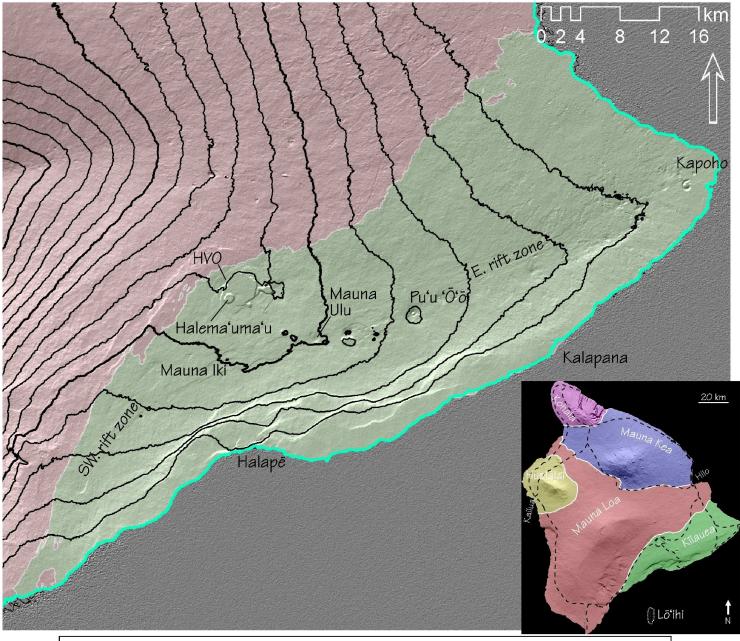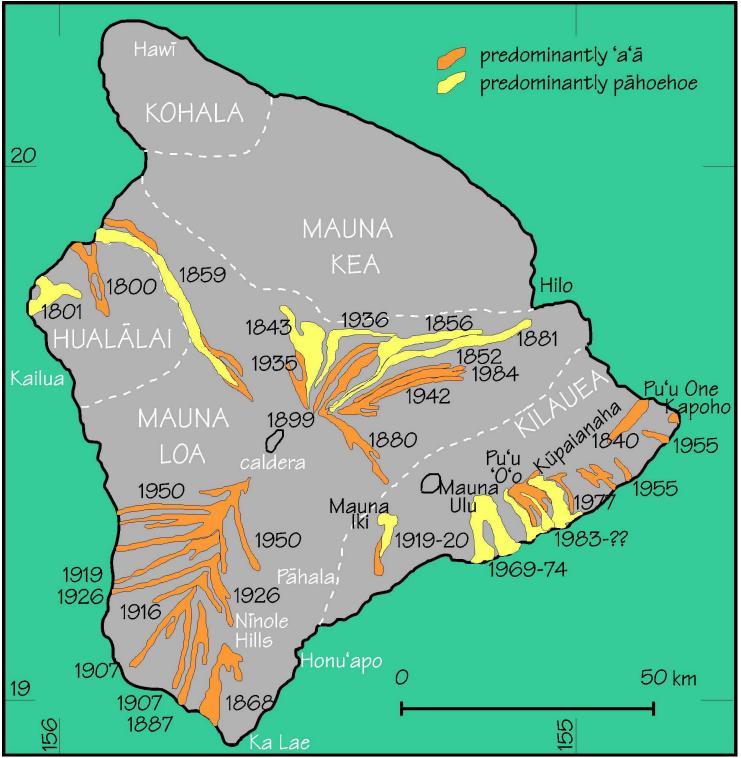# Field Trip Guide: KĪLAUEA

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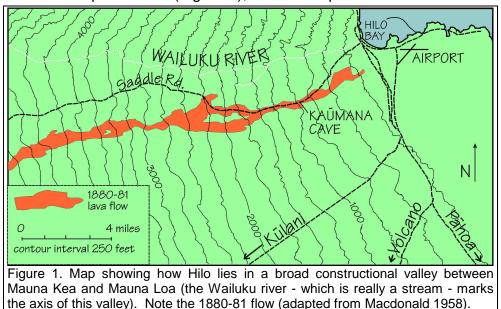
This field trip guide borrows from similar guides written by George P.L. Walker, Jack Lockwood, Rick Hazlett, Peter Lipman, and Norm Banks

predominantly ʻaʻā
predominantly pāhoehoe

Hawī

KOHALA

20

MAUNA
KEA

Hilo

1800
1859
1801
HUALĀLAI

Kailua

1843   1936   1856
1935   1852   1881
1984

MAUNA
LOA

1899
caldera

1942
1880

KĪLAUEA

Puʻu One
Kapoho

Kūpaianaha
1840
1955

1950

Mauna
Iki

Puʻu
ʻŌʻo
Mauna
Ulu

1977
1955

1919-20
1983-??

1950

1969-74

1919
1926
1916

1926

Pāhala

Nīnole
Hills

1907

Honuʻapo

0   50 km

1907
1887

1868

Ka Lae

Map of Hawaiʻi showing post-western-contact (i.e., since 1778) lava flows, and indicating geographic locations covered in this fieldguide. (adapted from Rowland & Walker 1990).
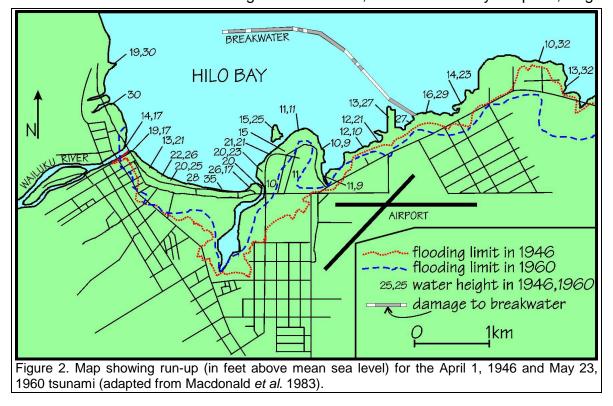
HILO

Hilo is built on pre- and post-contact lava flows of Mauna Loa. Most of the city is underlain by the ~1350 year-old Pana'ewa flow, which is a large-volume, mostly tube-fed pāhoehoe oceanite picrite (Lipman & Moore 1996). The Pana'ewa flow underlies the whole of the nearly flat land south and east of the airport. It is well-exposed in an industrial area just off HWY 11 a little past the Pana'ewa zoo while heading south from Hilo to Volcano, as well as along the coastline near Banyon Drive. During 1880-81, tube-fed pāhoehoe erupted from ~3200 m elevation on Mauna Loa's NE rift zone entered what is now part of Hilo (Figure 1), and it is exposed best at the Kaūmana cave.

Figure 1. Map showing how Hilo lies in a broad constructional valley between Mauna Kea and Mauna Loa (the Wailuku river - which is really a stream - marks the axis of this valley). Note the 1880-81 flow (adapted 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 Hāmākua coast are sea cliffs cut into deeply weathered Mauna Kea pyroclastics and lavas. The constructional valley extends beneath the ocean, and along with the coastline helps to funnel tsunami directly to the city of Hilo (Figure 2). 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; e.g. Macdonald *et al*. 1983). Hotels along the coastline that were built since 1960 have open lobbies designed to allow tsunami to wash through without causing structural damage.

From Hilo on a 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

Figure 2. Map showing run-up (in feet above mean sea level) for the April 1, 1946 and May 23, 1960 tsunami (adapted from Macdonald *et al*. 1983).

fluid lava. Lava fountains are relatively low and build small spatter cones barely visible from afar. Thus the slopes of Mauna Loa are very gentle and smooth-looking. Mauna Kea is in the post-shield alkalic stage, characterized by infrequent eruptions of gas-rich, cooler magma. These eruptions produce high lava fountains and in turn large

scoria cones and thick flows. The effect on the profile of Mauna Kea is to make it steep and bumpy as viewed from Hilo (Figure 3).
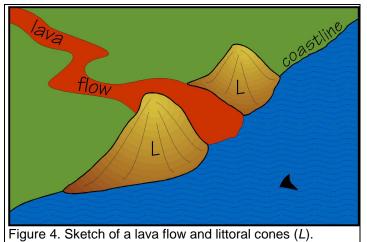

Figure 3. Photo from Hilo International Airport, looking approximately west towards the saddle between Mauna Loa (*ML*) and Mauna Kea (*MK*).

PUʻU ONE ("SANDHILLS")

The Puʻu One hills are littoral cones, formed by the explosive interaction of lava and water as a flow enters the ocean, in this case the 1840 Kīlauea lava flow (e.g. Moore 1992). Puʻu One is an example of the "typical" littoral cone, consisting actually of two half-cones on either side of an ʻaʻā flow (Figure 4; Fisher & Schmincke 1984). This is because any pyroclastic material that lands on the flow itself gets carried out to sea.

Studies by George Walker at Puʻu One and elsewhere (Walker 1992) helped to develop some of the criteria that distinguish littoral deposits (secondary) from actual vents (primary). Most of these rely on differences observable in the pyroclastic material comprising the deposits. The major difference is that magma at primary vents is gas-rich and has a relatively low viscosity whereas lava at littoral vents has flowed over the surface from the vent and is therefore slightly cooler (more viscous), and has lost considerable gas. Therefore, fragmentation of the lava at littoral cones can just as easily occur across phenocryst grains (because 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 from the vent, littoral pyroclasts do not show a density increase with smaller and smaller grain size.
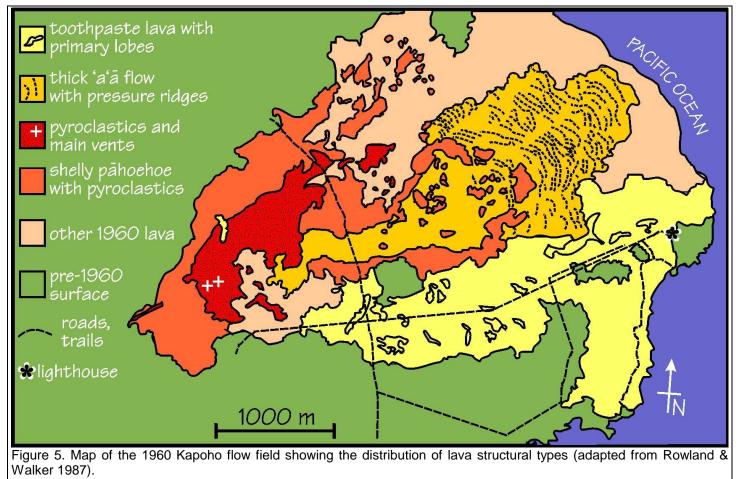

Figure 4. Sketch of a lava flow and littoral cones (*L*).

KAPOHO

Following the Kīlauea Iki eruption of Nov. - Dec. 1959, all geophysical (seismic and tilt) evidence pointed to the fact that Kīlauea's summit magma chamber was refilling (Macdonald 1962; Richter *et al.* 1970). Soon, collapse at Halemaʻumaʻu took place, accompanied by the migration of earthquakes far down the east rift zone. 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 January 13 to February 20, 1960 Kapoho eruption was notable for the compositional diversity of the lavas, the interaction between erupting magma and the shallow water table, and the fact that diversions were constructed to protect property. Also, some people said that the eruption meant that Pele was unhappy that Hawaiʻi had gained statehood only a few months earlier, whereas others said that the eruption was fireworks showing she was celebrating statehood.

