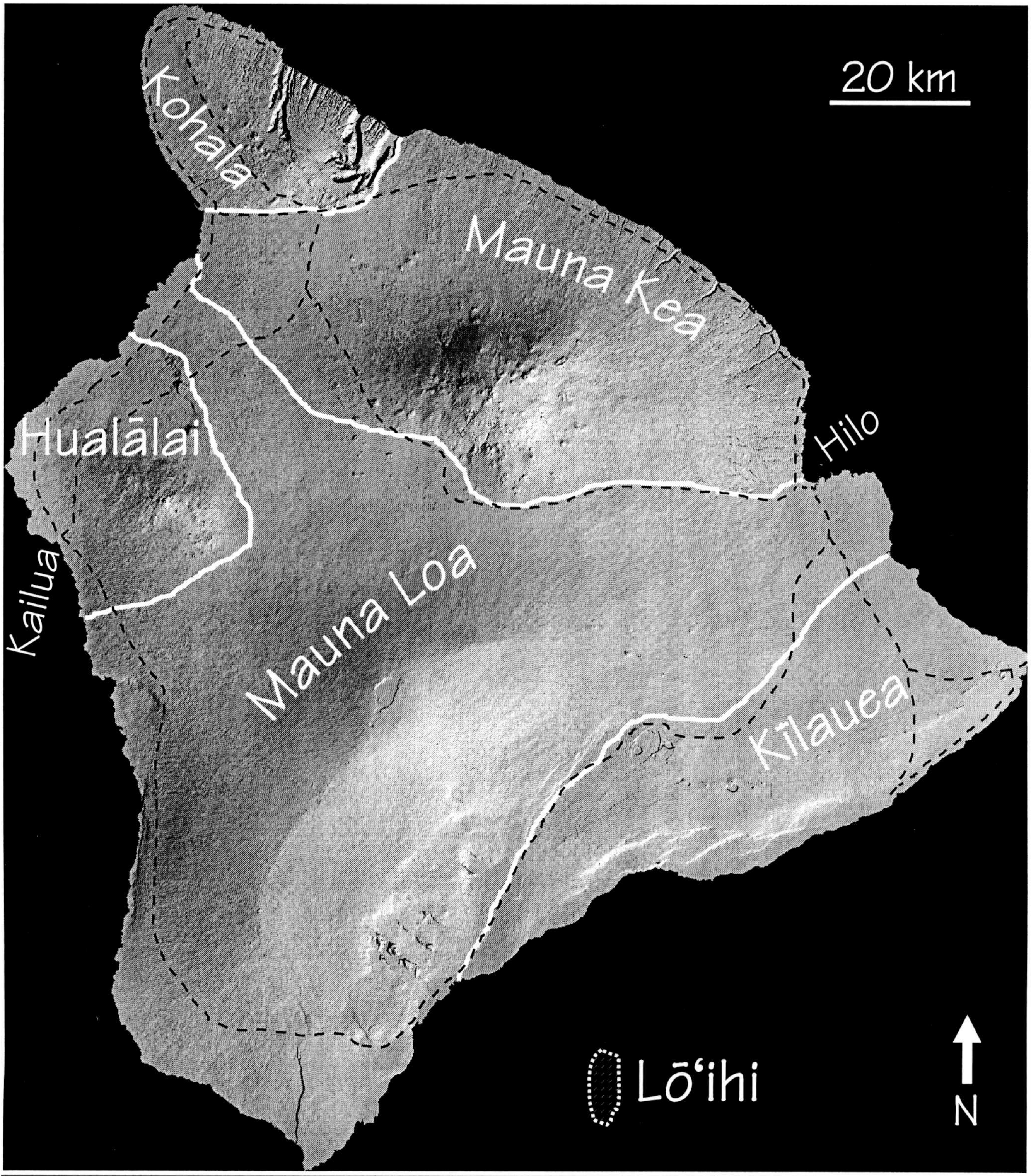
Field Trip Guide: ISLAND OF HAWAI'I
CSAV 2008



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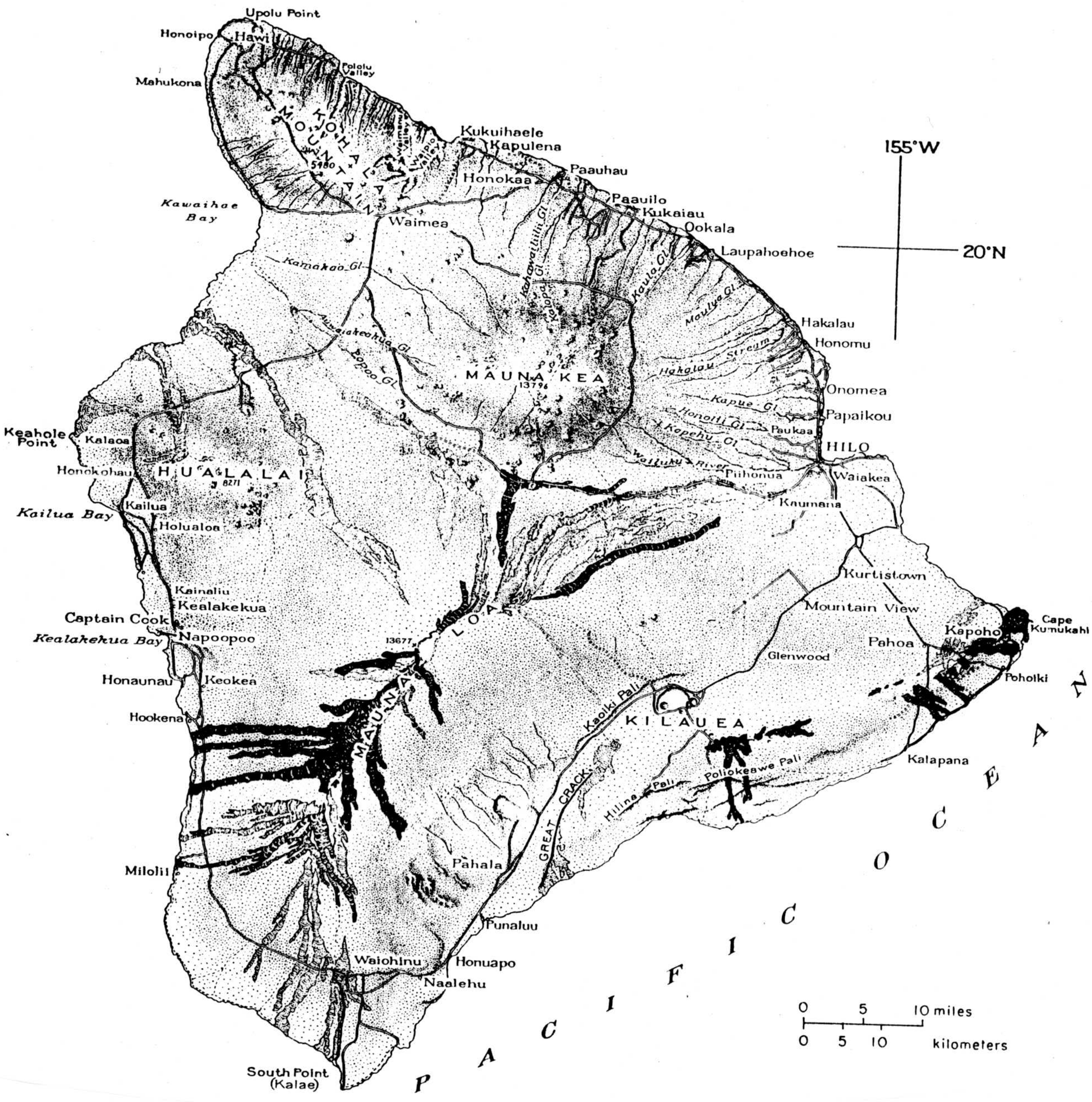
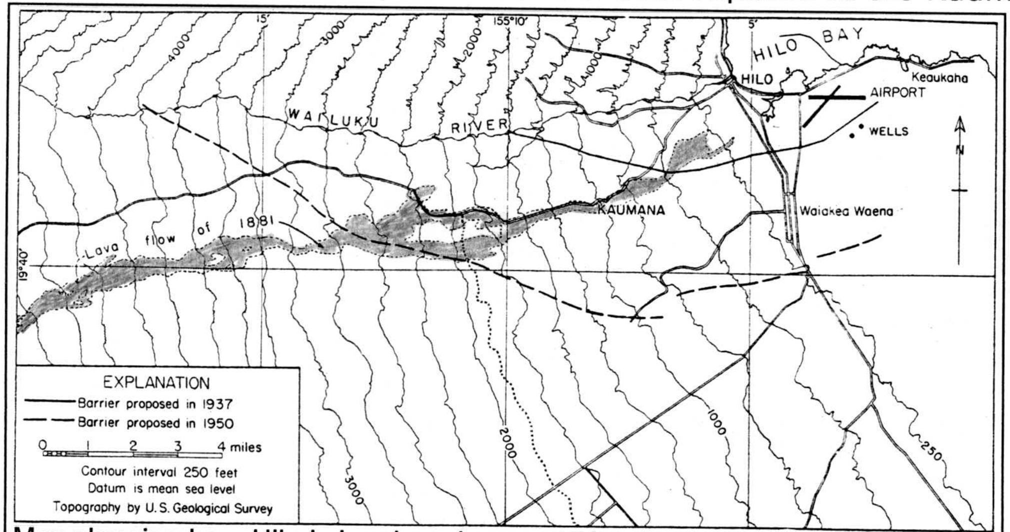
This field trip guide borrows (without permission) from similar guides written by George P.L. Walker, Jack Lockwood, Rick Hazlett, Peter Lipman, and Norm Banks



Geomorphic map of Hawai'i with some geological and cultural features added. Geologically it is out-of date, with the youngest indicated flows being Early Mauna Ulu lavas (below the "EA" in KILAUEA; from Macdonald *et al.* 1983).

HILO

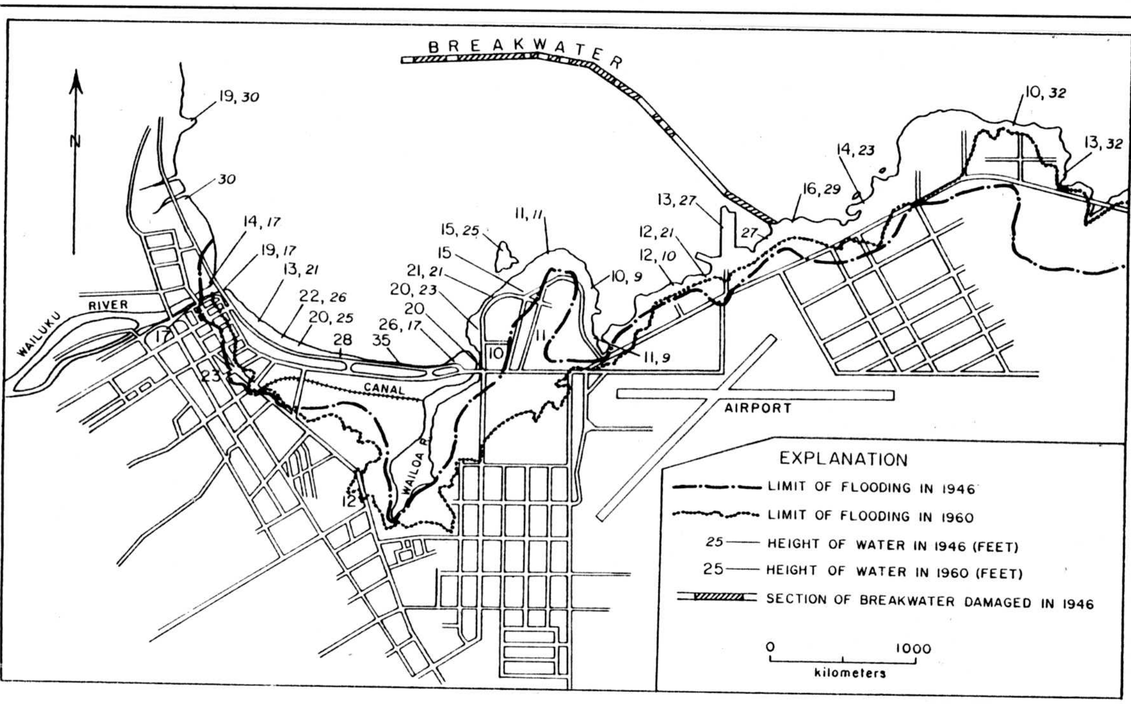
Hilo is built on pre- and post-contact lava flows of Mauna Loa. Most of the city is underlain by the ~1400 year-old Pana'ewa tube-fed pāhoehoe flow, an oceanite picrite. The Pana'ewa flow is well-exposed in an industrial area south of the Pana'ewa zoo. The youngest flow underlying Hilo is the 1880-81 tube-fed pāhoehoe flow best exposed at the Kaūmana cave.



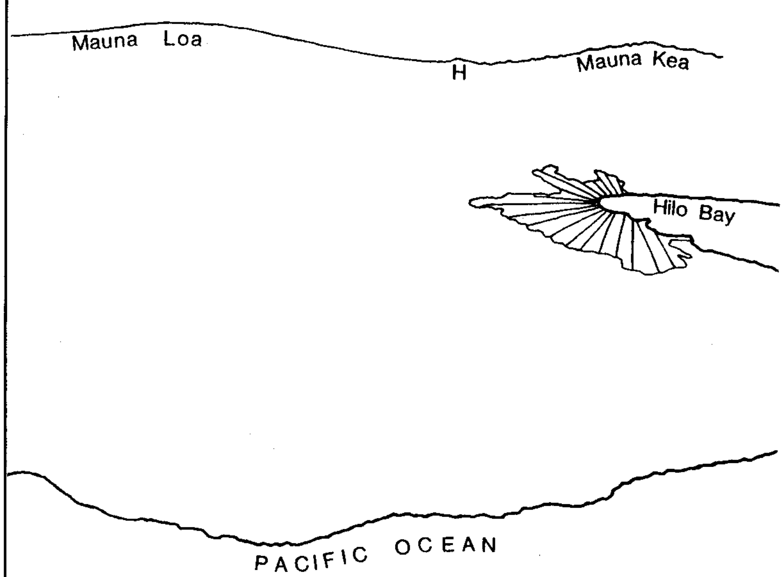
Map showing how Hilo is in a broad constructional valley between Mauna Kea and Mauna Loa (the Wailuku river marks the boundary). Note the 1880-81 flow. The dashed lines are the locations of proposed barriers for protecting the city (from Macdonald 1958).

Hilo is built in the subtle constructional valley formed by the boundary of Mauna Kea and Mauna Loa volcanoes. The cliffs to the north along the Hamakua coast are sea cliffs cut into Mauna Kea lavas. The "valley" extends beneath the ocean and along with the coastline helps to funnel tsunami directly to the city of Hilo. More than 150 people were killed here by a tsunami in 1946 (epicenter in the Aleutian Islands), and 61 people died in the tsunami of 1960 (epicenter in Chile). Hotels along the coastline that were built since 1960 have open lobbies designed to allow tsunami to wash through without causing structural damage to the entire building.

From Hilo on a (rare) clear day, you can compare the shield volcanoes of Mauna Loa and Mauna Kea. Mauna Loa is in the tholeiite stage of its lifetime, characterized by frequent, large-volume eruptions of fluid lava. Lava fountains during eruptions are relatively low and build small spatter cones barely visible from a long distance. Thus the slopes of Mauna Loa are very gentle and quite smooth-looking. Mauna Kea, however, is in the later alkalic cap stage, characterized by much less frequent eruptions of gas-rich but cooler magma. These eruptions involve high fountains and produce large cinder cones and thick flows. The effect on the profile of Mauna Kea is to make it steep and bumpy as viewed from Hilo.



Map showing run-up (in feet above mean sea level) for the April 1, 1946 and May 23, 1960 tsunami (from Macdonald *et al.* 1983).

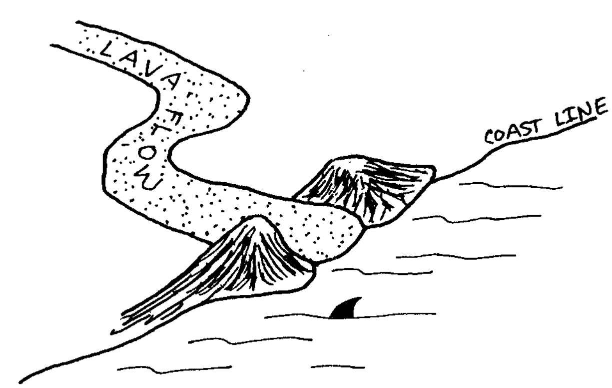


Sketch from an air photo taken from above the east coast of Hawai'i, looking west. Note the differences between the profiles of Mauna Loa and Mauna Kea. The bump (H) is the summit of Hualālai.

PU'U ONE ("SANDHILLS")

Pu'u One is a littoral cone, formed by the explosive interaction of lava and water as a flow enters the ocean, in this case the 1840 Kīlauea lava flow. Pu'u One is more-or-less an example of the "typical" littoral cone, consisting actually of two half-cones on either side of an 'a'ā flow. This is because any pyroclastic material that lands on the flow itself gets carried out to sea. We will see examples of not-so-typical littoral cones later in the trip.

Studies by George Walker at Pu'u One helped to develop some of the criteria that distinguish littoral deposits (secondary) from actual vents (primary). Most of these rely on the differences between the lava involved, namely that lava at primary vents is gas-rich and has a relatively low viscosity whereas that at littoral vents has flowed over the surface from the vent and is therefore slightly cooler (more viscous) and has lost considerable gas. In particular, fracturing of the lava at littoral cones can just as easily occur across phenocryst grains (since the lava is so viscous) whereas at primary vents the grains are left intact. Additionally, due to the loss of the smallest gas bubbles during flow, the density of littoral pyroclasts does not increase continually as the grain size decreases.



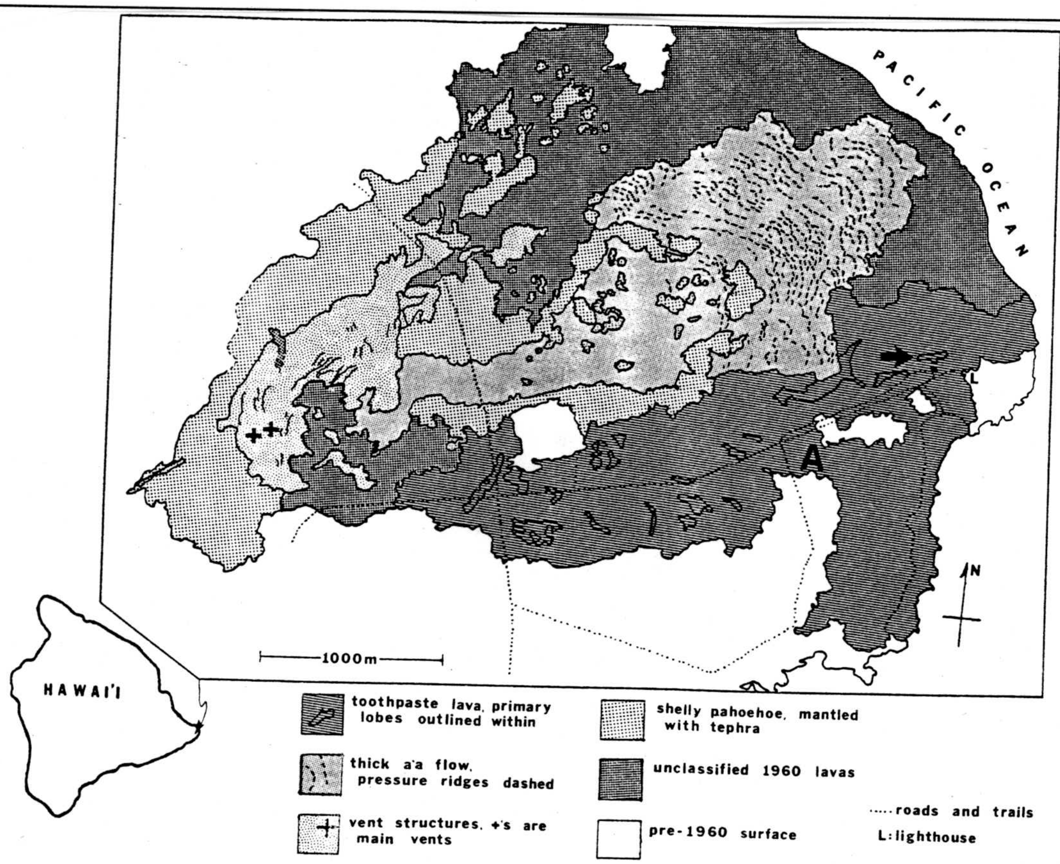
Sketch of a lava flow and associated littoral cones.

KAPOHO

Following the Kīlauea Iki eruption of 1959, all evidence pointed to the fact that the summit magma chamber was still refilling. Soon, collapse at Halema'uma'u took place, accompanied by the migration of earthquakes far down the east rift. The earthquakes stopped migrating when they got to lower Puna in the region of the small town of Kapoho, and obvious subsidence indicated that an eruptive dike was moving toward the surface. The Kapoho eruption was notable for the compositional diversity of the lavas, the interaction with the shallow water table, and the fact that diversions were constructed to protect property.

An eruption had taken place in the area 4 years earlier in 1955. The first phase of the 1959 eruption involved the "flushing-out" of plagioclase feldspar-rich magma left over from the 1955 eruption. Rather abruptly, the composition changed to oceanite and temperature of the erupting magma increased, indicating that the "fresh" magma was being erupted.

The low elevation meant that the water table was nearby. Violent jets of ash and steam were ejected whenever water was able to gain access to the eruptive conduits. Often a "peaceful" fountain of lava and a roaring jet of ash-laden steam were separated by only a few meters.



Map of the 1960 Kapoho lava flow showing the distribution of lava structural types (Rowland & Walker 1987).

Large barriers were pushed up with bulldozers in an attempt to divert the lava into the ocean. These efforts were valiant (in some cases the bulldozer operators actually pushed back on molten lava), but greatly hampered by the almost flat topography in this area. had there been a definite slope the lava could have been diverted with gravity doing most of the work. However, the lava just ponded behind the barriers until it was high enough to flow over the tops. A number of houses, the school, and stores were lost. Nothing remains of the walls; they were all covered by lava. The lighthouse was lucky; lava surrounded it on 3 sides but did not over-run it.

THE HGP-A GEOTHERMAL PLANT

A number of geothermal wells have been drilled in the lower East rift of Kīlauea, and the first one, HGP-A, has a small visitor center (the plant itself has been closed for about 5 years). Geothermal energy is used at many places around the world but in Hawai'i its use is in its infancy. there are many reasons for this, both technical and social. The most obvious is that many people don't want a big geothermal plant nearby. There is a lot of noise associated with the building and operating of a plant, particularly the "flashing" of the well (allowing the initial burst of steam through), which sounds like a jet engine. Many people also feel that draining the heat from Kīlauea is an insult to Pele. Large areas of sometimes pristine forest have had

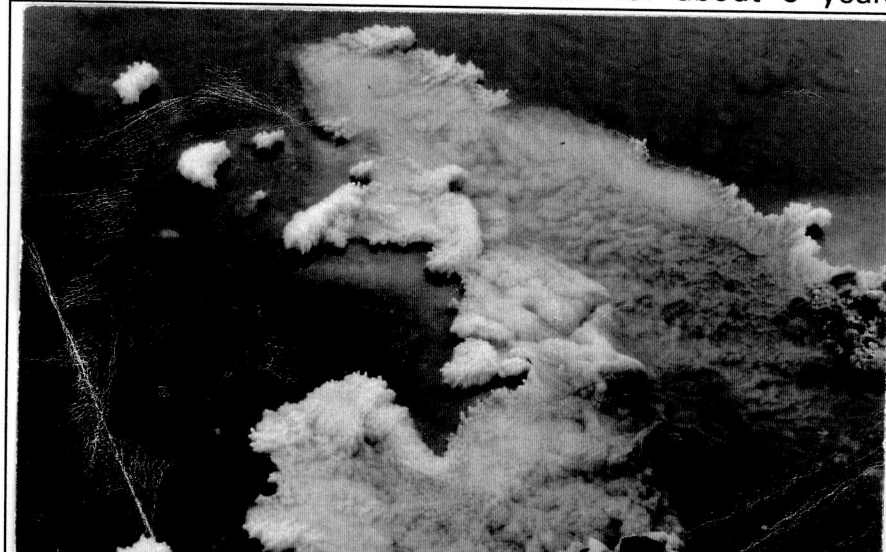


Photo of silica crystallizing in a settling pond at the HGP-A geothermal plant. Width of bottom of photograph ~1 m.

to be cut down and if not cut down, disturbed by the noise and people. It is not clear whether geothermal plants release more gas into the atmosphere than would be released naturally, however, that is a major concern to many people.

The water encountered at the base of the well was in excess of 300°C (the high pressure keeps it from boiling). this is the highest temperature ever recorded in a geothermal well and causes many problems with mechanical equipment. When brought to the surface where the pressure is of course lower, the water flashes to steam. this steam powers the generators that make electricity. Originally there were plans for a huge generating plant that would supply much of the state. Only recently these plans have been canceled until the reliability of geothermal energy to supply a single island can be determined. It was also obvious that the residents of Puna were not thrilled with having to give up their forest and quiet in order to supply energy to the rest of the state.

KALAPANA

Kalapana was always famous for being a nice Hawaiian town and for the beautiful black sand beach of Kaimū. Black sand forms from (often quite small) littoral explosions when lava flows enter the ocean. The sand is then carried along the coastline by currents and waves to be deposited elsewhere. Because the process that forms the black sand occurs only during the eruption, the sand supply is limited. Once the eruption ends, erosion takes over. The beach at Kaimū has thus been shrinking ever since the ~1750 eruption that generated the sand. In 1975 a M7.2 earthquake was accompanied by almost a meter of subsidence and a 4 meter tsunami at Kaimū (e.g. Tilling et al. 1976). This very short-lived event reduced the size of the black sand beach a great deal.


Lava flows entering Kalapana in December 1986 (photo by C. Heliker, USGS HVO).

Kalapana was always an ideal Hawaiian town. The old culture of Hawai'i was well-preserved there, and the many newcomers seemed to have blended easily into the community. The on-going eruption of Kīlauea changed Kalapana for ever. Starting in 1986, and continuing until about 1991, tube-fed pāhoehoe flows from the Kūpa'ianahā vent entered and buried Kalapana. A horst lies along the shore near Kalapana, and it prevented many of the lavas from directly entering the ocean. Unfortunately for most of the town, these flows were diverted to the east by the horst, and most of the houses and businesses plus Kaimū were destroyed. The new shoreline is about 0.5 km offshore from the old beach.

There were no attempts to divert lava flows away from Kalapana except for temporary measures taken long enough to rescue property from threatened homes. There are numerous reasons for this, not the least of which is the strong belief that Pele would have been offended. Pele is respected rather than feared (as long as you have a good heart), and many people feel that what she wants she should have. On a less elegant note there are a multitude of legal problems associated with diverting lava flows, namely, on to whose land do you divert them?

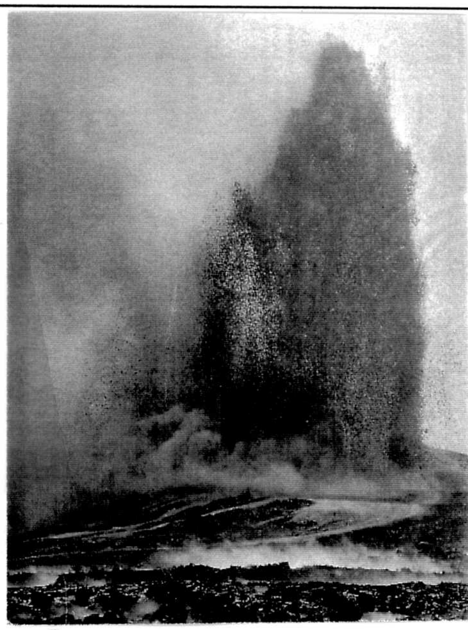
KĪLAUEA, THE YOUNGEST OF THE ISLAND'S 5 VOLCANOES

Kīlauea is the baby of the family (not counting yet-"unborn" Lō'ihi). Like Mauna Loa, Kīlauea is in its tholeiite shield stage and is characterized by gentle slopes. As you drive from Hilo to the Kīlauea summit, the gradient is only barely perceptible. Actually, you are on Mauna Loa lavas until about mile marker 24; flows from the two volcanoes inter-finger because Mauna Loa and Kīlauea have been active contemporaneously.

