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FIELD TRIP GUIDEBOOK #035

GEOLOGY OF KĪLAUEA VOLCANO AND NEARBY LOCATIONS OF MAUNA LOA AND MAUNA KEA VOLCANOES, BIG ISLAND OF HAWAI'I

September 17-20, 2009

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NWGS Field Trip Guidebook Series

Of particular note, some stops on these trips may be located on private property. ***Publication of this guide does not imply that public access has been granted to private property.*** If there is a possibility that the site might be on private property, you should assume that this is the case. ***Always ask permission before entering private property.***

Northwest Geological Society Field Guidebook Series
Field Trip Guidebook #035

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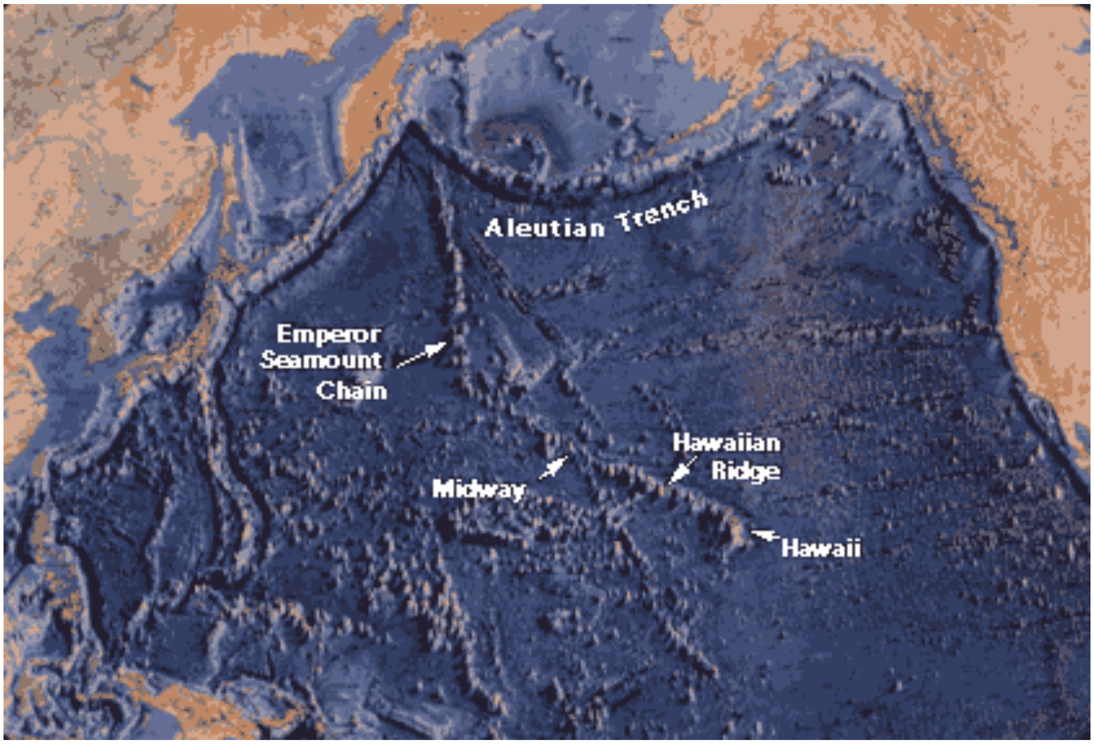
PLEASE BE AWARE OF THE FOLLOWING

- *Although most of the field trip stops will be roadside in nature and involve only short (<1/4 mile), easy walks, some stops may involve longer hikes (up to several miles) of moderate difficulty. You are welcome to opt out of any hikes that you feel are beyond your ability or desire. It is always a good idea to be prepared for warm temperatures and intense sun (hat, proper clothing, sunscreen), but the elevation at the rim of Kīlauea's caldera is 4,000 feet, so be prepared for cool (or cold), moist, rainy conditions as well.*

