THE ROLE OF LAVA TUBES IN HAWAIIAN VOLCANOES

By Ronald Greeley[1]

ABSTRACT

Lava tubes develop from eruptions that typically involve: (1) moderate rates of effusion, (2) durations greater than one or two days, and (3) effusion of fluid lava (for example, pahoehoe) that has not been greatly degassed. Although some fountain-fed lava and aa flows can form lava tubes, such occurrences are rare in Hawaii. Lava tubes feed flows: (1) directly from the vent (acting as extensions of the conduit), (2) from various holding reservoirs (for example, lava ponds, lava lakes, filled pit craters), and (3) from flows on the flanks of volcanoes. Historical flows of greatest length in Hawaii were emplaced primarily via lava tubes, and many subaqueous flows involve lava tubes. Sustained flow of lava in tubes appears capable of erosion into preflow terrain. Photogeological analyses suggest that at least 30 percent of the flows (by area) on Mauna Loa, 58 percent of the flows on Kilauea, and 18 percent of the flows on Mount Etna were at least partly emplaced via tubes.

INTRODUCTION

Lava tubes have been mentioned frequently in the literature on volcanology in Hawaii. From his visit to Hawaii in the 19th century, Dutton (1884) wrote "Probably no great eruption takes place without the formation of several such tunnels ***. There are literally thousands of these tunnels throughout the mass of Mauna Loa ***. So numerous are these caverns that it seems as if they must form some appreciable part of the entire volume of the mountain."

This paper reviews mechanics of lava tube formation, considers their role in various aspects of eruptions in Hawaii (including the emplacement of lava flows), and assesses their occurrence in Mauna Loa and Kilauea Volcanoes (fig. 59.1). Three sources of data were employed in this study: (1) previous descriptions of active eruptions involving lava tubes, (2) photogeologic studies of channels and lava tubes and the associated flows on Mauna Loa and Kilauea, and (3) field observations of active and inactive flows.

In the last two or more decades, new insight has been gained about Hawaiian lava tubes. This insight has been the consequence of several factors, including an increased interest in the morphology of volcanoes in general and the eruptions of Mauna Ulu in particular. Lava tubes were common in many of the Mauna Ulu flows (Wood, 1981) and their formation was readily observed (Greeley, 1971a, 1972a; Cruikshank and Wood, 1972; Peterson and Swanson, 1974). The eruption was relatively accessible, which, combined with frequent aerial photography, resulted in an unparalleled data set on the initiation and evolution of lava tubes and their associated flows.

Numerous studies of lava tubes have been made in areas outside Hawaii, including Mount Etna (Guest and others, 1980), Mount St. Helens (Greeley and Hyde, 1972), and New Mexico (Hatheway and Herring, 1970). From these studies and those in Hawaii, lava tubes clearly reflect a particular style of volcanism and are the primary means for the spread of some types of lava flows.

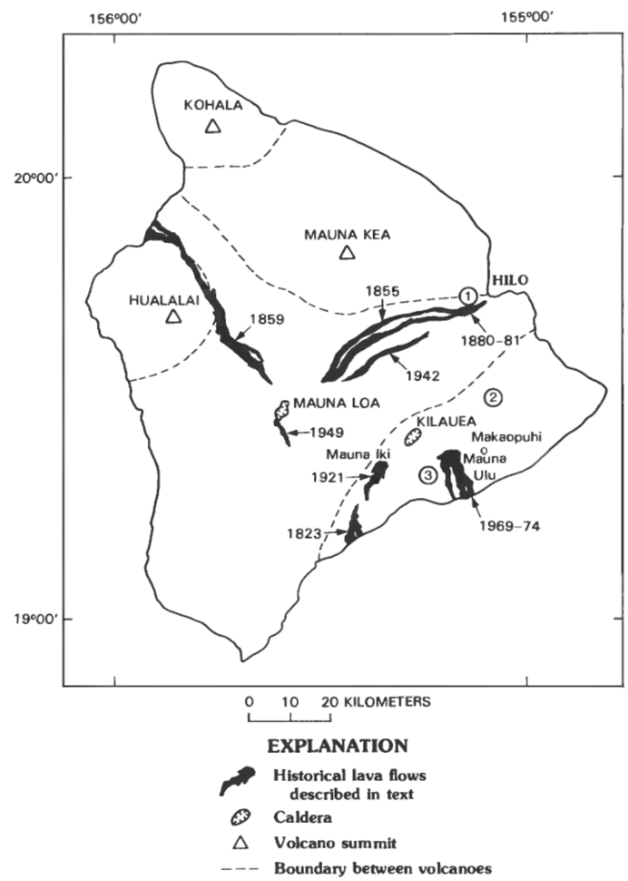

FIGURE 59.1.—Location map of some historical lava flows on Island of Hawaii, showing dates of flows and areas described in text: 1, Kaumana cave; 2, Kazamura cave; 3, Ainahou Ranch cave.

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Thus, analysis of prehistorical lava tubes can provide insight into eruption processes and the flows in which they occur.

The term "lava tube" may be defined as the conduit beneath the surface of solidified lava through which molten lava flows. "Lava channels," however, contain nonroofed rivers of lava that frequently develop surface crusts. Many (if not most) lava tubes develop from the roofing of lava channels. For discussion here, the distinction between channels and tubes is made in regard to the roof crust; so long as the crust remains mobile and free-floating on the active flow, the structure is regarded as a channel; sections in which the crust is continuous across the active flow and fixed to the immobile parts of the flow are considered lava tubes. Thus, even if the roof collapses when the flow drains, the feature is considered to be a lava tube. This distinction is important for considerations of heat loss and lava flow emplacement.

ACKNOWLEDGMENTS

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LAVA TUBE FORMATION

Various mechanisms of lava tube formation have been proposed and some have been confirmed by observations of active tubes—primarily in Hawaii.

CHANNEL-ROOFING

The most frequently observed mode of lava-tube formation involves roofing of lava channels. Roofing can occur in any of several ways, most of which appear to be partly related to the rate of flow and rheology of the lava. Where flow is sluggish to moderate ($\leq 1-3$ m/s) a crust may extend from the channel sides, meet near the middle of the active flow, thicken, and form a roof. Aerial views of this mode of formation show a medial bright zone (uncrusted lava) that closes like a zipper as roofing progresses along the flow (fig. 59.2).

Where channelized flow is more vigorous the crustal slabs are often torn free from the sides and are rafted downflow. Crustal slabs may also develop on the moving surface of the lava river. Analysis of photographs taken during the Mauna Ulu eruption shows that more than 50 percent of channel surfaces are commonly covered by these

FIGURE 59.2.—Aerial view of lava channel in process of roofing by formation of crust along channel margins; closure is occurring down middle of flow; bright area is unroofed; trees are about 12 m high. View is east. Photograph of Mauna Ulu eruption, August 1970.

crustal slabs. As they are rafted down the flow, stresses may fracture the slabs into pieces like a jigsaw puzzle. Their shapes permit the slabs to fit together well and allow the slabs to turn meander bends (fig. 59.3). At channel constrictions, however, the rafted slabs may jam together, fuse, and form a tube roof.