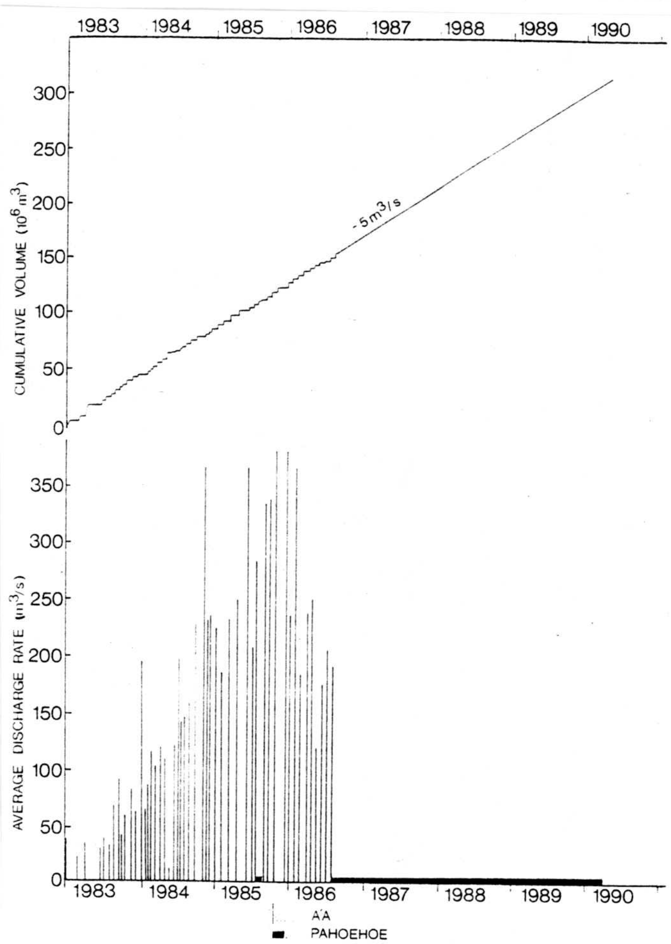
Just before mile marker 20 (Chevron station on the right), in the small town of Glenwood, we will stop to take a look at Pu'u 'Ō'ō. Pu'u 'Ō'ō is the product of 43 episodes of high fountaining. The episodes together are considered part of a single eruption because magma was essentially visible during the whole time, even between episodes. Pu'u 'Ō'ō is presently about 200 m high, but after the last high fountaining episode, was almost 300 m high. It is by far the dominant feature on Kīlauea's East rift zone (the skyline from the Glenwood viewpoint). The vent from which the fountains issued is on the east or upwind side of the cone, and during the high-fountaining episodes was about 20 m across. Since the end of the high fountaining episodes in June of 1986, collapse has widened the vent to more than 200 m. A lava lake has been visible about 70 m below the rim since 1988. A prominent plume issues from Pu'u 'Ō'ō, the source of annoying vog (volcanic fog).

Most of the eruptive episodes that built Pu'u 'Ō'ō lasted for 10-24 hours, with repose periods of up to 45 days in between. Tilt meters at the summit of Kīlauea recorded filling of the summit magma chamber during the periods between episodes, followed by rapid emptying during the episodes themselves.

The high discharge rates during these fountaining episodes (some > 300 m^3/sec) produced large 'a'ā flows, some of which over-ran portions of the Royal Gardens subdivision.



Pu'u 'Ō'ō fountaining, viewed from ~2 km downrift. (photo by Jim Griggs)

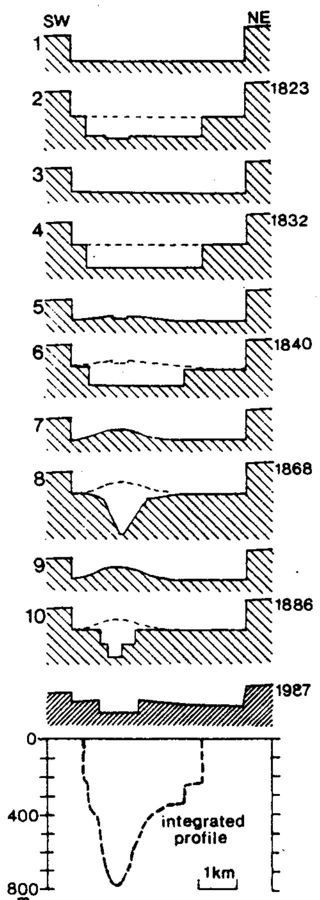


Graphs of average effusion rates and cumulative volume for the Pu'u 'Ō'ō and early Kūpa'ianahā portions of the current eruption (Rowland & Walker 1990). Note that the overall eruption rate did not change when the eruption changed character in mid-1986. Note also that the horizontal axis could now be extended nearly to 1996.

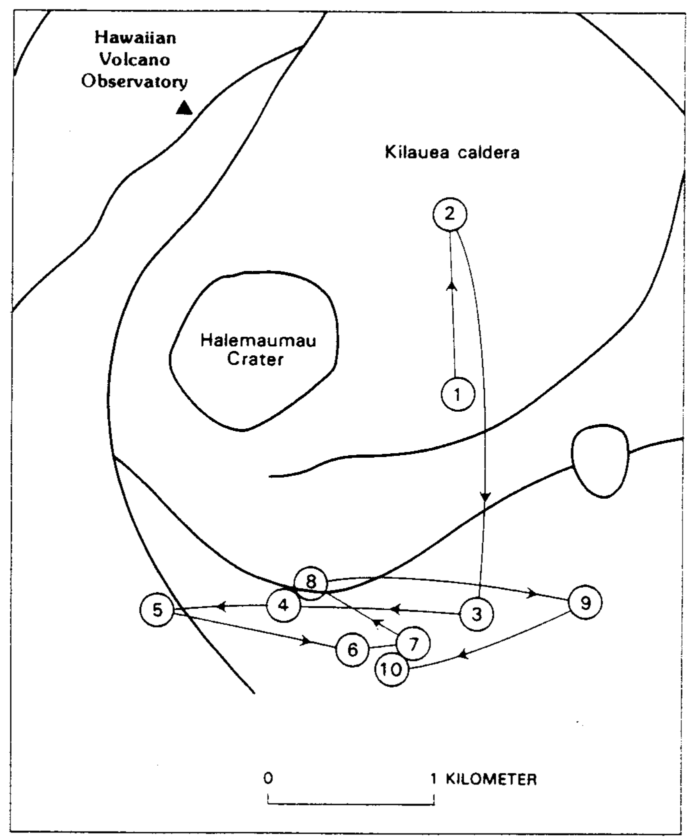
THE KĪLAUEA CALDERA

The top of Kīlauea contains a large depression about 5 km across. This summit caldera is a collapse feature but it almost certainly did not form all at once. Furthermore, it is important to note that this is just the most recent caldera.

Careful mapping by the USGS (e.g. Holcomb 1987) has shown that there have been times in the past when the caldera was full and overflowing (Moku'āweoweo, the summit caldera of Mauna Loa has also been full and overflowing (Lockwood & Lipman 1987). The caldera is not a piston-shaped block that has dropped into a large magma chamber. Walker (1988) compiled the post-contact collapse and infilling events of the Kīlauea caldera and showed them to have a funnel-shape rather than a piston shape. Moreover, it is very rare for magma to erupt from caldera-bounding faults, good evidence that they do not intersect the magma chamber. Finally, Fiske & Kinoshita (1969) showed that the magma chamber of Kīlauea is a plexus of small interconnected voids rather than one large fluid-filled balloon (as it is almost invariably drawn).



Profiles across, and integrated subsidence of, Kīlauea caldera (Walker 1988).



Map showing migration of inflation centers from 1/66 to 10/67. Total inflation was 70 cm and a summit eruption began in 11/67 (Decker 1987 after Fiske & Kinoshita 1969).

HVO

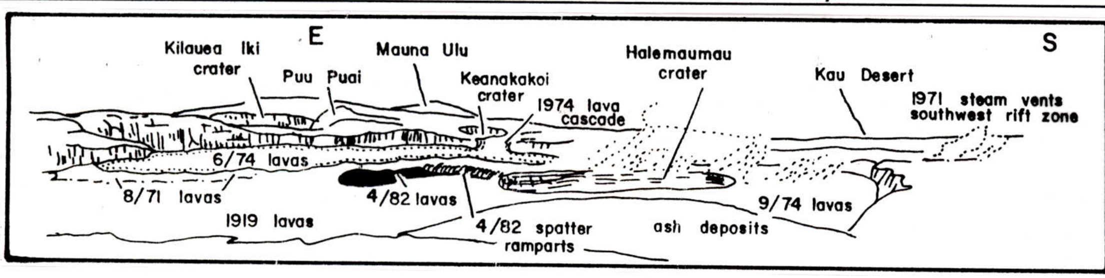
The U.S. Geological Survey's Hawaiian Volcano Observatory (HVO) is located on the W edge of the Kīlauea caldera. It was founded by Dr. Thomas Jaggar of M.I.T. in 1912. Jaggar's original observatory was a one-room building where the Volcano House hotel now stands. Having been impressed by the terrible destruction of St. Pierre, Martinique by pyroclastic flows from Mt. Pelee in 1902, Jaggar's motto became *ne plus haustae aut obrutae urbes* ("no more abandoned or buried cities"), and he dedicated his life to learning about volcanoes in order to lessen the danger they pose to humankind. Jaggar made the first collections of volcanic gases, numerous temperature measurements, compiled seismic and tilt records, and made hundreds of observations (see Apple 1987).

HVO has grown to become the premier volcanological observatory, and in the process allowed Kīlauea to become the most closely-monitored volcano on earth. The permanent staff numbers about 20 scientists and technicians, and there are always numerous students, volunteers, and visitors conducting all manner of volcanological research. The primary task of HVO is the monitoring of the active volcanoes in Hawai'i with regard to volcanic hazards, and in doing so the staff works with Hawai'i County Civil Defense, various State agencies, and government planners. Considering how much is still unknown about Kīlauea (in spite of all this work) it is no wonder that the rest of the world's volcanoes are so full of surprises. An excellent public museum has been made out of an old HVO building, and it has been named for Dr. Jaggar.

Three geophysical techniques have become particularly useful in studying Kīlauea. They are seismology, tilt measurements, and electronic distance measurement (EDM). A network of ~55 seismometers has been installed by HVO, and most of the data are telemetered directly to the observatory. Volcanic earthquakes are relatively small and are caused as a dike tip breaks its way down a rift zone, and as magma flows through the dike (harmonic tremor). The largest Hawaiian earthquakes occur as large portions of a volcano shift around in response to volcanic and tectonic stresses. Recently the data have started to be collected digitally for real-time analyses. This has allowed the scientists to track the propagation of dikes down the rift zones, and determine volcanic structure from aftershock sequences following strong earthquakes.

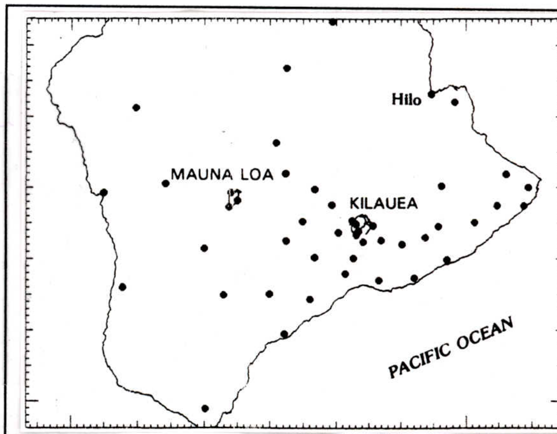
HVO, located on the W rim of Kīlauea caldera. This photo was taken while the museum end was being re-roofed.

As the magma chamber beneath Kīlauea fills and empties, the summit of the volcano tumesces and detumesces, respectively. Precise measurements of the tilting of the ground allows the HVO to monitor these changes and determine the activity of the magma chamber. Permanent water-tube or mercury-switch tilt meters provide a continuous record. Additionally, spirit-leveling or "dry tilt" stations allow tilt to be determined at many more locations than would be possible to continually instrument.



Panorama from HVO (Easton & Easton 1987; drawn by Rick Hazlett).

Additionally, during the tumescence and detumescence events, the distances between points on the ground get larger and smaller, respectively. Very accurate measurements with a laser ranging system allows these changes to be monitored. The EDM "gun" sends out a pulsed beam that is reflected from a corner reflector back to the gun. EDM measurements are accurate to 1 part in 1 million. Permanent trilateration networks are repeatedly measured to monitor changes in the volcanic structure. EDM survey lines can also be set up quickly in the field to allow for monitoring of short-term events.

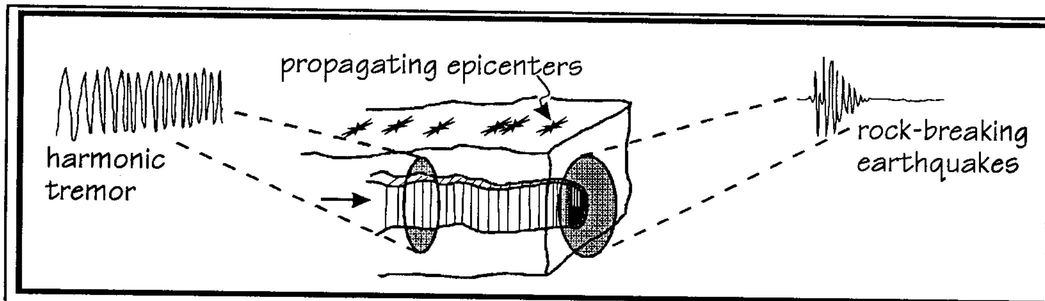


HVO seismometers on Hawai'i as of 1984 (Klein *et al.* 1987).

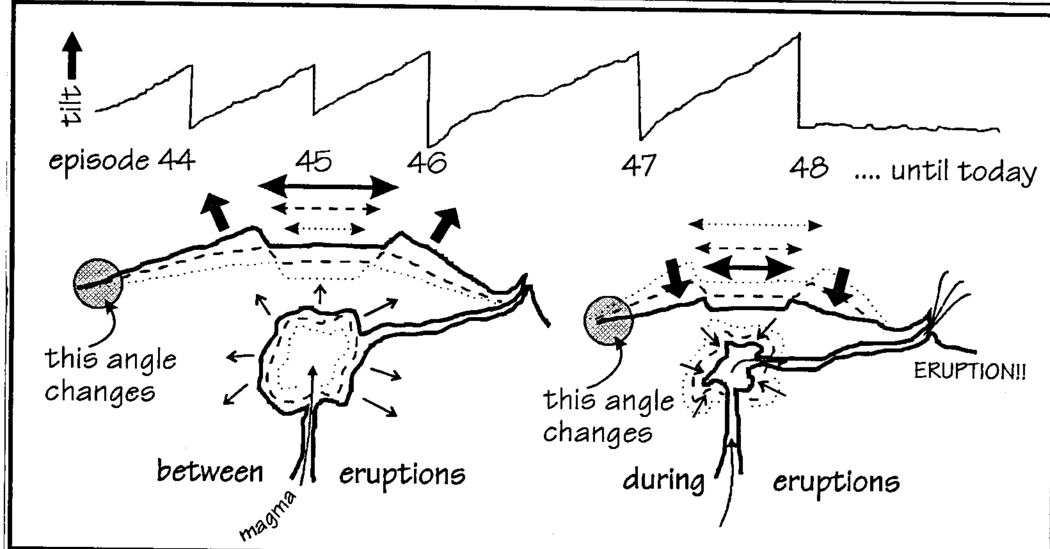
UPPER END OF THE SW RIFT ZONE

Crater Rim Drive crosses a number of fissures that mark the upper end of the SW rift zone. These fissures are mainly non-eruptive, and illustrate well the tensional regime that characterizes the surface trace of a rift zone. The ca. 1790 Keanakāko'i phreatomagmatic ash is well-exposed in the walls of these fissures. Discontinuous fractures comprise most of the rift along its upper half. Beyond this, the "great crack" is a yawning fracture 10's of m across and very deep. Unfortunately the great crack is not very accessible. Most of these fissures near the road opened up during the great 1868 earthquake.

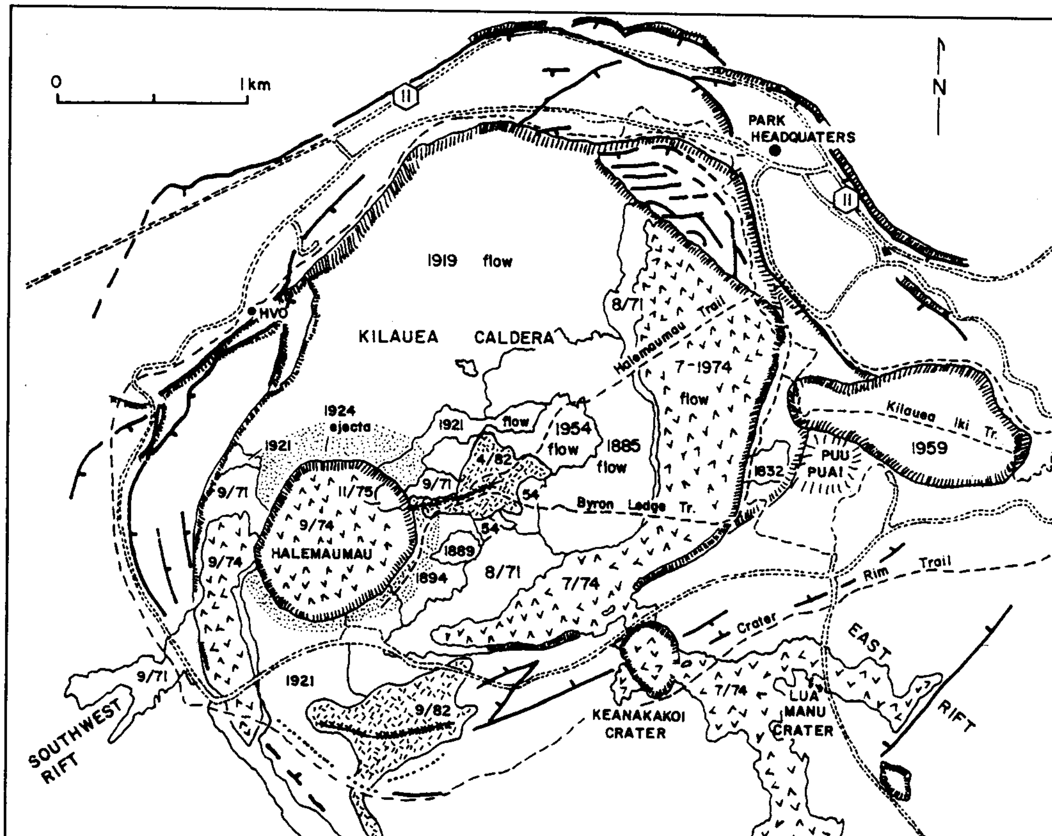
In September 1971, eruptive fissures opened from Halema'uma'u, across the southern floor of the caldera and up the wall to near these 1868 cracks. Lava flowed into the cracks and back down into the southern part of the caldera where it pooled before spilling out to the SW. Eruptive fissures eventually migrated ~11 km down the SW rift zone as far as Mauna Iki before this brief 5 day eruption ended. Since Westerners have arrived, the SW rift has been much less active than the E rift, having had eruptions only in 1823, 1868, 1919-1920, and 1971.



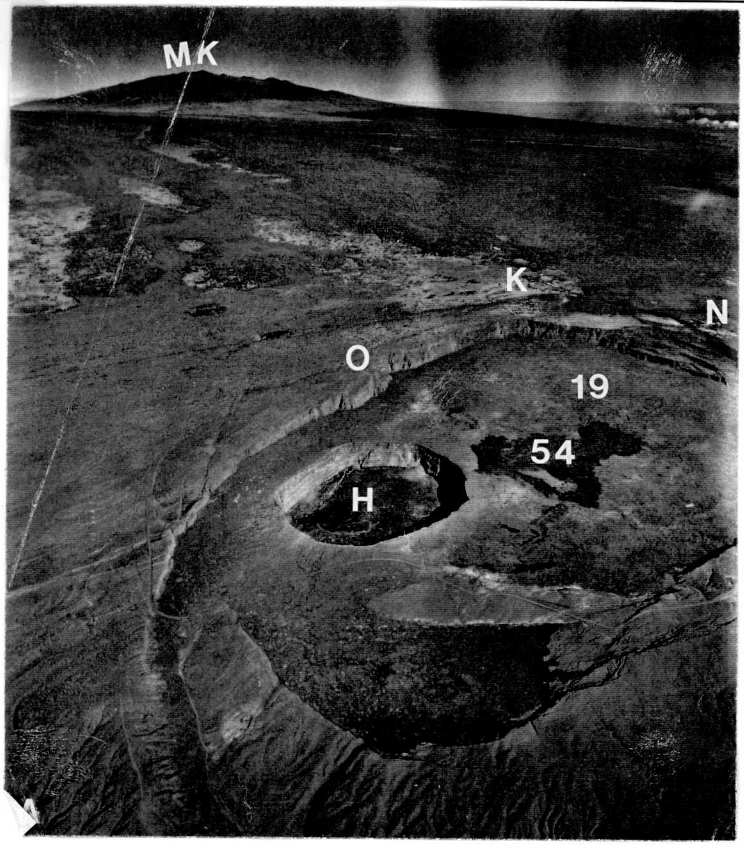
Types of earthquakes associated with a propagating dike: the dike tip fractures the country rock and real-time seismic data can allow the dike to be followed. Harmonic tremor indicates magma flowing in an open conduit.

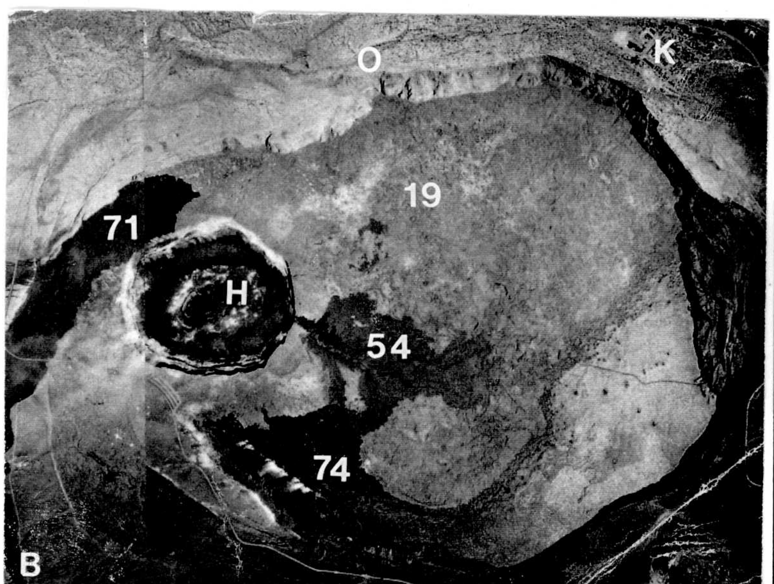


The relationship between inflation, deflation, tilt, and distance measurements for episodic and continuous eruptions.



Map of Kīlauea caldera showing post-contact lava flows (Easton & Easton 1987).





Air views of Kīlauea caldera: (A) oblique, looking north, taken in 1954; (B) vertical, north to top, taken in 1974. *Numbers* indicate 20th century flows, *H*: Halema'uma'u, *O*: HVO, *K*: Kīlauea Military camp, *N*: Park Service HQ, *MK*: Mauna Kea (modified from Carr & Greeley 1980).

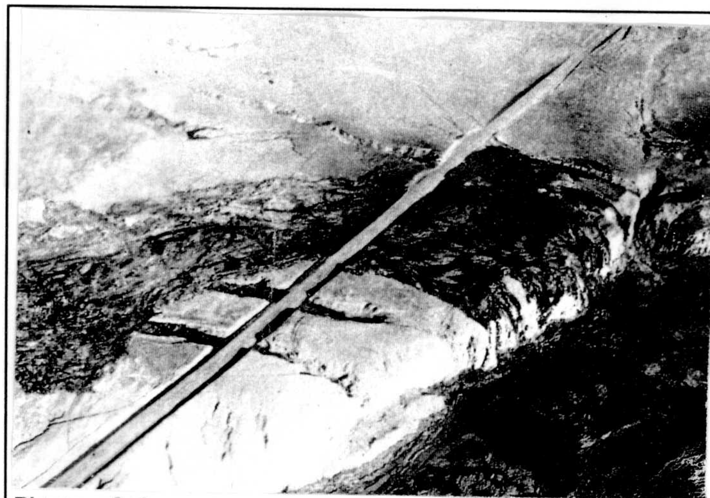


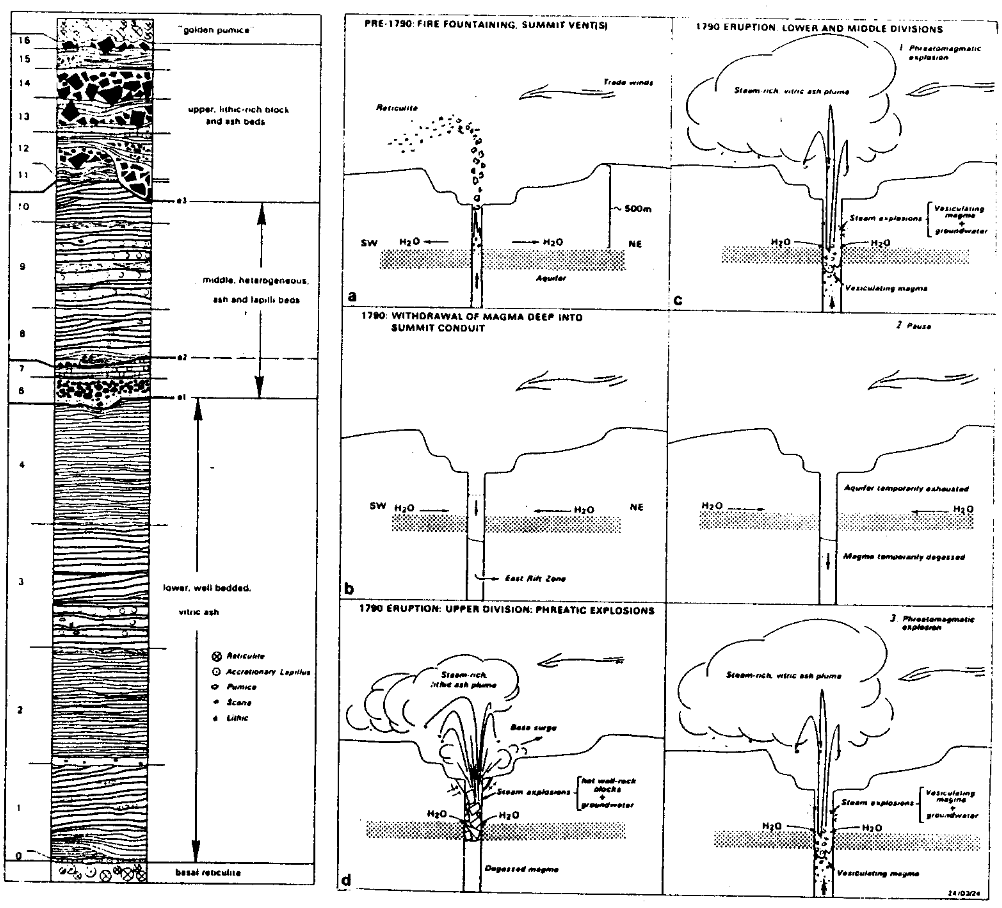
Photo of the uppermost end of the SW rift zone where it intersects the caldera. Lavas were erupted in Sept. 1971, and flowed into the caldera (from Greeley 1974).