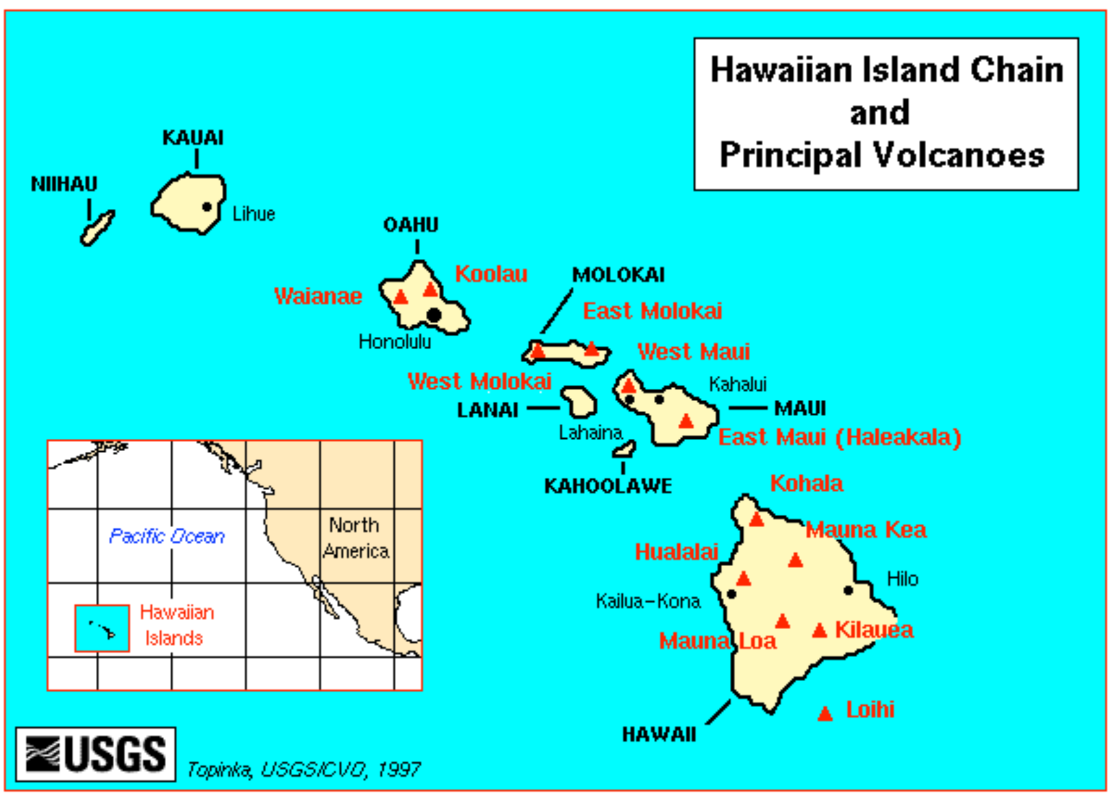
- *We may make an attempt to view lava or the lava ocean entry, either from a distance (several miles) or close up (<1/4 mile or closer), depending on the nature and accessibility of the activity. However, you should be aware that the eruptive activity can change daily, and there is no guarantee of seeing lava at all. Also, be aware that lava viewing, if accessible, can pose numerous hazards, including (but not limited to) inhalation of toxic or irritating volcanic gases, burns from lava or hot air, advancing lava, projectiles, lava bench collapses, dehydration, falling on uneven terrain, and heat exhaustion/heat stroke. Close-up observations of lava flows or ocean entries may require a long (up to 8 miles round trip), difficult hike over very uneven lava, perhaps, in part, in the dark by headlamp. Such a hike would, of course, be optional, if attempted at all. Many people have been injured and a several fatalities have occurred in areas that we may visit. You will be briefed on the prescribed safety precautions of Hawai'i Volcanoes National Park and the Hawai'i State Civil Defense and you will be expected to follow these precautions at all times. Every effort will be made to visit these exciting areas safely. Please search the Internet for Viewing Lava Safely - Common Sense is Not Enough, Volcano Fact Sheet (Johnson et al., 2004) for detailed information on these hazards.*

