N71-18965

NASA TECHNICAL
MEMORANDUM

NASA TM X-62,014

NASA TM X-62,014

OBSERVATIONS OF ACTIVELY FORMING LAVA TUBES AND ASSOCIATED STRUCTURES, HAWAII

by Ronald Greeley

Ames Research Center
Moffett Field, Calif. 94035
March 1971

OBSERVATIONS OF ACTIVELY FORMING LAVA TUBES AND ASSOCIATED STRUCTURES, HAWAII

Ronald Greeley

Space Science Division

Ames Research Center, NASA

Moffett Field, Calif. 94035

Abstract - Observations of active basalt flows in the Upper East Rift Zone of Kilauea Volcano, Hawaii, and considerations of previous flow descriptions permit speculation on mechanisms of lava tube and channel development. Fluid basalts were erupted in August, 1970 (period of observation), from a vent near Alae Crater and flowed southeast across Chain of Craters Road toward Poliokeawe Pali and the sea, all within Hawaii Volcanoes National Park. Forming exclusively in pahoehoe (fluid) basalt, tubes in general evolve from lava channels by crustal formation, although some tubes develop directly from the vent. Observations discussed here show that channel crusts and tube roofs form in several ways: 1) accumulation and thickening of thin surface scums which are fused together and attached to stationary channel sides; 2) accumulation and fusing of flexible, mobile crustal plates; 3) formation of stable, well-defined crusts along both channel sides; crusts grow to the center of the channel and merge; 4) agglutination of spattered lava in turbulent flows to form lateral levees; levees may arch over the channel and fuse; and 5) accretion of lava toe and lobe crusts at the flow front, extending an existing lava tube at about the same rate as the advance of the flow. Lava channels/tubes usually form along the axis of highest velocity within the flow and are often centered along older lava channels/tubes, stream beds, rifts, grabens, or fracture zones. Repeated flows or flow surges can result in vertically elongated tube cross sections or multiple stacked lava tubes or both.

1. INTRODUCTION

Interest in volcanic landforms has recently increased through the interpretation of these structures as terrestrial analogs to lunar and planetary surface features. The basaltic composition of lunar *mare* surfaces, shown by *Surveyor* results (Turkevich *et al.*, 1968) and *Apollo* samples (Hess and Calio, 1969), and possible basaltic composition of Martian surfaces (O'Conner, personal commun.), make terrestrial basaltic terrains particularly interesting. Several independent studies have shown a correlation between lava channels/tubes (which form only in basalt) and lunar sinuous rilles (Oberbeck *et al.*, 1969; Howard, 1969; Hatheway and Herring, 1970; Greeley, 1971). Most of these studies attempted to explain lava tube formation from one or two published accounts of active flows or from field work in prehistoric lava flows. Although some observations of active lava tube formation have been made (primarily for Hawaiian eruptions), the descriptions are scattered through the literature and often are incomplete. This report summarizes most of the previous observations and gives an account of lava channel and tube formation during part of the 1970 eruption along the Upper East Rift Zone of Kilauea Volcano, Hawaii.

I wish to acknowledge the field assistance of M. Lovas and the service provided by pilots T. Lodge and W. Griswold for airborne observations. I also thank Rangers G. Balaz and A. Hewitt of Hawaii Volcanoes National Park for providing access to the eruptions. This investigation was made during tenure as a National Academy of Sciences-National Research Council Research Associate.

2. HISTORICAL REVIEW

Although there are several references to active flows within lava tubes, there are relatively few published accounts of tubes during active formation. One report (Baldwin, 1953) describes observations of the 1880-1881 lava flow of Mauna Loa. Most of this 55-km flow, originating near the summit of Mauna Loa, advanced toward Hilo through tubes. Baldwin observed (1953, p. 3),

> "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."

He also noted that the system consisted of a central supply tunnel 3 to 16 m wide with numerous smaller branch tunnels (distributary tubes) extending from the main tube. The smaller tubes often clogged up, resulting in sudden outbursts of lava which was flung into the air, forming spatter. Flow within the main tube was measured at 70 km/hr.

In 1921, Jaggar wrote of lava tube formation in flows within Halemaumau pit crater of Kilauea. He described (1921, p. 22) very rapid lava flow down a narrow channel ("sluiceway") which closed itself by crusting over to form a tunnel. Lava within the sluiceway, where not crusted over, built up the sides of the channel and eventually formed an arched roof. He noted that gushing lava alternately destroyed and replaced the roof several times in the course of an hour.

Wentworth and Macdonald (1953, p. 45) cited H. T. Stearns' observations of the 1935 Mauna Loa eruption and Macdonald's observation of the 1942 Mauna Loa eruption, in which lava tube formation was described as surface crusting of a lava river. The roof thickened by the accretion of congealed lava *beneath* the crust. Eventually, molten material drained from beneath the crust and left a hollow void, or lava tube. They noted that tubes up to 16 m in diameter developed, but that the roof seldom remained unbroken throughout its length. Instead, "windows" (or perhaps more properly *skylights*, a term used by speleologists) broke through the roof to reveal flowing, molten lava within the tube. In addition, Wentworth and Macdonald (1953) noted surges of lava overflowing the tube (thickening the roof and burying the tube) and outflow of lava from the tube through skylights to form thin layers of lava over the roof. In describing the 1949 Mauna Loa eruption, Macdonald and Orr (1950, p. 10) noted that channels leading from lava fountain activity were initially open, but soon formed tubes, presumably by crusting over. Finch and Macdonald (1950, p. 8) described the Kahuku Flow of the 1950 Mauna Loa eruption in which tubes were formed by the lava river developing a crust, or skin, of wrinkled and ropy pahoehoe (fluid variety of basalt, in contrast to viscous aa basalt).

From these descriptions, there are at least three ways lava tubes form. The first, which seems to be the most widely accepted (if only for lack of knowledge), is a simple crusting-over procedure of an open channel, or lava river. If the crust develops sufficiently thick to support its own weight, then a lava tube results when molten lava drains from beneath the crust. Crustal formation can occur any time or place along the channel if flow conditions are favorable (i.e., nonturbulent). The second mechanism, described by Baldwin (1953), apparently takes place near the advancing flow front and consists of a complex system of overlapping and coalescing lobes of lava, each of which cools and becomes part of the tube roof. As the series of flow lobe formation-accretion continues, the system advances downslope and the lava tube lengthens. The third mechanism was described by Jaggar (1921) for rapid lava flow in narrow channels. Channel banks are built up by overflow of lava and by spatter-accretion. They eventually arch over the channel and merge, forming a roof and lava tube.

3. OBSERVATIONS OF ACTIVE LAVA TUBES AND CHANNELS

The Upper East Rift Zone of Kilauea Volcano can be traced through a series of pit craters known collectively as the Chain of Craters (FIG. 1). Some of the craters are connected intermittently by *en echelon* fractures and grabens. Eruptions of pahoehoe and aa basalt, occasionally with fountaining, have been occurring sporadically since the spring of 1969. From August 7 to August 11, 1970 (the period of observation described here), activity was restricted to pahoehoe flows emitted from one vent area situated in about the middle of a triangle with points at Aloi Crater, Alae Crater, and Puu Huluhulu cinder cone. Prior to August 7, a small shield volcano had accreted about 100 m high around Main Vent (FIG. 2a). Flows extended less than 1 km to the west, completely filling and obliterating Aloi Crater, and several km southeast and south across Chain of Craters Road toward Poliokeawe Pali and the sea. Although nearly filled with lava, Alae crater is drained sporadically through a graben-rift to the east (Jackson and Swanson, 1970) and possibly through other outlets, keeping the lava lake level a few meters below the former crater rim in most places. On occasion, however, flows have overrun the rim on the lower, east side of the crater.

At the time of observation, Main Vent was an elongate crater about 90 m long × 30 m wide with spatter ramparts several m high at each end. Several partly collapsed and inactive lava tubes extended from the vent.

Although the cauldron was always filled with molten lava to within a few meters of the rim, at no time during observation did lava overflow Main Vent. Main Vent, Vents 2 and 3, and Lower Vents are aligned northwest-southeast, subparallel to the general trend of the rift system. The vents apparently are situated along a rift and connected, but it was not possible to determine the depth of connection. As indicated in Figure 3, Vent 2 and Lower Vents are possibly rootless vents.

Limited ground observations were made from the western edge of flow activity near the position of former Aloi Crater and at a small lobe of the flow front immediately preceding the flow's crossing Chain of Craters Road near Poliokeawe Pali. Photography and aerial observations were made from light fixed-wing aircraft and helicopter on five occasions during the period of observation. Flow dimensions and velocities are approximations made during observation and derived later from photographs.