At moderate rates of flow (2–5 m/s), overflow of the channel banks by lava—as may occur during surges—often builds levees that grow upward and inward until they join (Holcomb and others, 1974). At still higher rates of channelized flow, splashing of lava along the channel also can produce levees of spatter that reach up and over the flow and merge to form a roof. This roofing mechanism commonly occurs where flows pass over steep gradients, as observed during Mauna Ulu eruptions in the filling of Alae Crater (Greeley, 1971a) and as flows crossed Hilina Pali (Holcomb and others, 1974; Swanson and others, 1979). Similarly, Jaggar (1921) described flow within Halemaumau in which lava "shot down the slope like a sluiceway" and roofed over to form a tube. However, such features may be short-lived. Jaggar noted that within one hour, surges of lava alternately destroyed and replaced the roof.

DEVELOPMENT OF TUBES VIA LAVA TOES

Some lava tubes form without involving a channel phase. Relatively slow-moving pahoehoe flows involve repeated budding of lava toes that can be several meters across at the flow front and along the flow margins. Depending upon poorly understood circumstances, but often involving topographic channeling, the budding and subsequent flow direction may localize, forming a primary conduit within the flow that develops as a lava tube. This mechanism was described by Wentworth and Macdonald (1953, p. 43) in which toes of lava broke free from the flow margin. The skin of the toes is plastic and stretches as the toe elongates. A crust quickly thickens to form a rigid shell, but continued flow exerts sufficient

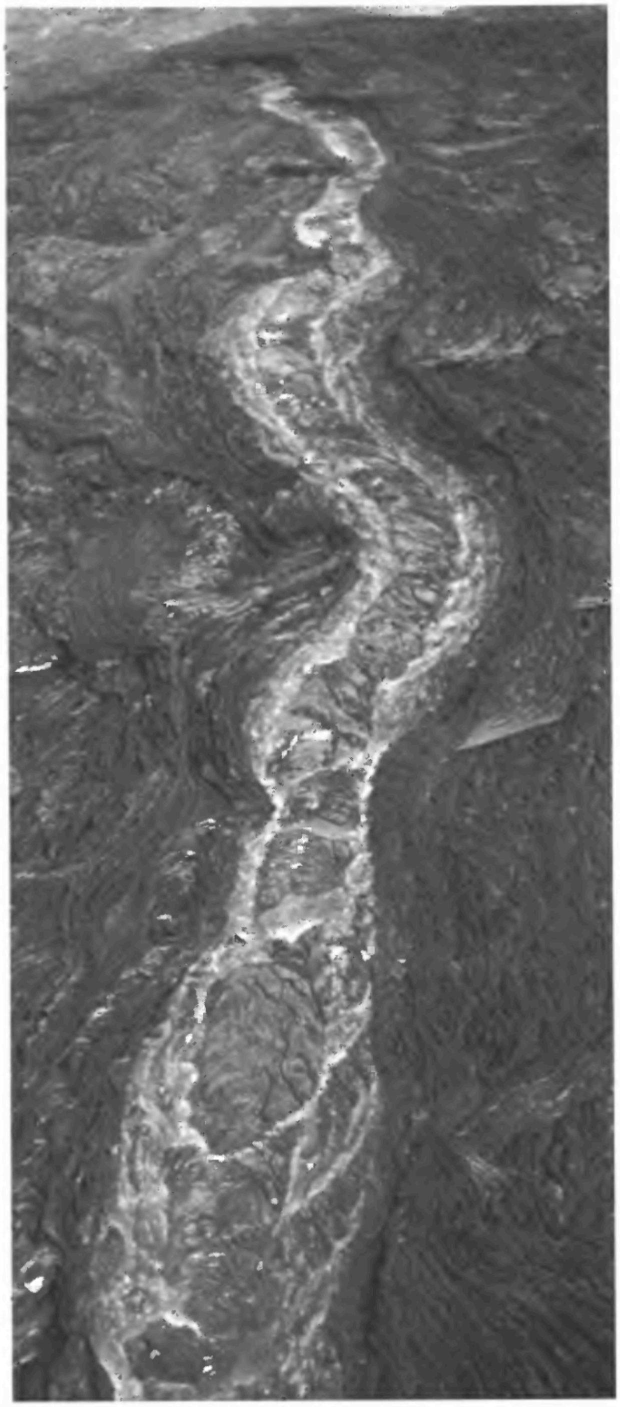

FIGURE 59.3.—Aerial view of channel (approximately 10 m wide) with rafted slabs of crust. Photograph of Mauna Ulu eruption, August 1970.

pressure to rupture the crust to produce a new toe. Repeated outbursts produce multiple toes, fed by an evolving lava tube.

This style of lava tube formation is invoked to explain complex networks of small lava tubes (fig. 59.4). In principle, it may also operate on larger scales. Many of the tubes formed by this mechanism, both large and small, may drain incompletely (or not at all) upon cessation of eruption. Some vast fields of hummocky pahoehoe are emplaced by such tubes and are termed "tube-fed pahoehoe" by Swanson (1973).

THE LAYERED-LAVA MECHANISM

From study of lava tubes principally in Australia, Ollier and Brown (1965) proposed that internal shearing within lava flows allowed conduits to develop between the shear zones. The conduits then evolved into lava tubes. Horizontal partings observed in some pahoehoe flows, along with features indicative of shear, are consistent with the concept on a small scale (<1 m), but evidence for this mode of formation for large lava tubes is absent in Hawaii (Peterson and Swanson, 1974).

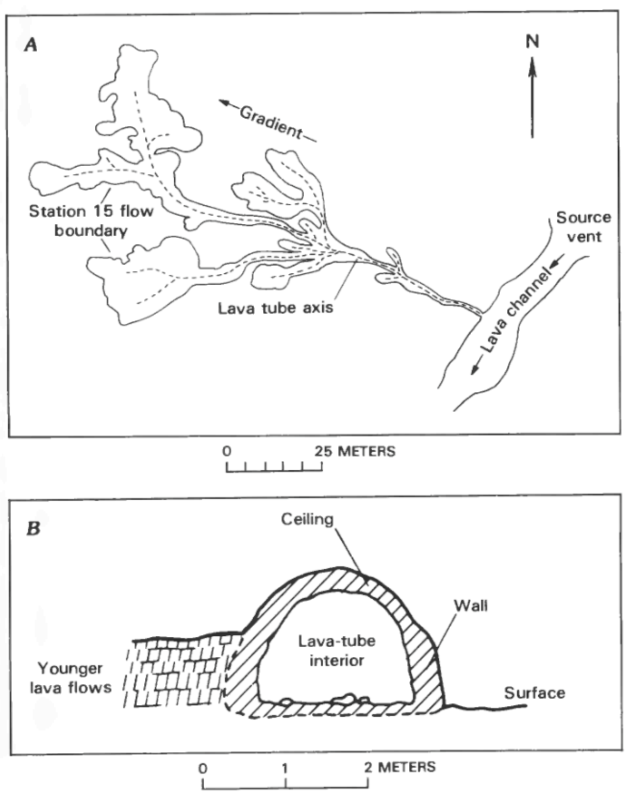

FIGURE 59.4.—Diagram based on plane-table survey of a small lava-tube network in California (south of Medicine Lake, Siskiyou County). ***A***, Distributary system of branches and toes. Nearly all branches contain hollow tubes (from Greeley, 1971b). ***B***, Simplified cross section of tube.