The great crack, the downrift end of the SW rift zone. View is uprift; dark lava erupted from the crack in 1823 (from Greeley 1974).

1790 KEANAKĀKO'I PHREATOMAGMATIC ASH:

Kīlauea erupted very explosively in 1790. There are transcripts of interviews with Hawaiians caught in the eruption as well as geologic interpretations to reconstruct the events (Swanson & Christiansen 1973; McPhie *et al.* 1990). The following chronology comes from Swanson & Christiansen (1973); passages in italics are from Dibble (1843). The army of King Keōua was marching from the E side of the island over to Kailua Kona to do battle with King Kamehameha. They had to traverse Kīlauea on their way and they stopped to spend the night near the N rim of Kīlauea's caldera. That night there was a violent eruption "*throwing out flame, cinders, and even heavy stones to a great distance*." The warriors (and their families and livestock) spent 3 days there, afraid to travel during the eruption. Finally they set off in 3 groups:

"*The company in advance had not proceeded far before the ground began to shake and rock...soon a dense cloud of darkness was seen to rise out of the crater...*" A great deal of debris was thrown out and then "*came down in a destructive shower for many miles around. Some few persons of the forward company were burned to death by the sand and cinders and others were seriously injured. All experienced a suffocating sensation...*" Members of the rear group, which had been closest to the eruptive source in the caldera, suffered little and hastened ahead to join the second party, which they found to have been totally exterminated, except for one pig. Some of the corpses "*were lying down, others [were] upright clasping with dying grasp their wives and children...So much like life they looked that they [the third party] at first supposed them merely at rest...*" Swanson & Christiansen believed that the Hawaiians were killed by a base surge. This is based on the lack of evidence of injuries, and that the victims appeared to be huddling against a strong wind rather than trying to flee from falling debris.



Section and interpretation of events for the 1790 phreatomagmatic eruption (McPhie *et al.* 1990). Section is schematic; total thicknesses and presence of beds varies with outcrop location.

McPhie *et al.* (1990) carefully pieced together the eruption from studies of the 1790 deposits. Most of the deposit indicates at least a small degree of water-magma interaction. In the first 2 stages (separated by "dry" strombolian fountaining), water contacted magma that was already being vesiculated by its own volatiles. This is indicated by very fine grain sizes (even near the vent), accretionary lapilli, and lamination of the deposit. The minor lithic content suggests that open-vent conditions existed from a vent with stable walls. Explosions then ceased and a small lava flow was erupted. The supply of magma to the vent apparently was cut off, and the third stage was phreatic with only steam contributing to the explosions. The fatal blasts took place during this last stage. There were several discreet explosions which were probably triggered and accompanied by vent wall collapse that disrupted the hydrothermal system surrounding the conduit. Pauses between explosions probably reflect temporary depletion of the aquifer in the vicinity of the magma conduit, followed by heating of water entrapped in the wall rocks and in the lithic debris that had accumulated in the conduit, leading to the next explosion.

The Keanakāko'i ash has been spectacularly gullied, and in these sections you can closely examine the phreatomagmatic and phreatic deposits. The lack of resistance to erosion is evident in these few-m deep gullies only 2 hundred years old. A duri crust ("case-hardened" crust of Malin *et al.* 1983) has formed on the top surface of much of the deposit and this has contributed to the lack of vegetation in this area. Another contribution to the Ka'ū desert being a desert is the continuous acid plume and consequent acid rain downwind from the Kīlauea summit.

Photo of particularly well-preserved footprint in the Keanakāko'i ash ~13 km SW of the Kīlauea caldera. Boot is men's size 9.

The Keanakāko'i ash was studied in detail by Malin *et al.* (1983) to try and understand the processes that degrade ash units on basaltic volcanoes as possible analogs to Mars. They found that during particularly heavy rains the duri crust, being impermeable, promotes sheet flow of water which then is very effective at erosion. Gullies up to 30 m in width have been cut through the ash to the underlying lava, but because that lava is so permeable, gullying has not proceeded further. In places where the ash was originally thinner, gullies form in the ash until most of it is stripped away. There is no trace of the gullies after that. Soil-water sapping was also found to be a significant contributor to erosion. Different layers within the deposit have markedly different permeabilities leading to significant lateral percolation of water once it has seeped into the ash. When this water reaches the edge of a gully, it causes undermining and leads to collapse into the gully.

Wall of gully cut into 1790 Keanakāko'i ash, SW of Kīlauea caldera.

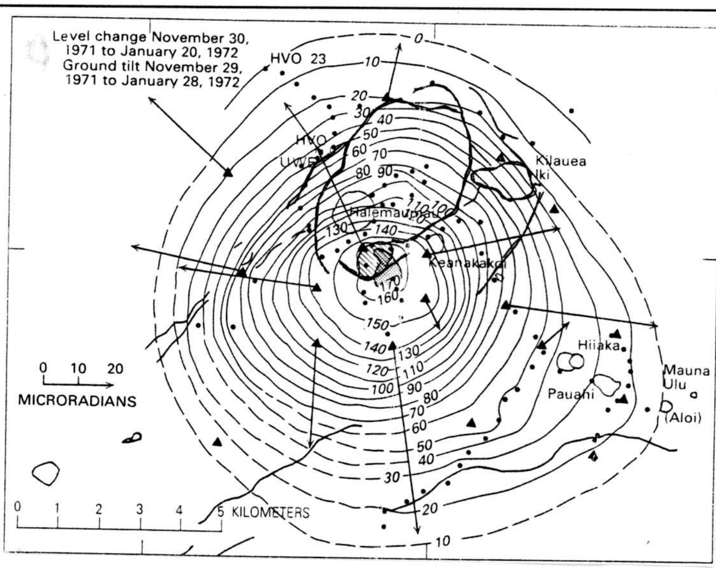
Malin *et al.* (1983) also found that depending on whether the ash was emplaced on pāhoehoe or 'a'ā, its mode of degradation (and probably its mode of emplacement as well) can be quite different. For instance, it is easy to completely obscure a pāhoehoe flow with only a few 10's of cm of ash. However, it is also easy to completely strip away that ash in a relatively short time of erosion, leaving the pāhoehoe surface much as it was before burial. Because 'a'ā flow margins are so high, a thick ash layer is required to obscure an 'a'ā flow. Furthermore, because of the intricacies of an 'a'ā surface, it is very difficult to completely remove an ash layer that has been deposited there. This leaves the 'a'ā surface greatly changed relative to its prior unburied state, namely all the low parts are filled in.

HALEMA'UMA'U AND THE 1924 PHREATIC ERUPTION

After leaving the upper end of the SW rift zone, we drop down onto the caldera floor. The complexity of the collapse that formed the caldera can be seen from here; in some places single scarps extend from the rim to the floor and in others multiple "steps" make up the displacement.

Lava lake in Halema'uma'u, 1894. The lake is held behind self-built levees of spatter and small overflows (from Macdonald & Abbot 1970).

In the southern part of the caldera is a pit crater named Halema'uma'u. Eruptions are common in and around Halema'uma'u and for the first hundred years after Western contact, an active lava lake was present here. The level of the lake moved up and down, at times higher than the surrounding caldera floor, perched behind self-built levees. Overflows built these levees higher, and occasionally flowed as far as 4 km away from the crater rim. The overflows also built up a small shield centered at Halema'uma'u, and this can be seen when standing away at a distance.



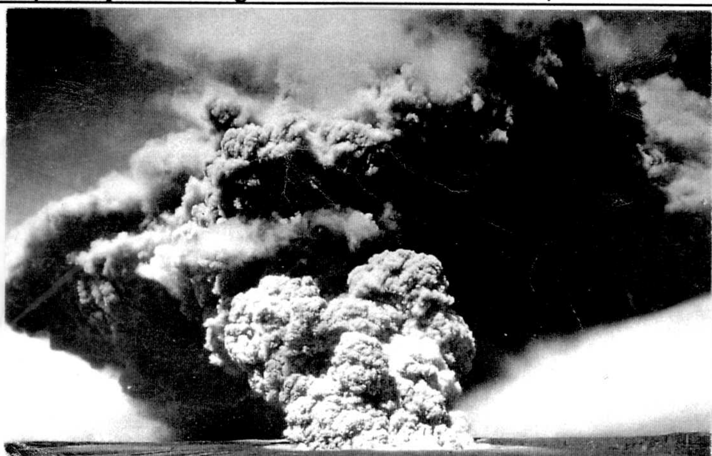
Summit uplift at Kīlauea prior to the second part of the Mauna Ulu eruption. Note that the center of uplift is offset from both the center of the caldera and Halema'uma'u, and that it rose >170 cm in <2 months (Tilling *et al.* 1987).

The lava lake has not been seen since 1924, however, there have been numerous eruptions in and around Halema'uma'u since then. The most recent lava in the pit dates from 1975 but it flowed in from vents outside. The most recent eruption actually within Halema'uma'u took place in 1982. Within the pit, the floor consists of ponded lava surrounded by talus that has fallen from the walls. A distinct bench indicates a previous level of the floor. Numerous fumaroles around the edge of the pit have deposited sulfur. It is tempting to say that Halema'uma'u directly overlies the Kīlauea magma chamber, however, the average center of radial deformation is usually located to the SW. It is thought that the magma chamber is actually a series of interconnected voids, and Halema'uma'u probably is closely connected with one or more of these.

Halema'uma'u is the home of Pele, and a place of considerable reverence to many Hawaiian people. For this reason, geologists avoid going into it. Once, on one of the rare visits to the floor of Halema'uma'u one of the HVO staff found an intact bottle of gin. His colleagues denied bringing it for good luck so someone must have thrown it in and Pele caught it.

The area around Halema'uma'u is littered with thousands of angular blocks. A close look at the blocks shows them to be mostly intrusive rocks and fragments of ponded flows. These dense rocks are pieces of the volcanic plumbing system. They were brought up during the explosive eruptions of May 1924, summarized here from Dvorak (1992). The eruption was preceded by a transfer of a large volume of magma from the summit reservoir to the E rift zone, which reduced pressure in the reservoir and lowered the magma column beneath Halema'uma'u. The lowering of the magma column drained the lava lake and caused collapse of the walls enlarging Halema'uma'u from ~700 m wide by ~150 m deep to ~1000 m wide by ~400 m deep, a volume increase of ~200×10^6 m^3 (Jaggar 1924).

This collapse reduced hydrostatic pressure beneath the summit and allowed groundwater to flow rapidly into areas of hot rock, producing phreatic explosions. The explosions threw rocks a kilometer into the air, and clouds of dust rose 6.5 km above the crater. Condensing steam led to heavy rains of mud, and the formation of accretionary lapilli. Blocks weighing a few thousand kg were thrown up to a km from Halema'uma'u. The total volume of blocks and dust ejected during the explosions was 7.5×10^5 m^3, accounting for less than 1% of the Halema'uma'u volume increase. Although many of the ejected fragments were red-hot, none were juvenile, and additionally no juvenile gases were detected, steam alone was powering the explosions.



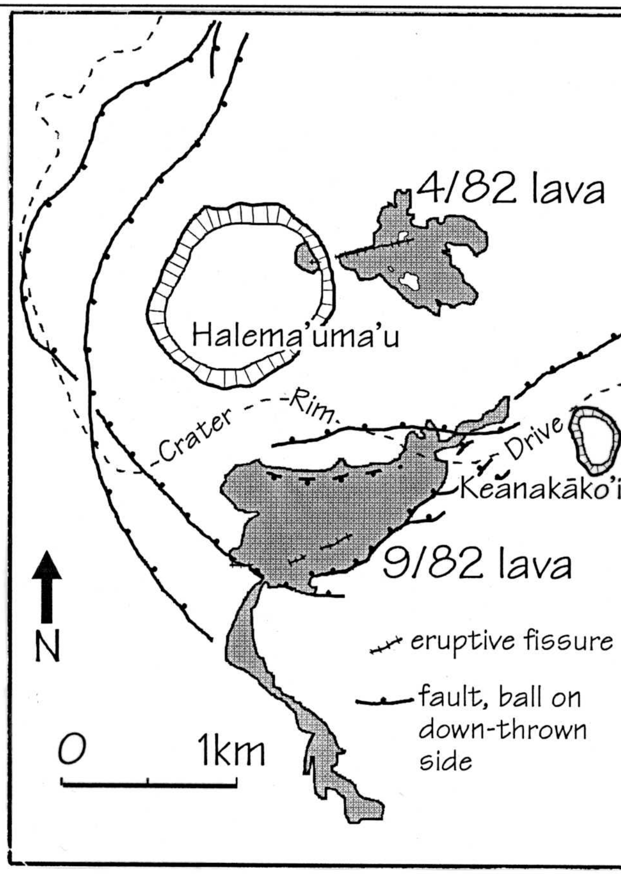
Phreatic eruption from Halema'uma'u in May 1924 viewed from the Volcano House (from Carr & Greeley; taken by Tai Sing Loo).

Explosion debris from the 1924 phreatic eruption. The large block in the foreground is >1 m across (from Macdonald *et al.* 1983).

APRIL 1982 SPATTER RAMPARTS

A small summit eruption took place on April 30, 1982 at 11:37 in the morning. ENE-trending fissures opened on the caldera floor NE of Halema'uma'u, S of some 1954 vents. The initial crack first issued dust, then steam and fumes, followed 2 minutes later by the first blobs of spatter. The vent lengthened in both directions to a total of ~1 km, and extending into Halema'uma'u crater. Activity peaked about 1 hour after the onset with a nearly steady curtain of spatter being thrown 5-10 m high, and occasionally up to 50 m. This continuous curtain of fire was active for about 5 hours, building spatter ramparts and feeding pāhoehoe flows to the N, E, and S.

Eruption rates began to decrease at about 16:30, and activity gradually became limited to a 150-200 m section in the central part of the fissure system. Lava drained back into the inactive parts of the fissure. The eruption stopped at 6:30 on May 1, having covered about 0.3 km^2 with 5×10^5 m^3 of new lava (from Baker 1987).



Map showing lavas of April and September 1982 (adapted from Baker 1987).

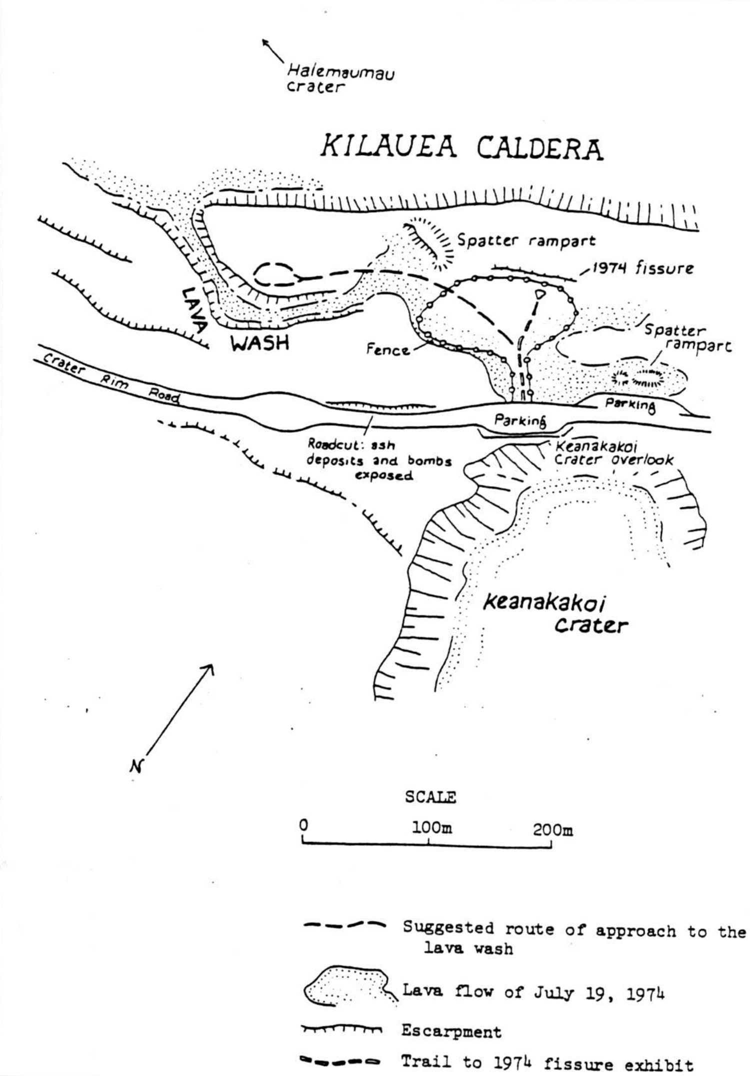
SEPTEMBER 1982 LAVA FLOW:

The second summit eruption of 1982 began September 25 at 18:44. The eruption was preceded by a seismic swarm. The initial eruptive fissures opened in the S part of the caldera, and formed an ENE left-stepping *en echelon* system about 1 km long, roughly parallel to the caldera wall. The vigorous fountains were 20-40 m high within minutes of the initial outbreak. A second vent system opened to the SW about 15 minutes later. In contrast to the somewhat linear earlier vents, this second group was distinctly arcuate and parallel to the circum-caldera fault system. This second system extended W for 45 minutes when a small vent opened on the caldera rim at the top of a fault scarp. Eruptions along or parallel to caldera boundary faults are rare for Hawaiian volcanoes, but these merge with the trace of the upper southwest rift zone so their orientation may be more related to that than the caldera boundary faults.

Lava from the first vents ponded in a fault-bounded depression and soon had surrounded the E group of spatter ramparts. At about 19:30, lava spilled out of this depression to the S. This lava flowed for ~1.5 km, covering part of the 1971 summit lavas which had spilled out of the caldera from the same place. Two hours later, lava from the ponded depression overflowed to the NE onto the main caldera floor. By 23:00 the W-most vents of the SW group had ceased erupting. By the next morning activity at the E group and the rest of the SW group had diminished. The final vent (in the central part of the SW group) ceased erupting by 8:30 on 9/26. Fluid lava under the solidified crust in the ponded depression continued to drain back into the eruptive fissures for ~34 hours after the cessation of effusion. The crust subsided 2-4 m, leaving a "bathtub ring" where lava had solidified against the enclosing walls. 3-4 x 10^6 m^3 of lava was erupted, and it is estimated that 1/4 to 1/3 of it drained back. (from Baker 1987).

JULY 1974 ERUPTIVE VENTS AND LAVA SLOSH CHANNEL

A short-lived eruption took place on the thin septum between the caldera and Keanakāko'i pit crater on July 19 and 20, 1974. This eruption is interesting because most of the lava flowed down a pre-existing erosional gully into the caldera. Lava from a 1971 eruption had earlier utilized this same gully. The dynamics of this flow were studied by Heslop *et al.* (1989). They made detailed traverses along the gully and compared the heights to which the lava rose on either side



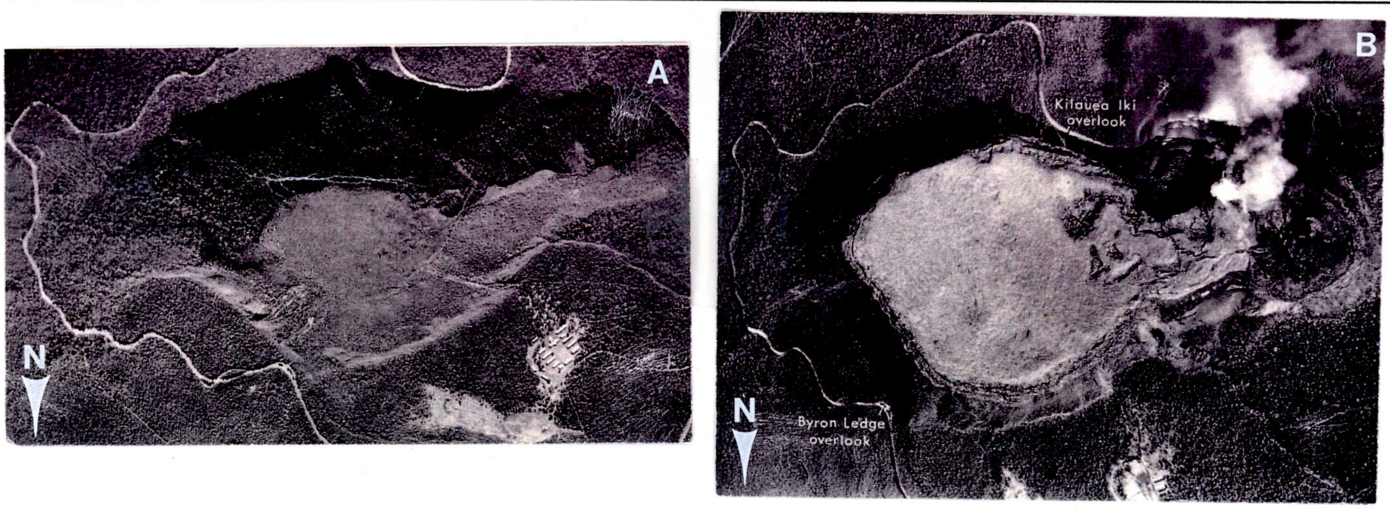
Sketch map of the 1974 lava-sloshed gully (from Easton & Easton; drawn by Rick Hazlett).

Photo of 1974 lava-sloshed gully (Heslop *et al.* 1989).

while flowing, noting that on the outsides of bends, the lava rose higher. By incorporating these measurements into a study of the lava rheology, it was found that the flow velocity (which wasn't carefully observed during the eruption) was ~8 m/sec and laminar. They also determined that the lava had a viscosity of 85-140 Pa-sec, and a negligible yield strength.

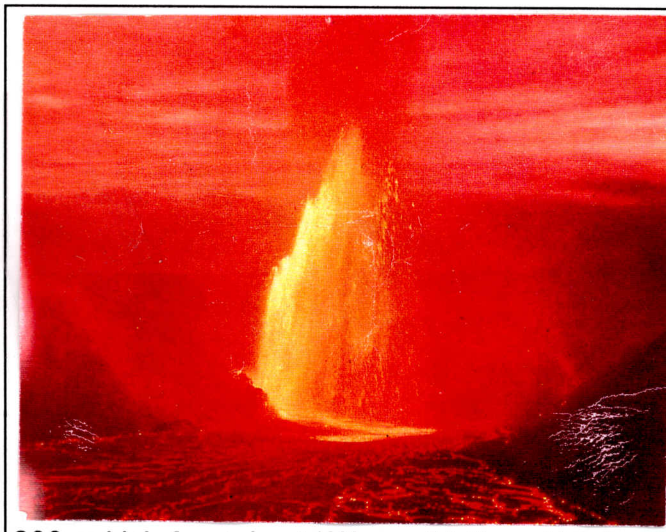
KĪLAUEA IKI AND PU'U PUA'I

Starting on November 14 1959, a spectacular eruption took place from vents half way up the 200 m high S wall of the Kīlauea Iki pit crater (Macdonald 1962; Richter *et al.* 1970). The initial fissure was 800 m long, and the lavas from the two ends were chemically distinct (Wright 1973). Within a day the eruption coalesced into a single vent, and the output rate and fountain height both increased. By November 21 Kīlauea Iki had filled to the level of the vent, and the fountaining was choked off when lava began to drain back down the vent. This alternation between fountaining and draining back was repeated 16 times over the next 4 weeks. Kīlauea Iki, once ~200 m deep is now 87 m deep. The volumetric eruption rates were high (up to 340 m^3/sec), and fountains were some of the highest on record, reaching 580 m.



Vertical air photos showing Kīlauea Iki pit crater before (A) and after (B) the 1959 eruption (from Richter *et al.* 1970).

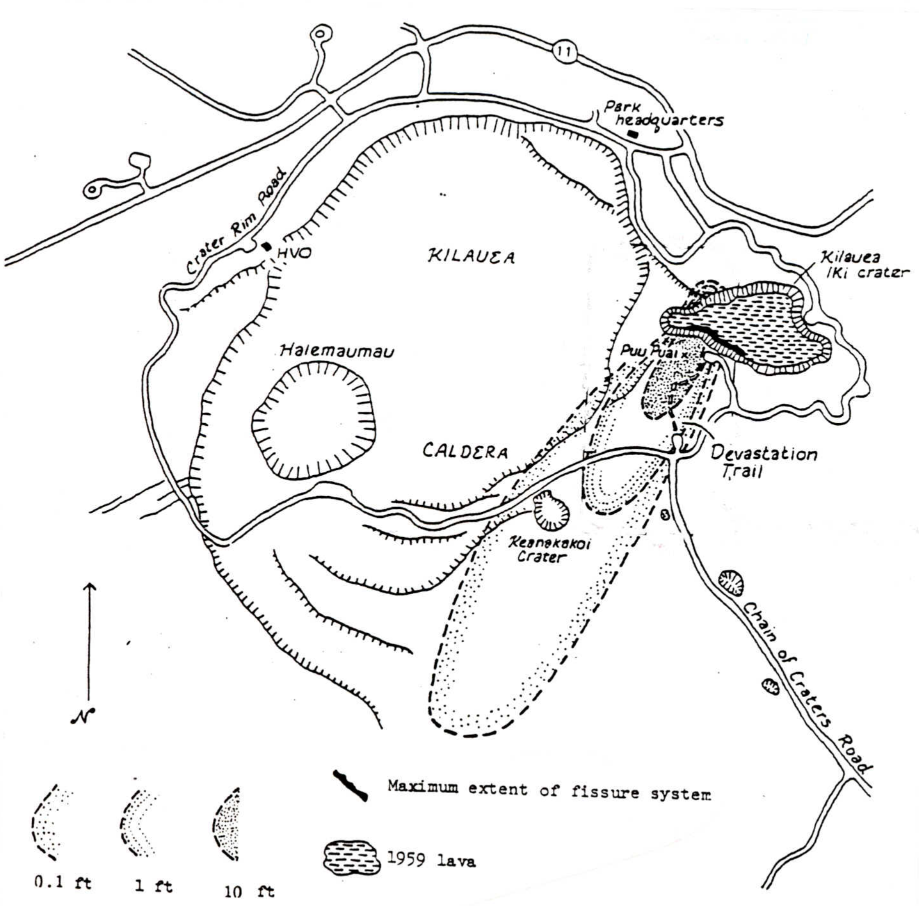
The high fountaining produced a large cinder cone on the edge of Kilauea Iki named Pu'u Pua'i, and a boardwalk (recently replaced by boring asphalt) was constructed by the National Park Service over part of the tephra deposit. One of the more dramatic sites is of the dead, bleached trees; the area where Pu'u Pua'i formed was thick forest prior to the eruption, but the rapid fall of tephra (at rates of several decimeters/hour) stripped the leaves of trees, killing many of them. Some of the surviving Ōhi'a trees have bunches of aerial roots. Apparently they reacted to the heat from the fountains, and thinking that their ground roots were about to be burned by a lava flow, produced the aerial roots. The various degrees of destruction followed by regrowth of the forest were closely monitored by geologists and botanists (Wentworth 1966; Smathers & Mueller-Dombois 1974). Many of the plants in this area are non-native introduced weeds (including blackberry, cotton, and *Myrica faya*). This is a big problem throughout most of Hawai'i, particularly where the native plants are under stress. Close examination of the tephra shows it to be olivine-rich (the lavas were of oceanite picrite composition). You can also find Pele's tears and Pele's hairs in the deposit (but please don't take them; this is a National Park).



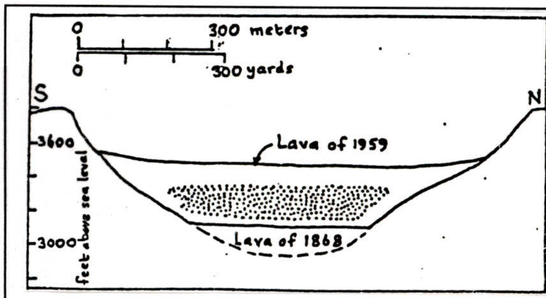
300 m-high fountain at Kīlauea Iki (from Macdonald *et al.* 1983).

