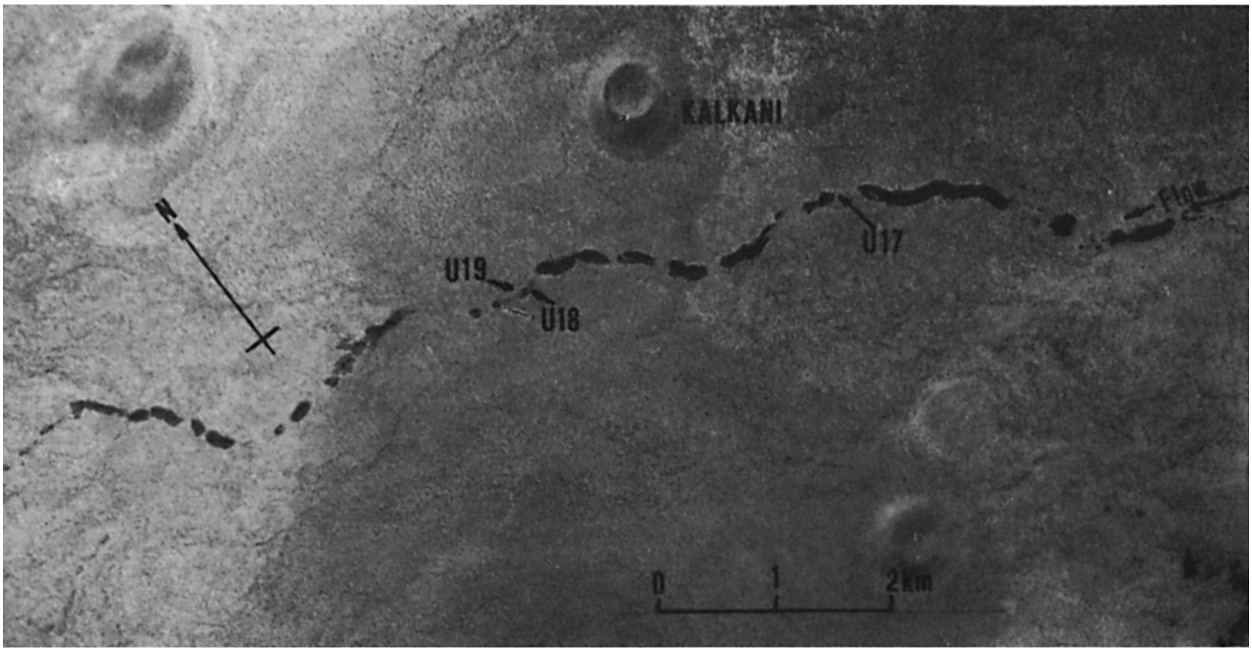


Figure 1c: Wide collapse depressions aligned with and/or adjacent to the Yaramulla Section of the Undara Lava Tube System, North Queensland. Air photograph: Department of National Mapping, Australia.

Great interest was aroused at NASA Headquarters, San Francisco,USA, when the author proposed in 1972 that the WALL SECTION of the Undara Lava Tube System might represent a terrestrial analogue to the sinuous ridges (Fig. 1d) on mare regions of the Moon. A request from NASA that an immediate detailed study of "The Wall" be made by a student of JCUNQ had to be ignored as neither party was willing to fund the project.