Friday Morning, August 7 (FIG. 2a)

Molten lava within Main Vent cauldron was turbulent and splashing; cooled crustal plates several m in diameter were, however, able to form on the surface of the lava. As the plates formed, they shifted to the east end of the cauldron and with the molten lava, appeared to drain from Main Vent toward Vent 2. No lava issued from Vent 2 at this time, rather, the lava appeared to flow along the possible rift to Vent 3. A spatter rampart about 6 m high had accreted on the upslope side of Vent 3. Although lava issued as broad sheets in all directions from Vent 3, four main channels or groups of channels could be defined. One channel, partly covered with mobile crustal plates (FIG. 4) carried lava to the north edge of the flow. Another flow connected with the lower Vents through a crusted channel. The third flow consisted of a series of braided channels trending straight downslope to Alae Crater, submerging beneath the crust of the lava lake. Most of the channels were partly covered with mobile crustal plates and were interconnected. The main flow curved to the south through a series of braided, ill-defined channels. Where the gradient steepened over the partly buried rim of former Alae Crater, the channels coalesced to one main channel and flow increased to a maximum estimated velocity of 26 km/hr. The main channel and one distributary channel were discernible about one-third of the way across the lava lake before they submerged beneath the crust.

At the Lower Vents, lava issued in broad flow lobes south into Alae lava lake, and north. Great pressure pushed a massive "boil" of molten lava about 7 m high from one vent, possibly as a result of the hydrostatic head derived from the upper vents. The main channel narrowed from about 23 m near the vent to less than 18 m where it crossed the former rim of the crater. Windows through the lake crust in line with the channel (FIG. 2a) revealed the forward motion of molten lava within the lake.

Friday Afternoon, August 7 (FIG. 2b)

Relatively few changes occurred in the five hours since the morning observation. Lateral flow along the postulated rift appeared to continue to feed lava to the lower vents. One of the northern channels of Vent 3 that had been fairly well crusted had ceased flow activity and drained, leaving a short, partly collapsed lava tube. The roof was arched over the channel and was extremely thin compared to its width. A dull red glow within the tube showed that it had not cooled completely. This mode of tube formation (draining of a crusted channel) appears to be rather common and is the explanation usually given in elementary geology texts.

The rift-channel from Vent 3 to the Lower Vents and the short braided channel network flowing into Alae Crater had all crusted solidly. Fractures in the crust showed flowing molten lava. The braided network of channels southwest of Vent 3 had coalesced into one main channel meandering toward Alae Crater. The upper part of the channel was partly covered with mobile crustal plates. Although the plates were seen during the morning observations, their function was not understood until viewed in this channel (FIG. 4). Within a few meters of the vent, a scum of cooled lava formed on the channel surface. Frictional drag of the crust along the sides of the channel caused the crust to deform into festoons typical of pahoehoe lava. At the first bend in the channel, the crust broke into shield-shaped plates which continued to float down the channel on the flow surface. The shape and arrangement of the plates permit flexibility of the crust while maintaining maximum heat retention within the flow and channel. Where the channel made an especially sharp bend, or where the flow velocity increased (because of increased gradient) and produced turbulence, the plates were broken and incorporated within the flow, probably by remelting. In some places, the plates were not broken, but jammed together fusing to the sides of the channel and forming a stable roof. Flow of molten lava continued beneath the roof. Thus, lava tubes can also form by fusing of mobile crustal plates over a formerly open-flow channel.

Flow within the main channel leading from the Lower Vents to Alae Crater had subsided and the channel was more narrow than it had been in the morning. Flow velocity was, however, about the same, and was rather turbulent. Splashing and overflow of molten lava resulted in accretion of lava along the sides of the channel. In some places, the lava levees were more than 3 m high and arched over the channel, occasionally merging to form a solid arched roof (FIG. 5). This third mechanism of lava tube formation was described by Jaggar (1921) for flows in "sluiceways" in Kilauea caldera.

Saturday Morning, August 8

Observations, considerably curtailed by poor weather and flying conditions, were restricted to a few aerial passes over Alae Crater and one pass over the vent area. Most of the data were derived later from photographs made during the passes, rather than from direct observation. During the night, major effusive activity had shifted to Vent 2 where multiple flows and sheets of basalt were flowing in all downslope directions. One prominent direction of flow was along the rift toward Vent 3; however, crusting made it difficult to determine the exact course of the channel. Multiple flows along rifts may account for unusual cross sections of some lava tubes. Each flow or surge of lava could produce a new, upper level with individual dimensions and characteristics dependent upon flow volume and velocity (FIG. 6). Formation of lava tubes in association with rifts was proposed by Harter and Harter (1971) from their study of prehistoric lava tubes.

The main channel from Vent 2 flowed south in a closely spaced braided network about 40 m wide into Alae Crater and passed beneath the lava lake crust very near the crater rim. The main channel of Vent 3 was almost completely crusted and continued to pour molten lava into Alae Crater. Similarly, the channel down the rift to the Lower Vents was crusted, possibly forming a continuation of the rift tube described above. The other channels and tubes from Vent 3 appeared to be inactive. Flow from the Lower Vents continued at about the same volume as the previous day; however, more of the channel had roofed over through spatter and accretion of lava along the channel sides.

Saturday Afternoon, August 8 (FIG. 2c)

Several prominent changes had occurred since the morning overflight. Vent 2 remained the primary source for major flows; the main braided flow had merged to a distinct channel (South Channel). The channel bypassed its former course of flow under the crust of Alae lava lake and shifted out of the crater, flowing south. At the channel front, the flow spread laterally about three times its normal width. Lava advanced very slowly (less than a few km/hr) through a series of anastomosing flow lobes and lava tubes similar to the process described by Baldwin (1953). The main channel had a prominent cut-off branch that apparently rejoined the channel after paralleling it for several hundred meters. Flow within most of the channel was uncrusted, although some sections had mobile crustal plates.

Flow from Vent 2 to Vent 3 was mostly restricted to a well-defined channel. A short distance downslope from Vent 2 the channel split around a large island. Initially, the channels were covered with mobile crusts, but within 2 hours the plates had fused, forming stable crusts.

A second prominent channel, equal in length and width to South Channel, flowed east from Vent 2. Unlike South Channel (which was mostly open channel flow), East Channel displayed braided channel flow, open flow, mobile crustal plates, and roofed channels. The differences in surface type appeared to be related, at least in part, to topographic slope and subsequent flow velocity. Steep slopes resulted in open, noncrusted channels, apparently resulting from turbulent flow which broke up the crust as soon as it formed. On gentle slopes the lava reverted to laminar flow, permitting surface crusts to form. East Channel flowed to the edge of the forest and ignited forest fires at the time of observation.

An additional form of crustal closure was observed in East Channel. Cooling along the edges of the channel produced lateral crusts. These merged in a "V" toward the center of the channel and produced a solid crust with a seam down its center (indicating the line of merger). As the channel and flow advanced, the point of closure shifted downstream, analogous to the closing of a zipper (FIG. 7). When fluid lava drains from the crusted channel, the roof may remain, forming a lava tube, or the roof may collapse. In either case the medial seam is preserved.

All tubes and channels of Vent 3 appeared to be inactive. The flow could have passed beneath Vent 3 from Vent 2 toward the Lower Vents along the rift or rift-tube. It is very difficult to access flow activity once a crust covers a channel since molten lava is no longer visible and the surface textures of active structures are identical to previously formed structures.

Flow from the Lower Vents continued through the main channel/tube. More of the channel had roofed over (through accretion of spattered lava) leaving most of the open channel in the area closest to the vent.

The most striking change that had occurred since the morning observation was the partial draining and subsequent subsidence of Alae lava lake. Drainage of the lake was noted by Jackson and Swanson (1970) for the eruptive phase of 1969 when lava drained through the rift-graben east of the crater. Although no flows were observed in or near the graben at this time, it is possible that drainage was quite deep with no surface expression. Drainage probably occurred also through rifts or lava tubes southeast of the crater, feeding lava to the flow front. Tubes and channels crossed the lower rim of the crater, but these probably could not account for drainage of the lake lower than the present rim.

The collapsed portion of the lake was a few meters lower than the uncollapsed part and seemed to correspond roughly to the outline of the former inner pit of Alae Crater, with discontinuous tension faults marking the outline of subsidence. The former main channel from Vent 3 to the center of the lava lake was cut by a series of *en echelon* faults (FIG. 8), exposing the interior of the drained lava tube. Crustal plates on the surface of the lava lake were shoved about as a result of subsidence and pushed up into a network of pressure ridges.

Several tubes and channels were observed downslope from the vent area within the advancing flow. Possibly in response to the lower gradient and velocities, the channels were meanderous with many cut-offs, distributary channels, and tributary channels. The channels (and subsequent tubes) appeared to be the axes of more rapid flow within the molten body of the containing flow.