The 111 m-deep lava lake that formed in Kīlauea Iki has been the subject of numerous studies. Periodic drilling surveys have determined cooling rates (e.g. Murata & Richter 1966; Hardee 1980). The most recent drilling (in 1988) found that some partial melt still exists, and seemed to indicate that the bottom is 15-25 m deeper than the original pit crater, perhaps because of sagging under the weight of the lava. Following the 1959 summit eruption, magma migrated down the rift zone to Kapoho, 48 km away at the easternmost point on the island. An eruption took place from fissures that opened up just outside the town and lasted from January 13 to February 20, 1960. The communities of Kapoho, Koa'e, and a Coast Guard station were destroyed. The Kīlauea Iki/Kapoho pair constitutes an example of a summit-flank eruption sequence, often touted as typical of Kīlauea and Mauna Loa.

Devastation trail and the downwind side of Pu'u Pua'i (viewed to the north; photo by Dwight L. Hamilton).



Map showing Isopachs of cinders deposited by the 1959 Kīlauea Iki eruption (from Easton & Easton 1987, adapted from Richter *et al.* 1970 by Rick Hazlett).

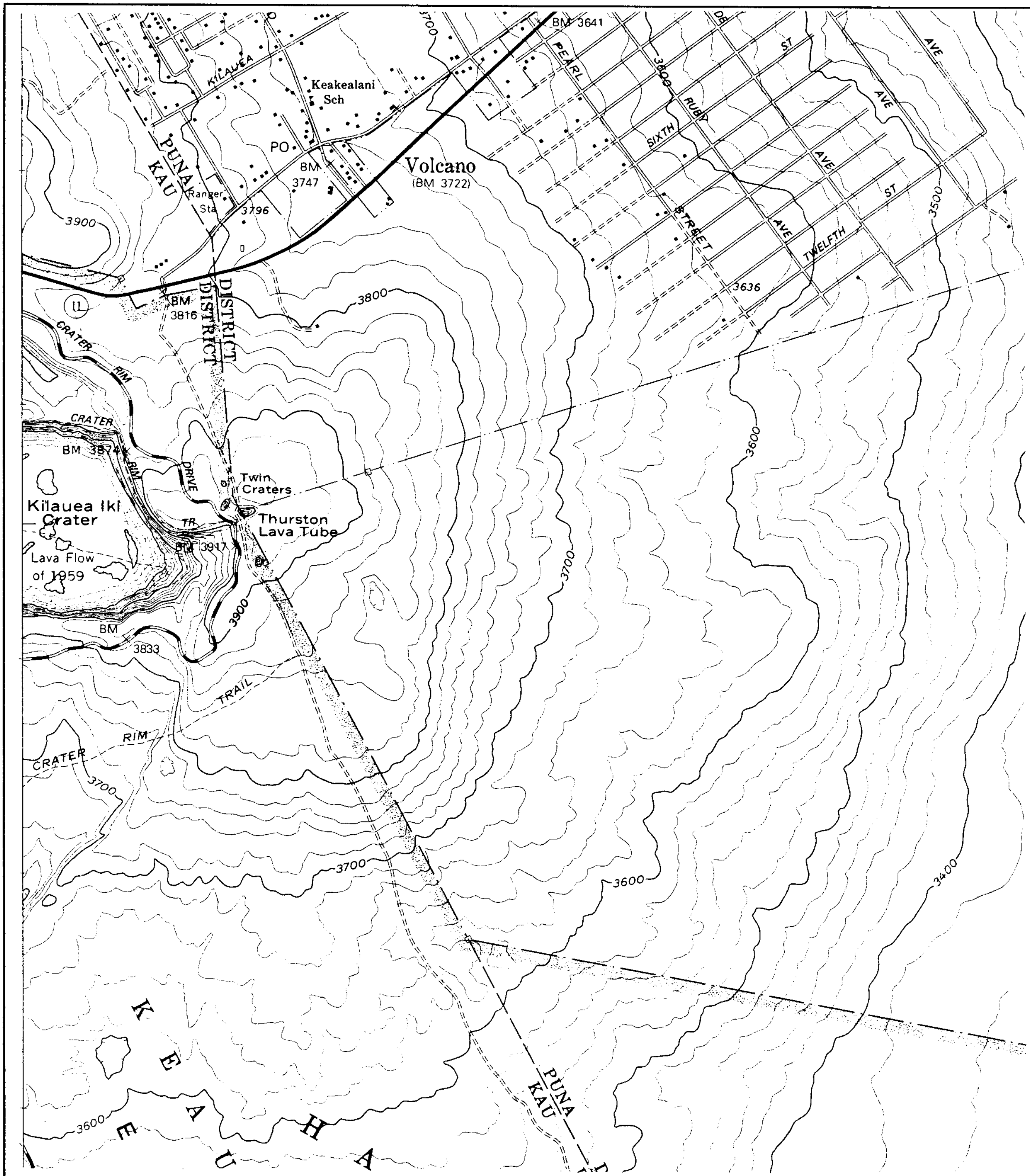


Cross-section of Kīlauea Iki to show the zone of still-molten slush (drawn by George PL Walker).

THURSTON LAVA TUBE

Lava tubes and satellitic shields are features associated with low effusion-rate pāhoehoe eruptions. One such eruption took place some 400 years ago from the E end of Kīlauea Iki crater. The form of the shield (named the 'Ai Lā'au shield) is easy to see in topographic contours, and most of the northern part of the E rift is covered by lavas from the 'Ai Lā'au eruption (Holcomb 1987). The trail leads into the central pit of the shield, and a bridge crosses over to where an average-sized master tube leads out through the pit wall. The official trail part of the tube is only a short segment of its entire length;

'Ai Lā'au lavas extend almost 40 km from the vent so during the eruption lava was flowing through tubes that long. Of course that doesn't mean that they are today drained out and explorable over that distance.



Portion of the USGS 1:24,000 Volcano Quadrangle map showing the 'Ai Lā'au shield and pit, from which the Thurston lava tube leads.

Within the tube you can see evidence of prolonged flow at different levels in the numerous shelves and benches along the walls. As lava flows at a constant level, the surface partially crusts over, building a thin skin from the walls toward the center. Remnants of these are the sub-horizontal protrusions preserved today. The walls of the tube have a glazed glassy surface of remelted lava that is found only on the insides of tubes and large vesicles.

The tube is named after Lorrin Thurston, a newspaper publisher from Honolulu and avid volcano buff. He popularized Kīlauea volcano for his readers and provided moral, financial, and physical support to Thomas Jaggar during the early days of HVO (Apple 1987). He played a big part in the overthrow of the Hawaiian monarchy in 1893, and for this he is today regarded as somewhat infamous.

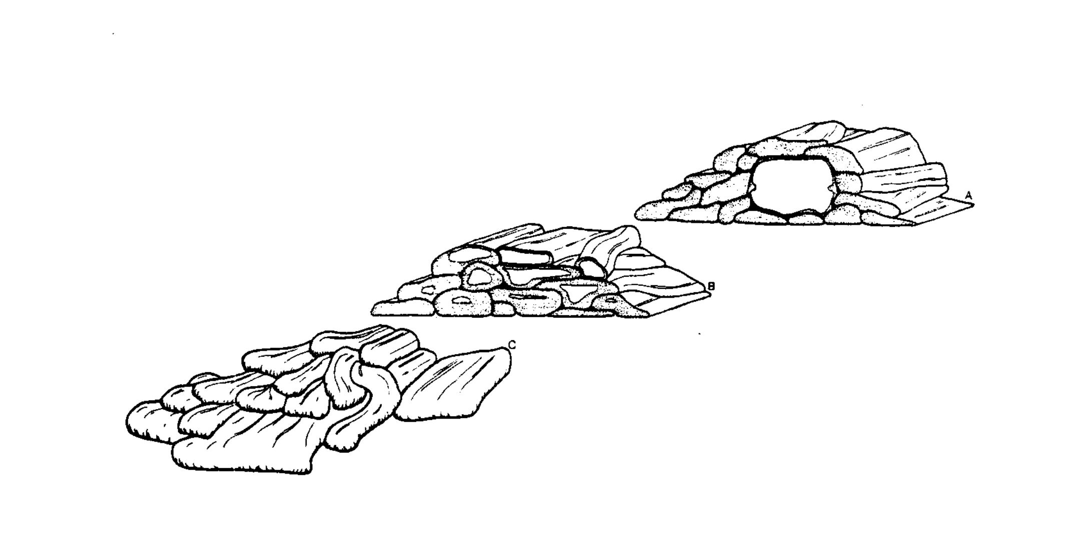
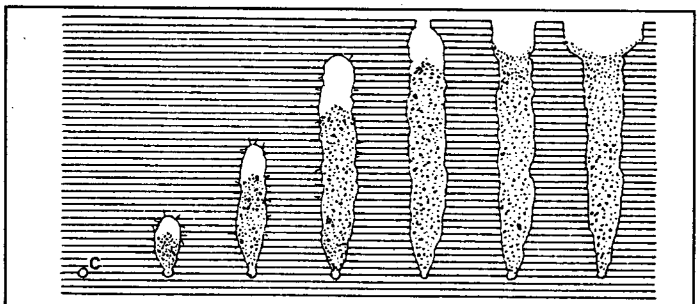


Diagram of 3 positions along a pāhoehoe flow to show the formation of a master tube by the coalescence of numerous single flow-unit tubes (Rowland & Walker 1990).

THE CHAIN OF CRATERS/UPPER EAST RIFT ZONE:

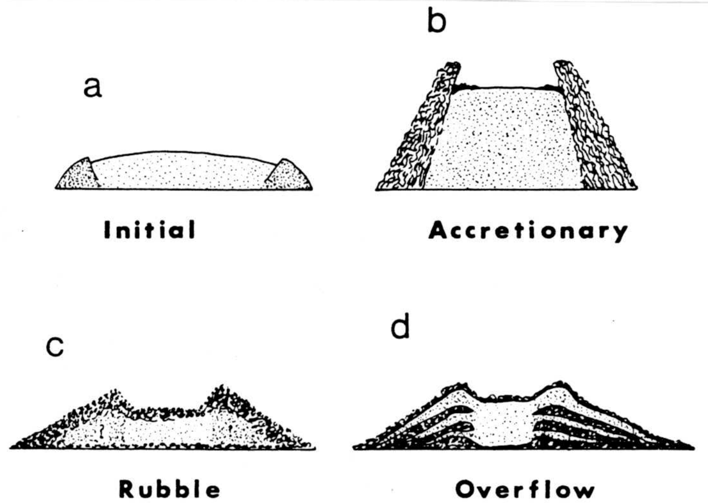
The upper part of Kīlauea's east rift zone is marked by a very prominent line of pit craters. These craters are derived purely by collapse, as evidenced by the lack of any build-up of material around their rims. Eruptive vents often happen to open within or across the craters, however, and lava often ponds within them. These craters are collapse features that are associated with some type of long-lived conduit that runs the length of the upper rift zone. As illustrated by Walker (1988), the craters form by the upward stoping of a void that develops in the roof of this large conduit. Devil's Throat initially consisted of a relatively small opening in the ground. Some time back in the 1800's an intrepid explorer was lowered by rope down into the hole. He had a lantern and as he went down he watched the rock layers pass by. All of a sudden he was in darkness and couldn't see the walls of the hole anymore. He quickly realized that the opening had widened out considerably and his feeble lantern couldn't illuminate the now-farther-away walls. He also quickly realized that this meant that the folks supporting him were on an overhang; he was within a large bell-jar shaped cavern and they were on the roof. He gave the signal to be pulled up. Since then the last layers have fallen in and Devil's Throat has a cylindrical shape. The walls of Devil's Throat are cracked, unstable, and ready to fall in. PLEASE BE CAREFUL HERE!!! If you feel an earthquake while near the rim, run away FAST!



Schematic diagram illustrating the formation of a pit crater. C: conduit, probably 1-3 km below surface in well-developed rift zone (Walker 1988).

MULIWAI A PELE:

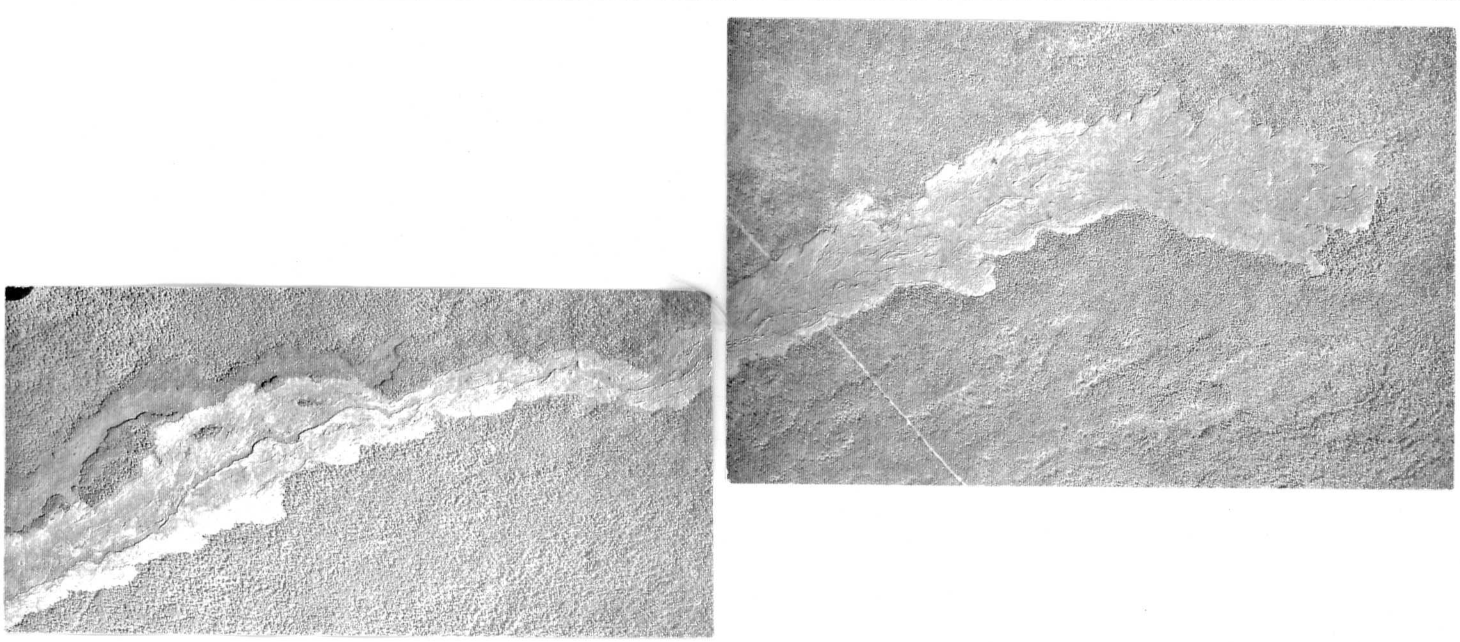
This is a fine example of a lava channel, formed during the last part of the Mauna Ulu eruption. It is also a very good location to examine ʻaʻā and pāhoehoe flows next to each other and compare their different characteristics. Most of the surface around this location is tube-fed pāhoehoe from Mauna Ulu. You can see the innumerable flow units, the smooth glassy skin, and the low topography very readily. These are the lavas that were erupted at constant, low volumetric flow rates. During the final stage of the Mauna Ulu eruption, however, the eruption became episodic and at the same time the volumetric flow rates of the flows increased. This resulted in the production of ʻaʻā flows. This ʻaʻā flow contrasts from the pāhoehoe in many ways. The most obvious is the rough ʻaʻā clinker surface on the margins of the flow. Second, the entire 'a'ā flow is a single unit as compared to the multi-unit pāhoehoe. Third, the thickness of the 'a'ā flow is much greater than that of any individual pāhoehoe flow unit. Finally, the 'a'ā flowed in an open channel, unlike the lava tubes that fed the pāhoehoe (not visible here).



Cross-sections (viewed up- or down-flow) of types of channels and levees seen on Mt. Etna (Sparks *et al.* 1976).

Channel formation is very common in 'a'ā flows. The theoretical relationships of channel formation were determined by Hulme (1974). He stated that is the possession of a yield strength that leads to channel formation. A flow spreads laterally due to the combination of gravity, the flow thickness, and the lava density. As a flow spreads laterally its thickness decreases (while gravity and density remain constant) so that eventually the yield strength of the lava can resist further spreading. This leads to the formation of zones of stagnation along the edges of the flow called levees. The fact that a lava flow consists of a hot fluid interior and a cooled strong crust makes the picture more complicated, but the general idea is still correct. These initial levees are often separated from the central channel by only a couple of shear lines which may not be obvious at all. As a flow continues, the levees become more stagnant, cooler, and the contrast between them and the flowing channel greater. Eventually the levees become completely solid and distinct from the flowing lava. This development of a well-defined channel proceeds downflow, lagging usually ~1 km behind the flow front. The levees are often modified by overflows of the channel.

The advancing front of a large flow is often clinkery 'a'ā due to the rapid shearing and heat loss. As the channel becomes more efficient (distinct from the levees), the lava being supplied downflow has an easier and easier journey, flows rapidly with a smooth surface, and is often considered to be pāhoehoe. This has caused a lot of confusion; if this lava overflows onto the levees it may produce a smooth pāhoehoe surface overlying the original 'a'ā levees (Sparks *et al.* 1976), but the rapid travel down a channel causes the flowing lava to eventually lose a great deal of heat and by the time it becomes part of the confused situation at the flow front it is 'a'ā.


Air photographs of the 1942 Mauna Loa lava flow to illustrate how the channel develops, from barely discernible shear zones near the flow front to a distinct channel 1-2 km upflow.

THE HILINA PALI SYSTEM:

Recent work has shown that Hawaiian volcanoes grow at least as much, if not more, by intrusions as by eruptions. This means that they expand laterally. The N side of Kīlauea abuts Mauna Loa, the largest volcano on Earth, whereas the S side slopes steeply to the ocean floor ~5 km below sea level. It is obvious then, which direction Kīlauea is going to expand. The driving force for the expansion is the intrusion of dikes down the E and SW rift zones, and the surface on which this motion is accommodated is probably the layer of slippery sediments at the interface between the ocean crust and the volcano. This surface dips towards the island at a few degrees because of the loading of the volcanoes. Such a surface is consistent with the focal plane solutions of a number of recent large earthquakes, which show a gently landward dipping plane at 6-10 km depth beneath the S flank of Kīlauea (e.g. Lipman *et al.* 1985).

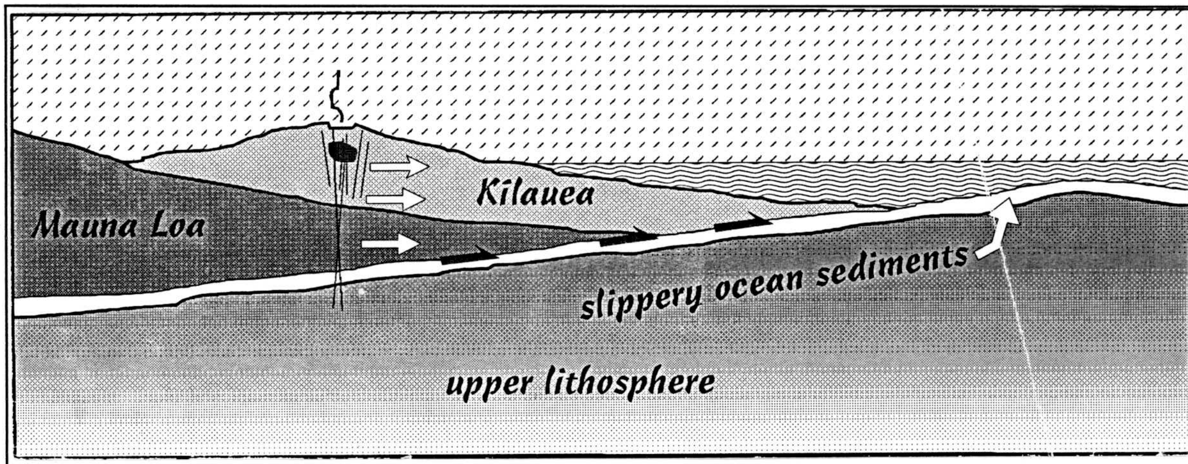
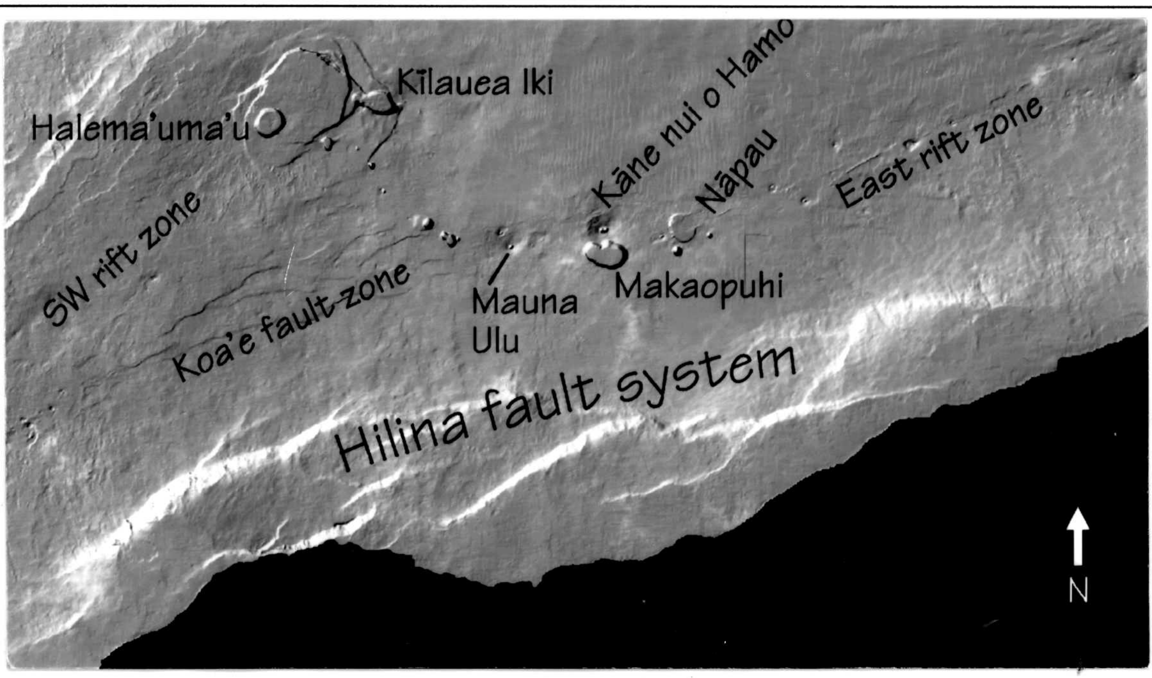


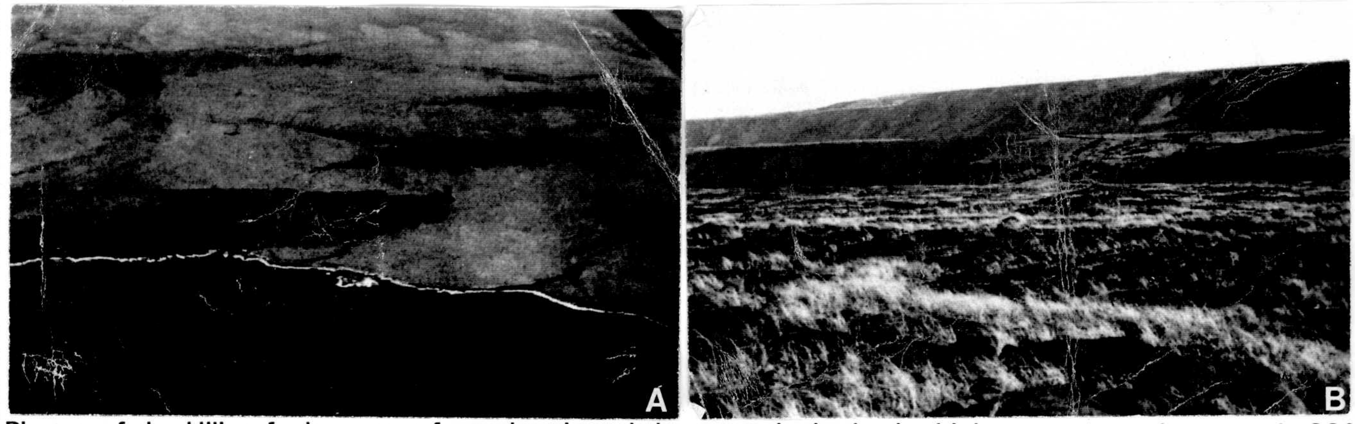
Diagram (not to scale) showing how dike pressure causes the S flank of Kīlauea (and part of Mauna Loa) to slide uphill on a layer of ocean sediments.

The S flank of Kīlauea is thus unstable and has broken into a number of large blocks along fractures that are roughly parallel to the rifts and coastline. Each time the south flank of Kīlauea gets shoved seaward during an earthquake, these blocks drop downward a few meters, and over the history of the volcano, the boundaries between them have become faults up to 500 m high. Lava flows mantle the faults only to be fractured themselves during the next earthquake. A step-wise lowering of the flank of the volcano culminates in the coastal terrace. This terrace is both the top of one of the blocks and a constructional feature formed from the coalescence of numerous lava deltas that have developed as lava flowed into the ocean (e.g. Mark & Moore 1987). The two most recent large south flank earthquakes occurred in June 1989 and November 1975 (M6.1 and 7.2, respectively). In the 1975 quake, maximum displacements were

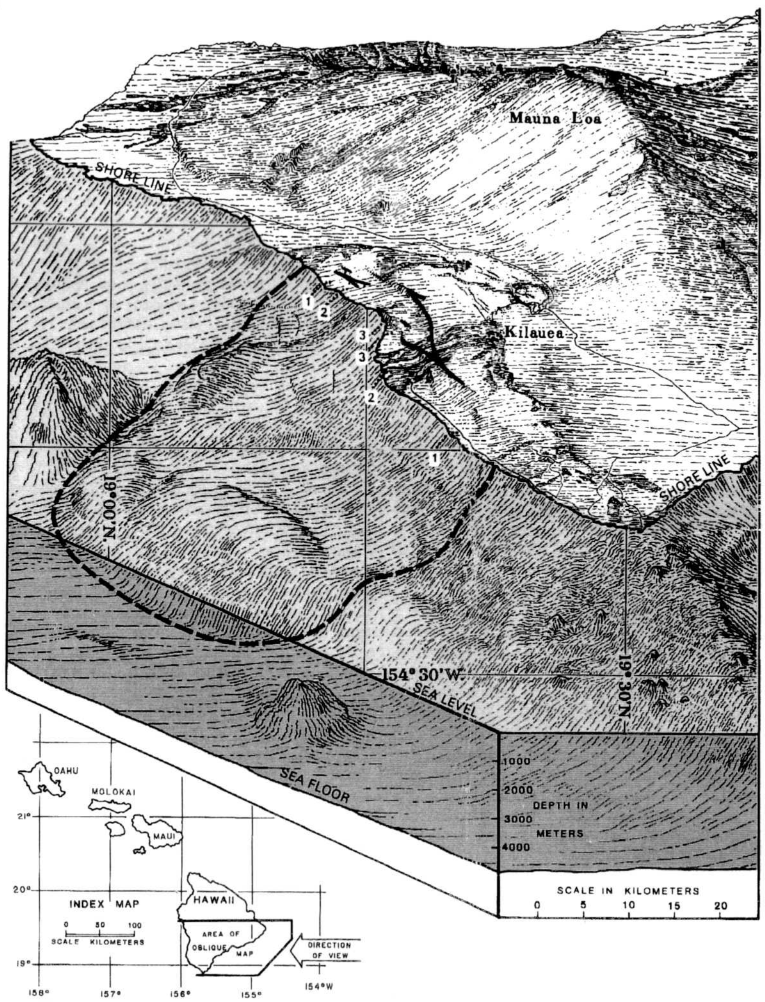


Shaded relief image of the S flank of Kilauea, including the upper and middle east rift zone, and the Koa'e and Hilina fault systems.