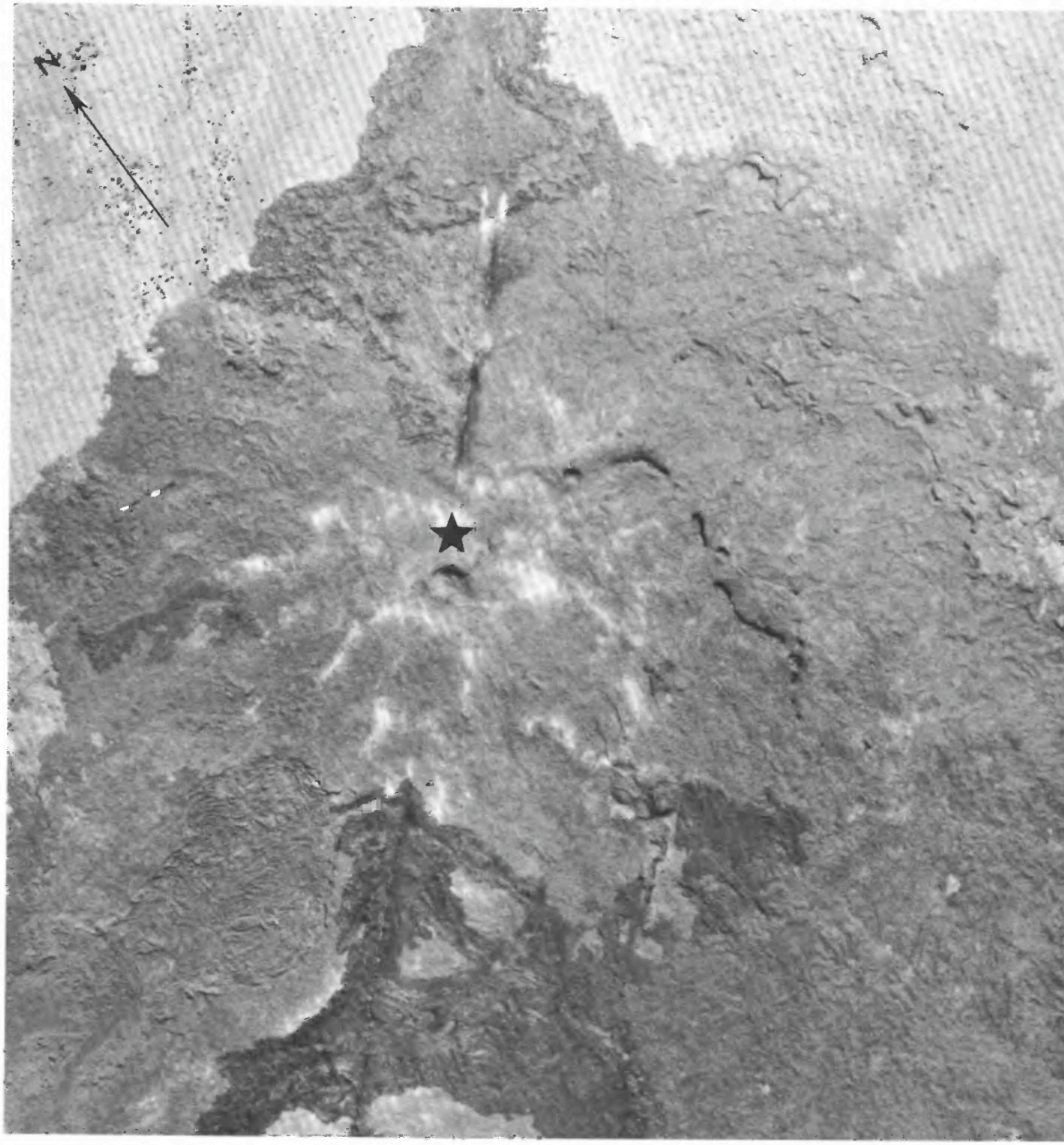

FIGURE 59.5.—Vertical aerial view of summit area of Mauna Iki; star marks summit pit crater; lava tube shown in figure 59.6 is southeast of summit area; area shown is about 1.5 km by 1.5 km. North is toward upper left. Photograph by R.M. Towill Corp., Honolulu.

ROLE OF LAVA TUBES IN FLOW EMPLACEMENT

Lava tubes are involved in many aspects of Hawaiian eruptions and can transport and emplace flows in various environments, including subaqueous settings. Observations of active flows in Hawaii (Greeley, 1971a; Peterson and Swanson, 1974; Holcomb, 1980) and on Mount Etna (Guest and others, 1980) in which lava tubes developed indicate that the eruptions had been occurring for more than one or two days before tube formation was initiated. Evidently, in order for tubes to form—either via channel-roofing or

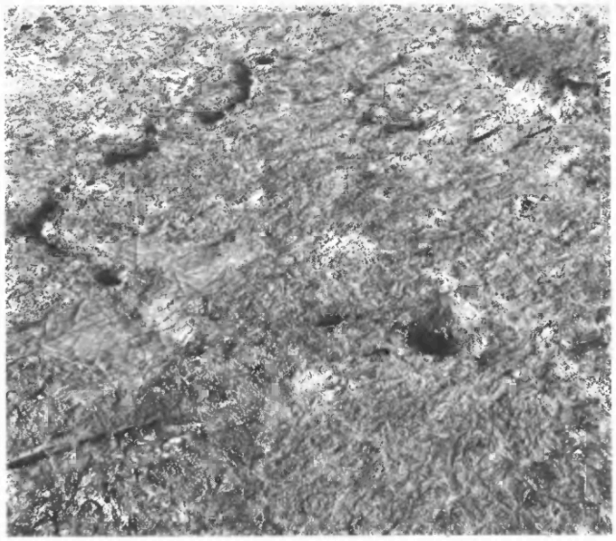

FIGURE 59.6.—Oblique aerial view across Mauna Iki summit area, showing collapses (skylights) that mark presence of lava tubes. View is south. Photograph taken summer 1974.

through advancing toes—effusion must be relatively stable for some minimal time, as discussed by Holcomb (1980). This stability is especially true for tubes formed in aa flows. Thus, it is rare for tubes to develop during the initial stages of eruption when the position of vents and flows are not fixed and the rate of effusion and fountaining are highly erratic.

NEAR-VENT ACTIVITY

Many eruptions involve multiple vents that may be interconnected by lava tubes. Jaggar (1921, p. 21) described this type of activity within the Halemaumau pit crater of Kilauea. In 1921, the crater consisted of multiple ponds and the lava rose and fell somewhat independently in each pond, although Jaggar also noted that active lava tunnels could be traced between some of the ponds. Sometimes, wall segments containing tunnels were exposed and showed that flows passed from one pond to another.

Although lava tubes rarely develop during the initial phases of eruption, tubes may form at or near the vent within a short time from onset of eruption. For example, the 1949 summit eruption of Mauna Loa (Macdonald and Orr, 1950) involved high-volume fountaining of lava that collected in a pool and fed several lava channels. Within a few days of the initial eruption, some of the channels had roofed over and were the main conduits for lava flowing southeast from the vent area.