Tuesday, August 11

Flow activity subsided considerably since the Saturday observation, with flows emanating from the Lower Vents only. Nearly all of the main channel had crusted over, forming a lava tube with an accreted roof. Skylights through the roof revealed active flow into Alae Crater. Cracks in the crust of Alae lava lake showed that molten lava was less than 1 m below the crust. Subsidence faults and pressure ridges on the lake crust were unchanged.

The flow front continued movement toward Poliokeawe Pali through anastomosing networks of tubes and channels. One small lobe of the flow front had shifted to the southeast toward Chain of Craters Road. The National Park Service, in an effort to prevent destruction of a unique forest east of the road, used bulldozers to construct a dike of soil and blacktop from the roadway. Ground observations were made at this time. The lava advanced less than a few meters/minute through coalescing lobes and lava toes oozing from the flow front. The newly formed pahoehoe toes quickly developed a heat-retaining, thin but tough skin of glassy basalt.

For several hours the flow near the road drained into a prehistoric lava tube. The course of the tube is not known; molten lava was not, however, seen emerging any place downslope and it is assumed that the tube was plugged at its distal end. Eventually, the tube filled with molten lava and the flow continued downslope on the surface. Prehistoric tubes, both on the Islands and Mainland, serve as conduits for later flows; some are completely filled, as was the case here, and some are only partly filled, as described for tubes in Washington (Greeley and Hyde, 1971). Flows emerging from tubes after considerable subsurface flow may account for seemingly anomalous patches of pahoehoe lava found in some fields of aa (FIG. 9).

4. CONCLUSIONS

From descriptions of previous lava flows and observations described here, there appear to be several different sequences which may lead to lava tube formation. Although some lava tubes form almost immediately from the vent, most tubes evolve from channels. Initially, pahoehoe basalt may flow from the vent in a wide sheet. Flow is eventually restricted to a few axes of more rapid flow, leading to the formation of braided channels. Channels within the braided network later coalesce to one or two main channels, often leaving cut-off branches, meander loops, and islands. Once the channel stabilizes, it may roof over to form a lava tube. Scum or crust may develop and fuse to the channel sides and remain fixed in place (Wentworth and Macdonald, 1953). This "pre-roof" can thicken by overflows on the surface and by accretion of cooled lava on its underside. Crust may also develop on channel edges and merge in a "V-shaped" pattern in the center of the channel like a zipper, resulting in a medial line of closure. In some channels, crustal plates form, tear loose, and drift along the surface of the flow. These mobile crustal plates can become locked together and fuse to the channel sides, forming a tube roof.

Lava channels may roof as the result of rapid, turbulent lava flows. Splashing, spattering, and overflow along the channel result in accretion of lava as levees (Jaggar, 1921). The levees may continue to build until they arch over the channel and fuse to form an agglutinated roof.

Lava tubes can form very close to the flow front if flow is relatively slow. Lava toes and flow lobes may crust over as soon as they form. The crusted lobes and toes are added to the previous section of tube and the tube advances with the flow front (Baldwin, 1953). Tubes constructed in this fashion are irregular in comparison to tubes formed from continuous surface crusts.

Lava channels and tubes usually represent the axis of most rapid flow within the body of the flow. This often corresponds to the thickest part of the flow or the axis of pre-flow topographic depressions or both. Thus, tubes may develop along stream channels (Greeley and Hyde, 1971), former lava tubes and channels, or structural elements such as rifts (Harter and Harter, 1971), fractures or grabens. These structures may be obliterated, partly filled, or eroded and enlarged by lava erosion. Depending upon flow velocity and viscosity (and probably other parameters) a single channel/tube may be roofed along some sections, unroofed along others, and display a variety of crustal types. Along its course it can have straight sections (following structural elements, i.e., grabens), meander loops, entrenched sections, and gently curving sections.

Although the results and conclusions presented here can be utilized in interpreting some basaltic terrains, there are limitations in their application. Lava tube and channel formation seems to be controlled largely by lava composition, viscosity, and flow velocity. For example, while tubes are found only in pahoehoe (fluid) basalt, channels can occur in both pahoehoe and aa (viscous) basalt. Additional observations of active flows under different conditions of lava composition, viscosity, and pre-flow topography should prove helpful in determining the influence of these parameters on surface feature configuration.

REFERENCES

Baldwin, E. D., 1953. Notes on the 1880-81 lava flow from Mauna Loa: Volcano Letter, no. 520, p. 1-3.

Finch, R. H. and G. A. Macdonald, 1950. The June, 1950 eruption of Mauna Loa, pt. 1: Volcano Letter, no. 508, p. 7-8.

Greeley, R., 1971. Lunar Hadley Rille: Considerations of its origin. NASA Tech. Mem. X-62,011, 11 p.

Greeley, R. and J. H. Hyde, 1971. Lava tubes of the Cave Basalt, Mount St. Helens, Washington (submitted to Bull. Geol. Soc. Amer.).

Harter, J. W. and R. G. Harter, 1971. Classification of lava tubes (submitted to Bull. Speleo. Soc. Amer.).

Hatheway, A. W. and A. K. Herring, 1970. Bandera lava tubes of New Mexico, and lunar implications: Commun. Lunar and Planetary Lab., Univ. of Arizona, v. 8, pt. 4, no. 152, p. 299-327.

Hess, W. N. and A. J. Calio, 1969. Summary of scientific results *in* Apollo 11 - Preliminary Science Report: NASA SP-214, p. 1-7.

Howard, K. A., 1969. Lava channels in northern California: Trans. Amer. Geophys. Union, v. 50, p. 341.

Jackson, D. B. and D. A. Swanson, 1970. 1968-70 Deformation: East Rift: Trans. Amer. Geophys. Union, v. 51, p. 441.

Jaggar, T. A., 1921. Volcanic conditions in February, Activity of Halemaumau: Monthly Bull. Hawaii Vol. Obser., v. 9, p. 21-37.

Macdonald, G. A. and J. B. Orr, 1950. The 1949 summit eruption of Mauna Loa, Hawaii: U. S. Geol. Sur. Bull. 974-A, p. 1-31.

Oberbeck, V. R., W. L. Quaide, and R. Greeley, 1969. On the origin of lunar sinuous rilles: Modern Geology, v. 1, p. 75-80.

Turkevich, A. L., E. J. Franzgrote, and J. H. Patterson, 1968. Chemical analysis of the Moon at Surveyor VI landing site: Preliminary results: Jet Propulsion Laboratory Report 32-1262, p. 127.

Wentworth, C. K. and G. A. Macdonald, 1953. Structures and forms of basaltic rocks in Hawaii: U. S. Geol. Sur. Bull., v. 994, 98 p.

FIGURE CAPTIONS

FIG. 1. Location map of observation area.

FIG. 2. Sequential diagrams of flow activity, August 7 to August 11, 1971.

FIG. 3. Diagrammatic cross section through vents, parallel along possible rift. Configuration of magma chamber and vent roofs are hypothetical.

FIG. 4A. Sketch of main channel from Vent 3 (Morning, August 7) illustrating *mobile crustal plates*. Cooling produces festooned pahoehoe crusts near the vent; flow beneath the crust breaks shield-shaped segments (plates) free; plates drift down channel until they jam together and fuse. Shape of plates permits maximum flexibility and heat retention in the channel.

FIG. 4B. Photograph of Vent 3 showing formation of plates as the flow emerges from beneath the thin crust covering the vent; spatter rampart is to the left of the vent.

FIG. 4C. View down channel containing crustal plates; lighter toned pahoehoe along channel flanks was deposited during overflow; repeated overflows build a topographic high along the axis of the structure.

FIG. 5. Part of main channel from Lower Vents; some of channel has roofed over by accretion of spattered lava along lateral channel levees.

FIG. 6. Hypothetical diagram illustrating possible formation and modification of lava structures as a result of subsequent lava flows. FIG. 6a: Flow 1 developed channel along graben or rift zone and was roofed by Flow 2; Flow 3 followed general trend, forming a tube which in some places drained into lower structure and in other places formed an upper level; Flow 4 eroded Flow 3 roof and drained, leaving a channel/tube structure; Flow 5 was situated over the channel and roofed the entire structure. FIG. 6b: Upon drainage of Flow 5, a lining was deposited throughout the system. Although the diagram is hypothetical, lava tube configurations similar to this are common in many areas (Greeley and Hyde, 1971).

FIG. 7. Lava tube formation by medial closure of lateral crustal elements. Resulting roof has a medial ridge indicating line of closure.

FIG. 8A. Subsidence crater in lava-filled Alae Crater; arrow marks the vent area; South Channnel and its fan-shaped flow front are left of the crater.