Another eruption had taken place in the area in 1955. The first phase of the 1960 eruption involved the "flushing-out" of plagioclase feldspar-rich magma left over from the 1955 eruption. During the eruption, the composition changed to oceanite, the temperature of the erupting lava increased, and the fountain height increased, all indicating that the fresh (i.e., similar to 1959 Kīlauea Iki) magma had finally arrived at the surface.

The low elevation of Kapoho 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.

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, at Kapoho the lava ponded behind the barriers until it was high enough to flow over the tops. Many houses, the school, and stores were lost. Nothing remains of the lava diversion barriers; they were all covered by lava. The lighthouse was lucky; the lava flow split into two branches, saving it and a triangular-shaped area of pre-1960 surface (Figure 5). The lighthouse keeper is said to have been a strong believer in Pele.

Figure 5. Map of the 1960 Kapoho flow field showing the distribution of lava structural types (adapted from Rowland & Walker 1987).

GEOTHERMAL ENERGY

A number of geothermal wells have been drilled in the lower East rift of Kīlauea. The first to produce energy, a demonstration plant named HGP-A, operated until the early 1990s. It had a small visitor center along the highway. The current Geothermal plant is hidden from view behind some scoria cones, which helps keep the viewscape more pristine and cuts down on noise pollution. 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 social reason 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. It is not clear whether geothermal plants release more gas into the atmosphere than would be released naturally, however, gas (particularly H_2S) is a major concern to many people. Many people also feel that draining the heat from Kīlauea is an insult to, or actually harms, Pele.

The water encountered at the base of the lower east rift zone geothermal wells has a temperature in excess of 300ºC (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. The old HGP-A geothermal plant had an open system, meaning that the geothermal water was pumped to the surface, where it flashed to steam due to the lower pressure at the surface. This expanding steam spun turbines that ran electrical generators. A major problem was that the geothermal fluids are extremely corrosive, and machinery did not last very long.   Additionally, when the geothermal waters boiled at the surface, all the silica and other stuff that was originally dissolved in it precipitated (Figure 6), and this silica had to be disposed of somehow. Finally, the gases other than water vapor had to be scrubbed from the emissions (sometimes not so successfully) to prevent air pollution.

Figure 6. Photo of silica crystallization and settling ponds at the HGP-A geothermal plant. This plant is now shut down. Width of pool in foreground ~8 m.

The current system is a much more modern, closed system (Figure 7).   The geothermal fluid comes to the surface under its own pressure, but instead of driving turbines, heat exchangers allow it to transfer its heat energy to clean surface water which in turn drives the turbines. The now cooler geothermal water is pumped back into the ground.   The generating turbines therefore are only in contact with clean surface water and therefore much less likely to corrode. More importantly, the geothermal water stays in pipes and is never exposed to the surface, so the release of toxic gases is reduced considerably.

Figure 7. Photo of one of the wells in the currently operating geothermal plant. It's pretty ugly and industrial-looking, but can't be seen from outside the plant area. And even standing right next to these pipes, you can barely hear a rumble of (very) hot water flowing through.

Originally there were plans for a huge geothermal plant that would supply electricity to much of the state. The current geothermal plant generates approximately 20% of the Big Island's electric power, and there are plans to increase this a little, but not a lot.

LAVA TREE STATE PARK

Lava trees form when pāhoehoe flows through a forest. A skin of lava solidifies around the trees up to the level of the flow surface. When the 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

(Figure 8). The trees always die and usually burn. 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.

The lava trees at Lava Tree State Park formed during an eruption some time around 1790. The eruptive fissure is just to the left of the restroom, and preserves drainback features, which formed at the very end of the eruption.

KALAPANA

Kalapana was famous for the beautiful black sand beach of Kaimū. Glassy black sand (called hyaloclastite) forms from the thermal shock of lava entering the ocean as well from littoral explosions. This sand is then moved around by ocean currents and deposited as beaches or carried offshore. Because the process that forms the hyaloclastite sand occurs only during an eruption, the sand supply is limited. Once an eruption ends, erosion dominates, and black sand from a different process - waves beating on the basalt - is produced, but usually at a much slower rate than the hyaloclastite was generated. The beach at Kaimū had thus been shrinking ever since the ~1750 AD 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.

Kalapana was also famous for being an ideal Hawaiian town. The old culture of Hawai'i was well-preserved there, and the many newcomers seemed to have blended easily

Figure 8. Diagrams showing the formation of lava trees (Macdonald *et al*. 1983).

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 Kūpaianaha vent entered Kalapana and buried most of the town. A horst lies along the shore near Kalapana (Figure 9), and it prevented most of the lava from flowing directly across the coastal plain and into the ocean. Instead, the flows filled in the lower land between the horst and the slope that they'd come down, and started to spread northeast. Unfortunately, this was where most of Kalapana was situated; most of the houses and businesses were destroyed. The bay where Kaimū beach once was is now completely filled in by lava, and in places the new shoreline is 500 m farther than before.

Figure 9. View to the east of Kalapana, with lava flows from Kūpaianaha entering the town from the lower left. The dotted line indicates the horst which eventually diverted flows towards Kaimū (Photo by C. Heliker, USGS HVO, in December 1986).
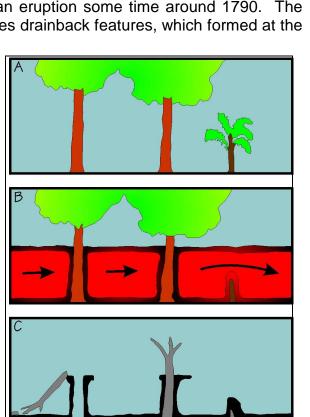
There were no attempts to divert lava flows away from Kalapana except for temporary measures taken long enough to rescue property from threatened homes. There are numerous reasons for this,

not the least of which is the strong belief that Pele would have been offended. Pele is more respected than feared, 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?

PU'U 'O'O: STILL ACTIVE AFTER ALL THESE YEARS

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. At depth, along their border, the two volcanoes inter-finger because Mauna Loa and Kīlauea have been active contemporaneously.

Just before mile marker 20 (Hirano Store on the right) in the small village of Glenwood, you can stop to take a look at Pu'u 'Ō'ō. Pu'u 'Ō'ō is the product of 43 episodes of high fountaining (from January 1983 to July 1986; Figure 10) followed by many years (still ongoing) of pāhoehoe overflows from a lava pond. The episodes together are considered a single eruption because magma was essentially visible during the whole time, even between high-fountaining episodes.

Pu'u 'Ō'ō is presently about 100 m high, but after the last high fountaining episode ended in 1986, it was almost 300 m high. At that time it was by far the dominant feature on Kīlauea's East rift zone (the skyline from the Glenwood viewpoint), and lots of geologists wondered about its uniqueness. 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 (Figure 11). A nearly continuous plume of water vapor and SO_2 issues from Pu'u 'Ō'ō (Figure 12); this is the source of annoying vog (volcanic fog - aerosols of HSO_4). Since the end of the high fountaining episodes in June of 1986, the crater widened to >200 m, collapse of the scoria part of the cone (Figure 13)

Figure 10. Pu'u 'Ō'ō fountaining (Episode 32, April 1985), viewed from ~2 km downrift. This fountain was ~350 m high; the uppermost 1/3 is out of the photo.

brought it down to the size of other eruptive features on the rift zone, and a growing satellitic shield has buried all but the highest part of the scoria cone. A semi-continuous lava lake first became visible around 1988. The now much larger crater is mostly crusted

Figure 13. Pu'u 'Ō'ō viewed from ~3 km uprift, a few days after its summit collapsed catastrophically (January 1997).

Figure 11. The Pu'u 'Ō'ō conduit between high fountaining episodes, viewed over the helicopter pilot's leg. The conduit at this time was ~20 m across, and the incandescence in this view is ~75 m below the rim. As a high-fountaining episode approached, the level of lava in the conduit slowly rose until it was spilling out. Within an hour or so, lava fountains would build .

Figure 12. Puʻu ʻŌʻō viewed from ~3 km downrift in August 1987. Note the prominent vog plume issuing from the crater, which at this time was ~80 m across.

Figure 14. Puʻu ʻŌʻō in August 1997, completely filled and overflowing.

over, but occasionally overflows (Figure 14).

Most of the eruptive episodes that built Puʻu ʻŌʻō lasted for 10-24 hours, with repose periods of up to 45 days in between. Overall, however, the time-averaged effusion rate was quite constant (Figure 15). 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 s^{-1}) produced large ʻaʻā flows, some of which over-ran portions of the Royal Gardens subdivision. Since 1986, when the activity switched to ~constant eruption of tube-fed pāhoehoe, the effusion rate has stayed relatively constant at ~5 m^3 s^{-1}.
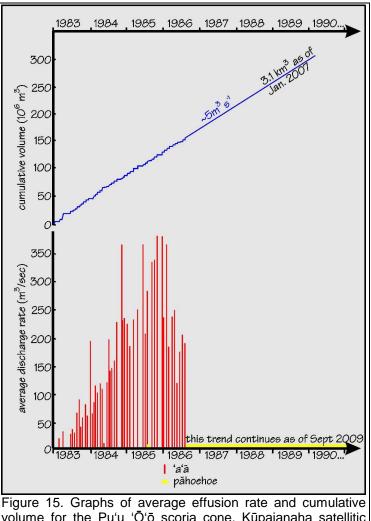
KĪLAUEA CALDERA

The top of Kīlauea contains a large depres-sion about 5 km across. This summit caldera is a collapse feature but it almost certainly did not form all at once. It is also 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. Mokuʻāweoweo, the summit caldera of Mauna Loa has similarly also been full and overflowing at times in the past (Lockwood & Lipman 1987). The caldera is not a piston-shaped block that has dropped into a large magma chamber. Walker (1988) compiled the cumulative collapse and infilling that has occurred since the first westerner visited Kīlauea,

Figure 15. Graphs of average effusion rate and cumulative volume for the Puʻu ʻŌʻō scoria cone, Kūpaianaha satellitic shield, and early Puʻu ʻŌʻō satellitic shield portions of the current eruption (after 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 can now be extended halfway into 2007.

showed that this has a funnel shape rather than a piston shape (Figure 16). 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; Figure 17) showed that the magma chamber of Kīlauea is a plexus of small interconnected voids rather than one large fluid-filled balloon (although some geochemists don't agree with this).