Part of Mauna Iki, on the southwest rift of Kilauea, was constructed by flows spread via lava tubes issuing from the vent area (fig. 59.5). As described by Jaggar (1947, p. 142), three lava pools developed over the site that eventually grew to be the low shield volcano Mauna Iki. Effusion of lava resulted in repeated overspilling from the pools; some of the spillovers formed channels and tubes oriented radially to the growing summit. Some of the tubes carried lava directly from the vent area more than 7 km to the distal part of the shield. By the fall of 1920 the eruption ceased, and as the lava drained, large (~15 m in diameter) lava tubes (fig. 59.6) were exposed as connecting the summit craters. Thus, tubes not only provided intercommunication between the summit pools, but also emplaced some of the lava that formed the upper flows of the small shield volcano.

TUBES DEVELOPED ALONG RIFT STRUCTURES

Eruptions in Hawaii commonly occur along the rift zones of the major volcanoes, and fractures and open fissures can serve as channelways for flows. This activity is especially evident along the southwest rift zone of Mauna Loa. Lava flowing within the channelways may develop roofs by the same mechanisms described for open channels and form lava tubes within the rift (fig. 59.7). The term "rift-tubes" was suggested by Finch (1946) as describing passageways developed along fissures and rift zones as part of the magma conduit. He noted that many eruptions on the rift zones of Kilauea were preceded by a sinking of the lava column in Halemaumau pit crater and suggested a connection via such tubes. These connections are more properly considered part of the intrusive dike-feeding system of the volcano and are not included in considerations of lava tubes developed from flows.

LAVA TUBES RELATED TO LAVA LAKES

Lava tubes are often involved in both the draining and filling of lava lakes. Entrances to lava tubes are frequently seen in walls of vents (fig. 59.8) and these tubes are often reactivated by subsequent eruptions. Some tubes may partly drain lakes, but become blocked or do not reemerge at the surface. For example, Jaggar (1947, p. 432) described a lava tube about 4 m high and 6 m wide in the wall of Halemaumau. In 1917, lava rose in the crater to the level of the tube, and for several hours lava poured into the tube. No outlet was obvious, and Jaggar suggested that the tube was filled to produce a sinuous cylinder of intrusive rock. Filled tubes of this sort when seen in cross section may show radial joint patterns, described by Waters (1960) for features in the Columbia Plateau basalts as war bonnet patterns, which he considered as filled tubes.

The best documented interaction of lava tubes and lava lakes is the sequence of repeated filling and draining observed for Alae Crater (fig. 59.9) during the Mauna Ulu eruptions (Swanson and others, 1972; Swanson and Peterson, 1972). Beginning in May 1969, lava from Mauna Ulu intermittently spilled into Alae Crater, filling it nearly to overflowing by August. Repeated spillover resulted in accretion of lava that raised the crater rim by several meters. A lava tube developed within the overflows and by late October a

FIGURE 59.7.—Oblique aerial view toward summit of Mauna Loa along southwest rift zone; dark holes in foreground mark presence of tube formed along rift segments; outflows from some skylights have produced local flows. Photograph taken August 1970.

master drainage system fed a series of pahoehoe flows a few hundred meters southeast of the crater (Swanson and others, 1972). Eventually, however, drainage through the tube(s) ceased, possibly because of clogging by solidified lava or blocking of their entrance by subsiding lava-lake crust.

By the summer of 1970, the Mauna Ulu vents fed flows downslope in several directions. In early August, two prominent vents (fig. 59.9, vents 1 and 3) fed lava into Alae lake through open

FIGURE 59.8.—View of lava tube ~1 m wide in wall of summit crater of Mauna Ulu. Such tubes may be reactivated as lava rises within vent and spills into tube. Photograph taken August 1971.

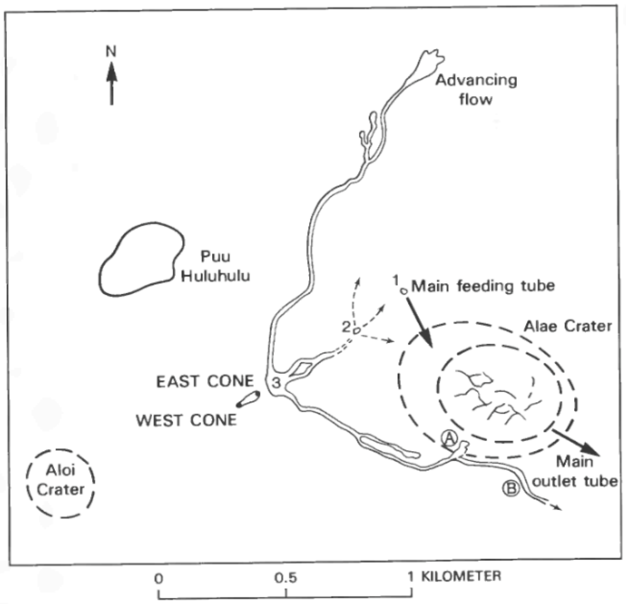

FIGURE 59.9.—Sketch map showing Mauna Ulu activity on August 8, 1970. Primary effusion was from vents 1 and 3, with flows from vent 1 entering Alae lava lake via a feeding tube. By afternoon, drainage of Alae Crater was taking place through an outlet tube to southeast. Southeast flow from vent 3 was via an open channel that initially (A) spilled onto crust of Alae lava lake; channel bypassed crater (B); dashed lines indicate preflow crater outline for Alae and Aloi.

channels (Greeley, 1971a), most of which emptied beneath the crust of the lava lake. One channel, however, appeared to form a tube that spread across the surface of the lake and fed small flows (fig. 59.10). Within one day, channels from the Mauna Ulu vents had nearly completely roofed over and continued to pour lava into Alae lake. However, a new channel had developed in flows from a newly reactivated vent on the fissure. Although the channel initially emptied on the lake crust, later in the same day (August 8, 1970), it bypassed the lake on the west side and fed flows to the southeast (fig. 59.9, A and B).

August 8 marked the beginning of the second episode of drainage of Alae lava lake. Aerial observations at about 0900 showed tube-fed flows that emptied into the lake. Sometime between these observations and midafternoon, drainage of the lake began, which resulted in subsidence of the lake crust by several meters (Greeley, 1971a). The subsidence formed a ring of tensional fractures in the lake crust (concentric to the former crater rim) and resulted in a series of pressure ridges as the crust slid inward toward the center of the ring (fig. 59.10). Swanson and others (1972) suggest that the lava tube that previously drained the lake was reactivated, perhaps as a consequence of increased pressure beneath the lake crust resulting from infilling. They suggest that the tube was 21–22 m below the surface and about 2–3 m above the preeruption level of the southeast crater rim. Subsidence of the lava lake crust continued for several days, after which the inflow was about equal to outflow via lava tubes. Lava emerged from the main outflow tube several kilometers downflow and fed a series of slow-moving pahoehoe flows. Over the next many months, tubes continued to carry lava from Mauna Ulu vents into the holding reservoir of the Alae lava lake, and then to feed lava to the flows spreading downslope to the south.

EMPLACEMENT OF LONG FLOWS VIA TUBES

The factors governing the lengths of lava flows have been of considerable interest to volcanologists and planetologists. With the discovery of extremely long flows on other planets (>1,000 km on the Moon and Mars), several assessments have been made of the viscosity, effusion rate, volume of lava erupted, and other parameters that might affect flow length (Walker, 1973). Many of these studies, however, have ignored the role of lava tubes, or given the matter only cursory attention. From his study of flows in Hawaii, Malin (1980) suggested that cross-sectional area, effusion rate, and volume of lava erupted were all important and that no single factor seemed more important. He also noted that tube-fed flows appeared to advance farther, all other factors held equal.