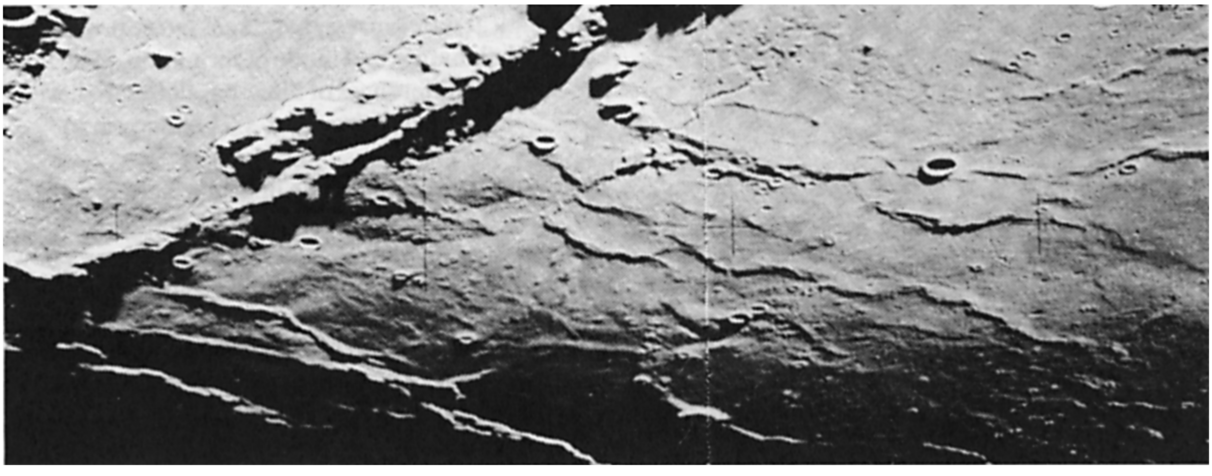
In the strictest sense, the words "lava" and "basalt" are not interchangeable, "lava" referring to rock in its molten state, "basalt" to a solidified volcanic rock within a restricted compositional range. Commonly, however, the word "lava" is used in either sense, and is used thus, in this paper. Similarly the words "cave", "tube" and "tunnel" are used here synonymously.

FIELD OBSERVATIONS

Data for mapping and details of geomorphology of the Undara System were collected during extended field trips over a period of two years. The author considers, however, that the opportunity to make the following observations overseas were of inestimable value and profoundly influenced conclusions reached in this and the preceding paper.

Eruptions and active lava flow were witnessed on the Island of Hawaii in 1972 and 1974. Some details are given in Atkinson 1988. During those visits and in 1980, young volcanic features were also studied there and in the states of Washington, Oregon and Idaho, U.S.A., and in Iceland, France, Sicily and the Eolian Islands.

Figure 1d: Flat basaltic areas surround a long jagged spine of mountains on the lunar surface near Aristarchus Plateau. Beyond the mountains, note the "ranks" of little ridges. (National Geographic Magazine, U.S.A.). Photo: Astronaut A.M. Worden, NASA Apollo 15 Mission.



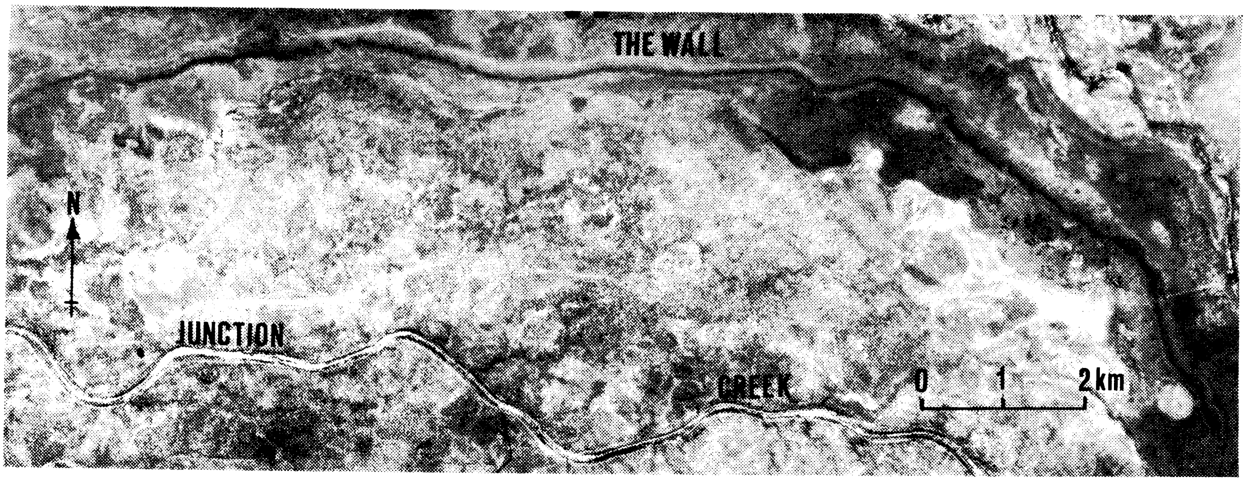


Figure 1e: Vertical aerial photograph of the western end of the Wall Section of the Undara Lava Tube System. This low basalt ridge is 37 km long and may be analogous to sinuous ridges on lunar basaltic areas. (See also Figures 10a and 10b, Atkinson 1988, this volume). Air photograph: Department of National Mapping, Australia.