- *This field trip will include a drive to the Mauna Loa Observatory, a NOAA facility, at an elevation of 11,000 feet on the slope of Mauna Loa volcano, and will involve walking several hundred yards from the parking area up a steep hill to the observatory area (NOAA facilities are not open to the public). We will be driving to this location from sea level in a short time (several hours), making several stops along the way to acclimate. However, even with precautions, acclimating to this elevation may be difficult for some people and altitude sickness may occur.*

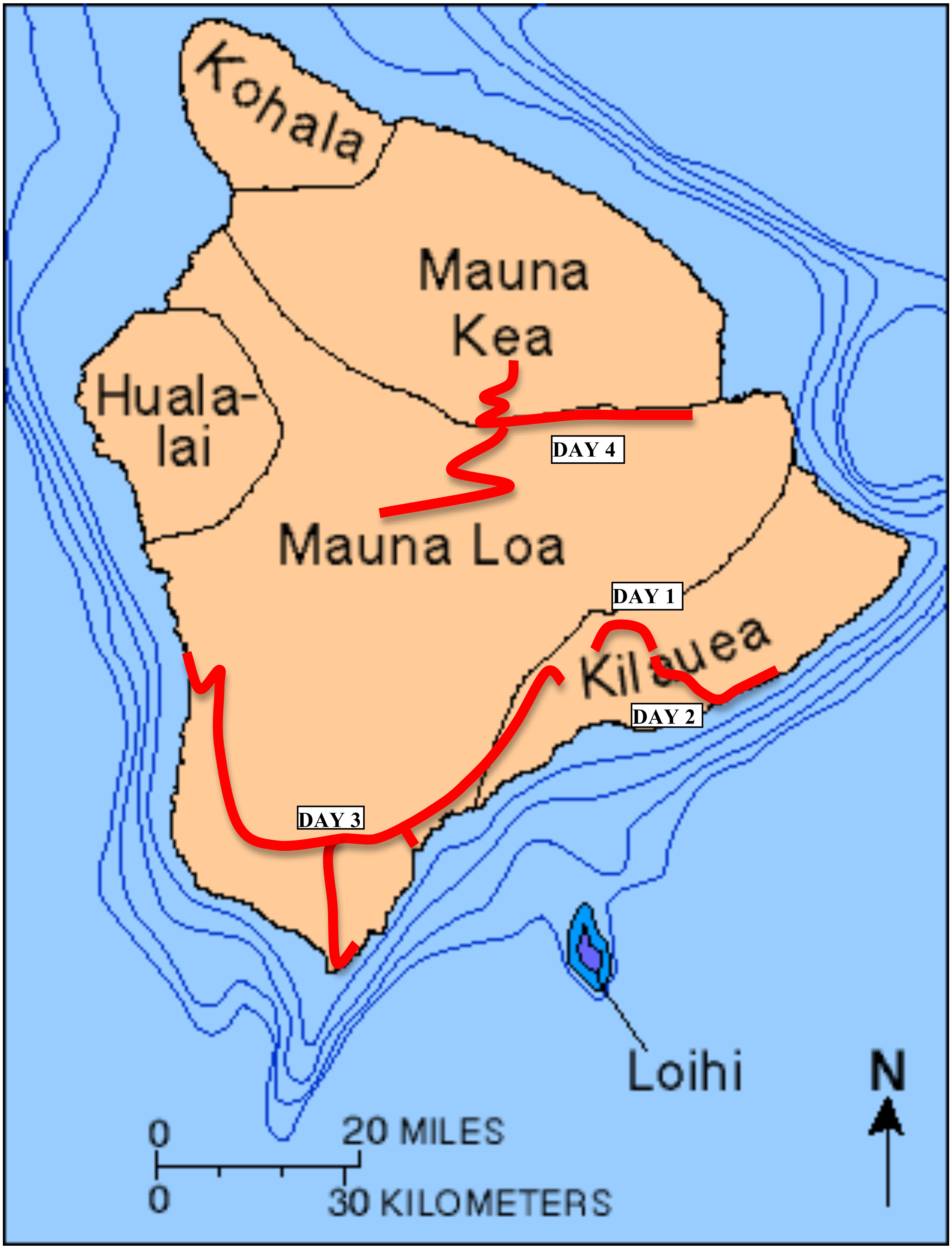
***Cover photo**: Fuming vent on the east-southeast floor of Halema'uma'u crater in the caldera of Kīlauea volcano, with fumes dispersed southwest by trade winds. Fume consists mostly steam of and other volcanic gasses. Measured emissions of SO_2 have been several times the 2003-2007 average of 140 tonnes/day since this vent first became active in March of 2008. Periodic explosions have produced small amounts of tephra, including juvenile volcanic glass. As of this writing, the webcam operated by the USGS Hawaiian Volcano Observatory (HVO) sometimes shows roiling lava within the vent ~185 m below its rim. Viewpoint is from Uwēkahuna Bluff on the NW rim of Kīlauea's caldera (the location of HVO), looking south-southeast from a distance of ~1.8 km. Photo from Hawaiian Volcano Observatory, 2009A.*