FIG. 8B. Enlargement of part of the collapse crater, showing tension fractures and the channel cut by subsidence ("A"); crustal plates on the lava lake were pushed into a network of pressure ridges ("B").

FIG. 9. Small patches of pahoehoe in field of aa, pahoehoe may have emerged from lava tube beneath aa. Tree skeletons indicate scale.

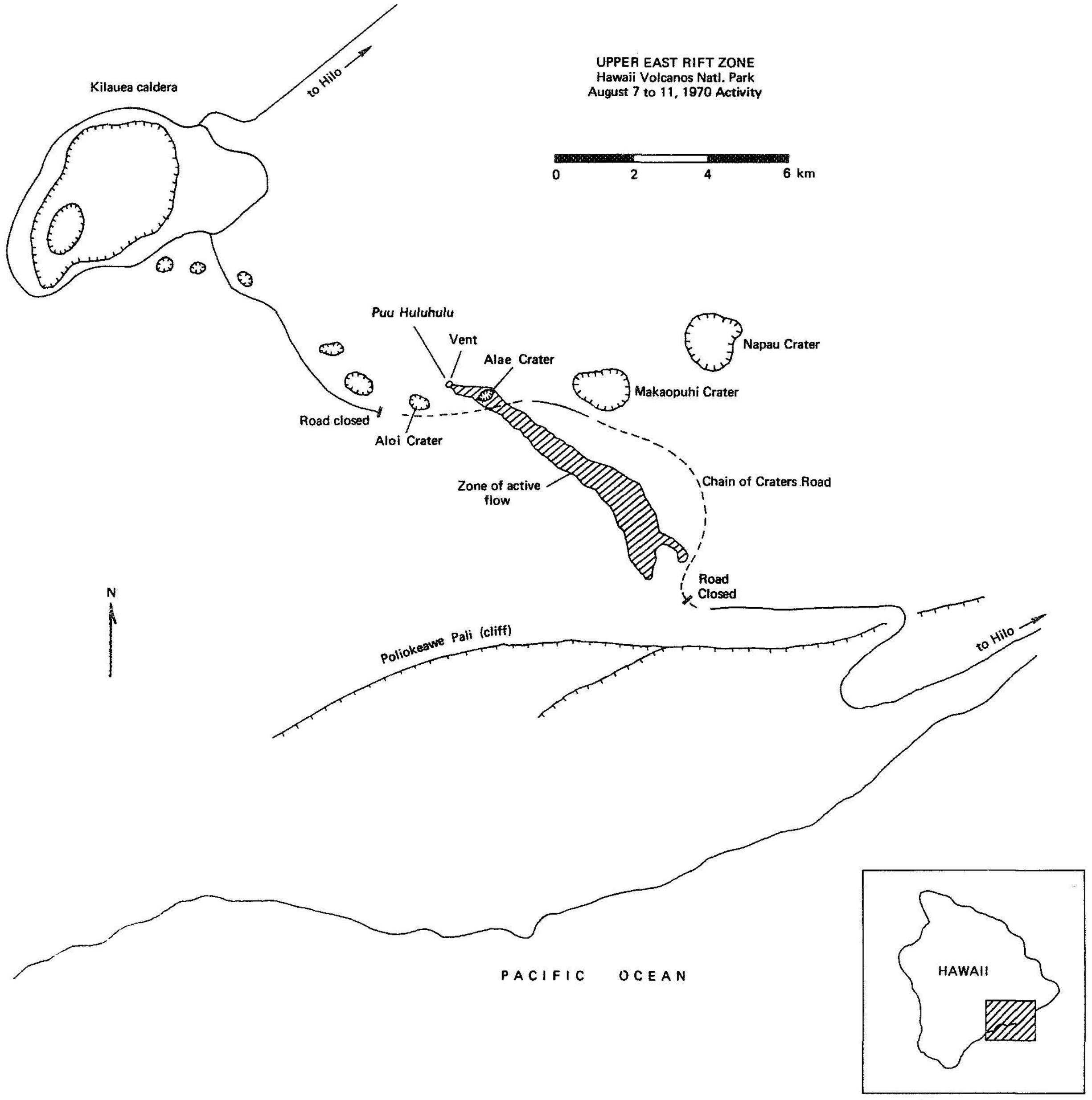

UPPER EAST RIFT ZONE
Hawaii Volcanos Natl. Park
August 7 to 11, 1970 Activity
0
2
4
6 km
Kilauea caldera
to Hilo
Puu Huluhulu
Vent
Alae Crater
Napau Crater
Makaopuhi Crater
Road closed
Aloi Crater
Zone of active flow
Chain of Craters Road
Road Closed
N
Poliokeawe Pali (cliff)
to Hilo
PACIFIC OCEAN
HAWAII

Figure 1

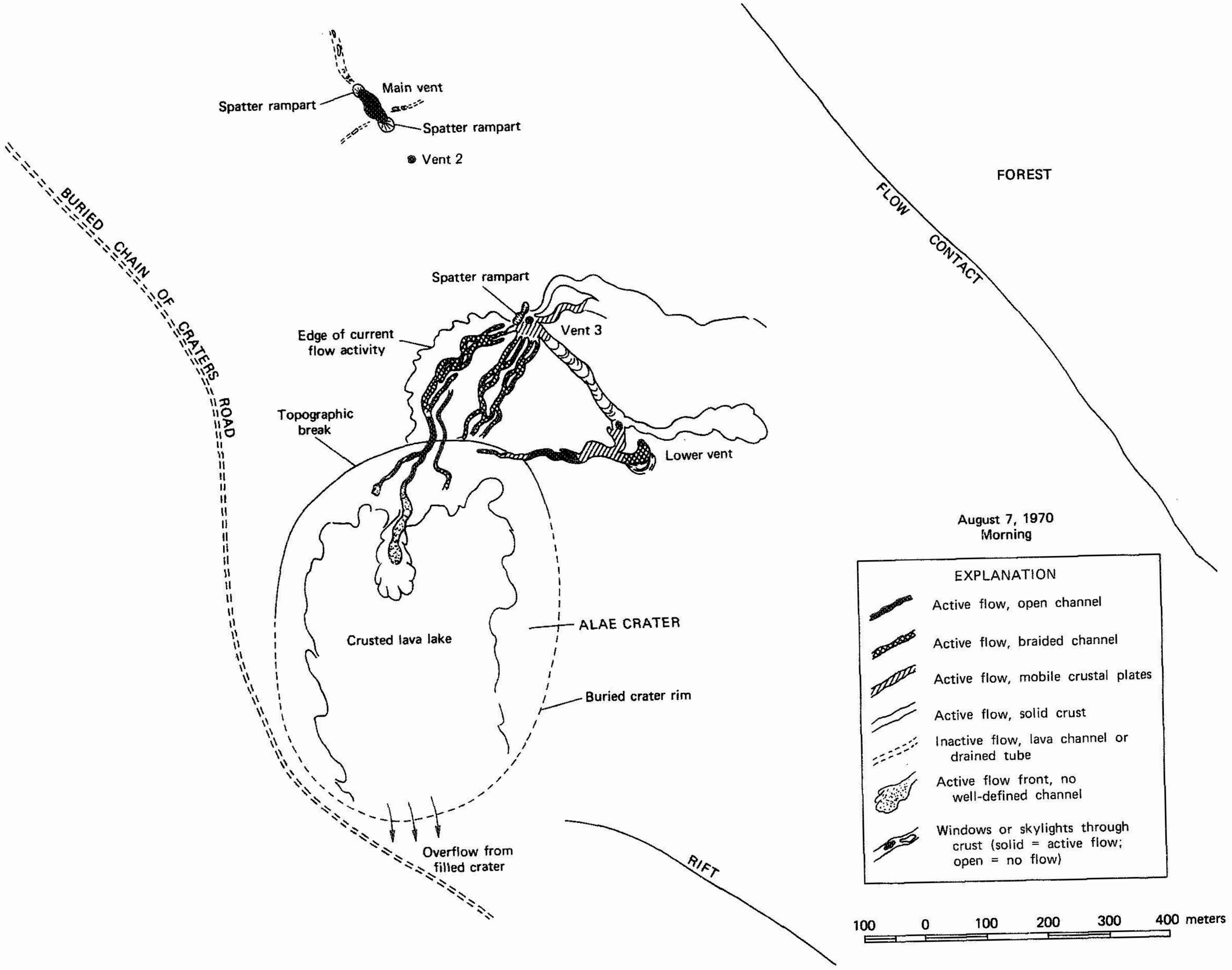

Main vent
Spatter rampart
Spatter rampart
Vent 2
FOREST
FLOW CONTACT
BURIED CHAIN OF CRATERS ROAD
Spatter rampart
Vent 3
Edge of current flow activity
Topographic break
Lower vent
Crusted lava lake
ALAE CRATER
Buried crater rim
Overflow from filled crater
RIFT
August 7, 1970
Morning
EXPLANATION
Active flow, open channel
Active flow, braided channel
Active flow, mobile crustal plates
Active flow, solid crust
Inactive flow, lava channel or drained tube
Active flow front, no well-defined channel
Windows or skylights through crust (solid = active flow; open = no flow)
100
0
100
200
300
400 meters