3.5 m and 8 m (horizontal and vertical, respectively). ~4 million dollars in damage occurred and a tsunami was generated that killed 2 members of a Boy Scout troop camped at Halapē, on the coast (e.g. Tilling *et al.* 1976; Lipman *et al.* 1985). Combining the 3.5 m of sudden subsidence with the 15 m tsunami, it's a wonder any of them survived.



Photos of the Hilina fault system from the air and the ground. In A, the highest scarp at the coast is 320 m high (from Swanson *et al.* 1976).



Physiographic drawing of S Hawai'i, viewed from the east, and showing subaerial and submarine features. *Heavy solid lines* show major faulting associated with the 1975 Kalapana earthquake, *numbers* along the coast indicate subsidence (in meters) during the earthquake, and the *dashed line* outlines a possible submarine slump (from Lipman *et al.* 1985; drawn by Tau Rho Alpha).

Photos of Halapē before (top) and after (bottom) the 1975 earthquake. The tsunami swept campers into the large pre-existing crack (arrows). Two were swept out to sea and drowned by the retreating wave (from Tilling *et al.* 1976).

PĀHOEHOE FLOWS:

While dropping down the Hilina faults, look closely at the roadcuts. In a number of places there are excellent cross-sections through pāhoehoe lava flows. These illustrate very well the compound nature of pāhoehoe flows (Nichols 1936; Walker 1971). The flow units themselves are sometimes hollow, showing that for at least a short period of time they acted as single flow-unit lava tubes (which later drained). It is the coalescence of a number of such tubes that can form a master lava tube.

Pāhoehoe flow units (toes) exposed in a roadcut along Chain of Craters Rd. Note the large number of individual flow units that make up the overall flow. The dark parts are drained-out single flow-unit tubes. The large flow near the center is ~3 m wide and ~1 m thick.

After driving along the coastal terrace we arrive at the presently active pāhoehoe flow field. These lavas were emplaced by tubes just as were those of Mauna Ulu. Recent work has shown that a pāhoehoe flow field grows by inflation beneath the original crust as much as by advancing over new ground (Hon & Kauahikaua 1991; Walker 1991; Hon *et al.* 1994). The entire flow field can be uplifted by a few m in this way without increasing the area of pre-existing ground that is covered. A place where uplift is particularly concentrated is called a tumulus (plural = tumuli).

The initial lava that forms a pāhoehoe flow field is vesicle-rich s-type ("s" stands for spongy; Walker 1989). During the inflation and storage process within the flow field, gas bubbles rise up and escape from the fluid lava. This means that when it erupts to the surface (usually out of the axial cleft of a tumulus), it is vesicle-poor. This lava is called p-type ("p" stands for pipe-vesicle bearing; Wilmuth & Walker 1993). Both types of lava are well displayed in the present flow field.

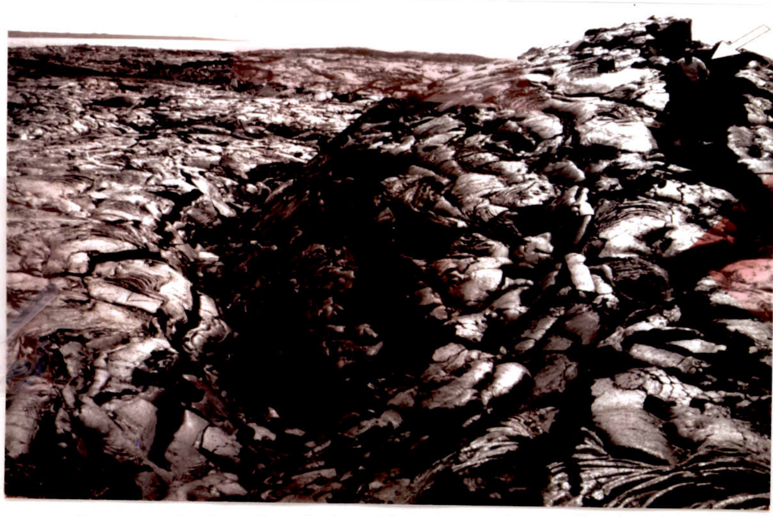


Photo of a typical tube-fed pāhoehoe flow field (the 1859 Mauna Loa flow near Waikoloa). Note the innumerable flow units, as well as the large tumulus at right; GPL Walker in axial cleft for scale (*arrow*).

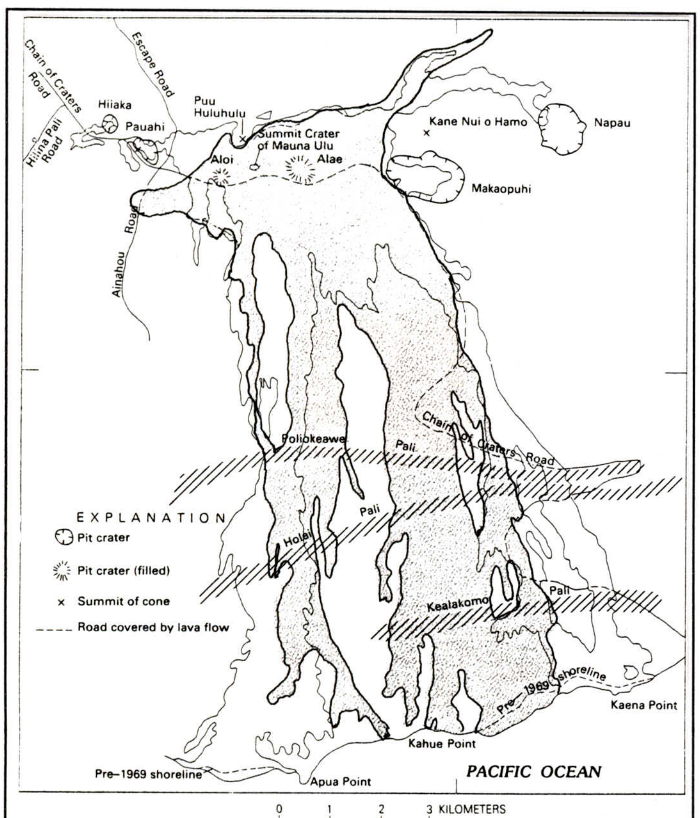
The flow map on the back cover shows a number of different parts of the Pu'u 'Ō'ō /Kūpa'ianahā flow field. The initial lavas were the 'a'ā of the high-fountaining Pu'u 'Ō'ō episodes (January 1983-June 1986). The eruption then shifted about 3 km downrift to Kūpa'ianahā, which produced tube-fed pāhoehoe from June 1986 until February 1992. At that time the eruption shifted back uprift, this time to a number of vents on the up-rift flank of Pu'u 'Ō'ō, where the eruption has localized since. Like the Kūpa'ianahā stage this most recent part of the eruption has produced mainly tube-fed pāhoehoe.

MAUNA ULU

Mauna Ulu is a classic satellitic shield, and the first that was studied intensively during its formation (e.g. Swanson *et al.* 1979; Tilling *et al.* 1987). The following chronologies are taken from these two references. The Mauna Ulu eruption lasted from May 1969 to July 1974, including a hiatus between October 1971 and February 1972. Part 1 (185 x 10^6 m^3 of lava, covering ~50 km^2; prior to the hiatus) was subdivided into 4 stages (Swanson *et al*. 1979): an episodic high-fountaining stage, a shield-building overflow stage, a tube-fed pāhoehoe stage, and a waning stage. The first and third stages generated lava flows (ʻaʻā and pāhoehoe, respectively) that reached the ocean.

The first stage lasted 7 months, during which there were 12 4.5-hr to 3-day episodes of high fountaining (up to 540 m) at discharge rates of 140-400 m^3/sec. Flows were predominantly ʻaʻā, and the one flow that reached the ocean traveled the 12 km distance from the vent at an average velocity of 400 m/hr. Between episodes of high fountaining only minor activity (small dome fountains and short flows) occurred at the vent area which consisted of spatter and cinder cones. ʻAlae pit crater was filled in with lava.

View of Mauna Ulu towards the south, as seen from Pu'u Huluhulu. Note the prominent channel leading down from the summit and the area of ponded lava in the foreground (studied by Wilson & Parfitt 1993).



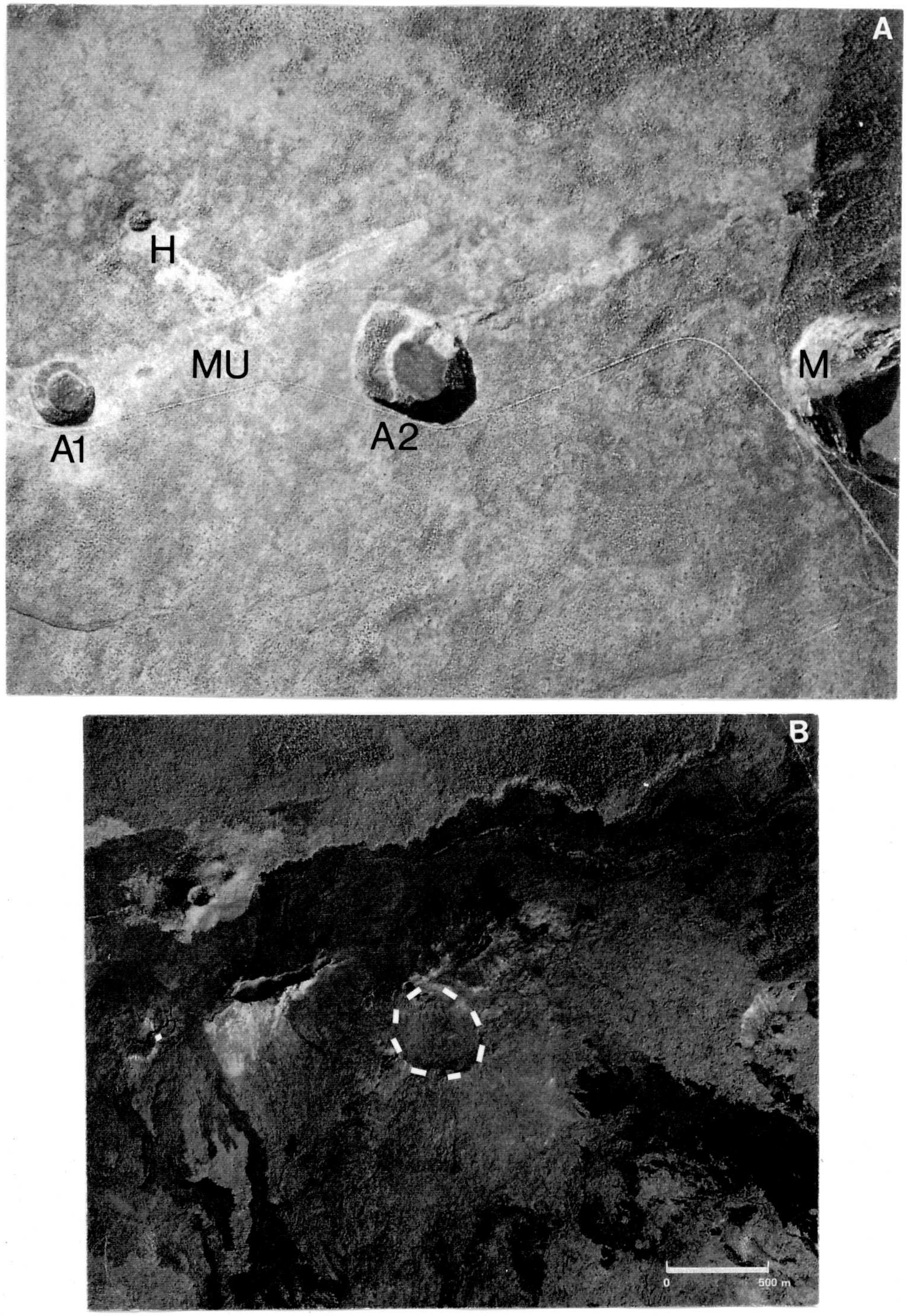
Map of Mauna Ulu lavas. Part 1 *outlined and stippled*, Part 2 *outlined* (from Tilling *et al*. 1987).

The second stage built the bulk of the Mauna Ulu shield to a height of 80 m with hundreds of overflows from the central vent. All the vent deposits from the earlier fountaining episodes were buried. Ālo'i pit crater was filled in by lava from a vent that opened across it. During the third stage much of the lava flowed from the main vent to the molten part of the ʻAlae crater lava lake, which acted as a holding reservoir that modulated the rate of outflow to the lava tube system despite fluctuation in the eruption rate at the main vent. When activity waned, the surface over ʻAlae subsided, forming a bowl-shaped depression approximately outlining the position of the former crater.

The first of these pāhoehoe flows to reach the ocean advanced at an average velocity of 12 m/hr. The average discharge rate during this period was 4 m^3/sec. The summit depression of Mauna Ulu became markedly elongate by engulfing a line of small pits that had formed at the locations of earlier vents. The eruption slowly died, and no active lava was seen after October 1971.

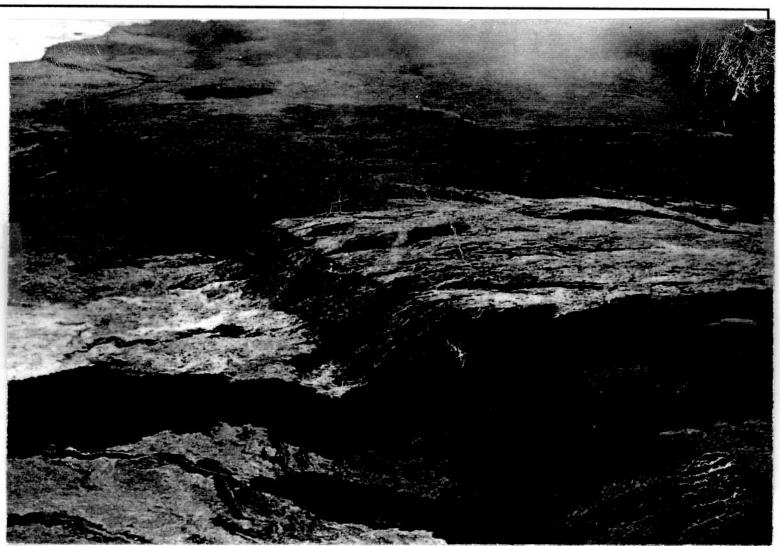
In early February 1972, lava quietly returned to the Mauna Ulu crater. Part 2 of the eruption (February 1972-July 1974; 106 x 10^6 m^3 of lava, covering 46 km^2) was divided into 5 stages, determined by the type of activity and the location of eruptive vents (Tilling *et al.* 1987). The first, third, and fifth of these stages produced significant volumes of lava. The first stage was similar to the tube-fed stages in part 1; the average discharge rate was 3.4 m^3/sec, and two pāhoehoe flows reached the ocean after advancing at average velocities of 6 to 20 m/hr. Most of these were again fed from the Alae lava lake, which also overflowed to form a parasitic shield on the SE flank of Mauna Ulu with a summit 80 m above the pre-eruptive surface. This stage of the eruption ended soon after the M6.2 Honomū earthquake (4/26/73), and the cessation was attributed to disruptions in both the plumbing feeding the vent and the lava tubes draining the vent.

The second stage of part 2 consisted of short-lived eruptions slightly uprift of Mauna Ulu. The third stage started with the rapid draining of Mauna Ulu leaving a pit ~200 m deep. Between May and November 1973, activity was limited to rising and falling of lava within the Mauna Ulu summit pit until it eventually filled to the top, but no significant lava flows were formed. Stage 4 consisted of a short outbreak in November 1973 of lava from fissures that cut through Pauahi crater and extended north of Pu'u Huluhulu, accompanied again by draining of Mauna Ulu. The fifth stage involved a return to episodic activity consisting of brief fountaining episodes separated by repose periods of low-level activity lasting 3 days to 5 weeks. The longest flow produced was 9 km long, emplaced at ~75 m^3/sec. Flows traveled in all directions but most went north directly towards Pu'u Huluhulu, and a prominent ponded area formed. By June 1974, the overflows had built Mauna Ulu to a height of 121 m above the pre-1969 surface. The eruption began its final demise soon after, and after a brief episode of fountaining at the summit, was declared over by July 1974.



Vertical air photos taken before, and halfway through, the Mauna Ulu eruption. In (A), *H*: Pu'u Huluhulu, *MU*: the future center of Mauna Ulu, *A1*, *A2*, and *M*: Alo'i, 'Alae, and Makaopuhi pit craters. In (B), *dashed* and *dotted* lines mark the former positions of 'Alae and Alo'i pit craters, respectively (photos from Carr & Greeley 1980).

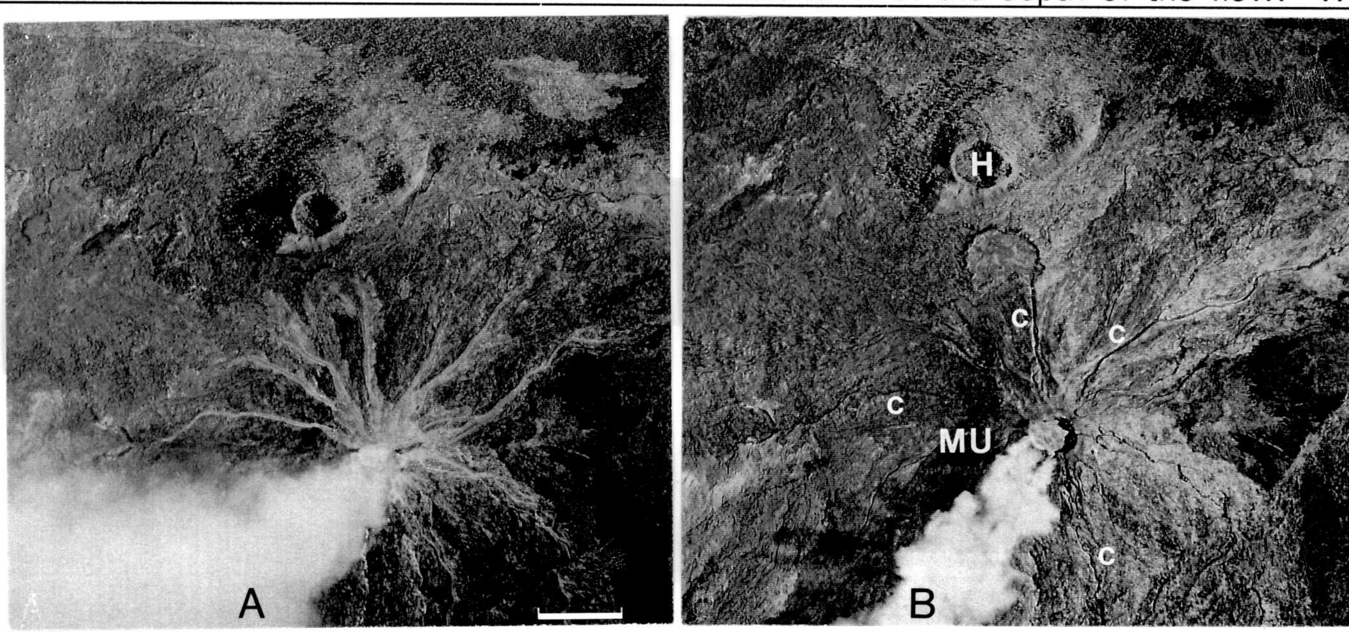
Since the eruption lasted for 5 years, many of the features formed were buried by later activity. Mauna Ulu possesses the classical shape of a satellitic shield, and at the summit of this shield is an elongate pit some 150 m deep. The edges of this pit are fractured and unstable. BE CAREFUL HERE!!



Mauna Ulu lava flowing over the Hōlei Pali (part of the Hilina Pali system) towards the ocean. Shiny lavas are fresh pāhoehoe, dark lavas are fresh ʻaʻā, and medium tones are older and vegetated flows (from Carr & Greeley 1980).

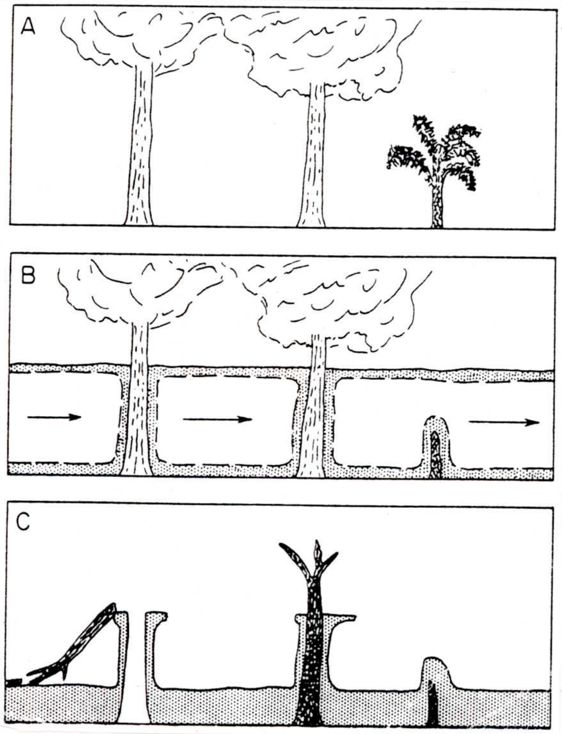
From the overlook on Puʻu Huluhulu one of the most obvious features is the perched lava pond formed from overflows of part 2 stage 5 (see Wilson & Parfitt 1993). There are numerous small channels in the Mauna Ulu flows. At many places on Mauna Ulu you can experience "shelly pāhoehoe" (e.g. Swanson 1973). Shelly pāhoehoe forms from gas-rich lava. A 2-5 cm-thick skin forms on a flow unit soon after it is emplaced. Beneath this, the bubble-rich lava separates, the lava collecting at the bottom of the flow unit and the gas collecting at the top to form a hollow. Although extremely dangerous only when still hot, cold shelly pāhoehoe is still a pain to walk on. Try to keep to the low seams between flow units or walk where the surface has already broken. If you feel yourself falling, just go along for the ride--don't lunge for "safety". You will only risk getting cut worse.

The brief part 2 stage 4 eruptions from Pauahi pit crater and north of Puʻu Huluhulu produced some spectacular features. The lava was extremely fluid, and along certain stretches no positive vent structures were constructed; the fissure now consists only of solidified drain-back into a narrow fracture. In places you can still find blobs of spatter in the crotches of tree branches, and there are numerous lava trees. Lava trees form when lava gas-rich pāhoehoe flows through a forest. A skin of lava solidifies around the trees at the level of the depth of the flow. When the

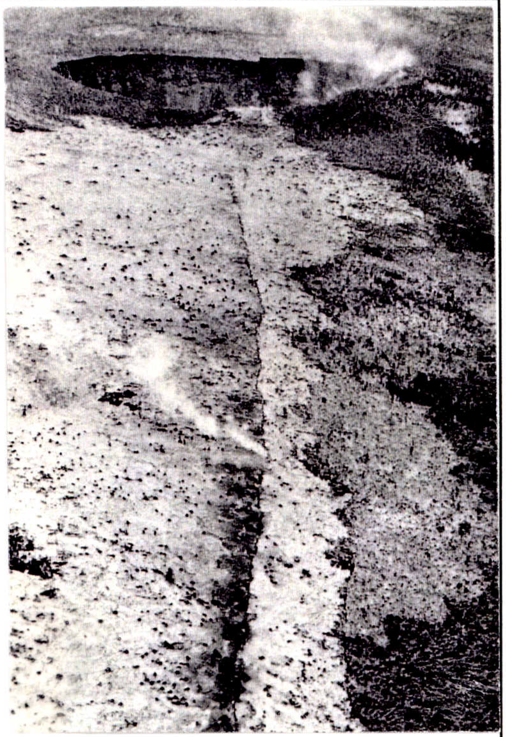


Vertical air photos of the last stage of part 2 of the Mauna Ulu eruption (north is up, scale bar = 200 m). In A, light-toned radiating flows are active channelized lavas flowing in all directions. In B (2 days later), all flows are inactive. Note ponded area between Mauna Ulu (MU) and Puʻu Huluhulu (H), and prominent channels (C). The formation of the ponded lava flow just south of Puʻu Huluhulu was modeled by Wilson & Parfitt (1993), however, they assumed that the entire eruptive output went into only the one flow that fed the pond, clearly not the case as seen in photo A. Photos from Carr & Greeley (1980).

eruption wanes, the lava level drops as lava drains away and gas-lava separation takes place, leaving a mold of the tree standing above the collapsed lava surface. The trees invariably die and usually burn in the process. The organic matter within the mold is often a good place for new plant seeds to collect and sprout, bringing life back to the lava trees.



Diagrams showing the formation of lava trees (Macdonald *et al.* 1983).



View west (from above and slightly north of Pu'u Huluhulu) of the part 2 phase 4 fissure trending off towards Hi'iaka pit crater. The eruptive fissure shows up prominently within the shiny pāhoehoe (dark spots are lava trees). Dark patches along the fissure are spatter cones and ramparts (from Greeley 1974).

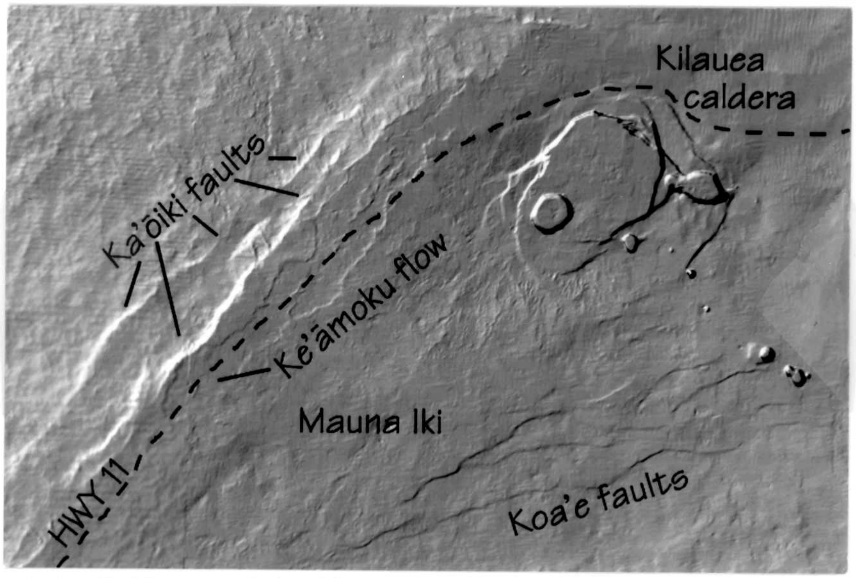
Photo of lava molds that formed around a stand of small trees. Note that the lava was fluid enough to drain away from between the trunks.

THE KA'ŌIKI FAULT ZONE

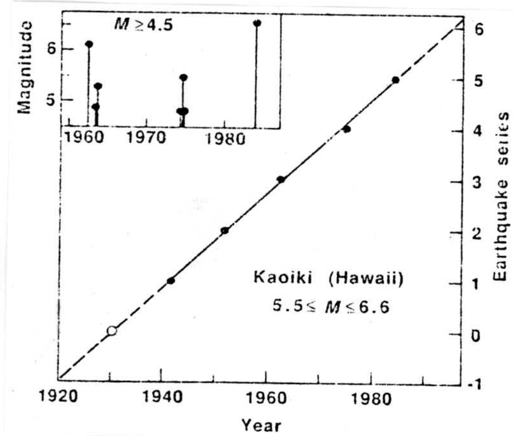
Prior to the growth of Kīlauea, Mauna Loa presumably had an unbuttressed south flank. Almost certainly this flank was unstable in the same way that the south flank of Kīlauea is today. The Ka'ōiki fault zone is a remnant of large normal faults much like the Hilina faults of present-day Kīlauea. They are today almost completely buried by Kīlauea lavas. They are mantled by what appears to be un-faulted Pāhala ash, indicating a lack of movement for the past 30,000 years.