Map 1. *The Hawaiian Ridge and Emperor Seamounts in the Pacific Ocean (Kious and Tilling, 1999).*



Map 2. *The Hawaiian Islands (Cascade Volcano Observatory, 2008).*



Map 3. *The Big Island of Hawai'i or Hawai'i Island showing location of Days 1-4 of this field trip (Hawaiian Volcano Observatory, 2000).*

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GEOLOGY OF KĪLAUEA VOLCANO AND NEARBY LOCATIONS OF MAUNA LOA AND MAUNA KEA VOLCANOES, BIG ISLAND OF HAWAI'I

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I. THE HAWAIIAN HOT SPOT—BACKGROUND AND DISCUSSIONS

Introduction

The Hawaiian Islands are located in the north-central portion of the Pacific Ocean at ~20° N latitude and 156° W longitude, approximately 4,300 km southwest of Seattle (Map 1, inside front cover), and form one of the most isolated island archipelagos in the world (Table 1). This field trip will take place on the island of Hawaiʻi, known as the Big Island or Hawaiʻi Island, at the southeastern end of this chain (Maps 2 and 3, inside and outside back cover). Hawaiʻi is composed of five overlapping shield volcanoes of Kohala, Mauna Kea, Hualālai, Mauna Loa, and Kīlauea. The primary focus will be on Kīlauea volcano, one of the most active volcanoes on Earth, and neighboring volcanoes Mauna Loa and Mauna Kea.

Location (city or nearest point)	*Air distance from Honolulu, Hawai'i (km)*
San Francisco	3,704
Alaskan Peninsula	3,717
Japan	5,895
Australia	7,278
Ecuador	8,401
Antarctica	10,300

Table 1. *Distances from the Hawaiian Islands to selected locations around the Pacific Rim.*

The Hawaiian Islands are volcanic in origin and consist of eight major islands extending northwest a distance of 500 km from the Big Island to Kauaʻi and Niʻihau (Map 2). However, atolls and submerged guyots and seamounts (henceforth referred to simply as *seamounts*) extend farther to the northwest for an additional distance of ~3,100 km and together with the Hawaiian Islands form the Hawaiian Ridge, including the military establishment of Midway, near the site of the pivotal June 4, 1942 WWII Battle of Midway with Japan (Map 1). The chain of seamounts then abruptly bends northward and extends for another ~2,300 km to the Aleutian trench at the northern end of the Pacific Ocean, forming the Emperor Seamounts (Map 1). Interestingly, the ages of these islands and seamounts increase in a broadly linear fashion from southeast to northwest along the Hawaiian Ridge to the Hawaiian-Emperor bend, and then to the north along the Emperor Seamounts. Volcanoes at the southeast end of the Hawaiian Ridge on the Big Island (including Loʻihi Seamount off its southeastern shore) are the youngest and are currently active, with the islands of Kauaʻi and Niʻihau being the oldest at the northwestern end of the archipelago dating at ~5 Ma. Seamounts at the Hawaiian-Emperor bend date at ~ 47-50 Ma (Sager, 2007), whereas the Meiji Seamount at the northern end of the Emperor chain dates at 82 Ma. The total length of the Hawaiian Ridge-Emperor Seamounts is about 5,400 km. This linear increase in age to the northwest and north is of great significance with respect to the origin of the Hawaiian Islands. Likewise, other island-seamount systems in the Pacific show a similar but less pronounced trend (such as the Line Islands directly south of Hawaiʻi and the Gilbert-Marshall Islands to the southwest of Hawaiʻi) (Map 1). Total volume of lava erupted to form the Hawaiian Ridge-Emperor Seamounts is estimated to be 750,000 km^3 (Kious and Tilling, 1999).