Figure 2a

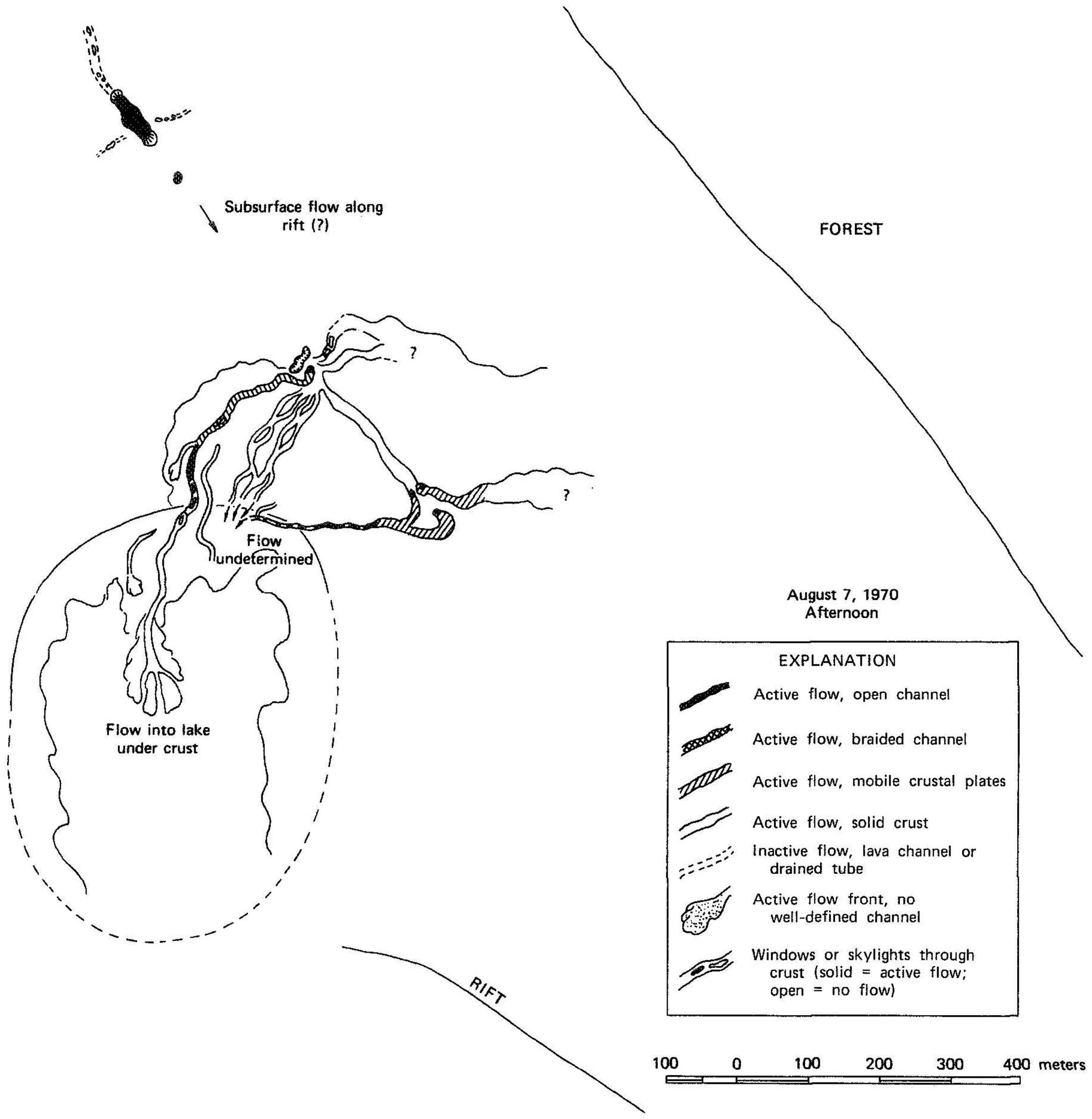
Subsurface flow along rift (?)
FOREST
?
?
Flow undetermined
Flow into lake under crust
RIFT
August 7, 1970
Afternoon
EXPLANATION
Active flow, open channel
Active flow, braided channel
Active flow, mobile crustal plates
Active flow, solid crust
Inactive flow, lava channel or drained tube
Active flow front, no well-defined channel
Windows or skylights through crust (solid = active flow; open = no flow)
100
0
100
200
300
400 meters

Figure 2b

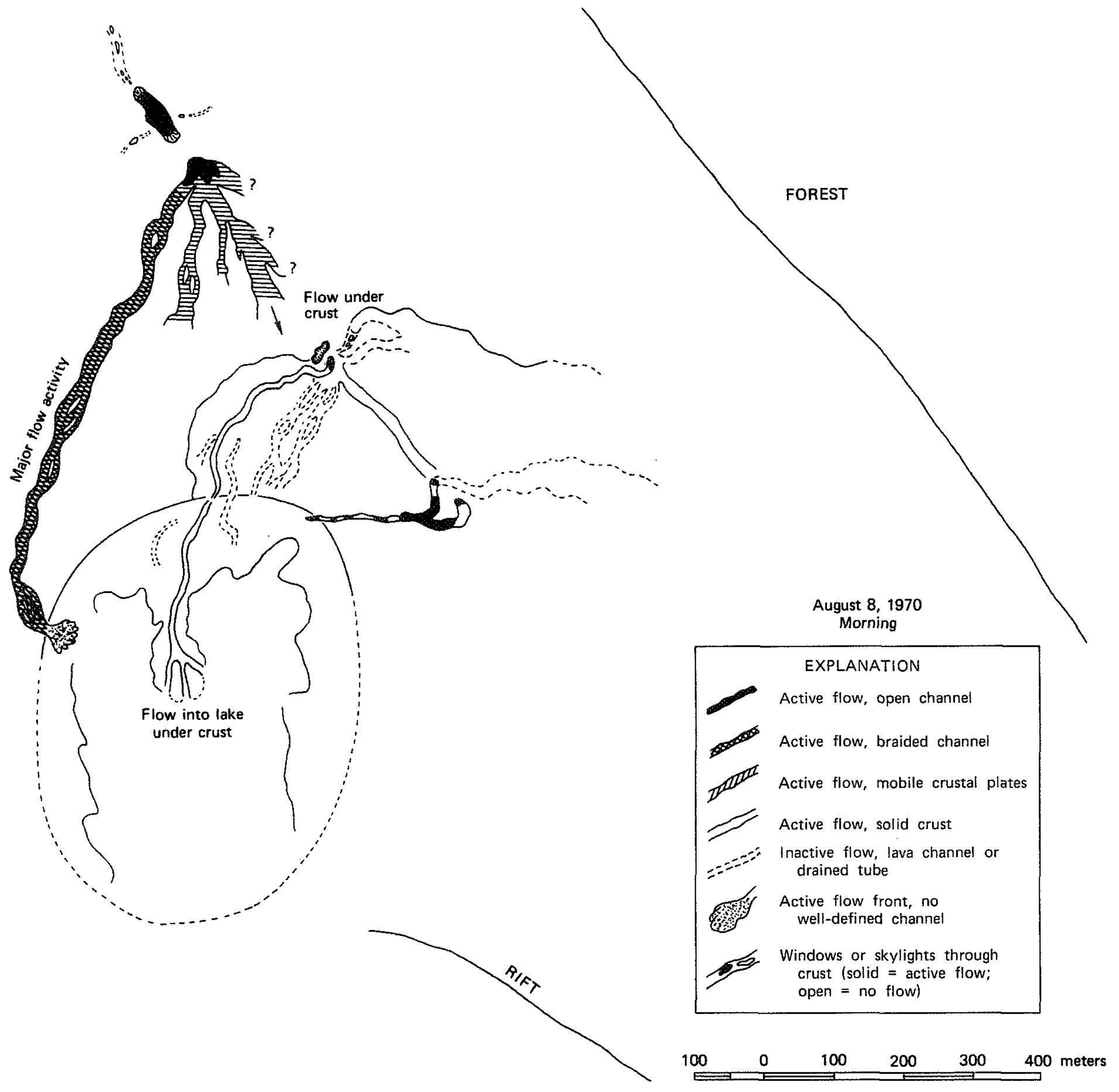

FOREST
Flow under crust
?
?
?
Major flow activity
Flow into lake under crust
RIFT
August 8, 1970
Morning
EXPLANATION
Active flow, open channel
Active flow, braided channel
Active flow, mobile crustal plates
Active flow, solid crust
Inactive flow, lava channel or drained tube
Active flow front, no well-defined channel
Windows or skylights through crust (solid = active flow; open = no flow)
100
0
100
200
300
400 meters