HVO

The U.S. Geological Survey's Hawaiian Volcano Observatory (HVO) is located on the W edge of Kīlauea caldera (Figures 18, 19). 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
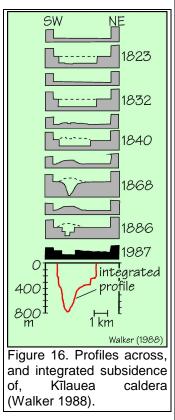

Figure 16. Profiles across, and integrated subsidence of, Kīlauea caldera (Walker 1988).
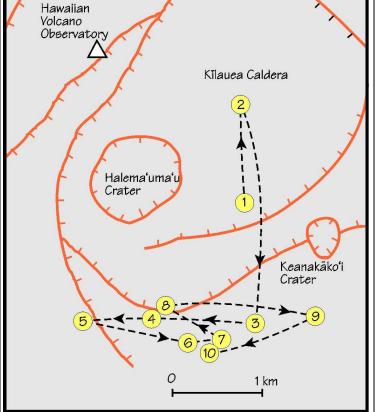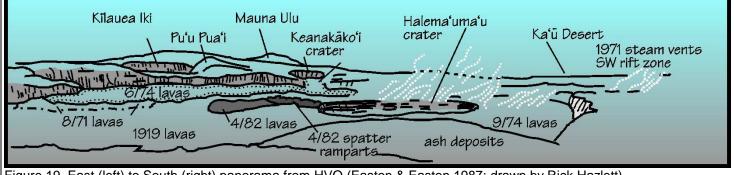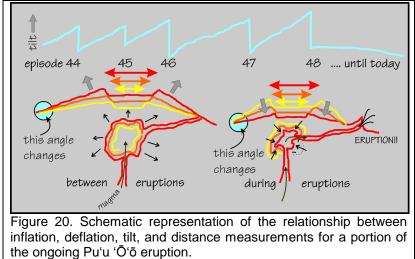

Figure 17. Map showing migration of inflation centers from Jan. 1966 to Oct. 1967. Total inflation was 70 cm, and a summit eruption began in Nov. 1967 (Decker 1987, after Fiske & Kinoshita 1969).

cities"), and he dedicated his life to learning about volcanoes in order to reduce the danger they pose to humankind. Jaggar recognized that Hawaiian volcanoes were not as destructive as those such as Mt. Pelee, and reasoned that Hawai'i was therefore the ideal natural laboratory in which to test monitoring methods and technologies in relative safety. Jaggar made the first collections of volcanic gases, numerous temperature measurements, compiled seismic and tilt records, and made hundreds of observations (Apple 1987).

As the Kīlauea magma chamber fills and empties,

Figure 18. HVO, viewed from the northwest, with Halemaʻumaʻu (*H*) beyond.

Figure 19. East (left) to South (right) panorama from HVO (Easton & Easton 1987; drawn by Rick Hazlett).

the summit of the volcano tumesces and detumesces (Figure 20). 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.

Figure 20. Schematic representation of the relationship between inflation, deflation, tilt, and distance measurements for a portion of the ongoing Puʻu ʻŌʻō eruption.
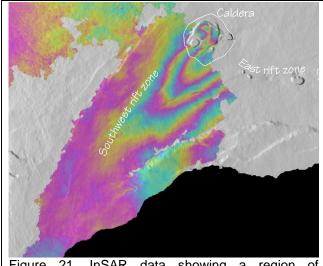

Figure 21. InSAR data showing a region of subsidence centered south of Kīlauea caldera. The time span covers Sept. 19, 2000 to April 4, 2007. (Data courtesy of F. Amelung, U. Miami.

EDM stands for Electronic Distance Measuring, and involves measuring the round-trip travel time of laser pulses between a "gun" and glass corner reflectors. EDM survey lines can be set up quickly in the field to allow for monitoring of short-term events. A series of EDM lines cris-crossing Kīlauea allows HVO to pinpoint the location, direction, and magnitude of ground movement that is related to magma migration and fault movement. Even as high-tech as EDM sounds, it is being phased out in favor of permanent GPS arrays and Interferometric Synthetic Aperture Radar (InSAR) surveys (Figure 21).

HVO also has an extensive seismic network covering most of Hawaiʻi Island (Figures 22, 23). The most numerous (but smallest) earthquakes in Hawaiʻi are caused by migrating magma (Figure 24). As a dike propagates down a rift zone, rocks at the dike tip break, and real-time plotting of these small, rock-breaking earthquakes allows tracking of the dike. Behind the dike tip, vibration of flowing magma produces harmonic tremor. Larger Hawaiʻi earthquakes are caused by deformation of volcanic flanks, slippage of volcanic flanks over the ocean floor, and flexure of the oceanic lithosphere due to the weight of the volcanoes.

Figure 22. HVO seismometers (*dots*) on Hawaiʻi as of 1984 (Klein *et al*. 1987).
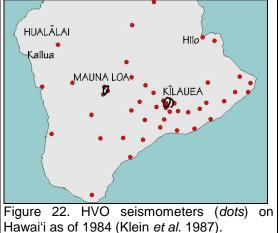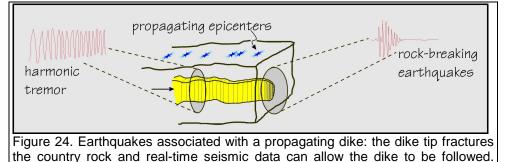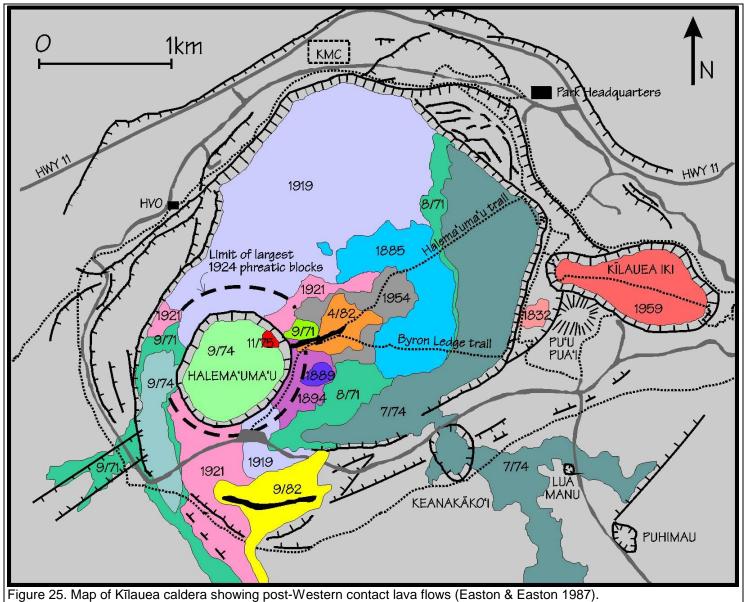

Figure 23. Photo of a typical seismometer installation on the south rim of Kīlauea caldera. The seismometer itself is housed in the brick enclosure for shielding against wind vibration, and the solar panel charges batteries for power.

Figure 24. 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.

HVO also produces geologic maps (e.g., Figure 25) to understand volcanoes and to assess volcanic hazards.

Figure 25. Map of Kīlauea caldera showing post-Western contact lava flows (Easton & Easton 1987).

UPPER END OF THE SW RIFT ZONE

Crater Rim Drive crosses numerous fissures that mark the upper end of the SW rift zone (Figure 26). These fissures are mainly non-eruptive, and illustrate the tensional regime that characterizes the surface trace of a rift zone. The Keanakākoʻi hydromagmatic ash is well-exposed in these fissures. Discontinuous fractures comprise most of the rift along its upper half. Most of these fissures near the road opened up during the great 1868 earthquake. The seaward-most 10 km of the SW rift zone axis is characterized by only one or two, very large fractures. This so-called "great crack" is a yawning fracture 10s of m across and very deep (Figure 27). In 1823 along some of its length, it was utilized by rising magma to feed fast-moving lava flows that reached the coastline. Unfortunately, the great crack is difficult to see because it is in a very inaccessible part of the National Park as well as on private land.

In September 1971, eruptive fissures opened from Halemaʻumaʻu, 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.

Figure 26. Air view of Kīlauea caldera, looking Northeast from directly above the uppermost SW rift zone. *Dashed lines* highlight major caldera-bounding faults. The brownish, gullied material in the foreground is the Keanakākoʻi ash.

Figure 27. Photo looking SW along the Great Crack. Here, it is 10-20 m across, and note that it was the source of the 1823 lava flow.

KEANAKĀKOʻI HYDROMAGMATIC ASH:

The Keanakākoʻi ash is an interesting deposit because it (along with other ash deposits) illustrates that although Kīlauea is usually considered a "safe" volcano that you run towards when it erupts, it occasionally is extremely explosive, and you should run away instead. In fact, the last, and possibly least-violent of the explosive activity was viewed from Kawaihae on the west coast of Hawaiʻi Island, and according to Jaggar (1921), this requires the eruptive column to have been 30,000 ft (>9000 m) high. The Keanakākoʻi ash is also interesting because it shows how geological thinking can change and change back again, specifically regarding the duration that the Keanakākoʻi ash represents, and whether or not all of it was associated with the destruction of a Hawaiian army under the command of Chief Keōua (see below). Although Powers (1948) states that previous geologists attributed all of the ash to the deadly 1790 explosions, these authors don't actually say this equivocally. Definitely, however, many early 20th century geologists came to the conclusion that because the Keanakākoʻi ash sequence includes numerous interbedded humus layers, the deposit formed over a long period of time, and only the uppermost layers were associated with the fatal explosions. The opinion changed in the 1980s and 1990s to thinking that the deposit represented a few weeks or months of explosive activity. Most recently, the pendulum has swung back in favor of a longer period, with evidence that is difficult to argue against - ^{14}C age dates. Finally, the eruptions that produced the ash probably played a role in one of the epic Hawaiian stories, that of Hiʻiaka and Pele, and definitely played a role in Kamehameha the Great's uniting of Hawaiʻi under one ruler.

The Keanakākoʻi eruption is probably most famous because its last gasp killed members of a Hawaiian army some time around 1790. Accounts of the demise of this army can be found in numerous references. The following version 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 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 (1973) believed that the people were killed, probably by suffocation, by a base surge, a somewhat dilute but fast-moving, ~horizontally-emplaced explosion cloud. This is based on the lack of evidence of injuries or burns, and that the victims appeared to be huddling against a strong wind (they would have seen the surge coming) rather than scattered about as if they had been trying to flee from falling debris. There is no doubt that these events can be correlated with the uppermost layers of the Keanakākoʻi ash, which include huge lithic blocks and indicate a very explosive eruption. The question is whether this account describes the entire sequence of Keanakākoʻi ash or merely the very last part.

Hitchcock (1911) presents a map of the Keanakākoʻi ash and recounts an oral description of the destruction of Keōua's army, but states clearly that he considers that destruction to have been accomplished by a relatively minor explosion compared to what would have generated the entire deposit. He mentions Hawaiian oral history of particularly violent explosions: "*About fourteen generations back, in the days of Liloa, 1420, a violent eruption broke out from Keanakakoi. As this seemed to be well known to the natives, it was probably of unusual importance…*" Hitchcock goes on to state: "*The enormous area thus covered with explosive material renders it probable that the comparatively mild discharge of 1790 was inadequate to account for so extensive an inundation. There must have been several such discharges, perhaps recurring during centuries of time. Only a tithe of the stones spread over the surface would have been needed to destroy a much larger detachment than that suffocated in 1790. It would seem more consonant with he facts to connect the prolific tuffaceous and scoriaceous discharges with the days of Liloa rather than of Keoua; and perhaps Keanakakoi may have been the vent through which the discharge came.*" Part of Hitchcock's evidence for a long time were "*…black seams, suggestive of vegetable growth…*" interbedded within the ash. These suggested lengthy periods when ash was not being deposited.