TYPES OF LAVA THAT HOST LAVA TUBES

Macdonald and Abbott (1972) state that, in Hawaii, lava tubes are common only in fluid pahoehoe* lava, that they are very rare in the viscous aa* type. S. Thorarisson (pers. comm., 1974) agreed that this was the case in Iceland also. A keen speleologist all his life, Thorarisson was, therefore, very interested in the discovery by the author and V.G. Atkinson in 1974, of a short tube, still warm, in the 1973 aa flow that threatened the township on the Island of Heimaey, Iceland.

OBSERVATIONS OF ACTIVE LAVA TUBE MECHANISMS

Wentworth and Macdonald (1953), Greeley (1971b, 1972a), Macdonald and Abbott (1972) and Peterson and Swanson (1974) have made observations of lava tube formation in active and Recent flows in Hawaii. Their work shows that the following are the stages in the development of major lava tubes. Figures 2a to 2d, from Macdonald and Abbott (1972), illustrate these stages. Figure 2e has been added for reasons explained below.

1. A river of pahoehoe lava, confined in a valley, quickly crusts over and develops a "roof". The flow also begins to solidify against valley walls and floor (Fig. 2a). The "roofing" occurs in several different ways, including growth of semi-solid surface crusts by cooling, crusts floating down the channel jamming and accumulating at obstructions, and by the growth of levees from the channel sides through repeated overflows, splashing and spattering. "Roofs" formed by any of these processes may be thickened and strengthened by new surface flow units.

2. As solidification of the "roof", walls and base continue, the flow becomes concentrated within a cylinder (Fig. 2b). If eruption ceases and the tube drains completely, its cross section is circular. (The author saw one such perfectly cylindrical straight section, 1.7 m diameter, over 6 m long and with an inclination of about 5°, in a cave in the Cascade Mountains, Oregon, U.S.A.)

3. When the supply of lava diminishes during an eruption it no longer fills the whole tube. Volcanic gases, escaping from the flow into this cavity, may ignite producing a temperature considerably higher than that of molten lava. This may cause some re-melting of the roof with drips of lava forming lava stalagtites (lavicicles) up to 30 cm (Fig. 2c). Occasionally lava stalagmites form. Lavicicles are commonly vertical. Deflection is rare and apparently caused by a current of very hot gas or air passing through the tube. In the Undara System, deflection has been noted only near the entrance to Barkers Cave.

4. Effusion rates fluctuate but whenever a constant rate is maintained, near-horizontal ledges of lava solidify on the tube walls - **lava level lines** (Atkinson, Griffin and Stephenson, 1975; Stephenson and Griffin, 1976b and Atkinson, 1988, text and figures 4a this volume). Further diminution of the flow lowers the level in the tube. Finally the flow congeals to form the floor of the tube (Fig.2d).

Note re Figure 2e

The author has taken the liberty of adding this to Macdonald and Abbott's Figures 2a to 2d (1972) in order to illustrate one mode of formation proposed for major ridges associated with a lava tube system, such as the WALL SECTION of the Undara System.

* *Aa and pahoehoe are Polynesian terms referring to physical state, not chemical composition.*