There are earthquakes along the Ka'ō iki fault zone, however. These have been proposed to be caused by the "rubbing" of Mauna Loa and Kīlauea as they inflate and deflate next to each other. The most recent large earthquake along the Ka'ōiki fault occurred in

November of 1983 (e.g. Buchannan-Banks 1987). It had a magnitude of 6.6 and a focal depth of 12 km. A study in the 1980's turned up a remarkable periodicity for earthquakes of greater than M4.5 along the Ka'ōiki fault (Wyss 1986). Based on the data, another large Ka'ōiki earthquake was predicted to occur around the end of 1994 (it didn't).



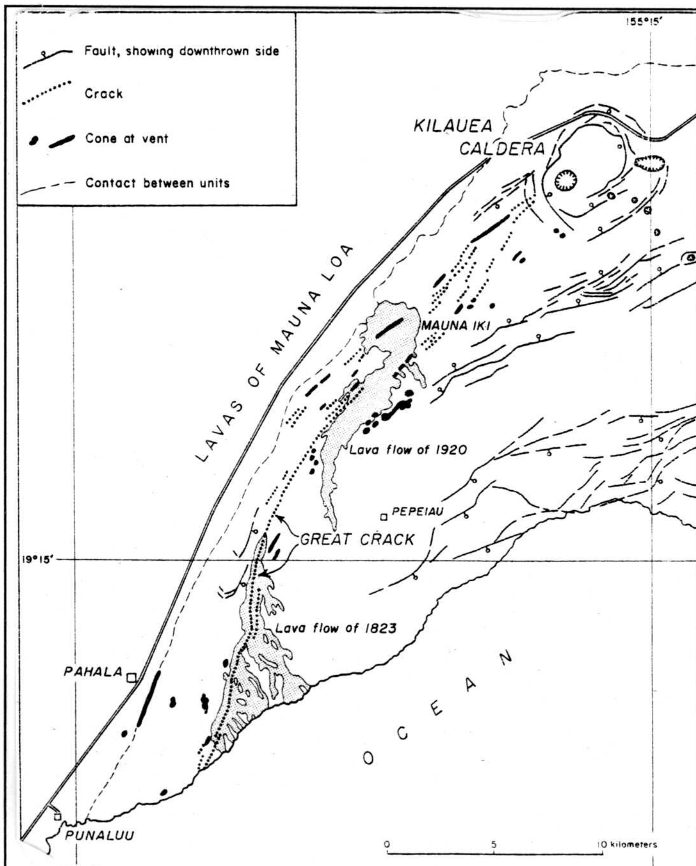
Shaded relief image of the Mauna Loa-Kīlauea boundary in the vicinity of the Kīlauea caldera.



Graph of cumulative Ka'ōiki earthquakes ≥M4.5 vs. time (Wyss 1986)

THE NĪNOLE HILLS AND WOOD VALLEY

The Nīnole hills are somewhat of a mystery. In general they have flat tops that slope somewhat parallel to the overall slope of Mauna Loa, however, they are taller than the nearby slopes of Mauna Loa. Most geologists would consider that they look like eroded remnants of a shield volcano that has now been almost entirely eroded away and buried by Mauna Loa lavas. Good age dates on these lavas have so far been difficult to obtain but it is at least possible to determine that they are a couple hundred thousand years old, much older than any other surficial Mauna Loa lavas, and almost as old as the lavas of Kohala volcano at the north end of the island. Was there an ancestral Mauna Loa at this location that has now been almost completely eroded and buried?

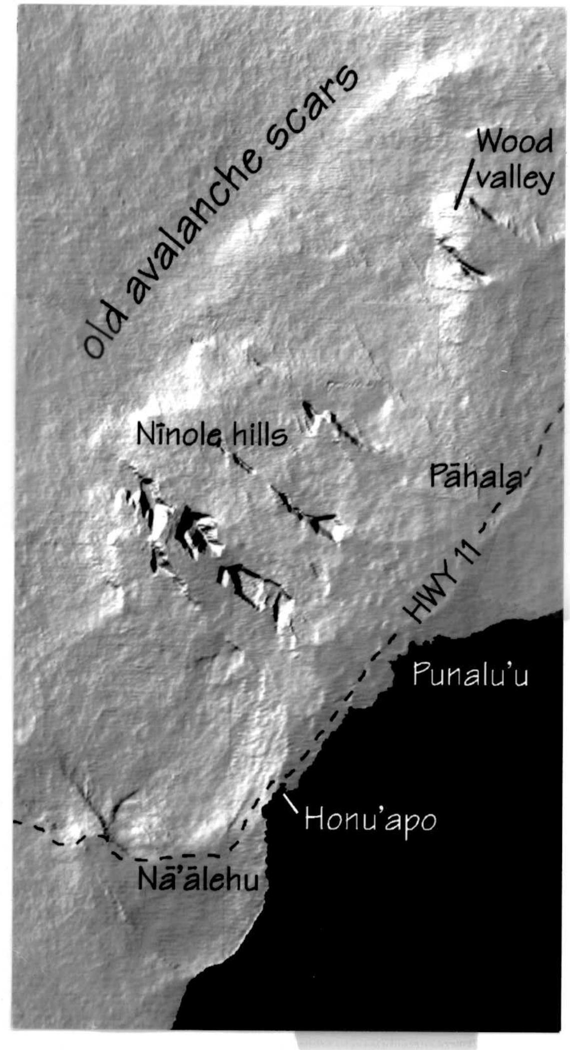


Map of major features along the SW rift zone of Kīlauea, most of which are quite inaccessible (Macdonald *et al.* 1983)

An alternative explanation (Lipman *et al.* 1990) is that the Nīnole Hills are part of the present Mauna Loa volcano that have been isolated by faulting. In this scenario most of the western half of Mauna Loa collapsed into the ocean, taking not only the western flank but most of the rift zone as well. This would have left the southeastern flank sloping upwards and ending in a (very high) cliff. Activity since the landslide was able to build up the western flank but because of the cliff the southeastern flank was not resurfaced, and instead became highly eroded. Eventually the rift zone built to the point that some lavas could spill down to the southeast, burying all but a few remnants which are now seen as the Nīnole hills.

This southeast flank has also been mobile, as evidenced by the subtle amphitheater-shaped scarps uphill from the Nīnole Hills (Mark & Moore 1987; Moore & Mark 1992). This topography is subtle, heavily vegetated, and usually cloud-cloaked but has the unmistakable shape of a collapse-derived headwall.

Wood Valley is a steep-sided amphitheater headed valley on the south flank of Mauna Loa. It was probably formed by both water erosion and landsliding. After its formation, lava flows cascaded over its walls to fill in the floor meaning that Wood Valley probably developed at a time when this flank of Mauna Loa was not resurfaced by lava for a long while. Such is the situation today because the southeastern caldera wall prevents lavas from spilling onto the southeastern volcano flank. However, when the caldera was last filled (1500-750 years ago; Lockwood & Lipman 1987) there was no rim to stop the lavas and the southeast flank was over-run. A mudflow/landslide generated by the M8+ 1868 earthquake killed 31 people and destroyed 10 houses in Wood Valley. The red color of the soil initially made witnesses think it was a huge fast-moving lava flow.



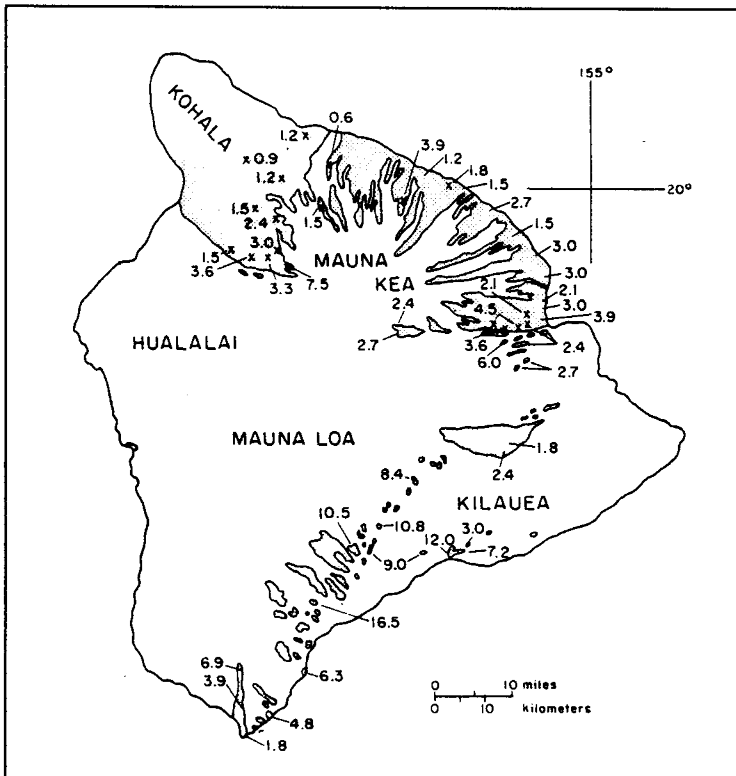
Shaded relief image of the SE flank of Mauna Loa.

THE PĀHALA ASH

The bright yellow-orange unit that you can see in numerous outcrops is the Pāhala ash. The Pāhala ash is somewhat enigmatic. It is usually considered to be the product of very explosive eruptions of either Kīlauea or Mauna Loa (perhaps some extreme phreatomagmatic activity). It has also been correlated with ash units on the flanks of Mauna Kea and Kohala, giving the impression of even greater explosivity. Recent work has shown that the Mauna Kea and Kohala ash units are almost certainly derived from those volcanoes themselves, and aren't particularly wide-spread. Since Mauna Kea is in, and Kohala was recently in, the alkalic cap stage (characterized by high-fountaining eruptions), it is not surprising that there is a large amount of pyroclastic material to be found. However, most of the time, careful mapping work can show that each outcrop of ash corresponds to one cinder cone.

Returning to the source of the "real" Pāhala ash, unpublished mapping by Dave Clague of the HVO points to a probable Kīlauea origin from strong phreatomagmatic eruptions (he has found evidence of base-surges). The Pāhala ash is actually but one of a number of large, widespread pyroclastic units that can be found in a few cliff outcrops on Kīlauea (Easton 1987). They are interbedded with soil layers and lava flows having abundant tree fern molds but are in localities that today support very little vegetation because of too little rainfall. Taken together they point to a time (about 22,000 years ago) when there was little resurfacing of the Kīlauea surface (so that thick soils could develop), which suggests there was a deep caldera. Additionally, the climate was wetter (the tree ferns), and perhaps a wetter climate combined with a deep caldera enhanced the possibility of explosive water-magma interactions, leading to the large explosive eruptions that produced the numerous ash layers (Easton 1987).

On the other hand, George Walker considers the Pāhala ash to be a loess deposit, glacier-ground dust that formed up on Mauna Kea and/or Mauna Loa during one of the recent glacial periods. It was then deposited on the southern side of the big island by the wind.

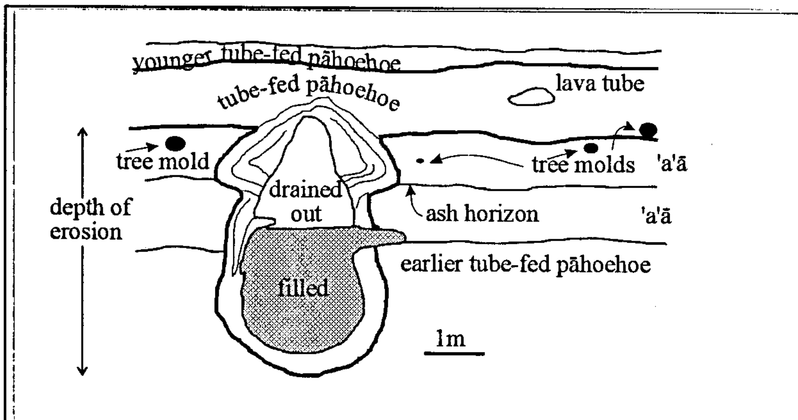


Map of pyroclastic outcrops that have at times been considered to be Pāhala ash (Macdonald *et al.* 1983).

HONU'APO THERMAL EROSION, AND LŌ'IHI

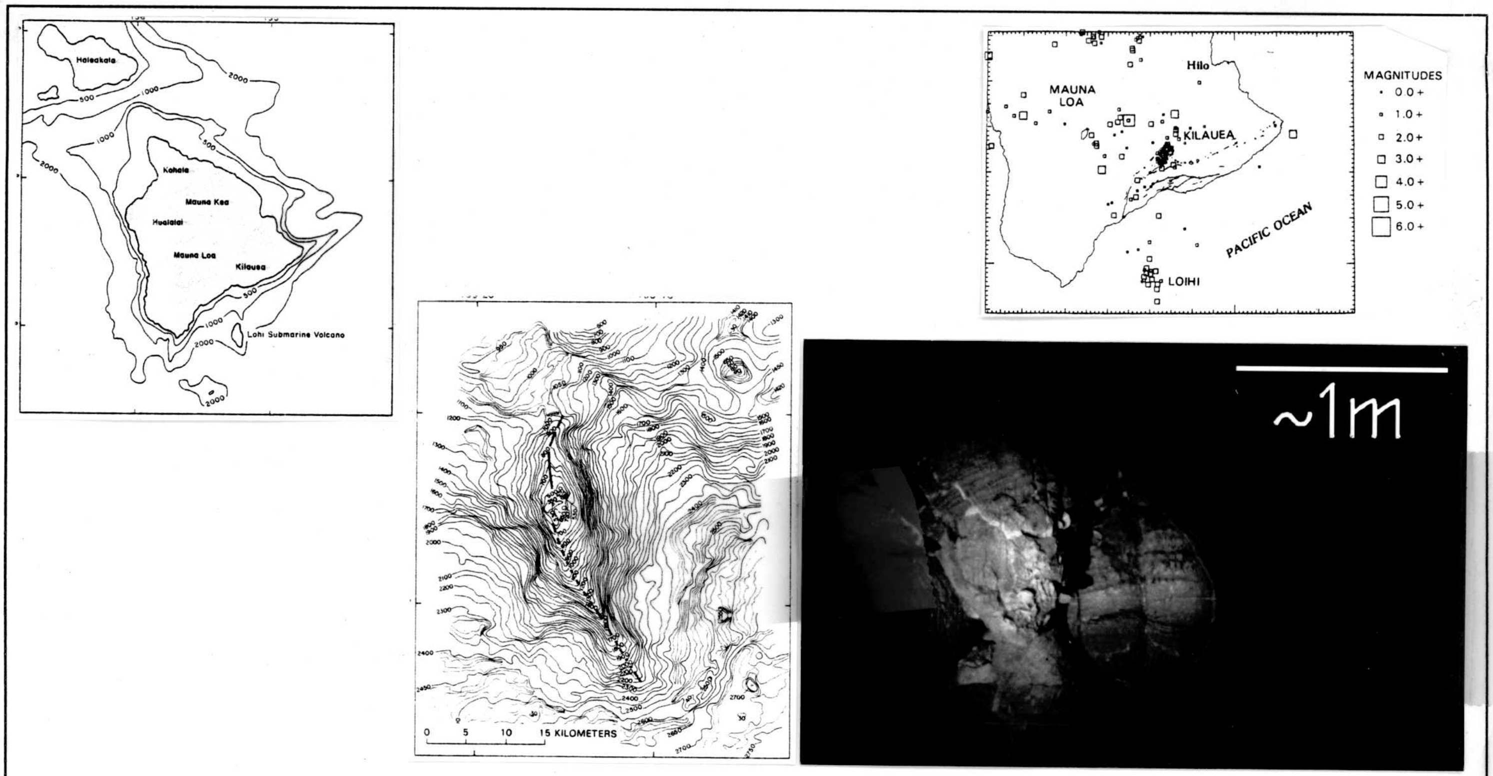
Honu'apo used to be a small harbor for fishing boats. Earthquakes and tsunami have caused so much damage and subsidence, however, that it has been abandoned and left to be a state park. A remnant of the pier remains. Geologically, this is an interesting place because there is a good example here of a lava tube that eroded into the underlying rocks while it was flowing. This was probably due to thermal erosion. As long as the flowing lava was constrained to the tube, heating of the underlying rock was strongly concentrated. Eventually this rock was softened and able to be plucked away by the flowing lava.

Thermal erosion has been relatively un-studied by terrestrial geologists and most of the work on this topic has been done by planetary geologists. They have hoped to use thermal erosion to explain some of the features seen in Martian and particularly Lunar volcanic areas (e.g. Coombs *et al.* 1990). The rates of erosion are difficult to calculate but preliminary estimates by Coombs & Rowland (1994) show that once the underlying rock was heated to the point of melting it would have required another 74 days of lava flowing in the tube to down-cut to the extent seen here at Honu'apo.



Sketch of the Honu'apo tube (Coombs & Rowland 1994)

Honu'apo is the location where a soon-to-be-installed undersea cable will come ashore. This will be the power and data cable for HUGO, the Hawaii Undersea Geo-Observatory, to be located on the summit of Lō'ihi seamount. Lō'ihi is the youngest Hawaiian volcano. It's summit (which appears to consist of a filled caldera) is about 970 m below sea level and its base is on the ocean floor almost 5 km below sea level. Two rift zones extend to the north and southwest (Malahoff 1987). It was first thought that Lō'ihi was a large landslide slump, but when fresh pillow lavas were dredged off its summit in the 1970's and the improved seismic network of the Hawaiian Volcano Observatory started picking up earthquake swarms centered on its summit, the true nature of Lō'ihi was realized. Since the mid-1980's there have been a number of submersible visits to the summit and flanks.

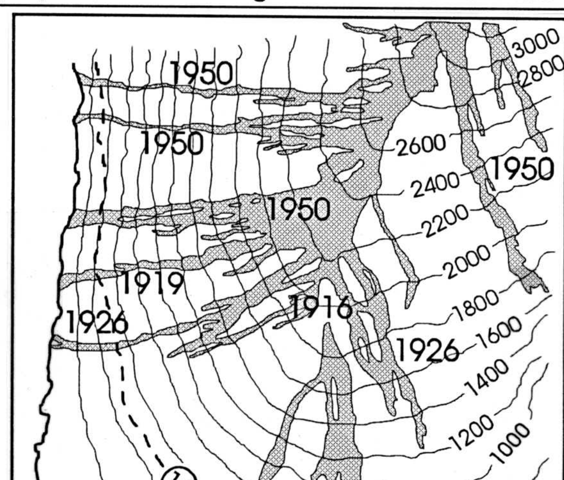


Evidence that Lō'ihi is the youngest Hawaiian volcano: A) its location (Macdonald *et al*. 1983); B) its form (filled caldera and rift zones; Peterson & Moore 1987 after Malahoff *et al*. 1982); C) seismicity (Klein *et al*. 1987); and D) young pillow lavas.

THE 1868 LAVA FLOW

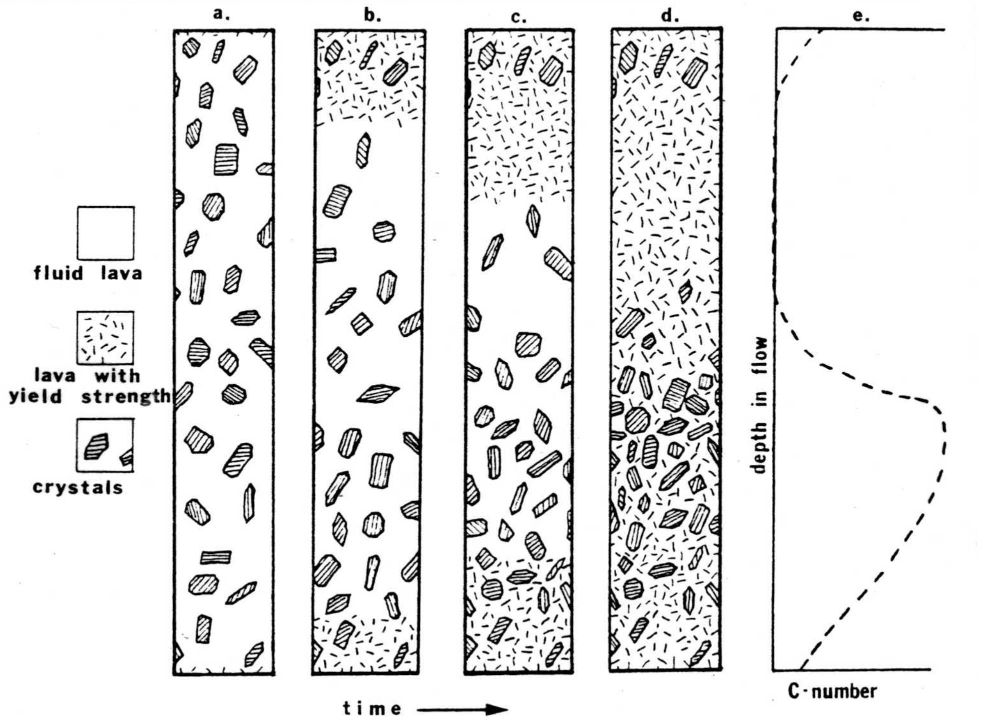
The 1868 eruption is interesting because it is the lowest-elevation post-contact eruption from the southwest rift zone of Mauna Loa, it is quite olivine-phyric, and a large littoral cone was produced when one branch of the flow entered the ocean. Early spring of 1868 was quite a time for Mauna Loa and the island of Hawai'i. As summarized by Barnard (1990) the order of events was: 1) a brief Mauna Loa summit eruption on March 27; 2) a great earthquake (perhaps ≥M8) on April 2 which was accompanied by a brief Kīlauea eruption, the Wood Valley landslide, and a tsunami; and 3) the Mauna Loa southwest rift zone eruption starting April 7. The vents for this eruption are centered at about the 800 m elevation. The eruption lasted for ~5 days and produced 73 x 10^6 m^3 of subaerial lava plus an estimated additional 50 x 10^6 m^3 offshore (Macdonald *et al* 1983; Lockwood & Lipman 1987). This total of 123 x 10^6 m^3 in 5 days yields an average effusion rate of 95 m^3/sec. Most of the lava is 'a'ā although there is considerable pāhoehoe near the vents and spilling over the numerous channels. Additionally, much of the lava near Pu'u Hou is toothpaste lava.

The 1868 flow divided into 3 branches. One headed southeast from the vents. The other two headed more directly south, the eastern of these banked against the foot of the Kahuku Pali, and the western of these spawned Pu'u Hou.



Post-contact flows on the Mauna Loa SW rift zone (simplified from Lipman & Swenson 1984).

The olivine-rich nature of the 1868 lava made it ideal for inclusion in a study of lava viscosity based on the ability of phenocrysts to sink (Rowland & Walker 1988). Good outcrops for determining viscosities are exposed along the highway. The method assumes that the distribution of olivine phenocrysts is constant throughout the depth of the flow while the lava is moving. When the flow stops the olivines start to sink (except for those frozen into the top and bottom crusts). The olivines sink until they "land" on a viscosity/yield strength front moving up from the bottom. If you know how thick the flow is, how fast the viscosity front moves upward, and the distribution of olivines, the rate at which they sink can be calculated. By then plugging this rate into Stokes' equation (and making some assumptions), the viscosity can be calculated. The calculated viscosity for the 1868 flow is 610 Pa-sec, near the low end for Hawaiian pāhoehoe flows.

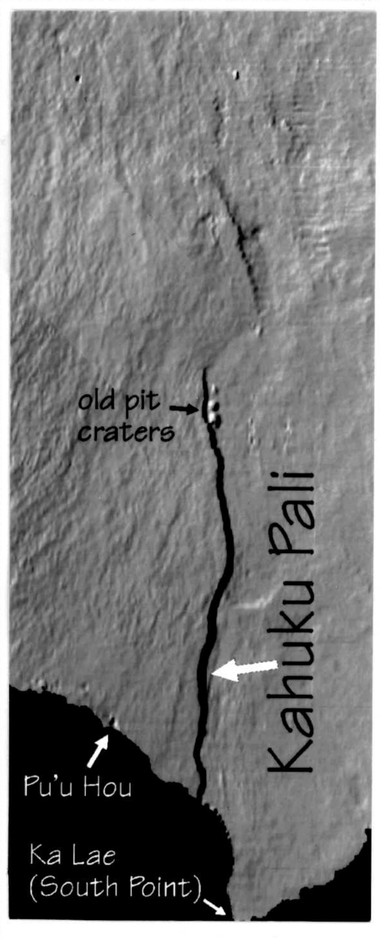


Olivines sinking in a lava flow to produce the often-observed distribution with depth (Rowland & Walker 1988).

THE KAHUKU PALI

The Kahuku Pali is a large fault scarp downdropped to the west. It has the appearance of a scissors fault, with the throw decreasing from the seaward end towards the uphill end and eventually disappearing. The Kahuku fault (which extends far offshore) is probably the eastern margin of a large arcuate slump scarp that has been mostly buried by later lava flows. Thus the scissors-like quality is actually due to the upper end having been buried more than the lower end. The other half of the large slump is perhaps the Kealakekua fault, some 70 km to the northwest.

The Kahuku Pali exposes numerous Mauna Loa flows, and has been sampled extensively by geochemists studying the evolution of Mauna Loa lava composition. Many of the flows are oceanite picrites (such as the 1868 flow). This seems to support the idea that dikes that feed lower-elevation vents tend to come from deeper depths in the magma chamber (where olivines have settled).



Shaded relief image of Ka Lae and the Kahuku Pali

LITTORAL CONES: PU'U HOU AND PU'U KĪ

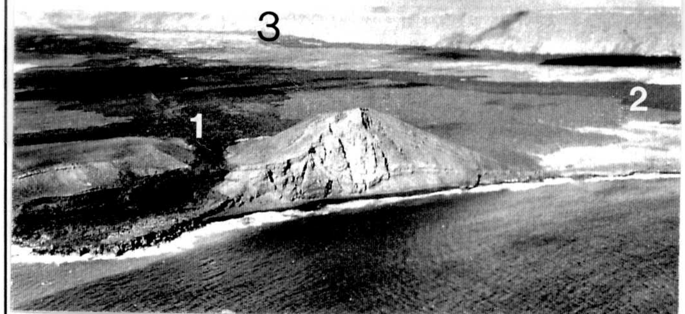


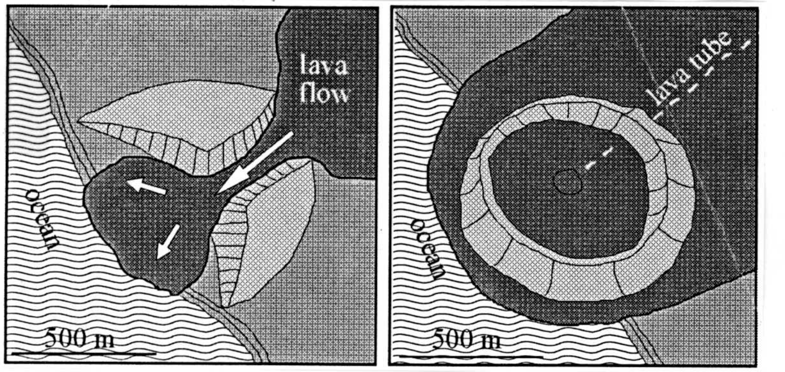
Photo of Pu'u Hou (from Macdonald *et al.* 1983). *1*, *2*, and *3* indicate the three main branches of the 1868 flow.

There are a number of pyroclastic cones visible on this Mauna Loa coastline. These are not vents, but rather littoral cones. The most prominent is Pu'u Hou, formed when the western-most arm of the 1868 flow entered the ocean (Fisher 1968). Pu'u Hou is actually a complex of 3 half cones arranged around the ocean end of the flow. Pu'u Hou fits the typical description of a littoral cone wherein a number of half cones are arranged on the sides of an 'a'ā flow at the coastline. The 1868 flow is toothpaste lava at this location instead of 'a'ā, but never-the-less the surface of the flow was moving while the littoral deposits were emplaced so that only the material that landed off to the side was preserved. Pu'u Hou means "new hill", an appropriate name for a large feature that formed in only a few days.