Powers (1916) also noted that there must be a significant age difference between the eruptions that killed Keōua's warriors and the majority of the deposit, noting specifically: "*The largest part of the ash must be of pre-historic age because it is overlain by the pre-historic Keamoku flow from Mauna Loa, is greatly altered in places where the steam-vents of past ages have been active…*" Powers (1948) produced excellent maps as well as a stratigraphic section (Figure 28), and also noted the important evidence of interbedded humus layers. He states: "*Not less than seven of these breaks were long enough for re-establishment of a vegetative cover on the humid windward rim.*" Powers (1948) estimated how long each humus layer would have needed to form, and added these to arrive at a total Keanakākoʻi eruption duration of perhaps 1500 years, culminating in the ~1790 AD eruption.

Later geologists, including Decker & Christiansen (1984), examining oxidized horizons correlative to the humus layers but close to the caldera (where vegetative growth is limited) decided that the layers represented in situ weathering of fine-grained ashes. As such, they would have oxidized even while buried by overlying ashes and therefore didn't represent long periods of exposure to the surface. Additionally, they interpreted unconformities to erosion by vigorous pyroclastic surge activity rather than water, as had been suggested by Powers (1948). Decker & Christiansen thus stated: "*The features described above indicate that the bulk of the Keanakakoi Formation was deposited without significant time breaks, and are consistent with its emplacement during the eruption of 1790*". McPhie et al. (1990)

noted that there were conflicting interpretations of the eruption's duration, and stated politely: "*We find merit and error in each interpretation.*" Nevertheless, they settled on a probable duration of several months.

Most recently, the careful work by Don Swanson of HVO has swung the pendulum back to the original idea of a long duration. He tackled the problem in two ways, traditional geology and careful reading of Hawaiian traditional stories. First, ^{14}C age dates and detailed field mapping shows that Kīlauea erupted explosively for almost 300 years, from around 1500 AD to around 1790 AD (Figure 28). The early part of this period is recorded by casts of large trees that grew in some ash layers but were buried by later ash, requiring at least decades of inactivity. Additionally, ruins of Hawaiian house sites similarly within the deposit require long hiatuses between explosive eruptions otherwise nobody would have settled there.
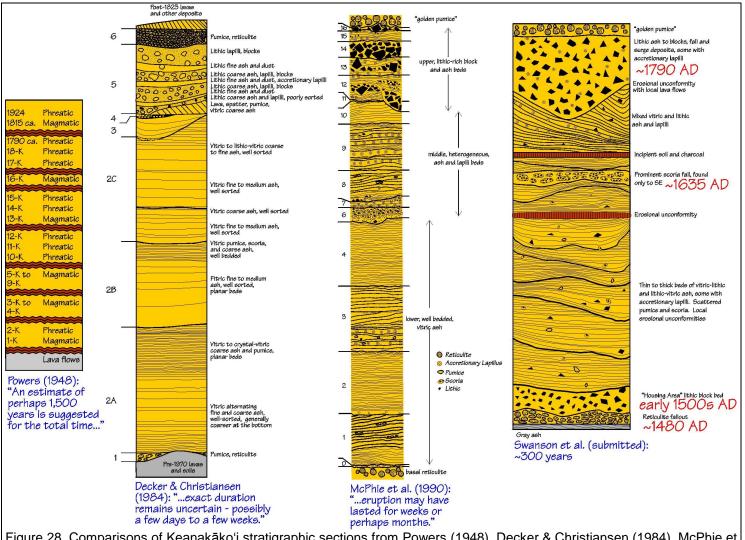

Figure 28. Comparisons of Keanakāko'i stratigraphic sections from Powers (1948), Decker & Christiansen (1984), McPhie et al. (1990), and Swanson (unpublished). Note that according to these various authors, the entire Keanakāko'i ash was laid down in ~1500 years, a few days to weeks, perhaps months, and 290 years, respectively.

Don Swanson also paid close attention to the fact that two very different stories seem to describe eruptions that would have produced the Keanakāko'i ash (Swanson 2006; 2008). The first is the destruction of Keōua's army, attributed by many to indicate that Pele was on the side of Kamehameha in the battle for supremacy of Hawai'i island. The second involves part of Hi'iaka's epic tale wherein she has to dig into Kīlauea to find her lover, Lohi'au, whom Pele has buried in a jealous rage. The description of Hi'iaka throwing out stones and sand was seen by Don Swanson to be a very accurate description of what a hydromagmatic eruption would have looked like. Emerson (1915) translates: "*She tore her way with renewed energy: rock smote against rock and the air was full of flying debris.*"

Moreover, near the end of the tale, Hiʻiaka is warned by the gods that she must stop digging or else she will encounter water. "*She came at last to the tenth stratum with full purpose to break up this also and thus open the flood-gates of the great deep and submerge Pele and her whole domain in a flood of waters.*" (Emerson 1915). It is entirely possible that the reason hydromagmatic eruptions became the norm for a few hundred years was that the caldera floor had dropped far enough to intersect the water table - essentially a lake had formed. Thus there are two very different explanations for explosive eruptions - a goddess (Hiʻiaka) digging for her lover, and Pele being angry at one warrior chief and his army. According to Don Swanson, these two very different reasons for explosive eruptions lend support to the idea that there was not one short eruption, but rather a long series of eruptions.

An additional possibly related geologic event is described earlier in the epic tale, specifically, Pele destroys Hiʻiaka's beloved Puna forests, and it is this destruction that convinces Hiʻiaka that she might as well fall for Lohiʻau's advances because Pele has clearly not held up her part of the bargain. Extensive tube-fed lava flows on the northeast flank of Kīlauea, where Hiʻiaka's forests were, have been ^{14}C dated to ~1500 AD, immediately before the onset of explosive activity (Figure 28). Geologically, the sequence makes considerable sense - a long-lasting eruption could have emptied the magma chamber, causing it to collapse. Collapse would have exposed water to any magma that rose into the caldera, producing the hydromagmatic explosions.

Regardless of the duration question, the work of McPhie *et al.* (1990) is important because they very carefully pieced together the eruption. 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 source vent (the exact location of which has yet to be determined), 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 1790 blasts took place during this last stage. Pauses between explosive phases perhaps 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.
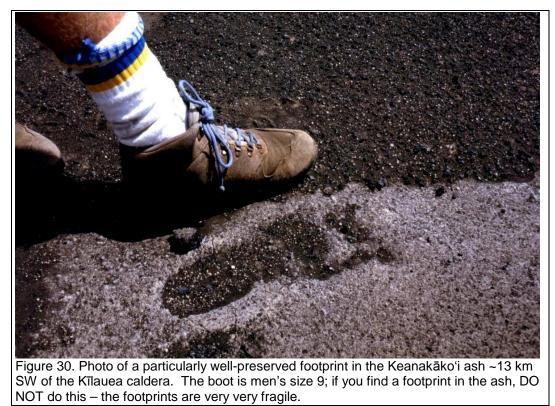
The Keanakākoʻi ash has been spectacularly gullied (Figure 29), and these locations provide good locations to examine the explosive deposits. The lack of resistance to erosion is evident in these few-m deep gullies in a deposit only a few hundred years old. A duri crust ("case-hardened" crust of Malin *et al.* 1983) has formed on the top surface of much of the deposit and this has contributed to the lack of vegetation in

Figure 29. Geologist examining the wall of a gully eroded into Keanakākoʻi ash.

this area. Another contribution to the Kaʻū desert being a desert is the continuous acid plume and

consequent acid rain downwind from the Kīlauea summit. Also spectacularly, footprints have been preserved in the ash at a number of locations (Figure 30; Jaggar 1921). These are not those of Keōua's warriors, but instead were made by many folks traversing this area between explosive episodes.

Figure 30. Photo of a particularly well-preserved footprint in the Keanakāko'i ash ~13 km SW of the Kīlauea caldera. The boot is men's size 9; if you find a footprint in the ash, DO NOT do this – the footprints are very very fragile.

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 any deeper. In places where the ash was originally thinner, gullies widen until most of the ash is stripped away. There are therefore no traces of the gullies after that. Soil-water sapping was found to be a limited 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. However, this seepage is probably unable to move the sediment that collapses into the heads of the gullies; this must be accomplished by surface runoff during heavy rains.

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 10s 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 extreme irregularity of 'a'ā surfaces, 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.

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 (Figure 31). The level of the lake moved up and down, and at times it was higher than

the surrounding caldera floor, perched behind self-built levees. Overflows built these levees higher, and occasionally broke through them to flow as far as 4 km from the crater rim. The overflows combined to build what is essentially a small shield centered at Halemaʻumaʻu, and this can be seen when standing away at a distance.

Figure 31. Lava lake in Halemaʻumaʻu, 1894. The lake is held behind self-built levees of spatter and small overflows (from Macdonald & Abbott 1970).

The lava lake drained spectacularly in 1924, and there have been a few eruptions in and around Halemaʻumaʻu since then. The most recent lava in the pit dates from 1975 but it flowed in from vents outside. The most recent eruption inside Halemaʻumaʻu 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 about 3 m a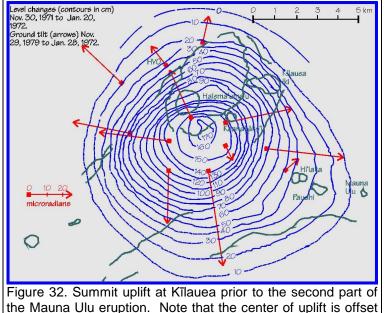bove the present floor indicates how much subsidence and cooling-induced shrinking took place as the most recent ponded lava cooled. Higher up is an obvious level below which light-colored alteration is extreme, and above which the rock appears to be much fresher. This probably represents a previous level of the caldera floor, prior to the eruption of the lavas within which Halemaʻumaʻu developed. Numerous fumaroles around the edge of Halemaʻumaʻu have deposited sulfur.

It is tempting to say that Halemaʻumaʻu directly overlies the Kīlauea magma chamber, however, the average center of radial deformation is usually located to the southwest (Figure 32). As noted above (e.g., Figure 17), it is thought that the magma chamber is actually a series of interconnected voids; Halemaʻumaʻu probably is closely connected to one or more of these.

Halemaʻumaʻu 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 Halemaʻumaʻu 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 from up on the rim. Who caught it? Pele is commonly said to like gin although of course there wasn't any in Hawaiʻi until Westerners showed up.