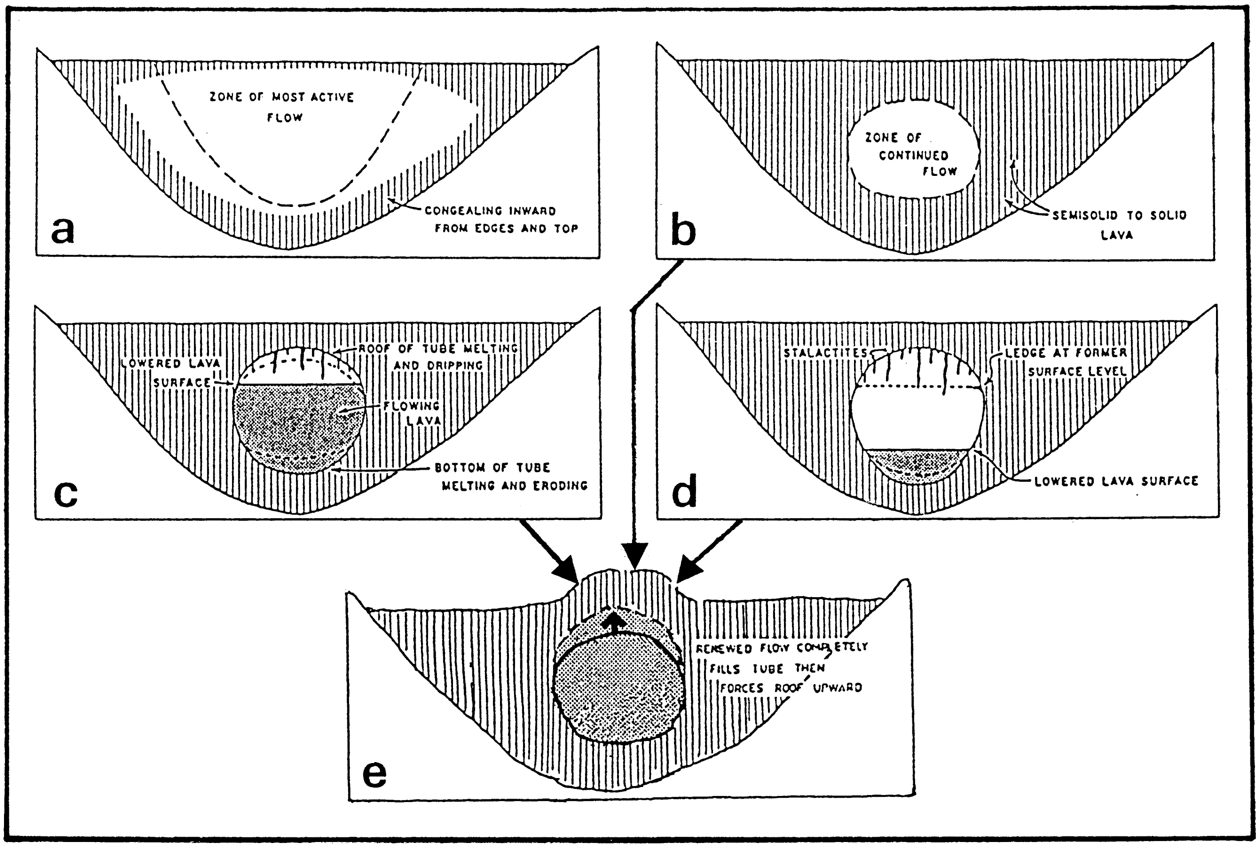


Figure 2a - 2d: Diagrams to illustrate stages observed in thedevelopment of lava tubes in Hawaii. (from Macdonald and Abbott, 1972)
a: The lava flow, confined in a valley, develops a thin crust and starts to solidify inward from the edges, but the centre continues to flow;
b: The active movement of liquid becomes restricted to a more or less cylindrical, pipelike zone near the axis;
c: The supply of lava diminishes and the liquid no longer fills the pipe. Burning gases above the liquid heat the roof of the pipe and cause it to melt and drip.
d: Further diminuition of the supply lowers the level of the surface of the liquid, which eventually congeals to form a flat floor in the tube.
e: Diagram to illustrate possible mode of formation of a basaltic ridge such as the Wall Section of the System near Mt. Surprise, North Queensland. (See also Figures 10a and 10b, Atkinson 1988).

To support this hypothesis it is noted that:

- the axis of a flow is commonly inflated above its surrounding lava field (Greely, 1971b, Greeley, 1972a and Greeley and Hyde, 1972)

- small drain tubes (up to 0.75 m wide and 6 m long on the flanks of Mauna Loa, Island of Hawaii, have semi-circular "roofs", no more than 3 cm thick (pers obs.).

As small tubes sometimes exhibit such convexity, it is proposed that the impetus of renewed, late stage activity from a source volcano could force a semi-solid roof of a large tube to arch upward.

The ballooning of 37 km of tube to an almost uniform level is difficult to envisage and L.M. Pearson suggests (Pers. comm. 1988.) an alternative hypothesis which fits more closely with observed features on the terminal section of "The Wall".

1. The location of "The Wall" section marks a watercourse in the paleo-drainage (the precursor of Elizabeth and Junction Creeks) down which the Undara lava flowed. The minimal slope would lessen the lava velocity, allow a longer time for cooling to take place and increase viscosity of the lava.

2. The lava field extended laterally by overflow from the channel. Levees formed, as observed by Greeley (1971b and 1972a) on the Island of Hawaii and depicted at Halemaumau (Fig. 19 Atkinson 1988), elevating the channel above the surrounding lava field.

