THE FORMATION AND EVOLUTION OF LAVA TUBES
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Lava tubes provide efficient transport structures for often low volumetric flow rates of lava: tube-fed flows can be as long or longer than flows emplaced rapidly by open channels. Our field measurements, including fractal studies of lava tube systems, show that pahoehoe flows are emplaced largely as sheets, within which complex tube systems form. Tubes grow inside the flows by coalescence, by expansion during inflation, and by thermally eroding the substrate. Tubes are not common in 'a'a flows, but can form when channels are roofed over. The observations should apply to lava flows on all terrestrial planets, the Moon, and Io.

LAVA TUBE FORMATION

Lava tubes form by coalescence of a stack of active lava toes, by the advancement and evacuation of individual lava toes, by roofing over when levees grow inward and meet at the center, and when fragments of channel surfaces accumulate downstream. Lava tubes are commonly found in locations where no channel has developed, such as on gentle slopes, so they must form internally. An original lava tube can be modified by subsequent flows filling it in or by thermal erosion causing it to become larger.

The spatial distribution (Fig. 1) of lava tubes in pahoehoe flow fields can provide information about lava flow emplacement. The extent to which a lava tube system fills a plane can be determined by measuring the fractal dimension, a measure of the extent to which an object fills a plane; for plan-view shapes, fractal dimensions lie between 1 (simple line) and 2 (completely filled plane). Using the box method (1), we measured the fractal dimensions of plan-view shapes of four lava tube systems. Their fractal dimensions are 1.25 to 1.34. These values are considerably lower than river networks, which are typically > 1.8 (2). This indicates that pahoehoe lava flows are not emplaced simply by a tube system that distributes the lava in an elaborate branching way; sheet flow accompanied by inflation must be important, consistent with recent observations of lava flows in Hawai‘i (3).

We also measured the cross-sectional areas of lava tubes in the 1970-1974 Mauna Ulu flow field on Kilauea Volcano and analyzed the data using a technique developed for crystal nucleation and growth (4,5); for tube size, we used the square root of the cross-sectional area. The data define a straight line (Fig. 2), suggesting that tube formation and growth is a steady-state process. We interpret this to mean that tubes form inside pahoehoe flows and grow. Growth occurs as a natural consequence of inflation and by coalescence of individual streams of lava, either at the advancing flow front (Fig. 3) or within the advancing sheet. Most tubes do not grow for a long time; their growth is impeded by cooling, local topography, and variations in magmastic pressure inside the flow.

THERMAL EROSION IN A LAVA TUBE

We investigated the role of thermal erosion in the evolution of the Honu'apo lava tube on the SE coast of the island of Hawai‘i. This is a flow from the SW rift zone of Mauna Loa, and is at least 13,000 years old (J.P. Lockwood, pers. comm.). The flow is tube-fed pahoehoe averaging 1.5 m thick, and it overlies two 'a'a flows, an ash layer, and another tube-fed pahoehoe flow (Fig. 4). The Honu'apo tube cut into the underlying flows to reach a dimension of 4.6 m high x 3.4 m wide, of which 1.9 m x 1.9 m has drained out (6). Thus, the tube cut -4 m below its original base. Using 3-5 m$^3$/s as an average volumetric flow rate for Hawaiian tube-fed pahoehoe (7) and assuming that the flow was 10 km long and 4 m wide flow, and that all thermal energy went into heating the substrate, we estimated an erosion rate of 5.4 cm/day over a period of 74 days once the country rock had reached critical melting temperature (making it soft enough to erode).
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INFERENCE FOR EMPLACEMENT OF FLOWS ON PLANETS

Lava tubes must play important roles in the emplacement of lava flows on the terrestrial planets, the Moon, and Io, especially in long (> 100 km) flows (8). Our work so far suggests that large pahoehoe flow fields will be emplaced as inflating sheet flows, with flow fronts supplied with lava from a tube system developed internally. Master tubes in such flows will grow by coalescence of streams of lava, inflation, and thermal erosion of the substrate. Tubes might form in long 'a'a flows; if so, they probably develop by roofing over of channels and can be subsequently modified by thermal erosion.