Figure 2c

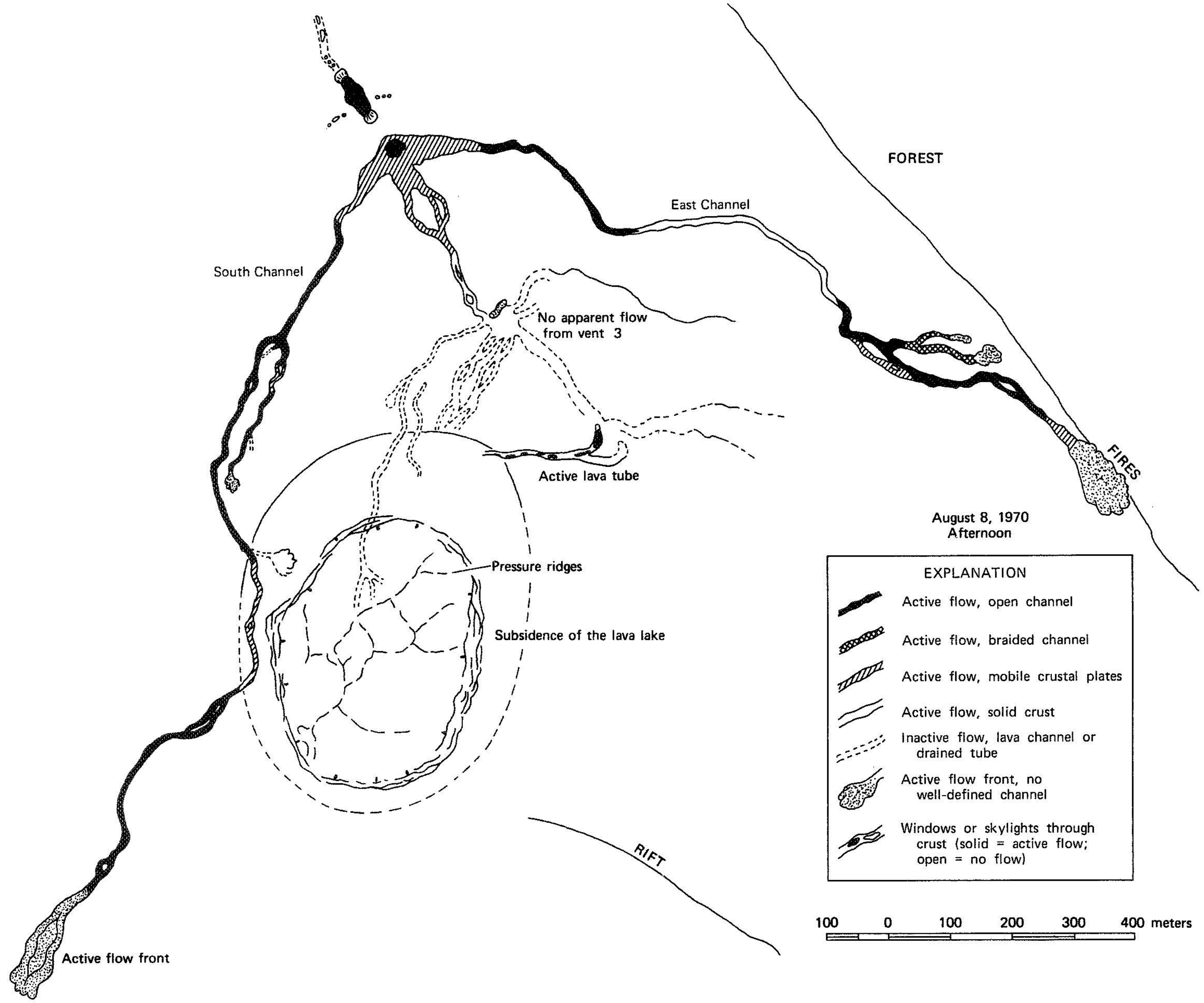

FOREST
East Channel
South Channel
No apparent flow from vent 3
Active lava tube
FIRES
August 8, 1970
Afternoon
Pressure ridges
Subsidence of the lava lake
RIFT
Active flow front
EXPLANATION
Active flow, open channel
Active flow, braided channel
Active flow, mobile crustal plates
Active flow, solid crust
Inactive flow, lava channel or drained tube
Active flow front, no well-defined channel
Windows or skylights through crust (solid = active flow; open = no flow)
100
0
100
200
300
400 meters