In some respects lava tubes act as extensions of the magma-feeding conduit. Because tubes are well insulated, little heat is lost and the lava can remain mobile longer than for nonchannelized flows or unroofed channels. Swanson (1973) measured a decrease in

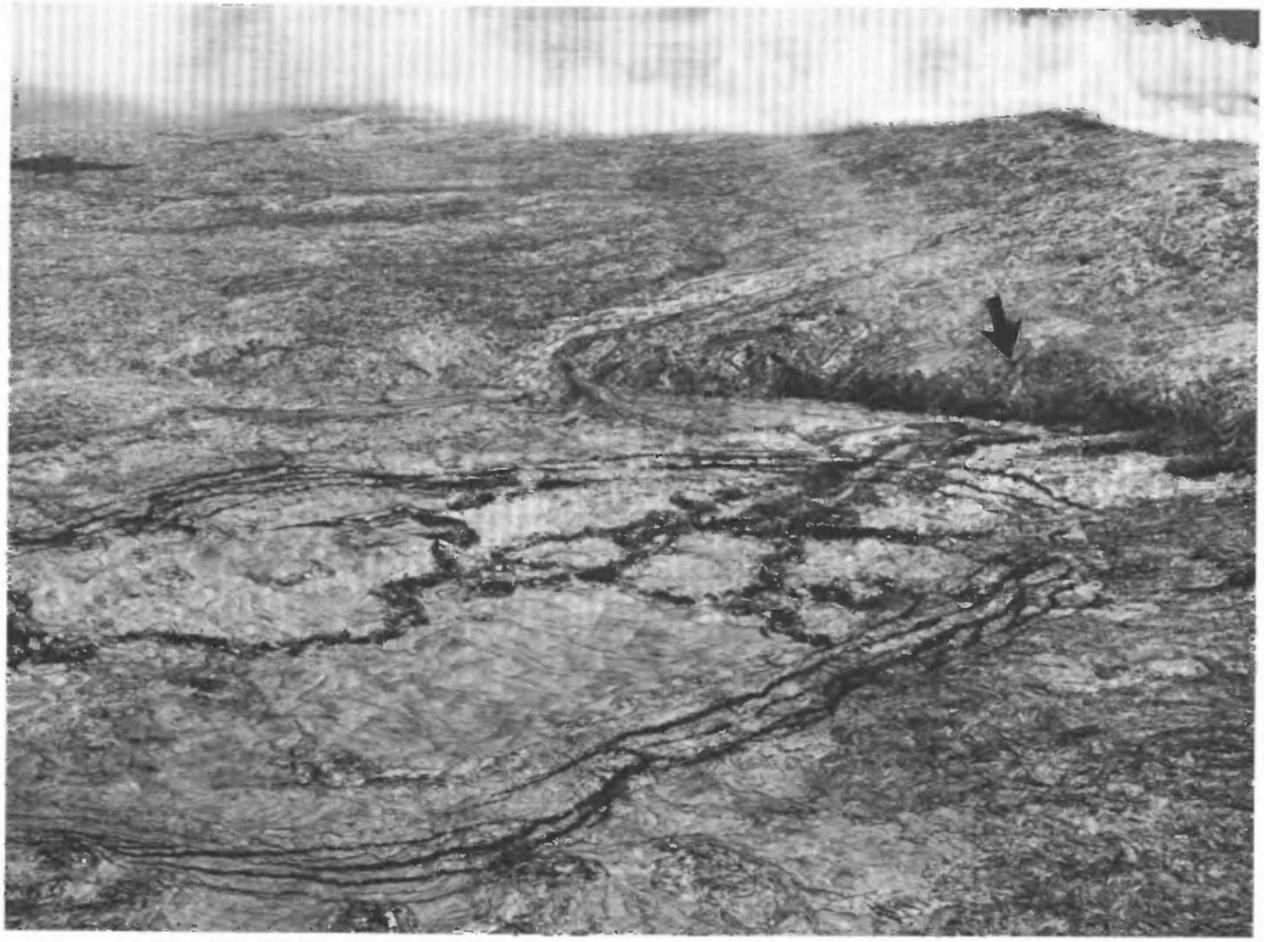

FIGURE 59.10.—Oblique aerial view across Alae lava lake taken in afternoon of August 9, 1970, after drainage of lake had begun via lava tube(s), showing concentric ring fractures and pressure ridges. Arrow marks small flows that spilled into lake from vents 1 (right side) and 3 (left side) and formed small tubes on lake crust. View is west. Photograph taken August 1970.

temperature of only 1–2 °C per kilometer for flow through a lava tube fed by eruption of Mauna Ulu. Even channel flow can be effective in heat retention if a thin crust is present. For example, the crust shown in figure 59.3 covers more than 55 percent of the active flow in the channel.

Two of the longest historical flows in Hawaii (fig. 59.1), the 1859 and the 1880–81 flows (both of Mauna Loa), were emplaced primarily through lava tubes. The 1859 flow erupted at the 3,355-m level and flowed more than 52 km to the sea (Stearns and Macdonald, 1946). The eruption lasted 7 months and extruded about 440×10^6 m^3 of lava (Macdonald and others, 1983, table 3.1). A complex lava tube system—in some places tube segments are more than 12 m across—can be traced through a series of collapsed sections visible in many sections of the flow. In some sections the tube exhibits complex anastomosing and vertically stacked branches, indicative of repeated eruptive surges and emplacement of multiple flow units (Greeley, 1972b).

The 1880–81 flow was erupted on the northeast rift zone of Mauna Loa (Baldwin, 1953) at about 3,325 m elevation. Lava issued quietly from an elongate fissure for 280 days and eventually reached nearly to the outskirts of Hilo. Except for some short aa flows, most of the lava was pahoehoe fed through a 40-km-long lava-tube system. Baldwin (1953) described the flow as follows: "At the advancing front the lava seems to come out of its tunnel and flow in an open red river of fire as much as several hundred feet long. This then appears to clog up and cool on top, and the lava pushes out in great and small lobes, piling one over the other and eventually forming a new tunnel underneath for the molten lava. The latter will then again break out and go through the same process as before." Kaumana cave is a section of this tube near Saddle Road a few kilometers from Hilo and is open to the public (Greeley, 1974).

The 1880–81 flow can be contrasted with the 1855 Mauna Loa flow, which it parallels for some of its length. Both the 1880–81 and the 1855 flows advanced slowly at a rate of only a few tens or hundreds of meters per day on the middle and lower slopes (Macdonald, 1958). However, the 1855 eruption lasted 450 days and involved vigorous fire fountaining. Most of the flow was aa and did not form tubes. Even though the duration of the eruption was greater than the 1880–81 eruption (Macdonald and others, 1983, table 3.1), the flow is much shorter. Evidently, the fountaining caused outgassing of the magma such that the lava was dominantly aa, and lava tubes were not able to form.