The area around Halemaʻumaʻu is littered with thousands of angular blocks (Figure 33). A close look at the blocks shows them to mostly be fragments of dense, non-vesicular ponded
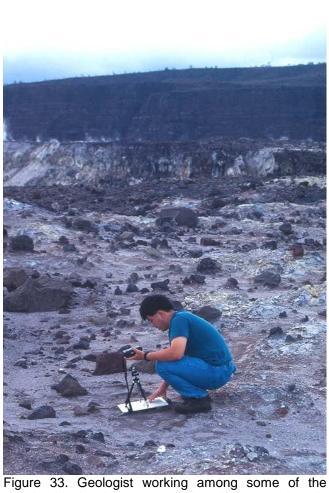

Figure 32. Summit uplift at Kīlauea prior to the second part of the Mauna Ulu eruption. Note that the center of uplift is offset from both the center of the caldera and Halemaʻumaʻu, and that it rose >170 cm in <2 months (Tilling *et al*. 1987).

flows as well as intrusive rocks. Many of these dense rocks are pieces of the volcanic plumbing system. They were brought up during the explosive eruptions of May 1924 (Figure 34), the major events of which are 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 Halemaʻumaʻu. The lowering of the magma column drained the lava lake and caused collapse of the walls, enlarging Halemaʻumaʻu from ~700 m wide by ~150 m deep to ~1000 m wide by ~400 m deep, a volume increase of ~200 x 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 Halemaʻumaʻu. The total volume of blocks and dust ejected during the explosions was 7.5 x 10^5 m^3, accounting for less than 1% of the Halemaʻumaʻu 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.
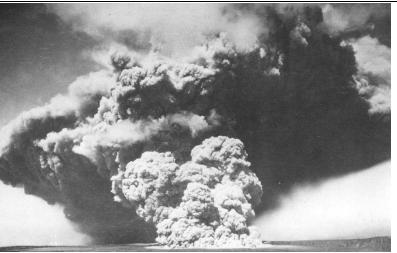

Figure 34. Phreatic eruption from Halemaʻumaʻu in May 1924 viewed from the Volcano House (from Carr & Greeley 1980; taken by Tai Sing Loo).

Figure 33. Geologist working among some of the angular blocks thrown out during the 1924 phreatic explosions at Halemaʻumaʻu.

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 northeast of Halemaʻumaʻu, south 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 the floor of Halemaʻumaʻu crater. Activity peaked about 1 hour after the onset, with a nearly steady curtain of spatter being thrown 5-10 m high, and occasiona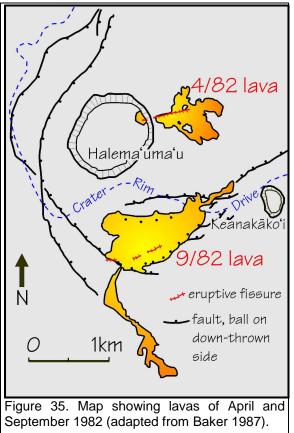lly up to 50 m. This continuous curtain of fountaining was active for about 5 hours, building spatter ramparts and feeding pāhoehoe flows to the north, east, and south (Figure 35).

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 x 10^5 m^3 of new lava (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 south 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 southwest 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 west 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.

Figure 35. Map showing lavas of April and September 1982 (adapted from Baker 1987).

Lava from the first vents ponded in a fault-bounded depression and soon had surrounded the eastern group of spatter ramparts. At about 19:30, lava spilled out of this depression to the south. 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 northeast onto the main caldera floor. By 23:00 the westernmost vents of the southwest group had ceased erupting. By the next morning activity at the east group and the rest of the southwest group had diminished. The final vent (in the central part of the southwest 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. $3\text{-}4 \times 10^6$ 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

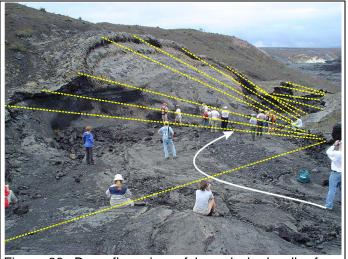A short-lived eruption took place on the thin septum between the caldera and Keanakākoʻi pit crater on July 19 and 20, 1974. The vent is a non-descript fissure just beyond the cable barrier. It shows very clearly that the last activity involved draining of the lava back into the ground. This eruption is also interesting because most of the lava flowed down a pre-existing erosional gully into the caldera (lava from a 1971 eruption utilized this same gully; Greeley 1974). 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 while flowing, noting that on the outsides of bends, the lava rose higher (Figure 36). By incorporating measurements of this "super elevation" 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 s, and a negligible yield strength.

Figure 36. Down-flow view of lava-sloshed gully, from right above where the lava makes a ~90º turn to the right (*arrow*). *Dashed lines* join opposite sides of the channel, and accentuate the height difference between the outside and inside of the turn.

KĪLAUEA IKI AND PUʻU PUAʻI

Starting on November 14 1959, a spectacular eruption took place from vents half way up the 200 m-high south 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, essentially half-filling the crater (Figure 37), 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. Because of the infilling, 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.
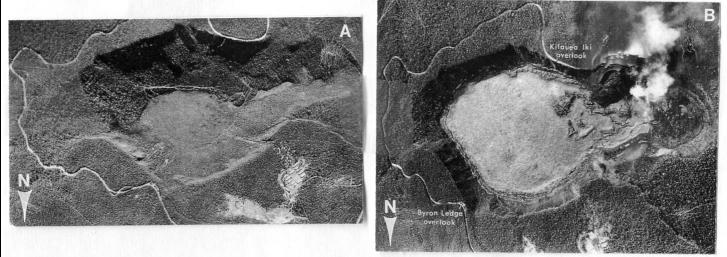

Figure 37. Vertical air photos showing Kīlauea Iki before (A) and after (B) the 1959 eruption (from Richter *et al.* 1970).
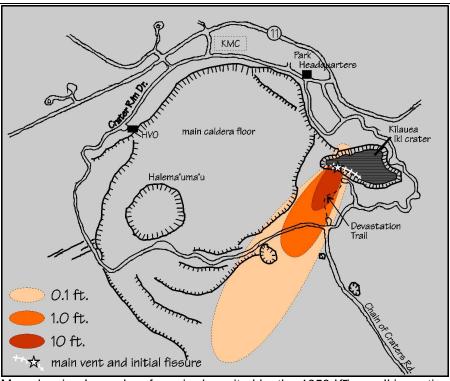
The high fountaining (Figure 38) produced a large scoria cone on the edge of Kīlauea Iki named Puʻu Puaʻi and a scoria deposit strongly shaped by the prevailing tradewinds (Figure 39). A boardwalk (Figure 40; recently replaced by boring asphalt) was constructed by the National Park Service over part of the tephra deposit. One of the more dramatic sites is of the dead, bleached trees; the area where Puʻu Puaʻi 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 ōhiʻa 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 re-growth 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 Hawaiʻi, 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).

Figure 38. ~300 m-high fountain at Kīlauea Iki (National Park Service photo).

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; Figure 41) 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 (see pp. 4-5). 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 and Koaʻe were mostly destroyed. The Kīlauea Iki-Kapoho pair constitutes an example of a summit-flank eruption sequence, often touted as typical of Kīlauea and Mauna Loa.

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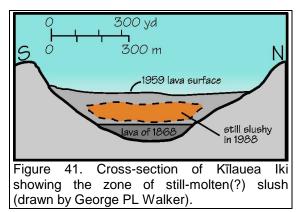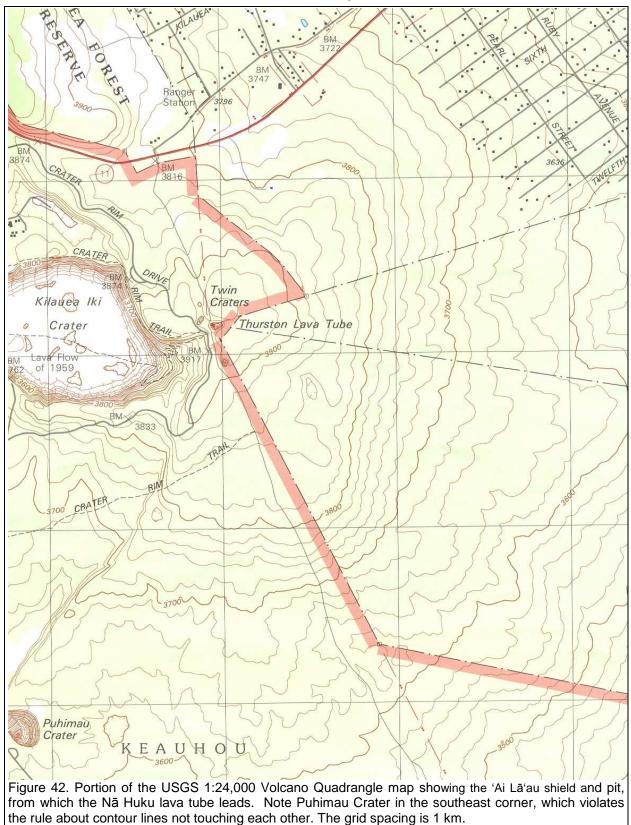

Figure 40. Devastation trail ~5 years after the Kīlauea Iki eruption (photo by Alan Rowland). Most of the dead trees in this photo have since rotted and fallen over.

Figure 41. Cross-section of Kīlauea Iki showing the zone of still-molten(?) slush (drawn by George PL Walker).

THE ʻAI LĀʻAU SHIELD AND NĀ HUKU (THURSTON LAVA TUBE)

Lava tubes and satellitic shields are features associated with low effusion-rate pāhoehoe eruptions. A major example of such an eruption took place some 600 years ago from a vent near the east end of Kīlauea Iki crater. Because of the thick forest, this ʻAi Lāʻau shield is difficult to see when you are on its flanks, however it is easy to see from a distance or in topographic contours (Figure 42), and most of the northern part of the E rift is covered by lavas from the ʻAi Lāʻau eruption (Holcomb 1987). The trail leads into the central pit of the shield (which would have been a lava pond during the eruption), 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; ʻAi Lāʻau 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.

Figure 42. Portion of the USGS 1:24,000 Volcano Quadrangle map showing the ʻAi Lāʻau shield and pit, from which the Nā Huku lava tube leads. Note Puhimau Crater in the southeast corner, which violates the rule about contour lines not touching each other. The grid spacing is 1 km.