Figure 2d

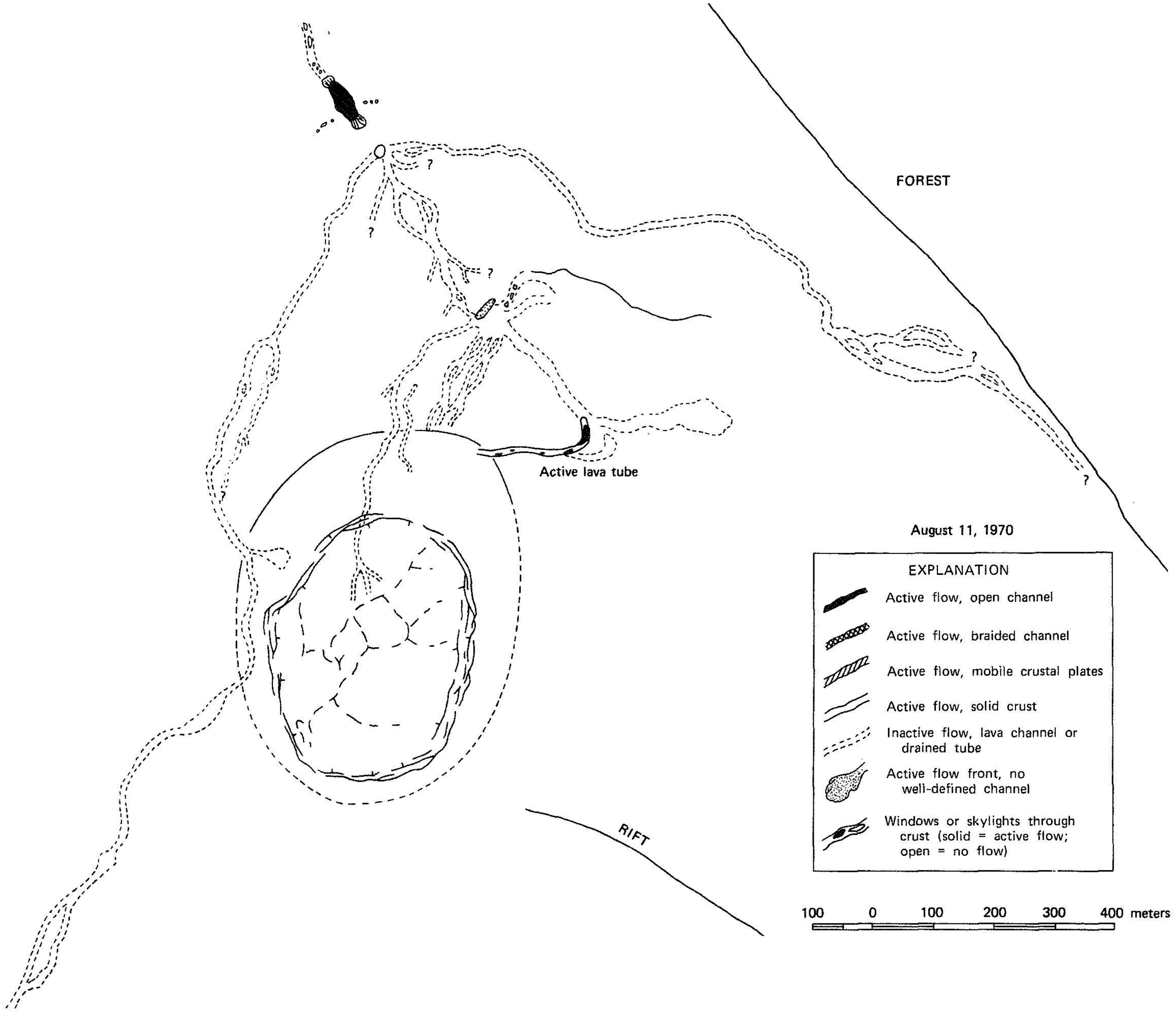
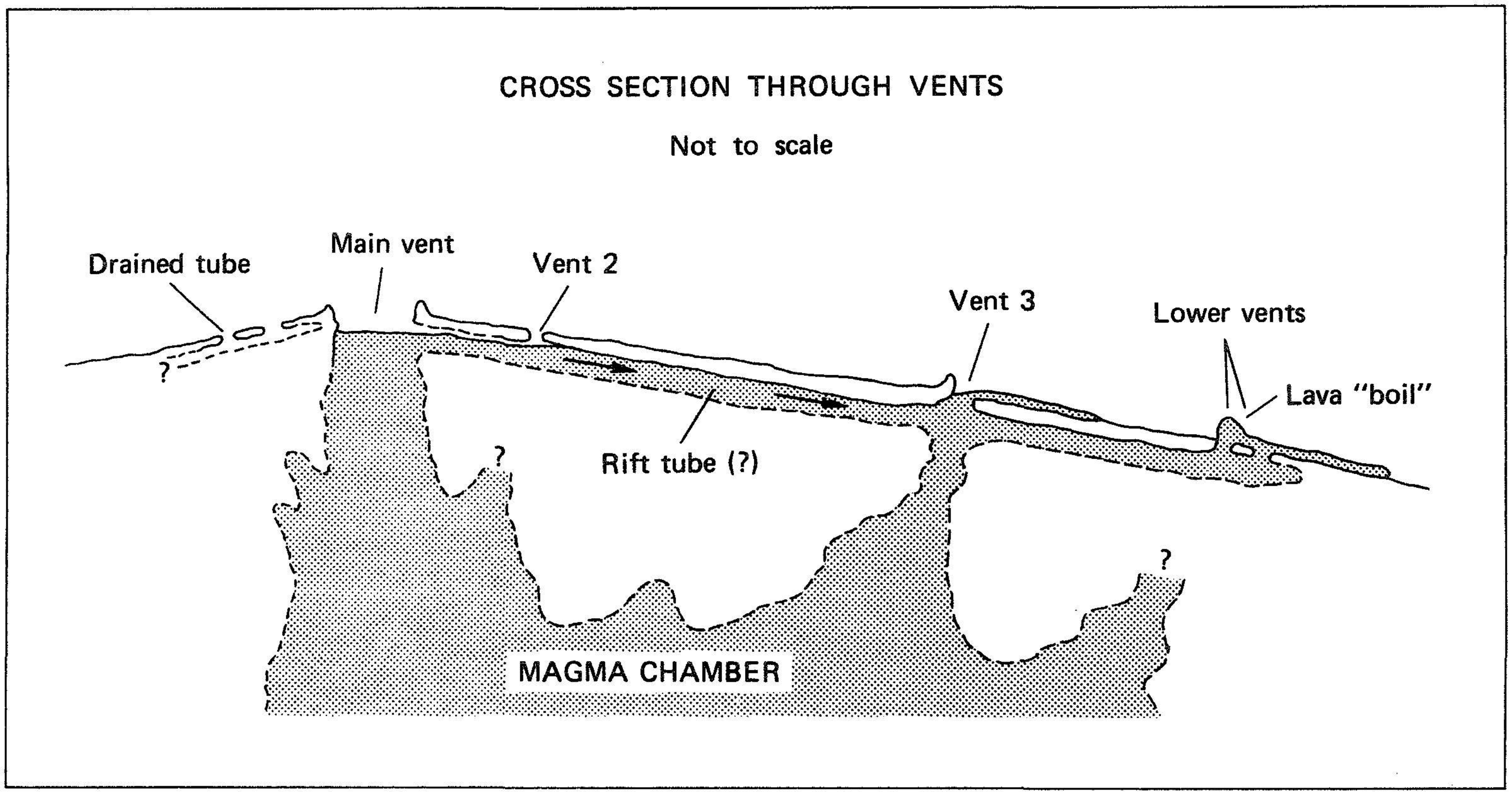
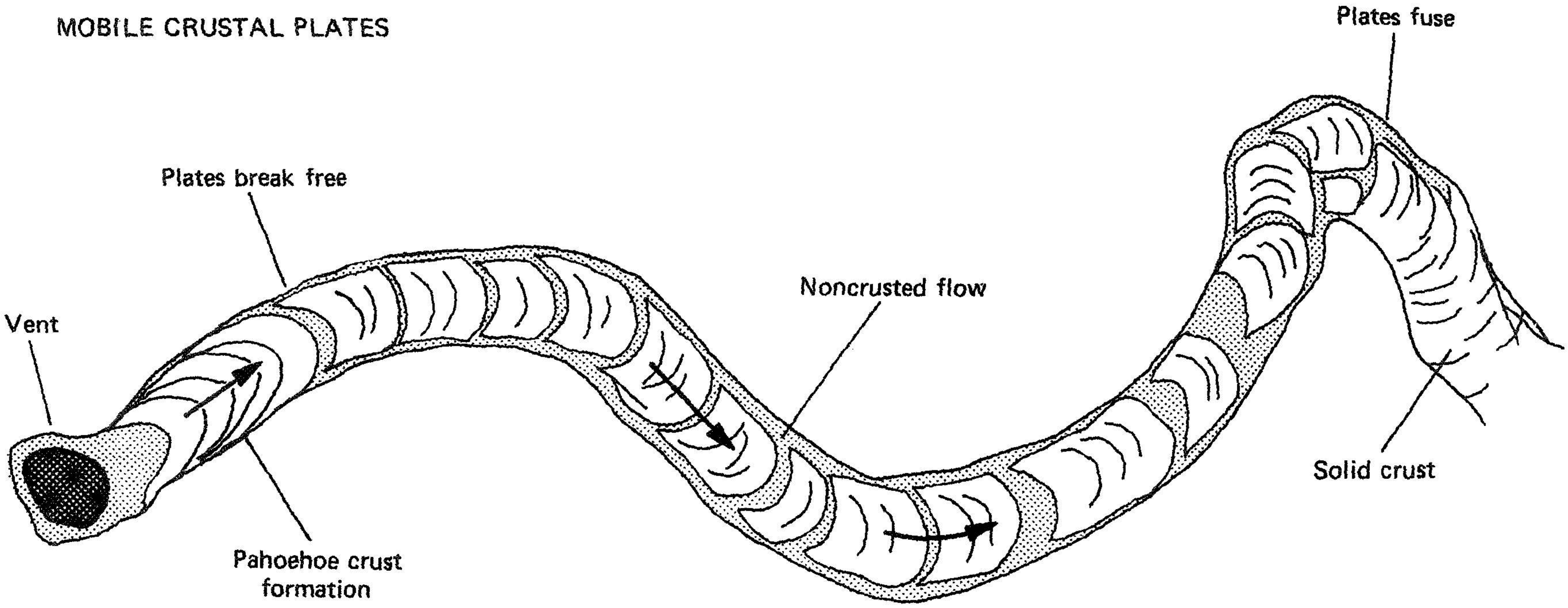

FOREST
?
?
?
?
?
Active lava tube
RIFT
August 11, 1970
EXPLANATION
Active flow, open channel
Active flow, braided channel
Active flow, mobile crustal plates
Active flow, solid crust
Inactive flow, lava channel or drained tube
Active flow front, no well-defined channel
Windows or skylights through crust (solid = active flow; open = no flow)
100
0
100
200
300
400 meters