During prolonged eruptions, lava tubes—once established—may be reactivated. Interiors of cooled tubes show evidence of multiple flow, including multiple linings of the walls and flows that only partly drained from the tube. As shown in figure 59.11, surface flows near the summit of Mauna Iki spilled into a tube system; similarly, the copious flows of the 1823 Keaiwa eruption of Kilauea (Stearns, 1926) emptied into an older tube at about 220 m elevation. In most cases, flow does not reemerge at the surface, but evidently blocks or fills the tubes. Occasionally, however, flows will intersect older lava tubes, drain into them, and reemerge in another place. For example, Macdonald (1943) described the 1942 flow of Mauna Loa as erupting at the 2,800-m level; lava also issued quietly 5 km downslope at the 2,380-m level, and Macdonald speculated that lava entered an old lava tube that intersected the eruption fissure higher up the mountain.

Emergence of lava from tubes—both primary tubes and reactivated systems—can produce flows and surface features different from the surrounding lava. Patches of seemingly anomalous pahoehoe set within aa flows (fig. 59.12) possibly can be emplaced through lava tubes. Similarly, tubes intially established in pahoehoe may transport subsequent flows of different properties. Macdonald and Orr (1950) noted that during the 1949 eruption of Mauna Loa, sluggish aa flows were fed by earlier formed lava tubes in the summit area.

Pressure of lava backed up within a tube may inflate the roof into small domes or may rupture the roof. Skylights—formed by collapse of roof sections—often became rootless vents and produced local flows (fig. 59.7) during surges that spilled lava from the tube.

FIGURE 59.11.—View of flows near summit of Mauna Iki that spilled into ~15-m-diameter skylight of lava tube. Photograph taken August 1970.

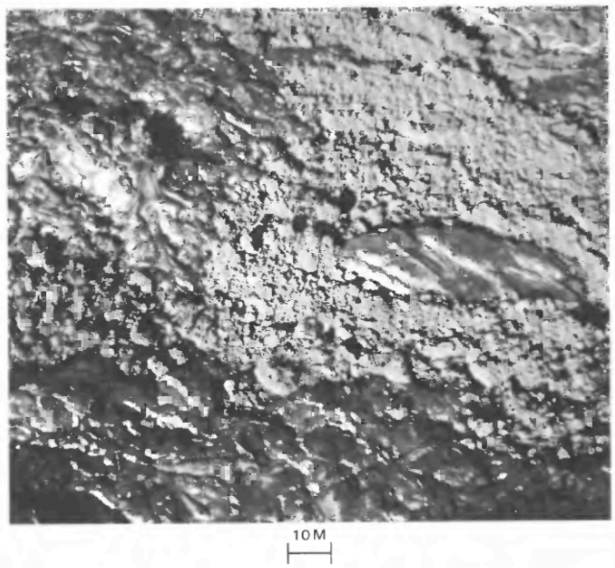

FIGURE 59.12.—Low oblique aerial view of patch of pahoehoe lava (smooth, shiny material) set within aa flow. Pahoehoe flow was possibly emplaced through lava tube. Photograph taken August 1970.

TALUS-AND-LAVA CONES

Lava flows often spill over steep cliffs and form features termed by Holcomb and others (1974) as "talus-and-lava cones." In observing flows that filled Makaopuhi Crater in 1972, they noted that some larger streams of lava cascaded over the crater rim onto the apex of these talus cones and developed lava tubes that transported flows over the cone and onto the crater floor. Some tubes extended from the crater rim to the apex of the cone, as well as through the cone. As observed by Swanson (1973), pahoehoe flows passing over such steep slopes ordinarily evolve to aa; however, development of tubes enables the flows to remain as pahoehoe.

LAVA DELTAS AND SUBAQUEOUS FLOW EMPLACEMENT

Many historical flows have reached the sea, and the addition of land through the accumulation of lava has been observed often (Peterson, 1976). The role of lava tubes, however, was not appreciated until the underwater observations by Moore and others (1973) for active flows erupted from Mauna Ulu. They noted a sequence of seaward extension of the advancing lava that began with flows spilling over the seacliff. As the hot lava poured into the sea water, it was quenched and fragmented into glassy sands and rubble that was further churned by wave action. This material accumulated to

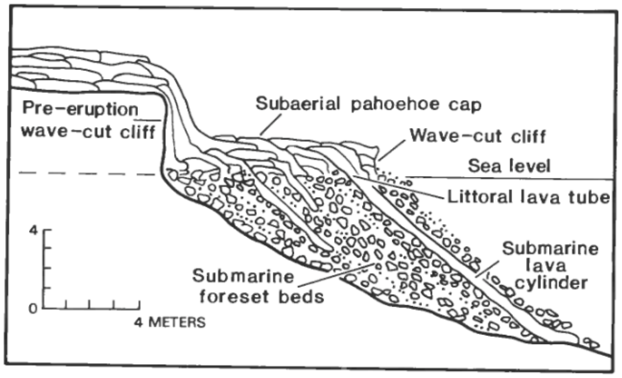

FIGURE 59.13.—Cross section of flows and delta built by Mauna Ulu lava entering the sea (from Peterson, 1976, which was modified from Moore and others, 1973).

produce foreset volcaniclastic deposits as an expanding lava delta (fig. 59.13). Some of the flows were fed by lava tubes; smaller tubes extended as pahoehoe toes that also were quenched and fragmented, whereas some larger tube systems moved forward rapidly enough to maintain coherence through the wave zone and established submarine lava flows. Peterson (1976) termed these "littoral lava tubes" and noted that their formation by abrupt quenching distinguishes them from tubes formed in subaerial environments. Once established, the submarine lava tubes fed complex, anastomosing networks of flow lobes that advanced as budding toes of lava.

Through alternation of volcaniclastic accumulation and tube-fed emplacement, the Mauna Ulu flows built a 470,000-m^2 delta to a depth exceeding 70 m. Moore and others (1973) note that many prehistorical flows from Kilauea display similar morphologies and suggest that the sequence they observed may be typical for many of the flows reaching the sea. Since their observations, dives by deep-sea submersibles around Hawaii (Fornari and others, 1980) and in areas of active sea-floor spreading in both the Atlantic and Pacific Oceans have led to the discovery of numerous submarine lava flows, many of which were emplaced via lava tubes (Heirtzler and Bryan, 1975). Thus, just as the emplacement of subaerial lava flows may be facilitated by lava tubes, substantial submarine lava may also involve flow through tubes.

EROSION BY LAVA TUBES

Several lines of evidence suggest that flow within lava tubes is capable of both downcutting and lateral erosion. Detailed mapping of lava tubes in Hawaii (Wood, 1981), in California (Greeley and Baer, 1971), and in basalt flows of Mount St. Helens shows the crosscutting relations of the flows and tubes to the preflow terrain (fig. 59.14). Wood noted that the thin wall of the Ainahou Ranch cave of Kilauea collapsed into the tube and exposed an older aa flow that he suggested had been eroded by the tube. In California and at Mount St. Helens, the preflow rocks are distinctive from the basalt flows and were easily recognized. In the Mount St. Helens tubes, pieces of preflow rocks—some as large as one meter across—were carried by lava down the tube and are further evidence of mechanical erosion (Greeley and Hyde, 1972). Blocks of solidified lava are also observed in Hawaii in open lava channels; Finch and Macdonald (1950) reported that blocks as large as 6 m high and nearly 10 m long were carried by lava in channel flow during the June 1950 eruption of Mauna Loa. Although these blocks were probably not from preflow lava, they indicate the capacity of flowing lava to transport large masses of solidified lava, and large blocks possibly are also often carried within lava tubes in Hawaii.