3. A temporary halt in eruption allowed solidification of the "toe" at the termination, damming the flow. Cooling and contraction led to some mega-jointing.

4. Renewed activity caused minimal inflation of the "toe" before the lava continued to flow down to the Einasleigh River beyond the termination of "The Wall".

5. Flow ceased and the tube drained, partially or totally. For most of its length the roof was self-supporting, or not drained, but near the termination, Edmonds Lake (here named) formed by axial collapse of a drained section. This collapse also left mega-columns flanking the slumped central area and the slope to the West.

For the formation of "The Wall" it is possible that both mechanisms operated but in the terminal section and possibly for most of the length of "The Wall", the second hypothesis is favoured.

MECHANISMS PROPOSED FOR SOME OLDER LAVA TUBES

It is difficult to understand that some would propose hypotheses so different from the mechanisms of tube formation actually observed in active lavas. Such hypotheses, however, have been proposed and are, perhaps necessary to explain some complex tubes.

In complex lava caves in Victoria, OLLIER AND BROWN (1965) observed that "layered" lava was a consistent feature and proposed that tubes developed as discordant late-stage structures by some process of residual lava segregation. Cylinders of flowing lava developed and eroded some of the virtually solid lava to form the final tubes. Drained tubes were left as caves with a congealed lining.

GREELEY and HYDE (1972) concluded that most of the tubes of the Cave Basalt, Mt. St. Helens, Washington, U.S.A., had formed by the mechanism proposed by Ollier and Brown (1965).

HATHEWAY (1971) extended the hypothesis of Ollier and Brown (1965) to explain the development of an extensive tube system. He proposed that tubes originated at the toes of individual flow units and began in the form of evacuating bodies which he termed mobile cylinders. Lava was freed in an up-slope process as the cylinder continually searched out a position of maximum gradient within the flow unit. In most cases, Hatheway supposed growth of the cylinder continued until the source area or vent was reached.

In 1976 Hatheway argued that his theory of tube formation was compatible with that based on observations of actively forming tubes in Hawaii, his theory being applicable to tubes more than 1 km long, the "Hawaiian" theory to tubes less than 1 km. Evidence in the Undara System supports formation by the "roofing" of a running channel. There, the hypotheses of Ollier and Brown (1965) and Hatheway (1971 and 1976) do not seem applicable.

WOOD (1974) maintains, as PETERSON and SWANSON (1974) also believe, that the "layered" lava, on which Ollier and Brown (1974) based their hypothesis, simply corresponds to a flow composed of successive flow units.

In discussing the size of lava tubes BULLARD (1977) claims that their size "is influenced by the the thickness of the flow, the viscosity, the rate of cooling, and the slope of the surface on which it flows". Bullard appears to support the mechanism of formation proposed by Ollier & Brown (1965).

OLLIER (1988) still does not seem to agree that the layers in a flow represent successive units of flow, as observers in Hawaii claim (see above). He appears to accept Nichols' (1936) explanation of the formation of flow units in preference to observations of active flow recorded by Greeley (1971b and 1972a and Peterson and Swanson (1974) and others. He points out that the term "layered lava" is still useful as a less specific term than "flow unit".

Presumably later additional Hawaiian observations, noted above, have persuaded Ollier (1988) to abandon the "layered lava" hypothesis, proposed by himself and Brown, (op. cit., 1965) as the main mode of formation of lava tubes. For tube formation, Ollier (1988) now considers that "three mechanisms appear to be dominant", the following two producing major tubes:

1. Channel "roofing" by accretion of spatter from levees - a process observed in Hawaii by Wentworth and Macdonald (1953), Waters (1960) Greeley (1971b and 1972a), Peterson and Swanson (1974) and in Iceland by Kjartansson (1940).

2. - and, quoting Hatheway and Herring (1970), "by the development of mobile cylinders of lava in a cooler, more viscous host rock. These cylinders transport fluid lava to the "toe" of the flow as long as the source provided a continuous supply. When this ceased the tube probably drained rapidly".

Ollier (1988) does not comment on the difference between the hypothesis of Hatheway and Herring (1970), quoted in the preceding paragraph, and Hatheway's 1971 hypothesis, viz. that "mobile cylinders" originated at the "toes" of flows and extended up-flow toward the source.