Lava tubes develop when a channel roofs over or when individual pāhoehoe flow units merge (Figure 43). Once formed, they rarely flow full, and within Nā Huku 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 re-melted lava that is found only on the insides of tubes and large vesicles.
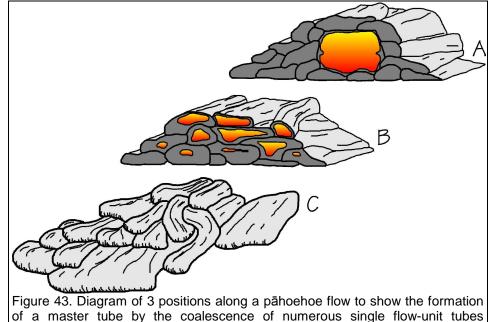
Although the original name of this place is Nā Huku, the signs and maps all call it the Thurston lava tube, named for Lorrin Thurston. He was a newspaper publisher from Honolulu and avid volcano buff. He popularized Kīlauea volcano for his readers and provided moral, financial, and physical support to Thomas Jaggar during the early days of HVO (Apple 1987). Unfortunately he was also a traitor, and felt more allegiance to American businessmen than to his fellow Hawai'i citizens. He played a major part in the overthrow of the Hawaiian monarchy in 1893, and for this he is still reviled by many today.
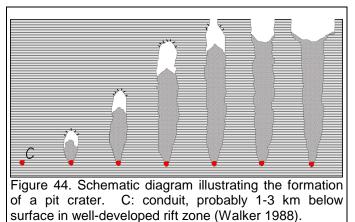
THE CHAIN OF CRATERS AND UPPER EAST RIFT ZONE:

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 occasionally open within or across the craters, however, and lava often ponds within them. These craters are collapse features that associated with some type of long-lived conduit

Figure 43. 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).

that runs the length of the upper rift zone. In one mechanism suggested 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 pit crater, for example, formed some time around 1921 (Macdonald & Abbott 1970), and initially consisted of a relatively small opening in the ground. In 1923, an intrepid explorer was lowered by rope down into

Figure 44. Schematic diagram illustrating the formation of a pit crater. C: conduit, probably 1-3 km below surface in well-developed rift zone (Walker 1988).

the opening. 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 realized that the opening had widened considerably and his feeble lantern couldn't illuminate the now-farther-away walls. He also 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 1923 the last layers have fallen in, and Devil's Throat now has a cylindrical shape.

A second pit-crater formation mechanism was proposed by University of Hawai'i undergraduate(!) Chris Okubo, and published as Okubo & Martel (1998; Figure 45). They considered the fact that when a dike propagates through a volcano, a pair of planar fractures extend upward from the top edge of the dike in a V-like pattern. The angle of this V is constant, which means that when the dike is deep the fractures will intersect the surface far from each other, but when the dike is shallow, they will intersect close by. The triangular segment of rock between the fractures will want to fall, but when the fractures are far apart, it means that they have a lot of surface area and therefore a lot of friction. When the fractures are close, however, they provide less surface area and less friction. Add the fact that lava flows are typically already fractured with cooling cracks and flow margins, and the smaller triangular segments between closely-spaced V-fractures are

likely to collapse into the dike, producing a pit crater. The key observation made by Okubo & Martel was that indeed, pairs of ground fractures often form hourglass-like traces, and pit craters, such as Devil's Throat, commonly occur at the point of closest approach.

Regardless of how they formed, 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!
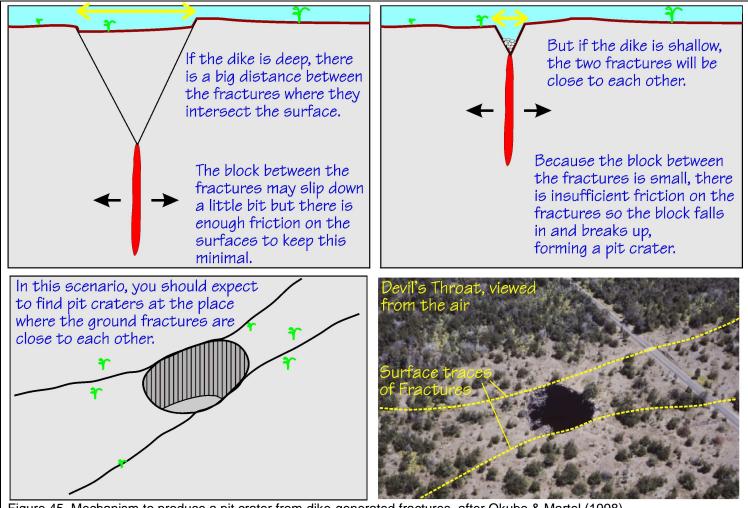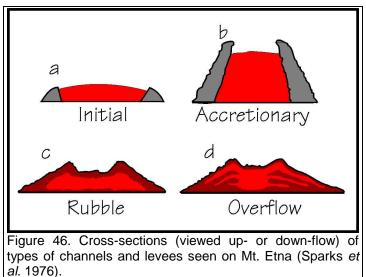

Figure 45. Mechanism to produce a pit crater from dike-generated fractures, after Okubo & Martel (1998).
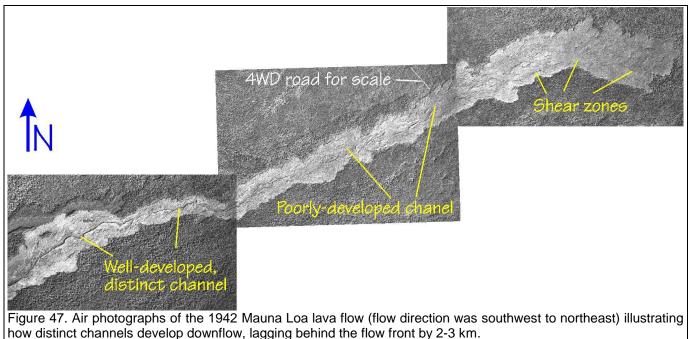
MULIWAI A PELE:

This is an excellent example of a lava channel. It formed during the last part of the Mauna Ulu eruption (see below). 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, which, when it is not too misty, you can see upslope from here. These flows posses innumerable flow units, smooth glassy skins, and low topographic relief. These lavas 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. Additionally, the entire ʻaʻā flow was emplaced more or less as a single unit as compared to the multi-unit pāhoehoe. Third, the thickness of the ʻaʻā flow is much greater than that of any individual pāhoehoe flow unit. Finally, the ʻaʻā developed an open channel, unlike the lava tubes that fed the pāhoehoe.

Figure 46. 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 additional spreading. This leads to the formation of zones of stagnation, called levees, along the edges of the flow (Figure 46). 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 increases. Eventually, the levees become completely solid and distinct from the flowing lava. This development of a well-defined channel proceeds downflow, lagging usually 1-2 km behind the flow front (Figure 47; Lipman & Banks 1987). Once formed, levees are commonly 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 down-flow has an easier and easier journey, flows rapidly with a smooth surface, and thus might be considered to be pāhoehoe, especially because if it slops out of the channel it can solidify as pāhoehoe. This has caused a lot of confusion, in particular because geologists look at this fast-moving, smooth lava and get the impression that pāhoehoe flows are therefore fast. But they are ignoring the fact that this very same lava is destined to become 'a'ā once it reaches the end of its journey down the channel. If one looks at the flow-front velocities of 'a'ā and pāhoehoe flows, it is very clear that 'a'ā is the fast one, and pāhoehoe is the slow one (Figure 48; Rowland & Walker 1990).
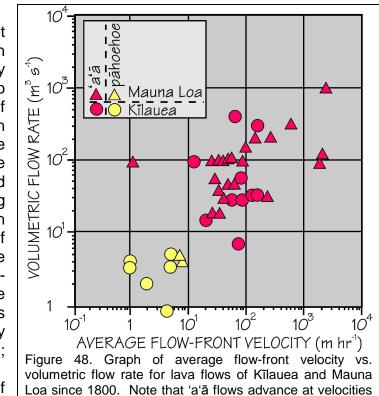

Figure 47. Air photographs of the 1942 Mauna Loa lava flow (flow direction was southwest to northeast) illustrating how distinct channels develop downflow, lagging behind the flow front by 2-3 km.

THE HILINA PALI SYSTEM:

Hawaiian volcanoes grow at least as much, if not more, by intrusions as they do by eruptions. In particular along rift zones this means that they expand perpendicularly to their rift zones in order to accommodate intruding dikes. The north side of Kīlauea abuts Mauna Loa, the largest volcano on Earth, whereas the south side slopes steeply to the ocean floor ~5 km below sea level. Kīlauea therefore only has one way to expand, both slowly and constantly, as well as rapidly and violently during large, south-flank earthquakes. The surface on which this motion is accommodated is 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. The focal plane solutions of large south flank earthquakes indicate a gently landward-dipping that is 6-10 km deep (Figure 49; Swanson *et al.* 1976; Lipman *et al.* 1985).

In addition to being mobile, the south flank of Kīlauea is unstable, and has broken into a number of large blocks along fractures that roughly parallel the rifts and coastline. Each time the south flank of Kīlauea gets shoved seaward during a south flank earthquake, these blocks drop downward a few meters, and over the history of the volcano, the boundaries between them have become fault scarps up to 500 m high. These fault scarps are collectively called the Hilina fault

Figure 48. Graph of average flow-front velocity vs. volumetric flow rate for lava flows of Kīlauea and Mauna Loa since 1800. Note that 'a'ā flows advance at velocities ranging between 10 and 3000 m hr^{-1}, whereas pāhoehoe flows advance no faster than 10 m hr^{-1}.

Figure 49. Cross-section perpendicular to Kīlauea, showing how dikes (~*vertical lines*) produce pressure (*arrows*) that cause the south flank of Kīlauea (and part of Mauna Loa) to actually slide uphill on a layer of ocean sediments. The *half-arrows* indicate the direction of sliding, and the *stars* show typical south flank earthquake foci.

system (Figure 50). Lava flows mantle the faults only to be fractured themselves during the next earthquake (Figure 51). 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 3.5 m and 8 m (horizontal and vertical, respectively). Approximately 4 million dollars in damage occurred and a tsunami was generated. Two 2 campers at Halapē, on the coast were killed (e.g. Tilling *et al.* 1976; Lipman *et al.* 1985). Their experience was terrifying, and with a combined 3.5 m of sudden subsidence and a 15 m tsunami, it's a wonder any of the campers survived (Figure 52). The downward-moving slump blocks continue offshore (Figure 53).