Erosion by melting or partial melting is more difficult to document. However, in one section of the Mount St. Helens tubes (Greeley and Hyde, 1972), a block of dacite from the preflow

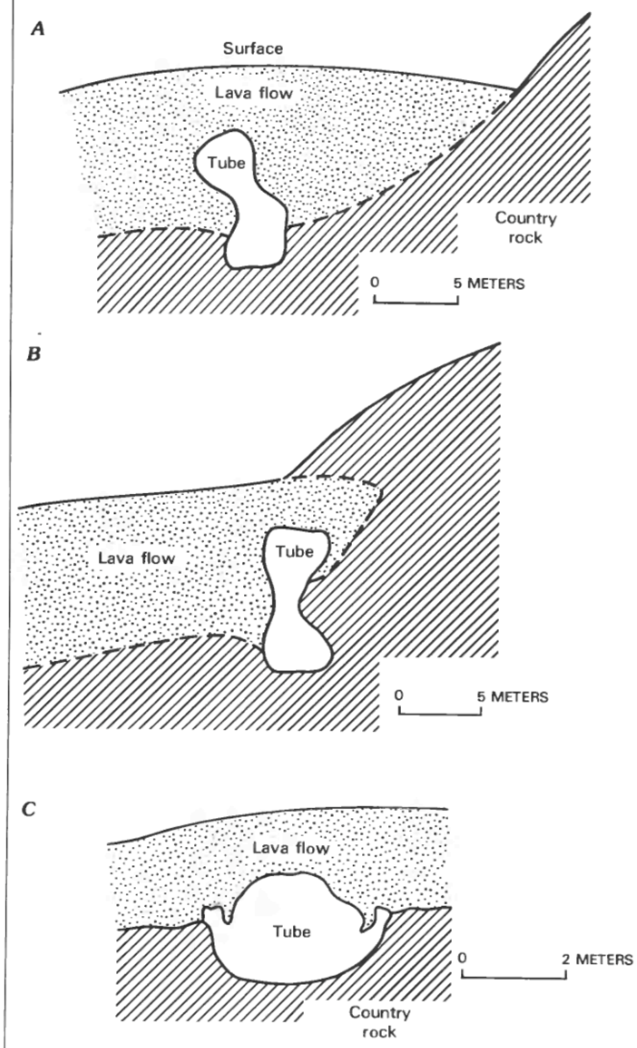

FIGURE 59.14.—Cross sections generated from surveys showing probable erosion by flow within a lava tube. ***A***, ***B***, Ape cave in Mount St. Helens (Wash.) basalt flows (from Greeley and Hyde, 1972). ***C***, Ainahou Ranch tube, Kilauea (surface of lava flow shown schematically, from Wood, 1981).

terrain was heated above the melting temperature for some of the minerals and flowed into the tube through a wall collapse and dripped onto the floor of the tube. Samples taken from the block were heated in a laboratory furnace at temperatures of 1,000 °C, 1,100 °C, 1,150 °C, 1,200 °C, 1,250 °C and 1,300 °C. After one hour, only the samples heated above 1,200 °C showed signs of melting, and it is assumed that a comparable temperature was reached when the lava tube was active. Thus, erosion by partial melting may also have contributed to entrenchment of the tube.

The examples cited above involved preflow rocks that were mostly unconsolidated and of a lower melting temperature than basalt. However, erosion of basalt by lava-tube flow may also occur, as proposed by Carr (1974) from theoretical models and suggested by Peterson and Swanson (1974) from observations of Mauna Ulu flows. Although direct evidence was absent, Peterson and Swanson inferred that the gradual lowering of the flow level in a Mauna Ulu tube (observed through a skylight) reflected downcutting. They noted that the rate of effusion and the rate of flow through the tube was constant and that the lowering of the flow level could not, therefore, be simply a diminution of flow volume.

It is not known if temperatures above melting for basalt are sustained in lava tubes. Several measurements, however, show that high temperatures do occur within tubes as a consequence of burning gases. Macdonald and Eaton (1964) noted during the 1955 eruption in East Puna that temperatures at the flow front for freshly exposed lava were 930–970 °C, but that blue flames were also visible within grottos where temperatures were measured at 1,025 °C. The flames and high temperatures were attributed to burning of gases generated from vegetation buried by the flow. Similarly, Jaggar (1947) described blue flames observed through cracks in a lava-tube roof formed in the Postal Rift flow of 1919 on the floor of Kilauea caldera. This gas probably was not generated from vegetation, but rather was magmatic gas. Cruikshank and others (1973) observed the burning of hydrogen at Mauna Ulu vents and measured temperatures well above the melting point for basalt. The conclusion is that temperatures can be reached within lava tubes that are sufficiently high to melt or at least soften the basalt, but it is not known if widespread melting of preflow rock occurs.

LAVA TUBE ABUNDANCES

In an attempt to determine the relative importance of lava tubes in the evolution of Hawaiian volcanoes, the abundance of lava tubes and associated flows was assessed for Mauna Loa and Kilauea. For comparison, a similar analysis was made for Mount Etna, Sicily. Although the methods of data collection were somewhat different for the cases studied (making comparisons less than ideal), the results demonstrate that for some basaltic volcanoes—especially in Hawaii—lava tubes play a key role in the volcanic history.

MAUNA LOA

Lava flows and associated tubes and channels were mapped on aerial photographs for sparsely vegetated parts of the shield (Greeley and others, 1976), representing summit, flank, and rift areas (fig. 59.15). Using 81 aerial photographs (U.S. Department of Agriculture, 1:20,000), about 15 percent of the shield was mapped on stereoscopic photographs and an additional 10 percent was mapped with monoscopic images; thus, about one-quarter of the areal extent of the volcano was analyzed. Lava tubes were identified by the presence of collapsed skylights, but because uncollapsed tubes could not be seen on aerial photographs, the value given for lava-tube frequency is a lower limit. Moreover, only exposed flows were examined. Thus, units buried by younger flows, those below sea level, and those covered by heavy vegetation are excluded.

For each photograph, a map was prepared that delineated the flow units and the presence or absence of lava tubes and channels. Three types of flow units were delineated: (1) those containing predominantly lava tubes, (2) those containing predominantly lava channels, and (3) those lacking tubes or channels. Areas for each flow unit were determined using a planimeter. Limited field work and comparison with maps (for example, Macdonald, 1971) provided additional data; ground checking of the photogeology was done for flows intersected by roads on the west flank of Mauna Loa and in the Saddle area.

The data were compiled on the basis of the percentage of the flows by area that were at least partly emplaced via lava tubes. The results show that 30 percent of the area is covered by flows spread at least partly via lava tubes. If channels are included in the analysis the percentage rises to 83 percent.

KILAUEA

Some of the longest uncollapsed known lava tubes in Hawaii are within Kilauea lava. For example, the Kazumura cave on the northeast flank has been mapped for more than 11.7 km and is only one of several large tubes in the area (Wood, 1981). Ainahou Ranch cave, in a flow on the southern flank of Kilauea, is more than 7 km long. To determine the frequency of lava tubes for Kilauea, data for Kilauea were compiled from mapping by Holcomb (1976, 1980), who noted the presence of lava channels and tubes and classified flows by age, morphologic assemblage (for example, small lava shield), and morphologic-lithologic type (for example, tube-fed pahoehoe). Holcomb's mapping is based on aerial photographs, supplemented with data from field work by himself and Wood (1981).