POSSIBLE DEVELOPMENT OF THE UNDARA LAVA TUBE SYSTEM

WALKER (1973) discussed the development of very long lava flows and concluded their formation is characterized by a high rate of effusion. At Undara, this was probably responsible for the rapid development of the main length of the flow which attained 160 km,with an average gradient of only 0.3° (0.12° over the last 100 km). Extrapolating Walker's relationships (op cit.), Undara's average effusion rate must have exceeded 1000 m^3/s. Walker (pers. comm., 1974) considered that to have reached a length in excess of 160 km to become the longest flow in Australia and one of the longest in the world, eruption must have been concluded in less than three weeks, possibly in less than one week.

The elongated ridge, the Wall Section of the Undara System, was probably part of a lava tube which acted as the main feeding channel for the long flow down the Einasleigh River (Atkinson 1988, Fig. 3). Lateral parts of the flow no doubt extended by breakouts and flooding away from the main lava channel. It is concluded that once formed, this main lava tube must have been continuously maintained. Accepting this, it is conceivable that a continuous lava tube system functioned between the Undara crater and the termination of "The Wall" - over a distance of 90 km (Atkinson et al., 1975).

Sand was found under the basalt (some apparently fused) in successful water bores in and adjacent to the Yaramulla and Wall Sections of the Undara Lava Tube System. This is interpreted as evidence that, at least in those areas, the flow was channelled by one or more former water courses.

The lava front was presumably fed by major channel flow along which tube formation was progressively occurring. Once initiated, the lava tube was maintained as an effectively heat-insulated channel, as PETERSON and SWANSON (1974) stressed. SHAW, (1969) claimed that lava flowing in the relatively confined tube / channel probably also partly maintained its temperature and fluidity through viscous frictional effects.

SUMMARY AND CONCLUSIONS

1. Interest in lava tubes and other terrestrial features was stimulated when some lunar rock samples proved basaltic.

2. In addition to recorded work, personal observation of younger volcanic features are of inestimable value to any who try to interpret features in older lava fields.

3. In Hawaii, more or less continuous crusts are observed forming on channels in active lava flows. When flow diminishes, its level drops, leaving a space or lava cave/tube/tunnel between the "roof" and the final flow.

4. Observation of the above mechanism, and of features of active and Recent lavas, provide a very satisfactory basis for hypotheses concerning the formation of lava tubes in general and of the Undara Lava Tube System in particular, though some authors still propose more complicated mechanisms based on their observations in older lava tubes.

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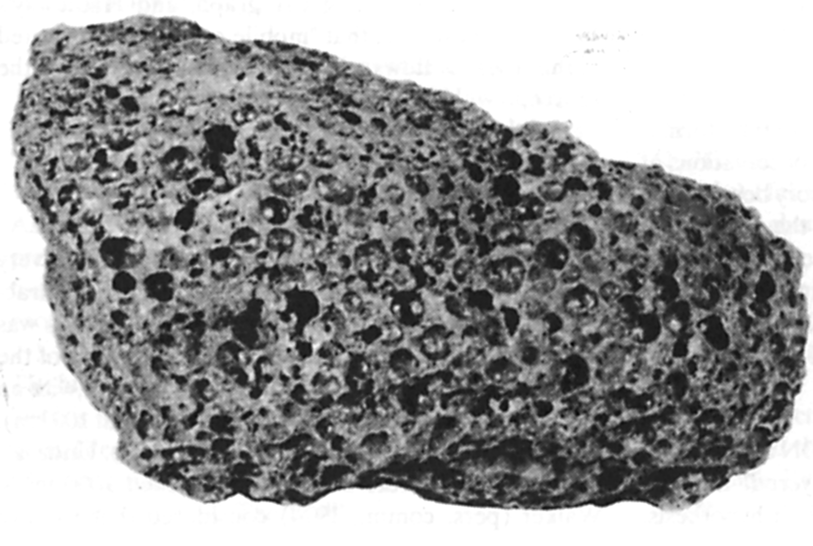

Figure 3. Lunar vesicular basalt. More than half this specimen is "pore" space. The "pores" or vesicles, are formed by frothing and bubbling during volcanism and indicate high gas activity at one time on the Moon. The appearance in hand specimen and under the microscope show no marked difference from terrestrial basalts but there are slight chemical differences. (National Geographic Magazine, U.S.A. & MacKenzie et al. 1982). Photo: NASA, U.S.A.

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