Wilson (1963) explained the linear age progression of the Hawaiian-Emperor Seamounts as being the result of the motion of the Pacific plate over a stationary hot spot in the mantle (Figure 1); Morgan (1971) expanded on this idea and proposed that such deep mantle plumes continually supply magma to about 20 hot spots around the world. The surface manifestation of the Hawaiian mantle plume is extensive hot spot volcanism, building seamounts and ocean islands atop the mantle plume. It is now accepted that this is the result of decompression partial melting of ultramafic mantle perodotite near the base of the oceanic lithosphere, producing large volumes of mafic magma, much of which eventually erupts on the seafloor, forming a large mass of pillow basalts. Eventually, these extrusions accumulate to form a seamount and finally, breach the ocean's surface to form a basaltic oceanic island.

In this model, the mantle plume is relatively fixed in its position (an idea now being challenged by some, to be discussed below) and the Pacific plate moves northwestward over the mantle plume. Recently constructed volcanic islands are carried away from the magmatic source and eventually become extinct (Figure 1). Concurrently, new volcanic islands form over the hot spot just behind the previously active volcano. As this process continues for an extended period of geologic time (at least 82 Ma for the Hawaiian Ridge-Emperor Seamounts), a chain of volcanic islands is produced, with a linear age progression increasing away from the active hot spot.

As the islands are removed from the mantle plume magmatic source, they enter a destruction phase. The volcanoes become extinct and are reduced in size by a long period of erosion. Eventually, the islands may shrink back into the sea due to runoff-dominated erosion, forming atolls and eventually guyots as they sink below sea level. Submergence is aided the aging oceanic lithosphere, upon which the islands are riding, As the plate moves away from its distant oceanic ridge-spreading source, it cools and increases in density, resulting in isostatic sinking of the islands as they are rafted away from the mantle plume, causing the gradual transition from ocean islands to atolls and later to guyots. Eventually, the structures may reach an oceanic trench, where they become deformed, accreted, or partially subducted.

Both the linear distribution and age progression of the Hawaiian Ridge-Emperor Seamounts can be explained by this model; the Hawaiian-Emperor bend could have been caused by a change in the direction of the Pacific Plate motion. When the Emperor Seamounts were formed, the Pacific Plate was moving northward, but when the Hawaiian Ridge was formed, the Pacific plate would have been moving northwestward. The timing of this change in motion would then correspond to the ages of the volcanoes at the bend, or about 47-50 Ma.

A Few Problems with the Fixed Hot Spot Idea

In the last decade, serious issues have been brought forward with regard to the fixed nature of mantle plume-hot spot systems, especially the Hawaiian hot spot. For several decades following the inception of the theory