Figure 50. Shaded relief image of the south flank of Kīlauea, including the upper and middle east rift zone, the upper southwest rift zone, and the Koaʻe and Hilina fault systems.
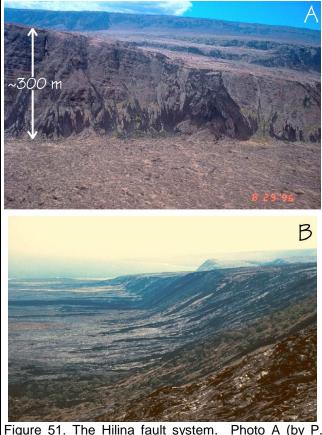

Figure 51. The Hilina fault system. Photo A (by P. Mouginis-Mark) shows one of the highest individual scarps in the fault system, and one that has not been mantled by lava flows - the dark streaks are talus. Photo B shows a section mantled by ʻaʻā (dark) and pāhoehoe (shiny) flows from Mauna Ulu.
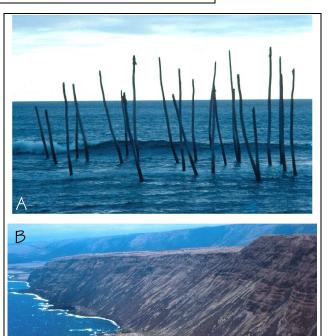

Figure 52. Halapē. A was taken in Dec. 1978, ~3 years after the Kalapana earthquake, and shows dead coconut trees out in the ocean and indicating the degree of subsidence that occurred here. B is an air view (by P. Mouginis-Mark), showing the present-day camping shelter as well as the crack into which the tsunami survivors were swept.
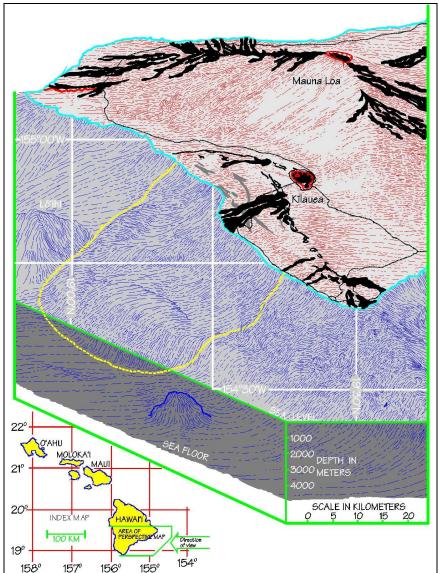
Figure 53. Physiographic drawing of S Hawai'i, viewed from the east, and showing subaerial and submarine features. The *dashed line* outlines a possible submarine slump (from Lipman *et al.* 1985; originally drawn by Tau Rho Alpha).
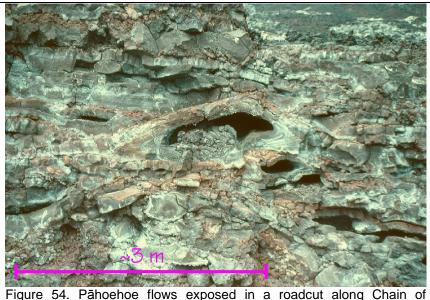

~3 m

Figure 54. Pāhoehoe flows exposed in a roadcut along Chain of Craters Rd. Note the large number of flows comprising the overall flow.
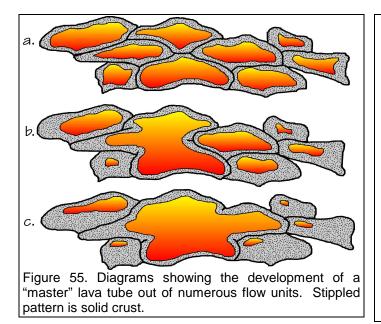
PĀHOEHOE FLOWS:

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 (Figure 54; Nichols 1936; Walker 1971). The flow units themselves are some-times hollow, showing that for at least a short period of time they acted as single flow-unit lava tubes (which later drained).

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, 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 (Figure 55). 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. Long ago, in dry areas, calabashes were placed under spots where water dripped through the ceiling, and thirsty hikers could stop for a drink.

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 up-

lifted by a few meters 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; Figure 56)

The initial lava that forms a flow field is vesicle-rich, and is called s-type pāhoehoe ("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 pāhoehoe ("p" stands for pipe-vesicle bearing; Wilmuth & Walker 1993). Both types of lava are common in the flow field of the Puʻu ʻŌʻō/Kūpaianaha eruption.

Figure 55. Diagrams showing the development of a "master" lava tube out of numerous flow units. Stippled pattern is solid crust.

Figure 56. Photo of the 1859 Mauna Loa tube-fed pāhoehoe flow field. Note the innumerable flow units, as well as the large tumulus at right; GPL Walker in axial cleft for scale (*arrow*).
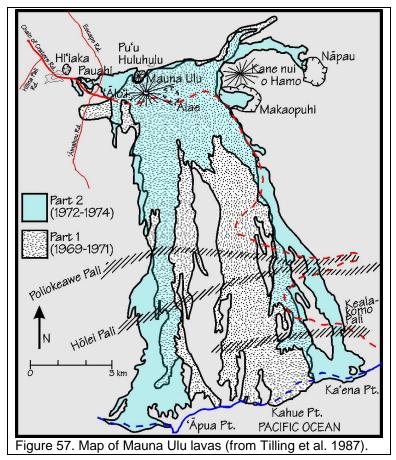
MAUNA ULU

Mauna Ulu (Figures 57, 58) is a classic example of a 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, and can be divided into two parts. Part I was all activity prior to an October 1971 to February 1972 hiatus, and Part II was all activity after the hiatus. Because the eruption lasted for 5 years, many of the features formed earlier were buried by later activity. At the summit of Mauna Ulu is an elongate pit some 150 m deep. The edges of this pit are fractured and unstable. BE CAREFUL THERE!!

Part 1 of the eruption produced 185 x 10^6 m^3 of lava and covered ~50 km^2, and was subdivided into 4 stages by Swanson *et al.* (1979): 1) an episodic high-fountaining stage; 2) a shield-building overflow stage; 3) a tube-fed pāhoehoe stage; and 4) a waning stage. The first and third stages produced ʻaʻā and pāhoehoe respectively, that reached the ocean.

Figure 57. Map of Mauna Ulu lavas (from Tilling et al. 1987).

This 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 $m^3 s^{-1}$. Flows were predominantly 'a'ā, and the one flow that reached the ocean traveled the 12 km distance from the vent at an average velocity of 400 m hr^{-1}. Between episodes of high fountaining, only minor activity (small dome fountains and short flows) occurred at the vent area, which consisted of spatter and scoria cones. 'Alae pit crater was filled in with lava by the stage 1 activity.
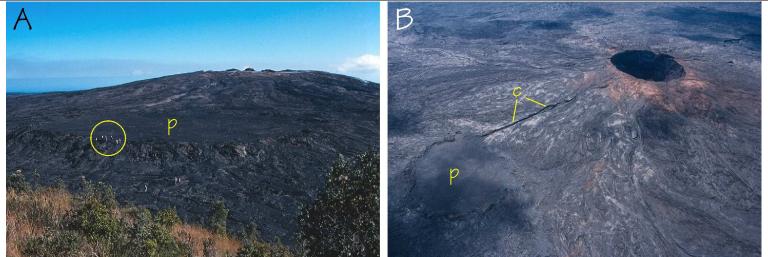

Figure 58. Mauna Ulu viewed from the ground (A) and from the air (B). In A, viewed to the south from Pu'u Huluhulu, note the people (circled) standing on the margin of a perched pond (p), which developed when lava flowed down a channel and ponded within self-made levees. In B, viewed approximately to the southeast, the channel (c) and pond (p) are indicated. This perched pond was studied by Wilson & Parfitt (1993).

The second stage of Part I built the majority 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 into a lava lake that developed in 'Alae crater, and this lava lake acted as a holding reservoir that modulated the rate of outflow to the lava tube system thereby dampening the effects of fluctuations in the eruption rate. When activity waned, the surface over 'Alae subsided, forming a bowl-shaped depression approximately outlining the position of the former crater.
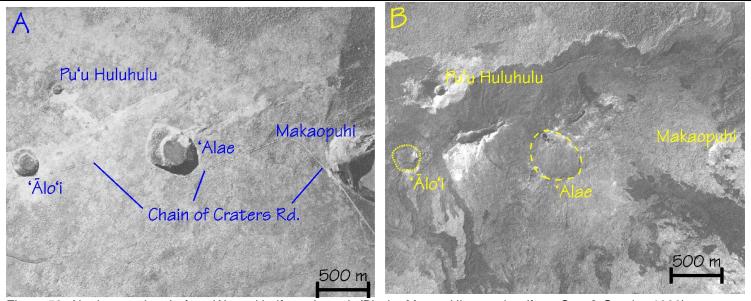

Figure 59. Air photos taken before (A), and halfway through (B), the Mauna Ulu eruption (from Carr & Greeley 1980).

The stage 3 pāhoehoe flows reached the ocean, advancing at an average flow-front velocity of 12 m hr^{-1}. The average discharge rate during this period was 4 m^3 s^{-1}. The summit depression of Mauna Ulu eventually became elongate by engulfing a line of small pits that had formed at the locations of earlier vents. The eruption slowly died (stage 4), and no active lava was seen after October 1971.
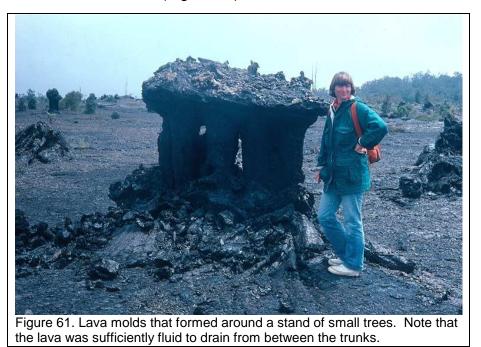
In early February 1972, lava quietly returned to the Mauna Ulu crater, signaling the start of Part 2 of the eruption (February 1972-July 1974; 106 x 10^6 m^3 of lava, covering 46 km^2). Part 2 was divided into 5 stages, determined by the type of activity and the location of eruptive vents (Tilling *et 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 s^{-1}, and two pāhoehoe flows reached the ocean after advancing at average velocities of 6 to 20 m hr^{-1}. Most of these were again fed from the 'Alae lava lake, which also overflowed, forming a parasitic shield on the SE flank of Mauna Ulu. This stage of the eruption ended soon after the M6.2 Honomū earthquake (April 26, 1973), 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 from fissures that cut through Pauahi crater and extended north of Pu'u Huluhulu, accompanied again by draining of Mauna Ulu. The brief part 2 stage 4 eruptions from Pauahi pit crater and north of Pu'u 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 (Figure 60), and there are numerous lava trees (Figure 61).

Figure 60. Spatter blobs hanging in trees near the Nov. 1973 fissure.

Figure 61. Lava molds that formed around a stand of small trees. Note that the lava was sufficiently fluid to drain from between the trunks.