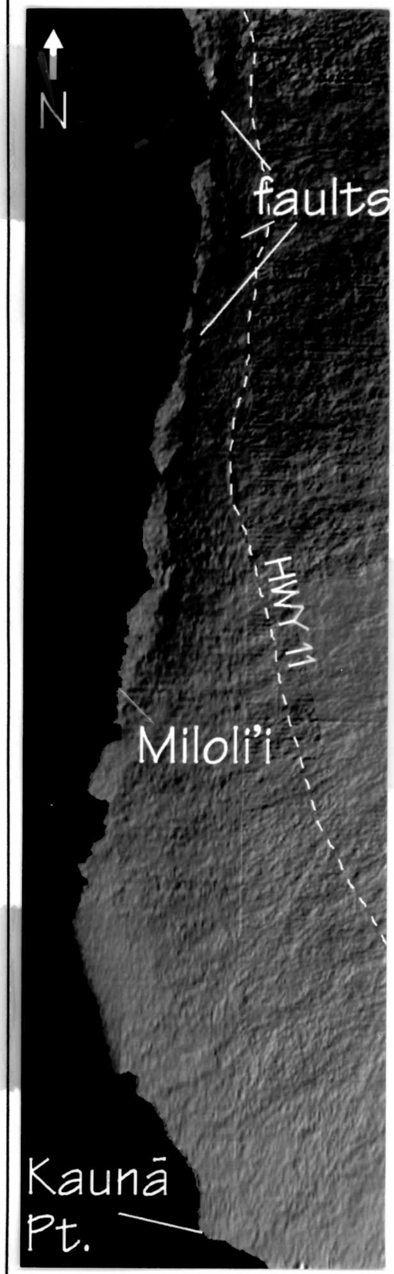
About 10 km up the coast is a cluster of cones distributed along the coastline, all associated with the Pōhue Bay flow. The largest of these is Pu'u Kī, and collectively these cones are usually called the Pu'u Kī cones. These cones do not have the typical pair-of-half-cones arrangement, and instead are complete rings of pyroclastic material (or show evidence that they once were complete). Thus their form is very similar to tuff cones. Moreover, the Pōhue Bay flow is pāhoehoe rather than 'a'ā. It is worthwhile to determine whether these are actually primary vents (such as tuff cones) or a rather different type of littoral cone. If they turn out to be primary vents, they are in a strange place relative to Mauna Loa's rift zones, and we need to re-think our ideas on the magma plumbing on this part of the volcano. On the other hand, if they are littoral they represent a much more explosive type of littoral activity associated with pāhoehoe flows than has been seen at any recent activity (such as the Mauna Ulu and the present Pu'u 'Ō'ō /Kūpa'ianahā eruptions; Peterson 1976; Mattox 1994).

Oblique air photo of the Pu'u Kī littoral cone complex viewed to the SE. Photo by JP Lockwood.

Jurado-Chichay *et al.* (1996a) have used various lines of evidence to show that this particular set of cones on the SW coast of Mauna Loa cones are indeed littoral. This evidence includes the unequivocal association with the Pōhue Bay flow (which has a mapped source on the rift zone), and the degassed nature of the littoral pyroclasts. The fact that the Pōhue Bay flow is tube-fed pāhoehoe at the coast provides an explanation of the complete circular nature of the cones. The explosions occurred some distance inland (perhaps when the bottom dropped out of an active tube and lava was able to contact wet underlying hyaloclastites). Because the carapace of an active pāhoehoe flow is solid and unmoving, complete rings of pyroclastic material were able to develop. Much smaller circular littoral cones have recently been witnessed forming on the Puʻu ʻŌʻō/Kūpaʻianahā flow field (Mattox 1994).



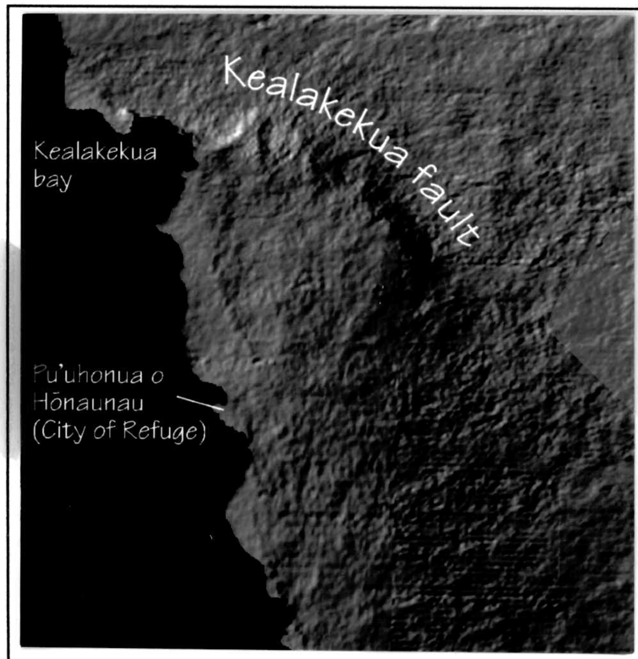
Diagrams to show the form of a "typical" littoral cone (modified from Fisher & Schmincke 1984), and a circular littoral cone (Jurado-Chichay *et al.* 1996b).



Shaded relief image of the SW flank of Mauna Loa. Note the coastal faults north of Miloliʻi; south of Miloliʻi similar faults are presumably buried.

THE STEEP WESTERN FLANK OF MAUNA LOA

Active uneroded Hawaiian volcanoes are famous for having broad gentle slopes, probably a factor of the high effusion rate of the erupted lavas as well as their low viscosities and yield strengths. This general rule is violated in a number of places where obvious faulting has occurred. It is also violated along the western flank of Mauna Loa. There aren't really any good places to stop and look at this so you'll have to watch out the window as we wind along. Why are the slopes so steep here? The best explanation is that faulting and giant landslides have steepened this unbuttressed volcanic flank (e.g. Normark *et al.* 1978), and indeed numerous giant avalanche deposits can be found offshore (Lipman *et al.* 1988). The youngest of these is probably the Alika slide, dated at around 150,000 years old. The fault- and landslide-steepened slopes have subsequently been mantled by younger lava flows. As we drive north, we go from downhill of the SW rift zone (the source of many flank-mantling flows) to downhill of the western caldera rim (which protects the lower flanks), and the slopes of Mauna Loa consequently become more and more steep. We will be crossing numerous 19th and 20th century Mauna Loa south-

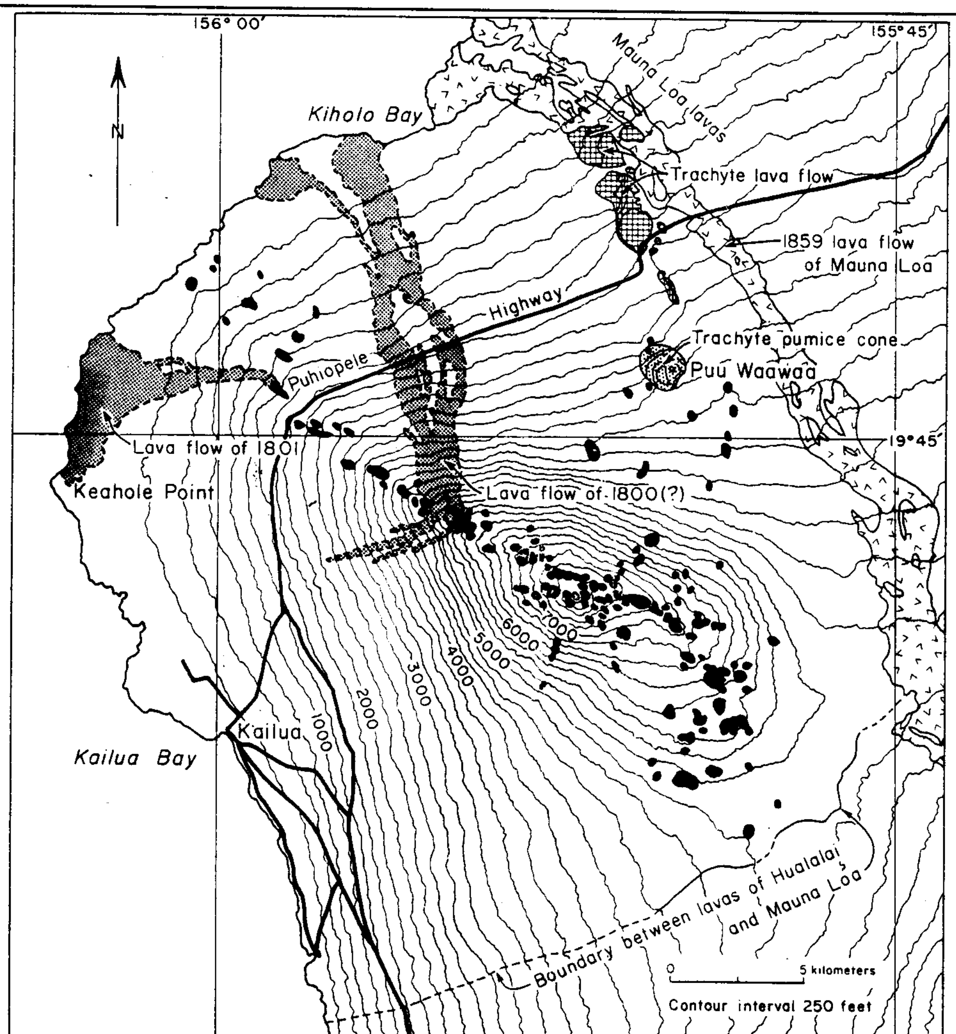


Shaded relief image of the Kealakekua fault, which has been draped by many lava flows. The small south-pointing peninsula in Kealakekua bay is the location of a monument to Captain Cook.

west rift zone flows, most of which reached the ocean. These include (from south to north) lavas of 1887, 1907, 1916, 1919, and 3 flows of the huge 1950 eruption.

HUALĀLAI

Hualālai has moved off the hotspot and is in its post-shield alkalic stage, sometimes called the alkalic cap stage. This stage is characterized by alkalic lavas (duh!), an ever-decreasing eruption rate, generally (but not always) cooler eruption temperatures, the solidification of the high-level magma chamber, more xenoliths and gas in the erupting lava, and a tendency for vents to be more concentrated near the summit. Since Europeans arrived, Hualā lai has only erupted in 1800 and 1801 (the Ka'ūpūlehu and Hu'ehu'e flows, respectively). The Hu'ehu'e flow is a fine example of a tube-fed pāhoehoe lava, and the Keāhole airport (where you probably flew in to) is built on this flow.



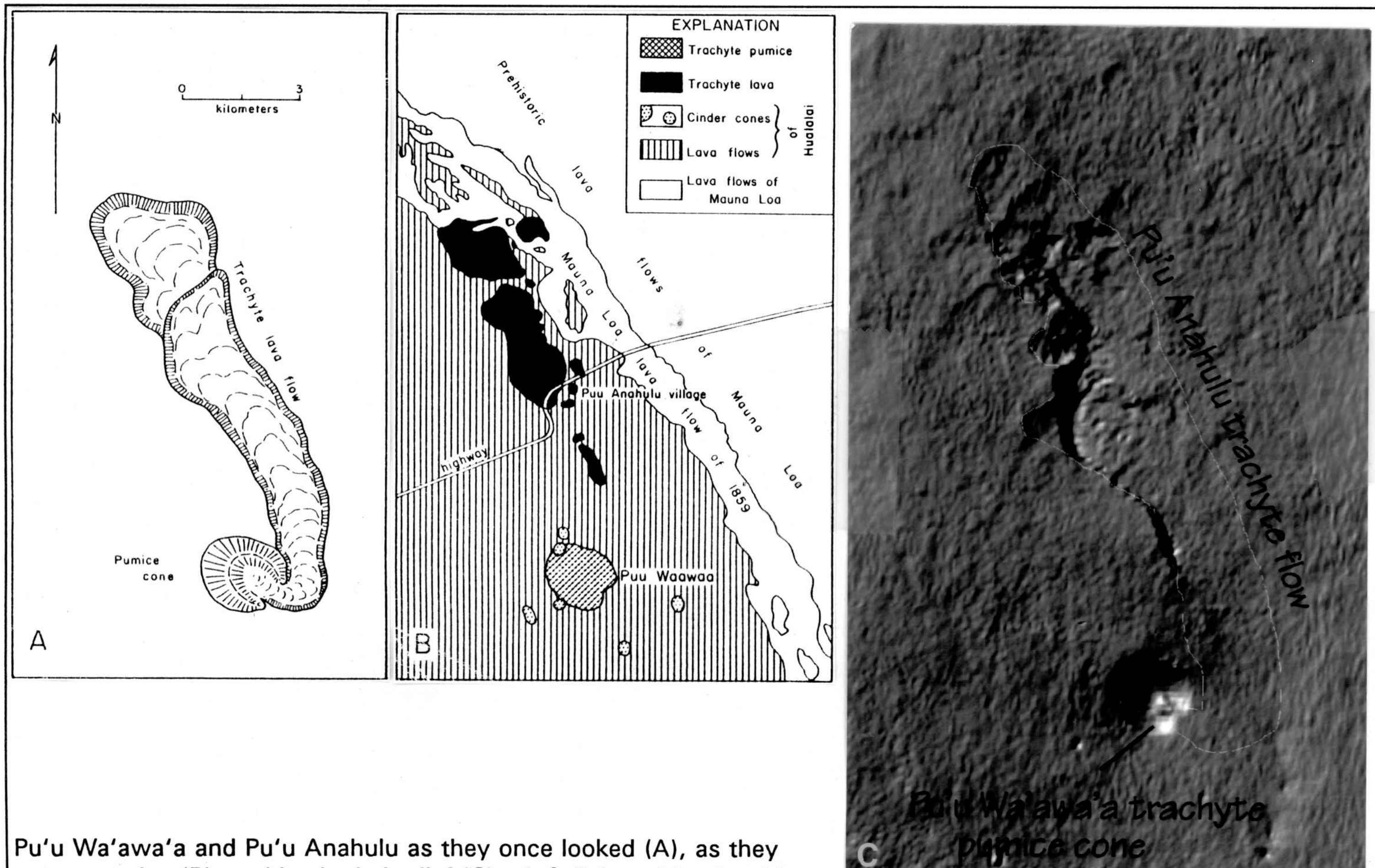
Map of Hualālai, showing the two 19th century flows, the 105,000 year-old trachyte pumice cone and flow, and the 1859 Mauna Loa flow (*v-pattern*). (Macdonald *et al.* 1983)

A consequence of not having a magma chamber is that magma that is going to erupt must make the entire trip from its source to the surface without pausing anywhere along the way (otherwise it will freeze and not erupt). This means that any xenoliths that may have been entrained in the lava never have a chance to settle out. The 1800 Ka'ūpūlehu lava is an exceptional example of a xenolith-rich flow, most of which dropped out to form lag deposits within 5-6 km of the vent. The xenoliths in the Ka'ūpūlehu flow are mostly dunites, with a few pyroxenites and rare gabbros. The xenoliths can be found in an amazing abundance; as far as anyone knows this is the only such locality on Earth. The Ka'ūpū lehu flow is alkalic basalt, and upon eruption had a very low viscosity. It flowed rapidly down the nearly 10° upper slopes and there are stories of people in coastal villages being overwhelmed by lava (Brigham 1909). At the xenolith localities the low viscosity is evident in the fact that the lava almost completely drained out from between the xenoliths leaving only 1-2 mm-thick selvages. Near the upper highway there is also ample evidence of the velocity at which the lava was traveling in the form of splash and overflow features on the levees of the lava channels.

From here we can look uphill towards Pu'u Wa'awa'a and Pu'u Anahulu. Hualālai is an unusual Hawaiian volcano in a number of respects, including the occurrence of huge individual eruptions of trachyte. Trachyte is relatively rare in Hawai'i, confined to the alkalic cap stage, and for some reason it is more common on some volcanoes than others (i.e. Hualālai and West Maui). Pu'u Wa'awa'a is a large trachyte pumice cone containing some fragments of obsidian. Pu'u

Wa'awa'a is cut by erosional gullies giving it a fluted look, and some local folks call it "cupcake mountain." A thick lava flow issued out of the uphill end of the cone, wrapped around the north side, and flowed about 9 km downslope. This flow is about 200 m thick, and forms Pu'u Anahulu. From the air, Pu'u Anahulu has many prominent flow ridges perpendicular to the direction of flow. The cone and flow together make up by far the largest volume of trachyte on the surface of any Hawaiian volcano, and have been dated at ~105,000 years old (Moore *et al.* 1987).

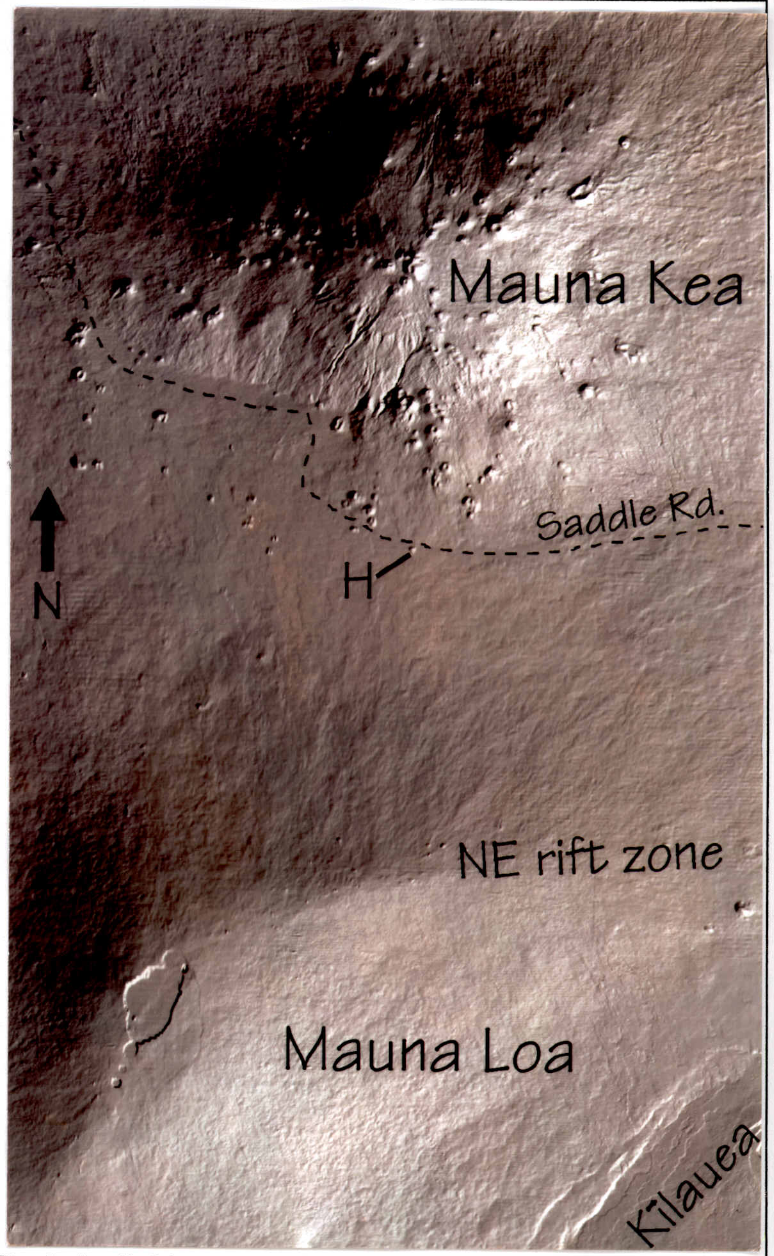
Trachyte is the end result of the fractionation of alkalic basalt, and is characterized by a texture of many blade-like feldspar crystals ("trachytic" or "felty" texture). It is presumed that pockets of magma can become isolated within the volcano where they fractionate without being re-heated by further influxes of new magma (e.g. Macdonald *et al.* 1983). In temperature-pressure space this fractionation is not easy to accomplish at shallow depths (J. Sinton, pers. commun.), and presumably occurs within a deep magma chamber that has been proposed to develop at the base of the volcano (Frey *et al.* 1990). The great thickness of Pu'u Anahulu and the presence of obsidian attest to a very high viscosity and yield strength, and the large size of Pu'u Wa'awa'a to a very gas-rich (and explosive) eruption. Possibly this body of highly-viscous magma only erupted because of the build-up of volatiles. The trachyte cone and flow have formed a prominent barrier which has protected the area to the south; and numerous flows of Mauna Loa and Hualālai have banked against the northern edges of the barrier. The younger flows have filled in to the top of Pu'u Anahulu, and the 1859 Mauna Loa lava almost flowed over before deciding to take an easier path to the ocean.



Pu'u Wa'awa'a and Pu'u Anahulu as they once looked (A), as they outcrop today (B), and in shaded relief (C). A & B from Macdonald *et al.* (1983).

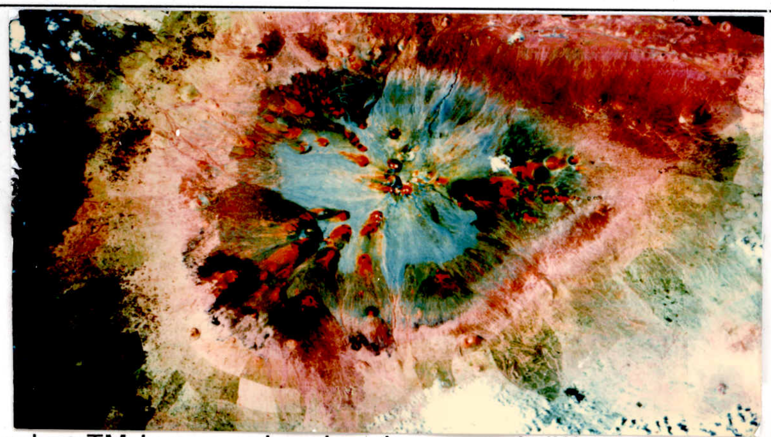
THE SADDLE

The saddle is the low area between the two largest shield volcanoes in Hawai'i, Mauna Kea ("white mountain") to the north, and Mauna Loa ("long mountain") to the south. Both volcanoes are over 4200 m high (above sea level), and Mauna Kea is slightly higher. The differences in their profiles are obvious and due mainly to the types of eruptions that are common to each. Mauna Loa is in the tholeiite stage; eruptions are concentrated along the rift zones, vents are mainly spatter cones less than 50 m high, flows are thin, fluid, and long, and consequently the slopes are very gradual. Looking towards the summit of Mauna Loa, many flows can be seen, both 'a'ā and pāhoehoe. Lava flows are black when first erupted, and oxidize to red as they weather. Pāhoehoe flows tend to weather more slowly because of their armor of glassy skin. 'A'ā flows, on the other hand, weather more quickly because their extremely rough surfaces provide many pockets for moisture, seeds, and lichens to take hold. Additionally, 'a'ā flows are often oxidized to some degree within a few hours after they stop flowing. This is because the clinker layer provides such poor insulation that the upward-escaping heat causes the surface to oxidize rapidly. The climate in the saddle is relatively dry because it is above the major trade wind cloud zone. Lava flows here and especially on the higher slopes weather very slowly.



Shaded relief image of the saddle area between Mauna Kea and Mauna Loa (H: Pu'u Huluhulu). The morphological differences between the two volcanoes are very obvious in these data.

Looking north to Mauna Kea provides a much different view. Mauna Kea is in its alkalic stage; eruptions are scattered over the summit area, vents are large cinder cones a few hundred meters high, flows tend to be thick and stubby, and consequently the slopes of Mauna Kea are steep. Few, if any, fresh flows are visible, and the surface is covered with wind-blown cinders and ash. An additional difference is that during the last ice age, there were glaciers on Mauna Kea. Up in the summit area you can find striated rocks, 'a'ā flows that have had their clinker layers scraped off, and sub-glacial (glassy) lava flows. From the saddle, the visible evidence of glaciation is a


Landsat TM image, enhancing the spectral differences between cinder cones, moraines, and talus (it looks better in color).

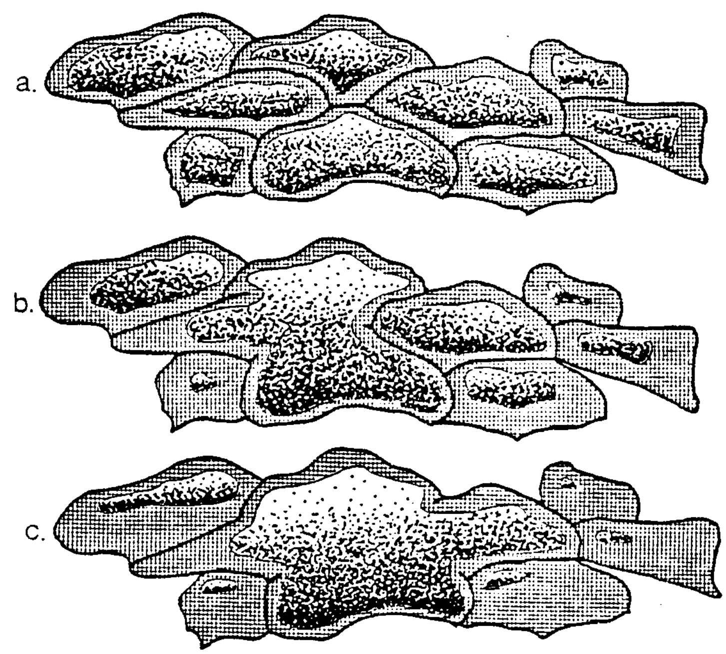
prominent set of terminal moraines, and a couple of outwash channels. There is no evidence for glaciation on Mauna Loa although it was undoubtedly just as high; either all evidence has been covered by more recent lavas, or the heat from the more active volcanism never allowed snow to build up to the point of glacier formation.

The flow at the top of the saddle is pāhoehoe from the 1935-36 eruption of Mauna Loa. The flow surrounds Pu'u Huluhulu, a Mauna Kea cone which has been quarried extensively, in places exposing interior dikes. About 50 m west of the hunter check-in station is a small un-cemented rock wall. In places this wall was able to halt the advance of the pāhoehoe.

KAŪMANA CAVE

Kaūmana cave is a lava tube. It is in the 1880-81 flow of Mauna Loa. This eruption lasted for about 255 days and came down to the elevation of the present University of Hawai'i Hilo campus (fortunately the eruption was ~110 years ago!). The 1880-81 flow is a fine example of a "paired" lava flow (Rowland & Walker 1990). A paired eruption consists of a period of high effusion that produces fast-moving 'a'ā flows for 1-2 weeks, followed by months of low effusion rates that produce tube-fed pāhoehoe flows. The 'a'ā and pāhoehoe flows often cover similar distances and areas (but at greatly different rates). The other good example of a paired eruption on Mauna Loa occurred in 1859. The Mauna Ulu and Pu'u 'Ō'ō/Kūpa'ianahā eruptions also both consisted of high effusion rates, high fountains, and 'a'ā flows at first, followed by low effusion rates, no fountaining, and tube-fed pāhoehoe flows. However, the details of these Kīlauea eruptions differ from the Mauna Loa paired flow eruptions.