Figure 2e


CROSS SECTION THROUGH VENTS

Not to scale

Figure 3



MOBILE CRUSTAL PLATES

Figure 4a

Figure 4b

Figure 4c

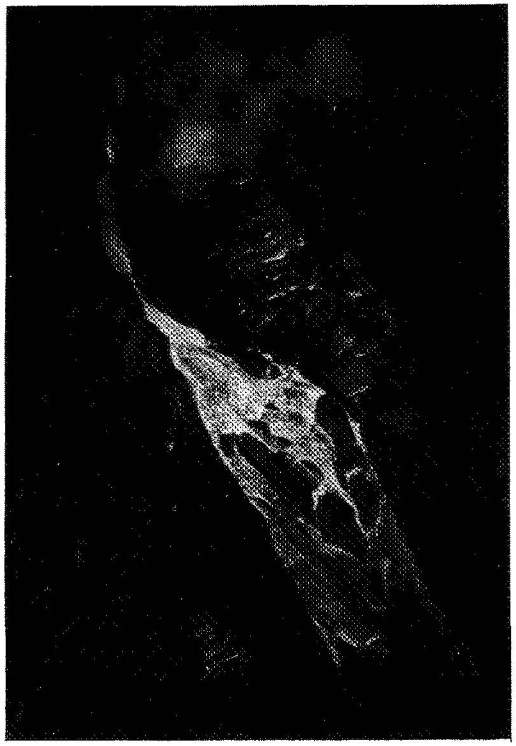


Figure 5

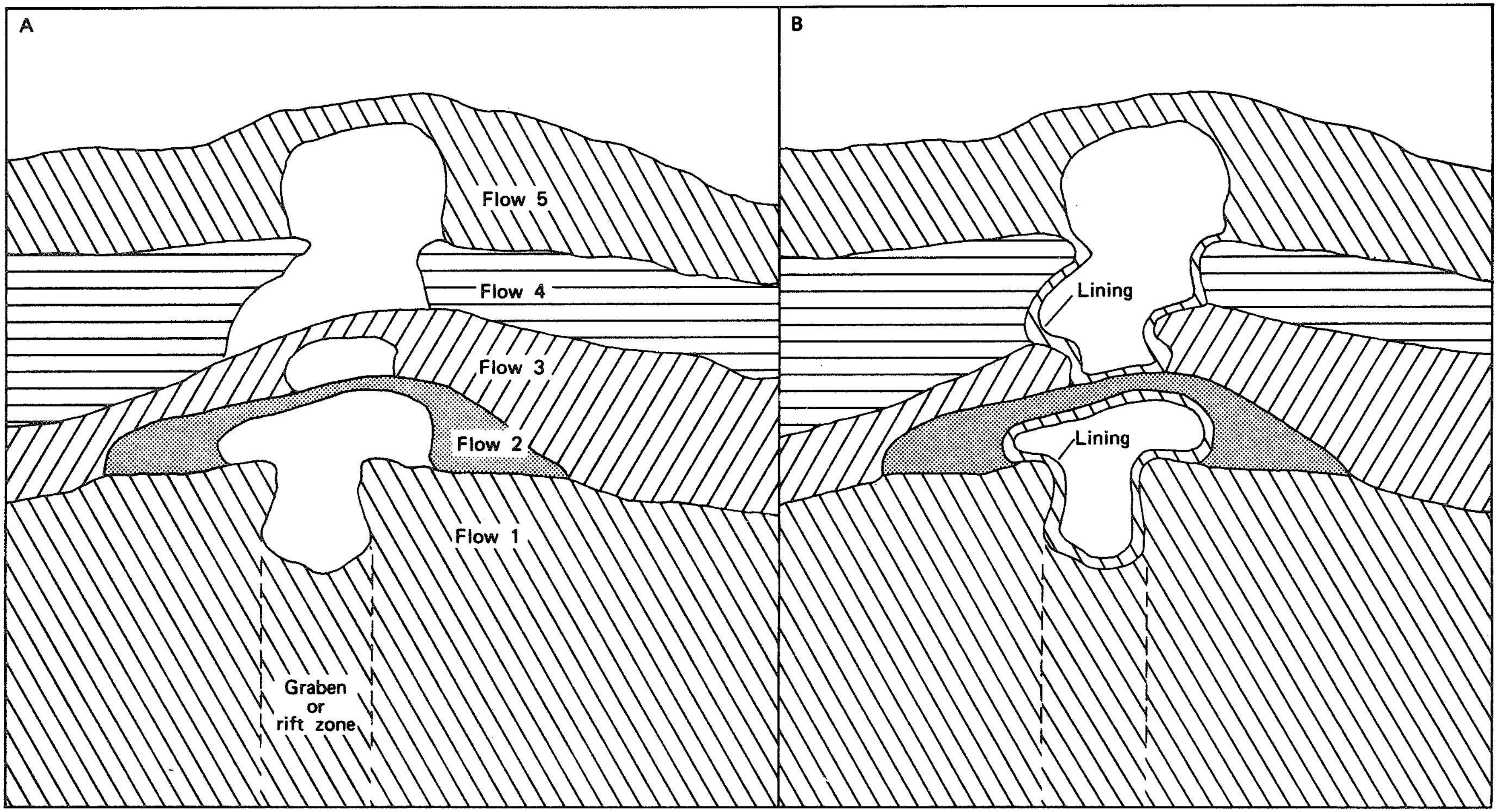

A
Flow 5
Flow 4
Flow 3
Flow 2
Flow 1
Graben
or
rift zone
B
Lining
Lining

Figure 6

Figure 7

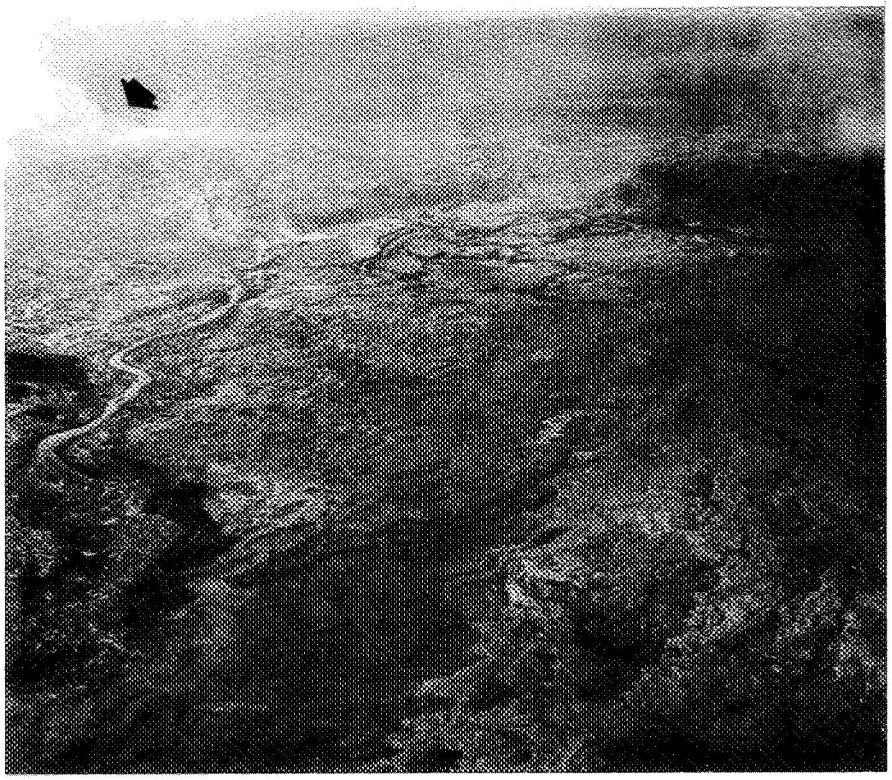


Figure 8a

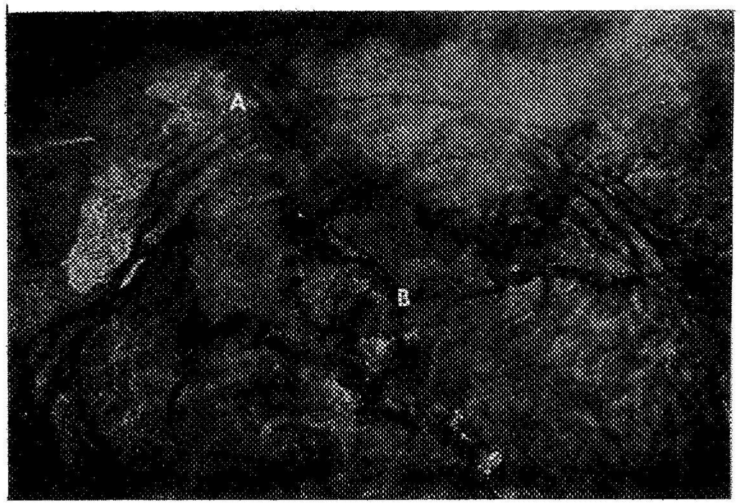


Figure 8b

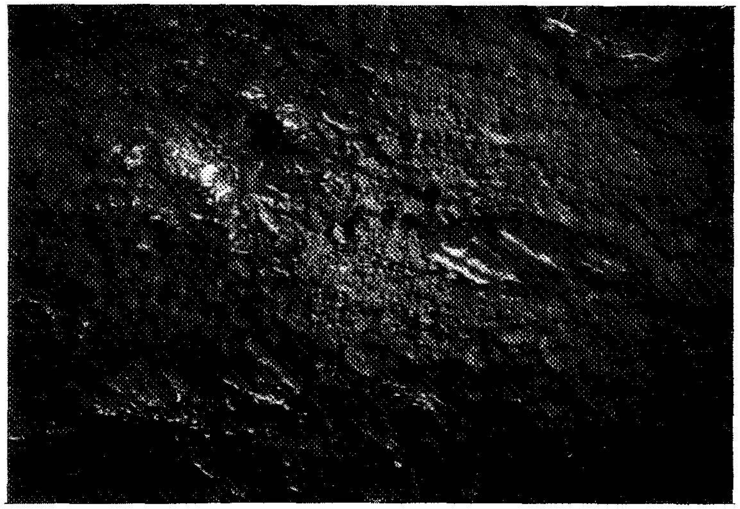


Figure 9