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 s^{-1}. Flows traveled in all directions including due north towards Pu'u Huluhulu, an old scoria cone, and a prominent ponded area formed (Figures 58, 62). By June 1974, the overflows had increased Mauna Ulu's height to 121 m above the pre-1969 surface. The eruption began

its final demise soon after, and after a brief episode of fountaining at Kīlauea's summit in July 1974, the Mauna Ulu eruption was declared over.
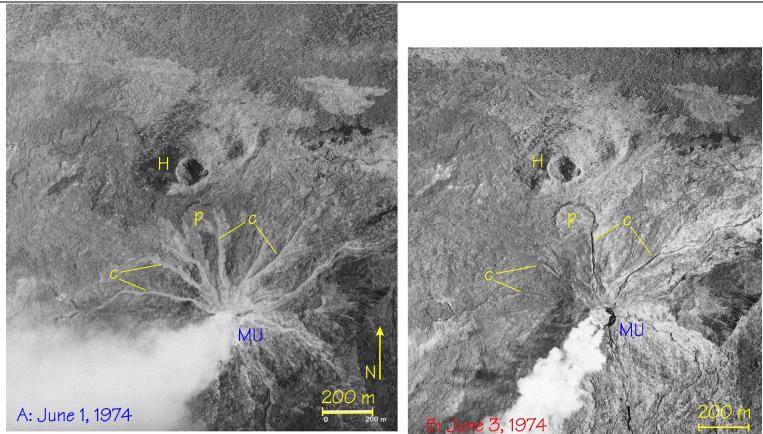

Figure 62. Vertical air photos of the last stage of part 2 of the Mauna Ulu eruption. In A, light-toned radiating flows are active channelized lavas (*c*) flowing in all directions. In B (2 days later), all flows are inactive, and the channels (*c*) have drained. Note ponded area (*p*) between Mauna Ulu (*MU*) and Puʻu Huluhulu (*H*). The formation of the ponded lava 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).
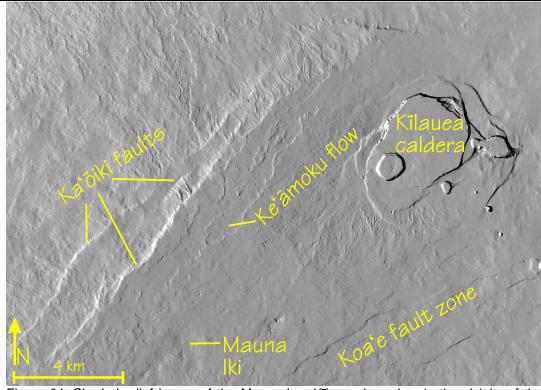

Figure 63. Mauna Ulu lava that flowed over the Hōlei pali, viewed from Chain of Craters Rd. Medium-toned lava is pāhoehoe, dark lava is ʻaʻā, and the lightest tones (upper left) are grasses on pre-Mauna Ulu surfaces.

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. Chain of Craters Rd. was re-built following the Mauna Ulu eruption, and from it there are many spectacular views (Figure 63).

THE KAʻŌIKI FAULT ZONE AND MAUNA IKI

Prior to the growth of Kīlauea, Mauna Loa would have had an unbuttressed south flank. Almost certainly this flank was unstable in the same way that the south flank of Kīlauea is unstable today. The Kaʻōiki fault zone is a remnant of large normal faults much like the Hilina faults of present-day Kīlauea (Figure 64). They are today almost completely buried by Kīlauea and Mauna Loa lavas that have ponded in the subtle saddle between the two volcanoes. In places they are mantled by what appears to be un-faulted Pāhala ash, indicating a lack of movement for at least the past 26,000-30,000 years.

Figure 64. Shaded relief image of the Mauna Loa-Kīlauea boundary in the vicinity of the Kaʻōiki fault zone and Mauna Iki.

There are earthquakes at depth in this region. One proposed mechanism is the differential expansion of Mauna Loa and Kīlauea as they inflate and deflate next to each other (Wyss 1986). The most recent large earthquake along the Kaʻōiki fault zone occurred in November of 1983 (Buchannan-Banks 1987). It had a magnitude of 6.6 and a focal depth of 12 km. Wyss (1986) presented data showing a rather remarkable periodicity for earthquakes of greater than M4.5 on the Kaʻōiki fault (Figure 65). Based on the data, another large Kaʻōiki earthquake was predicted for some time around the end of 1994. As of this writing (October 2007) it has not occurred.

Mauna Iki is a satellitic shield that formed during a 9 month-long eruption in 1920. Parts of the eruption indicated the existence of an obvious fluid connection between the then-active Halemaʻumaʻu lava lake and the eruption site some 11 km downrift (Rowland & Munro 1993). From a distance, Mauna Iki has an even better satellitic shield profile than Mauna Ulu (Figure 66).
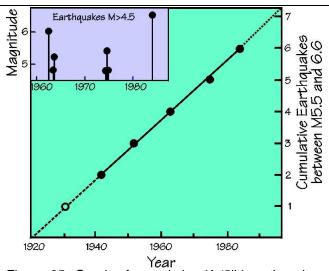

Figure 65. Graph of cumulative Kaʻōiki earthquakes of magnitude >5.4. Open circle indicates date of poorly-located earthquake, probably on the Kaʻōiki fault. Inset shows all Kaʻōiki earthquakes of magnitude >4.5, and shows that the regular relationship does not hold for smaller shocks.

The flow map on the back cover shows a number of different parts of the Puʻu ʻŌʻō/Kūpaianaha flow field (e.g., Wolfe *et al.* 1987; 1988; Heliker et al. 2003; Heliker & Mattox 2003). The initial lavas were the ʻaʻā flows of high-fountaining Puʻu ʻŌʻō episodes 1-47 (January 1983-June 1986). The eruption then shifted about 3 km downrift to Kūpaianaha, which produced tube-fed pāhoehoe from June 1986 until February 1992 (episode 48). Episode

Figure 66. View southward of the Mauna Iki satellitic shield.

49 lasted 18 days in Nov. 1991, overlapping with the last waning of activity at Kūpaianaha (Kauahikaua *et al.* 1996). Episode 49 occurred on the downrift flank of Puʻu ʻŌʻō, and therefore represented a shift back uprift. Ten days after activity finally ceased at Kūpaianaha, lava broke out on the uprift flank of Puʻu ʻŌʻō, signaling the start of Episode 50. Episodes 51-53 erupted from an ever-enlarging vent system associated also with collapse pits developing on the flanks of the Puʻu ʻŌʻō cone. Episode 53 ended on the night of January 30, 1997 accompanied by a very large collapse which essentially split Puʻu ʻŌʻō in two (Figure 13). This was associated with a brief outbreak of lava in Nāpau crater (episode 54). After a 3-week break, lava reappeared in the collapsed floor of Puʻu ʻŌʻō, signaling the start of episode 55. Episode 55 continued essentially uninterrupted until June of 2007, during which time a number of major, long-lived pāhoehoe flows erupted, including the Mothers' Day flow, the PKK flow, and the Campout flow, among others. Starting on June 17, 2007, an intrusion of magma from Kīlauea's summit started downrift, pausing for a couple days beneath Mauna Ulu, and then continuing on a couple more km to localize under Kāne nui o Hamo, a 500-600 year-old satellitic shield between Mauna Ulu and Puʻu ʻŌʻō. Activity at Puʻu ʻŌʻō slowly waned (accompanied by collapse of the Puʻu ʻŌʻō crater floor), and stopped altogether on June 18. A few hour-long eruption in the early morning of June 19 produced Episode 56, probably the tinniest of all the episodes. On July 2, lava returned to Puʻu ʻŌʻō crater, and it slowly began to re-fill. A complex series of vents and lava ponds filled Puʻu ʻŌʻō crater nearly to its brim. Just after midnight on the morning of July 21, the lava pond began to drain, and lava started erupting from four fissures on the downrift (east) flank of Puʻu ʻŌʻō, in the approximate vicinity of where the Nov. 1991 episode 49 vents had been. The activity localized at the easternmost of these fissures within a couple of weeks, and activity here continues as of this writing (late October 2007). To date, the flows have mostly been channelized ʻaʻā and pāhoehoe, and none have extended more than 5-6 km from the vent. If these flows do extend farther downslope, they pose a potential risk to numerous homes and towns (Kauahikaua 2007).

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.

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.

Decker RW, Christiansen RL (1984) Explosive eruptions of Kilauea Volcano, Hawaii. in: Explosive Volcanism: Inception, Evolution, and Hazards. Nat Acad Press, Washington DC:122-132.

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.

Emerson EB (1915) Pele and Hiiaka A Myth from Hawai'i, (1997 ed.), 'Ai Pōhaku Press, Hilo: 250 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.

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.

Heliker C, Mattox TN (2003) The first two decades of the Pu'u 'Ō'ō-Kūpaianaha eruption: chronology and selected bibliography. US Geol Surv Prof Pap **1676**:1-27.

Heliker C, Swanson DA, Takahashi TJ (2003) The Pu'u 'Ō'ō-Kūpaianaha eruption of Kīlauea Volcano, Hawai'i: the first 20 years. US Geol Surv Prof Pap **1676**:206 pp.

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

Hitchcock CH (1911) Hawaii and its Volcanoes. Hawaiian Gazette Co., Ltd., Honolulu.

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, & McKay 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 (1921) Fossil human footprints in Kau Desert. In: Monthly Bulletin of Hawaiian Volcano Observatory **9** no. 7:114-118.

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

Kauahikaua JP, Mangan MT, Heliker CC, Mattox TN (1996) A quantitative look at the demise of a basaltic vent: the death of Kupaianaha, Kilauea Volcano, Hawai'i. Bull Volcanol **57**:641-648.

Kauahikaua J (2007) Lava flow hazard assessment, as of August 2007, for Kīlauea east rift zone eruptions, Hawai'i Island. US Geol Surv Open-File Rpt. 2007-1264.

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, Banks NG (1987) Aa flow dynamics. US Geol Surv Prof Pap **1350**:1527-1567.

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, Moore JG (1996) Mauna Loa lava accumulation rates at the Hilo drill site: Formation of lava deltas during a period of declining overall volcanic growth. J Geophys Res **101**:11,631-11,641.

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

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

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 RB (1992) Volcanic geology and eruption frequency, lower east rift zone of Kilauea volcano, Hawai'i. Bull Volc **54**:475-483.

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.

Okubo CH, Martel SJ (1998) Pit crater formation on Kilauea volcano, Hawaii. J Volcanol Geotherm Res **86**:1-18.

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.

Powers HA (1948). A chronology of the explosive eruptions of Kilauea. Pacific Science **2**:278-292.

Powers S (1916) Explosive ejectamenta of Kilauea. Am. J. Sci. **41**:227-244.

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 (1987). Toothpaste lava: characteristics and origin of a lava structural type transitional between pahoehoe and a'a. Bull. Volc., **49**:631-641.

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

Rowland SK, Munro DC (1993). The 1919-1920 eruption of Mauna Iki, Kilauea: chronology, geologic mapping, and magma transport mechanisms. Bull. Volcanol. **55**:190-203.

Smathers GA & Mueller-Dumbois D (1974). Invasion and Recovery of Vegetation after a Volcanic Eruption in Hawaii. 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.

Swanson DA (2006) Pele legends merge with oral history to describe 400 years of Kīlauea's activity. Cities on Volcanoes IV (Quito, Ecuador) Abstract vol

Swanson DA (2008) Hawaiian oral tradition describes 400 years of volcanic activity at Kīlauea. J Volcanol Geotherm Res **176**: 427-431

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.

Walker GPL (1992) Puu Mahana near South Point in Hawaii is a primary Surtseyan ash ring, not a littoral cone. Pacific Science **46**:1-10.

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 influence 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.

NE PLUS HAUSTAE   AUT OBRUTAE URBES

this part (dashed) of Crater Rim Dr. is closed

from Hilo

Halemaʻumaʻu Crater

New Vent ★ ■ Overlook

Parking lot

from Hilo

November 7, 2009

Flow field on November 7

Flow field on October 30

Halemaʻumaʻu vent viewed from HVO, June 2008

1986–1992

Royal Gardens Subd.

2007–2010

Kalapana

parking area

public viewing area

April 19, 2010

Flow field on April 19

Flow field on April 15

Pacific Ocean

maps from the USGS Hawaiian Volcano Observatory eruption update website:

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