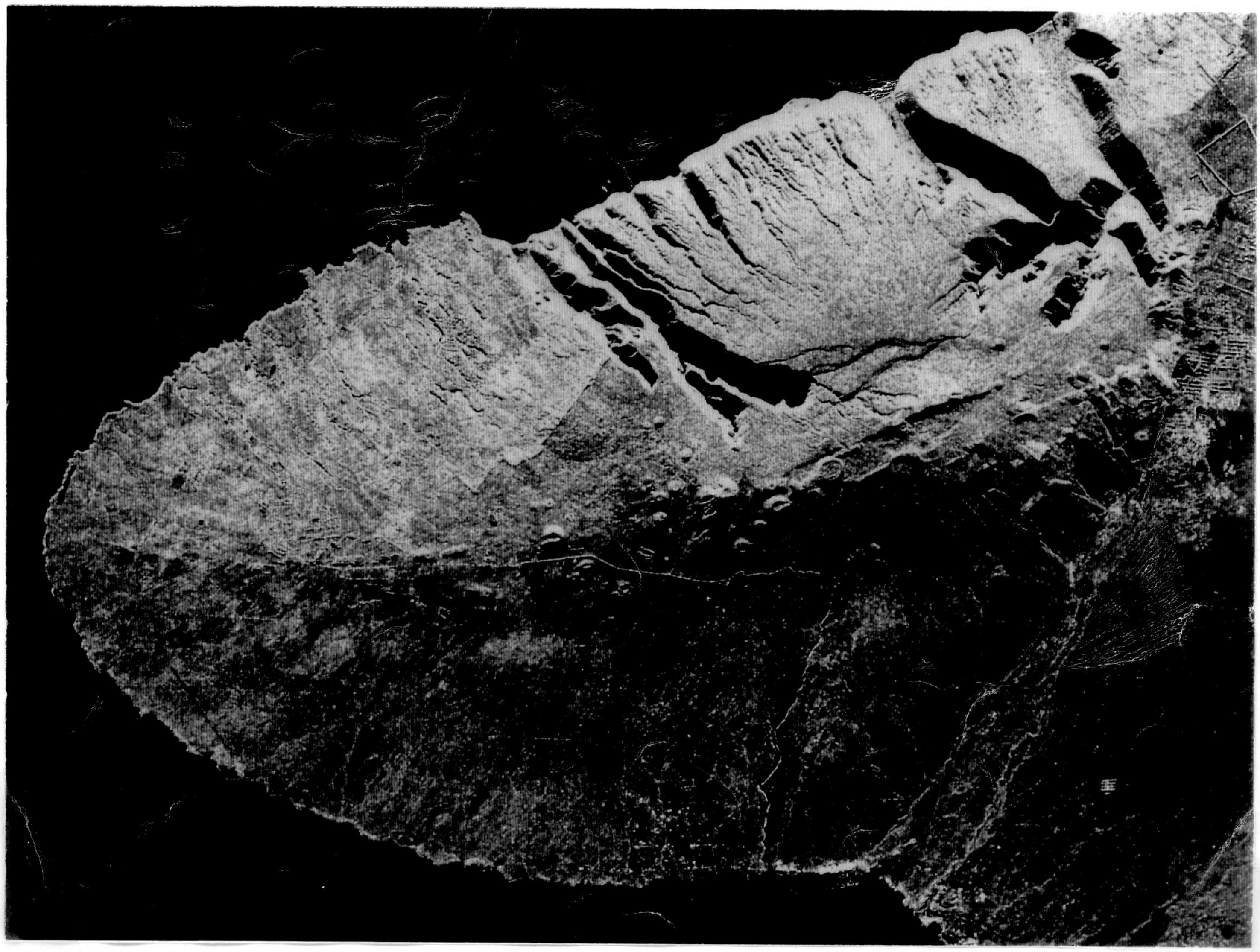
Lava tubes form in a number of ways, and once formed, lava is able to flow in a well-insulated conduit from vent to flow front while losing only minimal heat; the 1880-81 flow is about 47 km long. The most often-cited mechanism for the generation of a lava tube is the roofing-over of a lava channel (i.e. Peterson & Swanson 1974; Peterson *et al.* 1994). An equally important mechanism for the formation of tubes is the coalescence of single flow units. If a number of pāhoehoe toes are flowing simultaneously and on top of one another, the skins that separate them become softened by the heat. as these skins begin to give way, the space available for the lava to flow increases, and a "master" tube is formed. Subsequent flows on the surface from breakouts will armor and strengthen the roofs of tubes. Places where the tops of tubes have collapsed are called "skylights," and on active tubes are extremely dangerous. We will enter Kaūmana cave through a skylight.



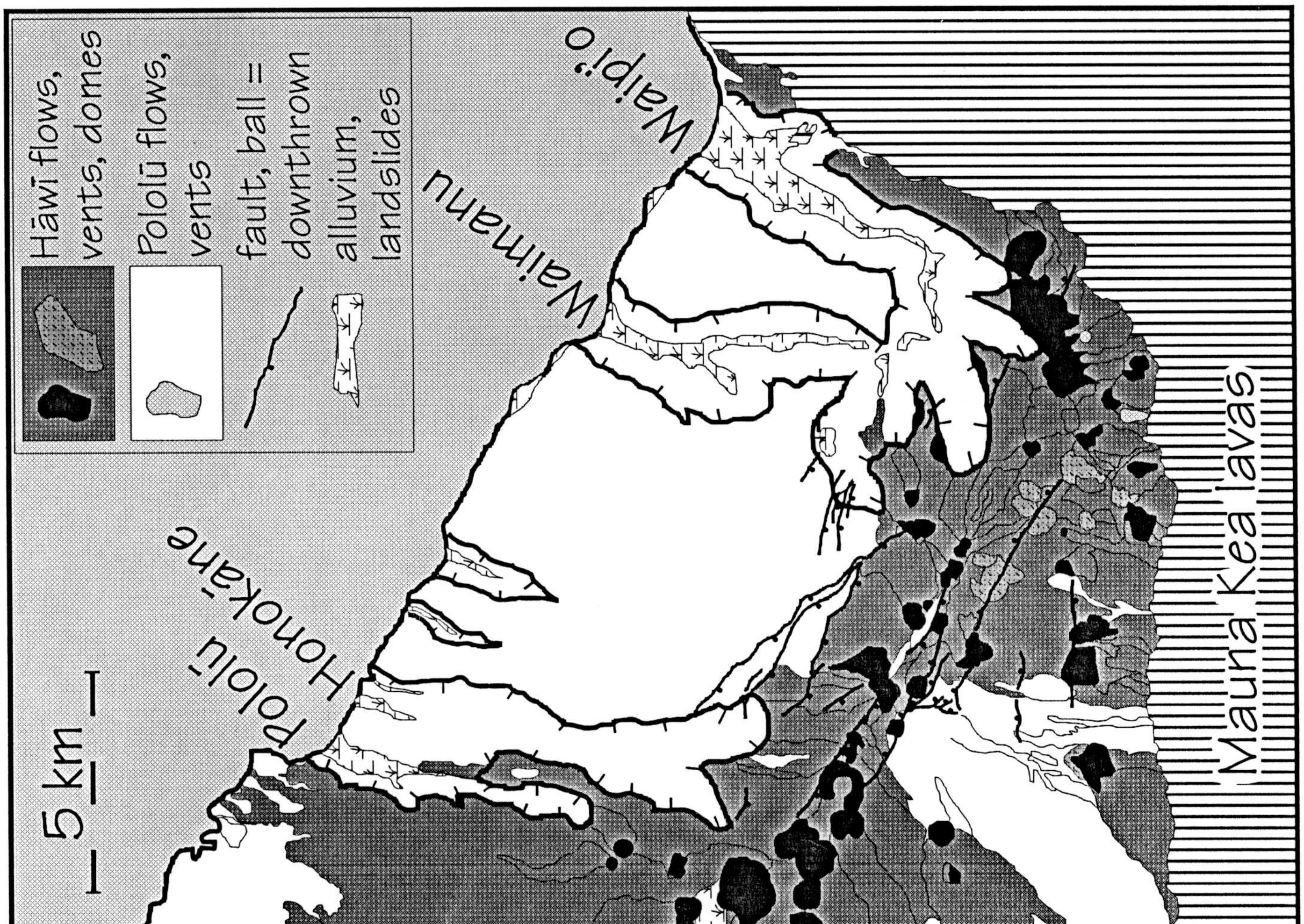
Diagrams showing the development of a "master" lava tube out of numerous flow units. Stippled pattern is molten lava, grid pattern is solid crust.

KOHALA

Kohala is the oldest subaerial volcano in the Big Island cluster (Mahukona may or may not have ever broken sea level). Kohala last erupted around 60,000 years ago. It is apparently in the erosional stage between the post-shield alkalics and the post-erosional volcanism. Kohala's older rocks are tholeiites of the Pololū series, and it is capped, but not completely covered by alkalic rocks of the Hāwī series. Cinder cones marking vents of both series are aligned in a NW-SE direction. The summit region is cut by a number of normal faults parallel to the cone alignment, and all of them are downdropped toward the SW. There is an amazing difference in the degree of erosion on the windward and leeward sides of Kohala. For one thing, the windward slopes receive 100 to >150 inches of rain per year whereas the lowermost leeward coast receives less than 10 inches per year. Spectacular erosional valleys are found on the windward side, and one of the finest examples of stream piracy is illustrated by the cutting of the headwaters of Waimanu valley by Waipi'o valley. Additionally, the fault scarps prevented young, more erosion-resistant Hāwī lavas from flowing over and protecting most of the windward slopes. Finally, a good portion of the windward flanks were slumped into the ocean by the giant Pololū landslide.



Shuttle Imaging Radar (SIR-C) image of Kohala. North is towards the upper left, illumination is from the east (upper right).



Geologic map of Kohala compiled by Mike Garcia, Bill Wise, and others. If the Big Island mapping project map is ever published, this will be part of it.

CITED REFERENCES

Apple RA (1987). Thomas A. Jaggar Jr., and the Hawaiian Volcano Observatory. U.S. Geol. Surv. Prof. Pap. **1350**:1619-1644.

Baker NA (1987). A petrologic study of the 1982 summit lavas of Kilauea Volcano, Hawaii. Unpb. Senior Thesis, U. Hawaii: 61 pp.

Barnard WM (1990). Mauna Loa--A source Book vol. **1**: 353 pp.

Brigham WT (1909). The volcanoes of Kilauea and Mauna Loa. Mem. of the Bernice Pauahi Bishop Museum of Polynesian Ethnology and Natural History **2**, no. 4: 222 pp.

Buchannan-Banks JM (1987). Structural damage and ground failures from the November 16, 1983, Kaoiki earthquake, Island of Hawaii. U.S. Geol. Surv. Prof. Pap. **1350**:1187-1195.

Carr MH & Greeley R (1980). Volcanic Features of Hawaii. NASA pub. **SP-403**: 211 pp.

Coombs CR, Hawke BR & Wilson L (1990). Terrestrial analogs to lunar sinuous rilles: Kauhako crater and channel, Kalaupapa, Molokai, and other Hawaiian lava conduit systems. Proc. 20th Lunar. Planet. Sci. Conf:195-206.

Coombs CR & Rowland SK (1994). Thermal erosion in a lava tube: Honuapo, Mauna Loa volcano, Hawaii. Geol. Soc. Am. Ann. Mtg. abs. vol:118-119.

Dibble S (1843). A history of the Sandwich Islands. Thos. G. Thrum Pub., Honolulu.

Decker RW (1987). Dynamics of Hawaiian volcanoes: an overview. USGS Prof. Pap. **1350**:997-1018.

Dvorak JJ (1992). Mechanism of explosive eruptions at Kilauea Volcano, Hawaii. Bull. Volcanol. **54**:638-645.

Easton RM (1987). Stratigraphy of Kilauea Volcano. USGS Prof. Pap. **1350**:243-260.

Easton RM & Easton MG (1987). Highway Geology of the Hawaiian Islands. Easton Enterprises, Brampton, Ontario. 158 pp.

Fisher RV (1968). Puu Hou littoral cones, Hawaii. Geol. Rundschau **57**:837-864.

Fisher RV, Schmincke H-U (1984). Pyroclastic Rocks. Springer-Verlag, Berlin, 472 pp.

Fiske RS & Kinoshita WT (1969). Inflation of Kilauea Volcano prior to its 1967-1968 eruption. Science **165**:341-349.

Frey FA, Wise WS, Garcia MO, West H, Kwon S-T, & Kennedy A (1990). Evolution of Mauna Kea Volcano, Hawaii: petrologic and geochemical constraits on postshield volcanism. J. Geophys. Res. **95**:1271-1300.

Greeley R (1974). Geologic Guide to the Island of Hawaii. Office of Planetary Programs, NASA. 257 pp.

Hardee HC (1980). Solidification of Kilauea Iki lava lake. J. Volcanol. Geotherm. Res. **7**:211-224.

Heslop SE, Wilson L, Pinkerton H, & Head JW (1989). Dynamics of a confined lava flow on Kilauea volcano, Hawaii. Bull. Volcanol. **51**:415-432.

Holcomb RT (1987). Eruptive history and long-term behavior of Kilauea volcano. U.S. Geol. Surv. Prof. Pap. **1350**:261-350.

Hon K & Kauahikaua J (1991). The importance of inflation in formation of pahoehoe sheet flows. EOS **72** #44:557.

Hon K, Kauahikaua J, Denlinger R, & Mc Kay K (1994). Emplacement and inflation of pahoehoe sheet flows: Observations and measurements of active lava flows on Kilauea Volcano, Hawaii. Geol. Soc. Am. Bull. **106**:351-370.

Hulme G (1974). The interpretation of lava flow morphology. Geophys. J. Roy. Astro. Soc. **39**:361-383.

Jaggar TA (1924). Volume relations of the explosive eruption 1924. Monthly Bull. Hawaiian Volcano Obs. **12**: 117-123.

Jurado-Chichay Z, Rowland SK, & Walker GPL (1996a). The formation of circular littoral cones from tube-fed pāhoehoe Mauna Loa, Hawai'i. Bull. Volcanol. (in press).

Jurado-Chichay Z, Urrutia-Fucugauchi J, Rowland SK (1996b). A paleomagnetic study of the Pohue Bay flow and its associated cones, Mauna Loa Volcano, Hawaii: constraints on their origin and temporal relationships. Phys. Earth Planet. Int. (in press).

Klein FW, Koyanagi RY, Nakata JS, & Tanigawa WR (1987). The seismicity of Kilauea's magma system. U.S. Geol. Surv. Prof. Pap. **1350**:1019-1185.

Lipman PW & Swenson A (1984). Generalized geologic map of the southwest rift zone of Mauna Loa Volcano, Hawaii. U.S. Geol. Surv. Misc. Investig. Ser. Map **I-1323**.

Lipman PW, Lockwood JP, Okamura RT, Swanson DA, & Yamashita KM (1985). Ground deformation associated with the 1975 magnitude-7.2 earthquake and resulting changes in activity of Kilauea volcano, Hawaii. U.S. Geol. Surv. Prof. Pap. **1276**: 45 pp.

Lipman PW, Normark WR, Moore JG, Wilson JB, & Gutmacher CE (1988). The giant submarine Alika debris slide, Mauna Loa, Hawaii. J. Geophys. Res. **93**:4279-4299.

Lipman PW, Rhodes JM, & Dalrymple GB (1990). The Ninole Hills basalt-implications for the structural evolution of Mauna Loa Volcano, Hawaii. bull. Volcanol. **53**:1-19.

Lockwood JP, & Lipman PW (1987). Holocene eruptive history of Mauna Loa volcano. U.S. Geol. Surv. Prof. Pap. **1350**:509-535.

Macdonald GA (1958). Barriers to protect Hilo from lava flows. Pacific Science **12**:258-277.

Macdonald GA (1962). The 1959 and 1960 eruptions of Kilauea volcano, Hawaii, and the construction of walls to restrict the spread of the lava flows. Bull. Volcanol. **22**:249-294.

Macdonald GA & Abbot AT (1970). Volcanoes in the Sea the Geology of Hawaii. University of Hawaii Press, Honolulu. 441 pp.

Macdonald GA, Abbot AT, & Peterson (1983). Volcanoes in the Sea the Geology of Hawaii (2nd ed.). University of Hawaii Press, Honolulu. 517 pp.

Malahoff A (1987). Geology of the summit of Loihi submarine volcano. USGS Prof. Pap. **1350**:133-144.

Malahoff A, McMurtry GM, Wiltshire JC & Yeh HW (1982). Geology and chemistry of hydrothermal deposits from active submarine volcano Loihi, Hawaii. Nature **298**:234-239.

Malin MC, Dzurisin D, & Sharp RP (1983). Stripping of Keanakakoi tephra on Kilauea volcano, Hawaii. Geol. Soc. Am. Bull. **94**:1148-1158.

Mark RK & Moore JG (1987). Slopes of the Hawaiian ridge. USGS Prof. Pap. **1350**:101-107.

Mattox TN (1994). Where lava meets the sea: Kilauea Volcano, Hawaii. Earthquakes and Volcanoes **24**:160-177.

McPhie J, Walker GPL, & Christiansen RL (1990). Phreatomagmatic and phreatic fall and surge deposits from explosions at Kilauea volcano, Hawaii, 1790 AD: Keanakakoi ash member. Bull. Volcanol. **52**:334-354.

Moore JG & Mark RK (1992). Morphology of the island of Hawaii. GSA Today **2**:257-262.

Moore RB, Clague DA, Rubin M, & Bohrson WA (1987). Hualalai Volcano: A preliminary summary of geologic, petrologic, and geophysical data. U.S. Geol. Surv. Prof. Pap. **1350**:571-585.

Murata KJ & Richter DH (1966). Chemistry of the lavas of the 1959-60 eruption of Kilauea volcano, Hawaii. U.S. Geol. Surv. Prof. Pap. **537-A**: 26 pp.

Nichols RL (1936). Flow units in basalt. J. Geol. **44**:617-630.

Normark WR, Lipman PW, Lockwood JP, & Moore JG (1978). Bathymetry and geology, Kealakekua Bay, Hawaii. U.S. Geol. Surv. Misc. Fiwld Studies Map **MF-986**.

Peterson DW (1976). Processes of volcanic island growth, Kilauea Volcano, Hawaii, 1969-1973. in Gonzales-Ferran, ed. Proc. Symp. Andean and Antarctic Volcanol. Problems (Santiago, Chile, Sept. 1974). IAVCEI Spec. Ser:172-189.

Peterson DW & Moore RB (1987). Geologic history and evolution of geologic concepts, island of Hawaii. USGS Prof. Pap. **1350**:149-189.

Peterson DW & Swanson DA (1974). Observed formation of lava tubes. studies in Speleology **2**:209-222.

Peterson DW, Holcomb RT, Tilling RI, & Christiansen RL (1994). Development of lava tubes in the light of observations at Mauna ulu, Kilauea Volcano, Hawaii. Bull. Volcanol. **56**:343-360.

Richter DH, Eaton JP, Murata KJ, Ault WU, & Krivoy HL (1970). Chronological narrative of the 1959-60 eruption of Kilauea volcano, Hawaii. U.S. Geol. Surv. Prof. Pap. **537-E**: 73 pp.

Rowland SK & Walker GPL (1988). Mafic-crystal distributions, viscosities, and lava structures of some Hawaiian lava flows. J. Volcanol. Geotherm. Res. **35**:55-66.

Rowland SK & Walker GPL (1990). Pahoehoe and a`a in Hawaii: volumetric flow rate controls the lava structure. Bull Volc **52**:615-628.

Smathers GA & Mueller-Dumbois D (1974). <u>Invasion and Recovery of Vegetation after a Volcanic Eruption in Hawaii</u>. National Park Service Scientific Monograph Series **5**:129 pp.

Sparks RSJ, Pinkerton H, & Hulme G (1976). Classification and formation of lava levees on Mount Etna, Sicily. Geology **4**:269-271.

Swanson DA (1973). Pahoehoe flows from the 1969-1971 Mauna Ulu eruption, Kilauea volcano, Hawaii. Geol. Soc. Am. Bull. **84**:615-626.

Swanson DA & Christiansen RL (1973). Tragic base surge in 1790 at Kilauea volcano. Geology **1**:83-86.

Swanson DA, Duffield WA, & Fiske RS (1976). Displacement of the south flank of Kilauea volcano: the result of forceful intrusion of magma into the rift zones. U.S. Geol. Surv. Prof. Pap. **963**: 39 pp.

Swanson DA, Duffield WA, Jackson DB, & Peterson DW (1979). Chronological narrative of the 1969-71 Mauna Ulu eruption of Kilauea volcano, Hawaii. U.S. Geol. Surv. Prof. Pap. **1056**: 55 pp.

Tilling RI, Koyanagi RY, Lipman PW, Lockwood JP, Moore JG, & Swanson DA (1976). Earthquake and related catastrophic events, island of Hawaii, November 29, 1975: a preliminary report. U.S. Geol. Surv. Circular **740**: 33 pp.

Tilling RI, Christiansen RL, Duffield WA, Endo ET, Holcomb RT, Koyanagi RY, Peterson DW, & Unger JD (1987). The 1972-1974 Mauna Ulu eruption, Kilauea volcano: an example of quasi-steady-state magma transfer. U.S. Geol. Surv. Prof. Pap. **1350**:405-469.

Walker GPL (1971). Compound and simple lava flows and flood basalts. Bull. Volcanol. **35**:579-590.

Walker GPL (1988) Three Hawaiian calderas: an origin through loading by shallow intrusions? J Geophys Res **93**:14,773-14,784

Walker GPL (1989). Spongy pahoehoe in Hawaii: a study of vesicle-distribution patterns in basalt and their significance. Bull. Volcanol. **51**:199-209.

Walker GPL (1991). Structure and origin by injection of lava under surface crust, of tumuli, "lava rises", "lava-rise pits", and "lava inflation clefts" in Hawaii. Bull. Volcanol. **53**:546-558.

Wentworth CK (1966). The eruption and the original population. pages 330-334 in MS Day & D Mueller-dumbois, Atlas for bioecology studies in Hawaii Volcanoes National Park. Hawaii Bot. Sci. Pap. 2.

Wilmuth RA & Walker GPL (1993). P-type and s-type pahoehoe: a study of vesicle distribution patterns in Hawaiian lava flows. J. Volcanol. Geotherm. Res. **55**:129-142.

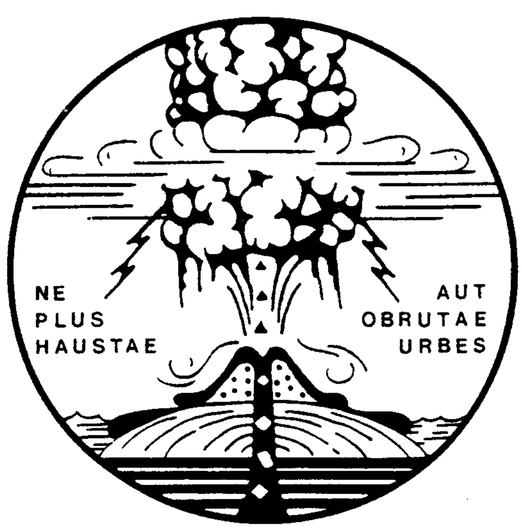
Wilson L & Parfitt EA (1993). The formation of perched lava ponds on basaltic volcanoes: the inluence of flow geometry on cooling-limited lava flow lengths. J. Volcanol. Geotherm. Res. **56**:113-123.

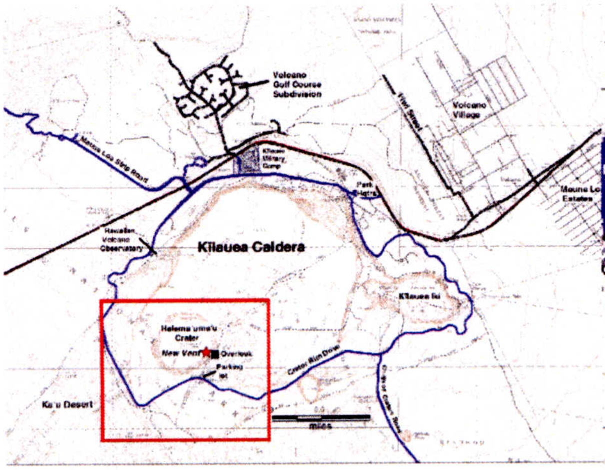
Wolfe EW, Garcia MO, Jackson DB, Koyanagi RY, Neal CA, & Okamura AT (1987). The Puu Oo eruption of Kilauea Volcano, episodes 1-20, January 3, 1983 to June 8, 1984. USGS Prof. Pap. **1350**:471-508.

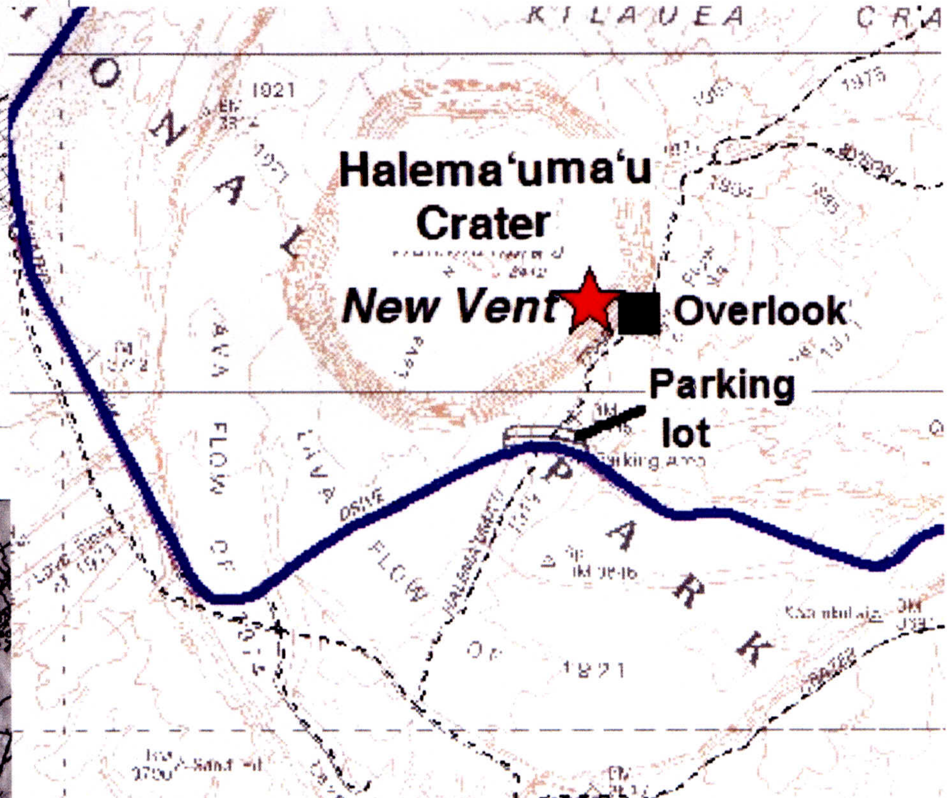
Wolfe EW, Neal CA, Banks NG & Duggan TJ (1988). Geologic observations and chronology of eruptive events. USGS Prof. Pap.**1463**:1-97.

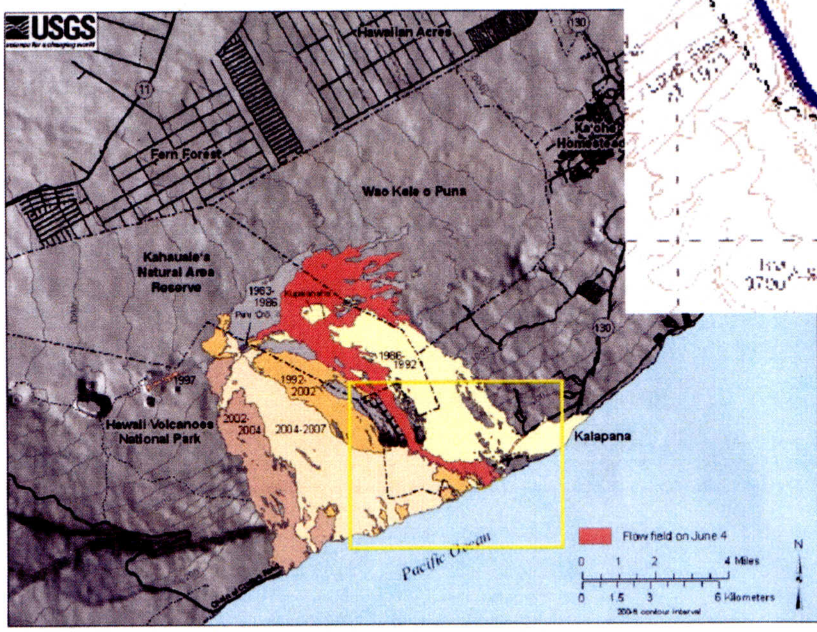
Wright TL (1973). Magma mixing as illustrated by the 1959 eruption, Kilauea volcano, Hawaii. Geol. Soc. Am. Bull. **84**:849-858.

Wyss M (1986). Regular intervals between Hawaiian earthquakes: implications for predicting the next event. Science **234**:726-728.









maps from the USGS Hawaiian Volcano Observatory eruption update website:

http://hvo.wr.usgs.gov/kilauea/update/maps.html