Holcomb's map for Kilauea shows both flow boundaries and the trace of lava tubes. Areas for the flows containing lava tubes were found to represent 58 percent of the surface area for Kilauea. It should be noted that some of Holcomb's tube-fed flows were excluded from this analysis, as only those flows in which he indicated the presence of tubes were employed.

MOUNT ETNA

The presence of lava tubes in flows on Mount Etna was determined from data in Brunelli and Scammacca (1975) and Bella

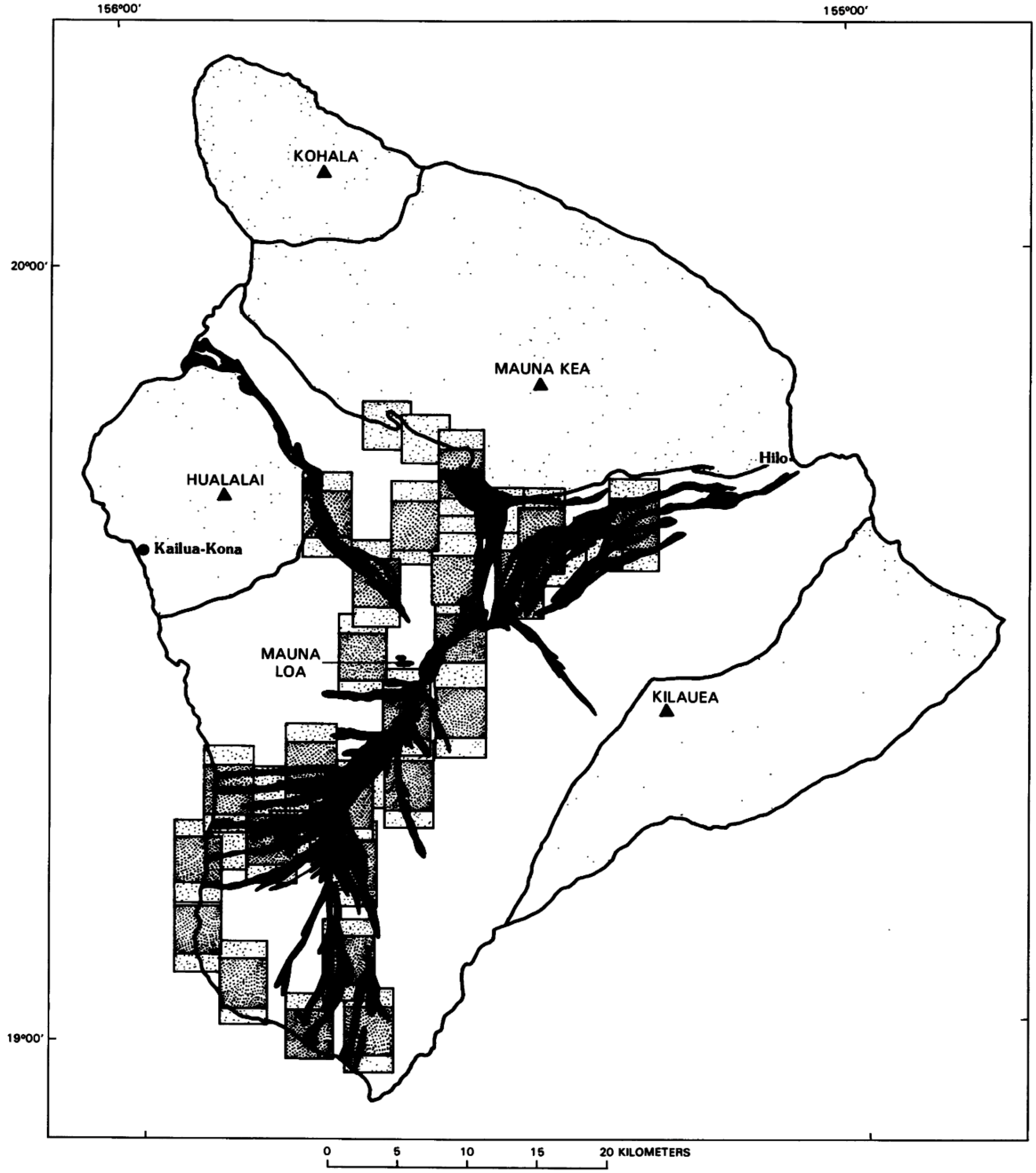

FIGURE 59.15.—Sketch map showing areas of Mauna Loa analyzed for lava tubes; rectangles outline aerial photographs studied; heavy stipple indicates stereoscopic coverage. Solid black, historical flows.

and others (1982), and supplemented by photogeologic study, limited field work, and discussions with members of a speleological organization in Catania, members of which routinely search for and map lava tubes on the volcano. Locations of lava tubes (longer than 100 m) from these sources were plotted on the geologic map of Mount Etna (Romano and others, 1979) and treated statistically like the Hawaiian volcanoes. Of the total surface area of Mount Etna flows, 18 percent was emplaced at least partly via lava tubes.

DISCUSSION

Studies of active and inactive flows show that lava tubes are involved in many aspects of Hawaiian eruptions. Rarely are either tubes or channels produced in the early phase of eruption, regardless of flow type (aa, pahoehoe, or others). Thus, short duration eruptions (that is, less than one or two days) seldom produce lava tubes (Holcomb, 1980). The often-stated comment that lava tubes form nearly exclusively in pahoehoe flows appears to be correct, although some tubes are documented in aa flows (Wentworth and Macdonald, 1953). Guest and others (1980) note that tubes are often found in aa flows near vents on Mount Etna formed from long-duration eruptions. Not all pahoehoe flows develop lava tubes, however, and factors other than the rheology must be involved. These factors are at least partly related to the style of eruption, especially in regard to the vigor, rate, and duration. Highly vigorous eruptions, as reflected by fire fountaining, cause rapid changes in flow regime and lack well-defined channels to evolve to tubes. In addition, fire fountaining may degas the lava rapidly (Swanson and Fabbi, 1973), producing aa flows, most of which are too viscous to form roofs, or producing degassed pahoehoe which may not become channelized.

High rates of effusion, exemplified by the 1823 flow of Kilauea, may spread out rapidly as sheets and fail to become channelized. Moreover, high effusion is often associated with fissure vents in which the zone of eruption shifts along the fissure; as such, there is not a focused flow of sufficient duration for channels and tubes to develop. Thus, the presence of lava tubes (Holcomb, 1980, chapter 3) reflects a style of volcanism involving moderate rates of effusion and durations typically greater than one or two days, and eruption of relatively fluid lava (for example, pahoehoe) that has not greatly degassed.

Lava tubes may transport lava between vents, along rift zones, and directly from vents to flow fronts. They are effective conduits for the emplacement of the longest flows on Hawaii and play a critical role in the submarine extension of many flows. Although not well documented in Hawaii, erosion by both thermal (melting) and mechanical (plucking) means appear to take place by flow within some tubes.

Analysis of Mauna Loa, Kilauea, and Mount Etna volcanoes shows that lava tubes were involved in the emplacement of one-fifth or more of the flows exposed at the surface. Differences in the percentages for the three volcanoes studied may reflect differences in data analysis or may represent differences in evolution or stage of development. Nonetheless, their high occurrence in all cases demonstrates that lava tubes emplace many of the flows in the evolution of basaltic volcanoes.

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