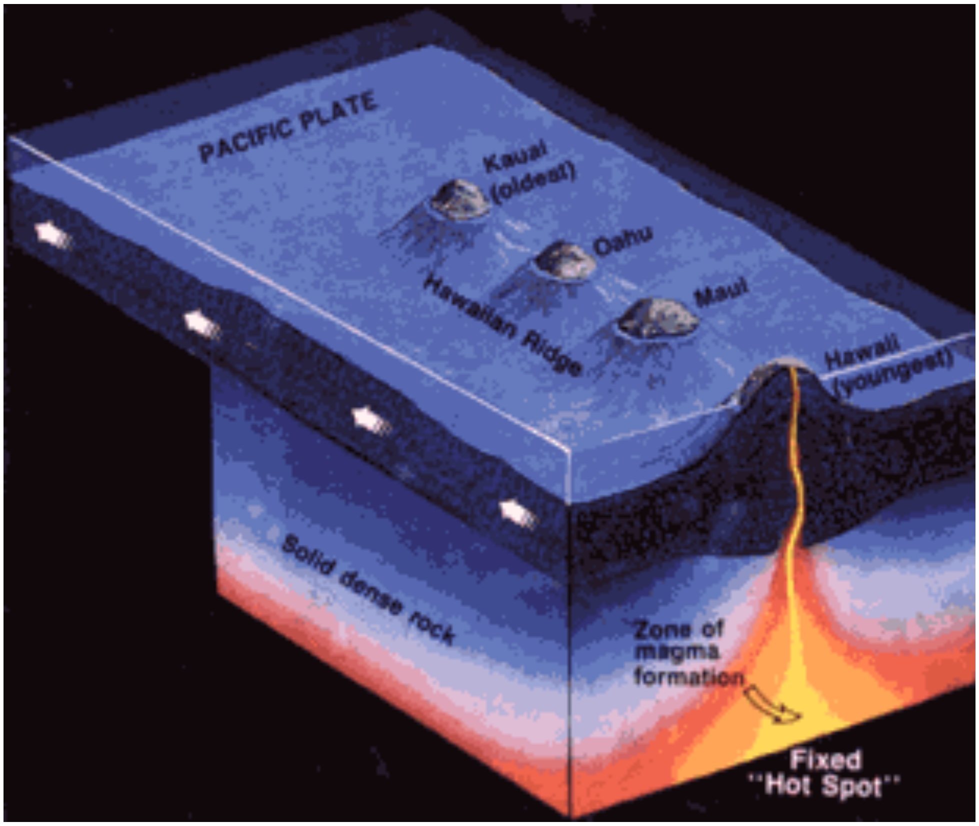

Figure 1. *Illustration of the formation of the Hawaiian Islands as the Pacific plate moves over the fixed hot spot beneath (Kious and Tilling, 1999).*

of plate tectonics, the idea that hot spots are stationary or nearly so, was widely accepted due to its simplicity and its consistency with the existing model of plate tectonics. In light of recent observations, however, many workers now assert that this concept needs to be reconsidered.

One complication has to do with the bend in the Hawaiian-Emperor Seamount chain. The theory that this bend resulted from a change in Pacific plate direction at about 47-50 Ma is problematic. The bend is sharp, and would require an abrupt change in the direction of the Pacific plate motion. However, it is unlikely that there are plate boundary forces that would be adequate to cause such an abrupt change in plate direction (Foulger and Anderson, 2006). Furthermore, an analysis of fracture zones and Pacific floor ages in the eastern Pacific shows no evidence for a change in plate motion at 50 Ma (Figure 2) (Foulger and Anderson, 2006).

Additionally, the direction of Pacific plate motion suggested by the Hawaiian Ridge is inconsistent with the direction of motion derived from fracture zones in the eastern Pacific. Generally, fracture zones develop perpendicular, or nearly so, to the spreading centers from which they extend, and the spreading direction is parallel to the fracture zones. In the northeastern Pacific, fracture zone orientation is roughly east-west, consistent with east-west spreading from the Juan de Fuca ridge and its neighbors. These fracture zones extend out to, and cut across, the northwest trend of the Hawaiian Ridge (such as the Maui Fracture Zone). However, a northwest trend of volcanoes could be produced if a southward drifting hot spot motion is combined with the westward movement of the Pacific plate.

Another obstacle is seen in the paleolatitude data from the Emperor Seamounts. If the Hawaiian hot spot is fixed, then each volcano

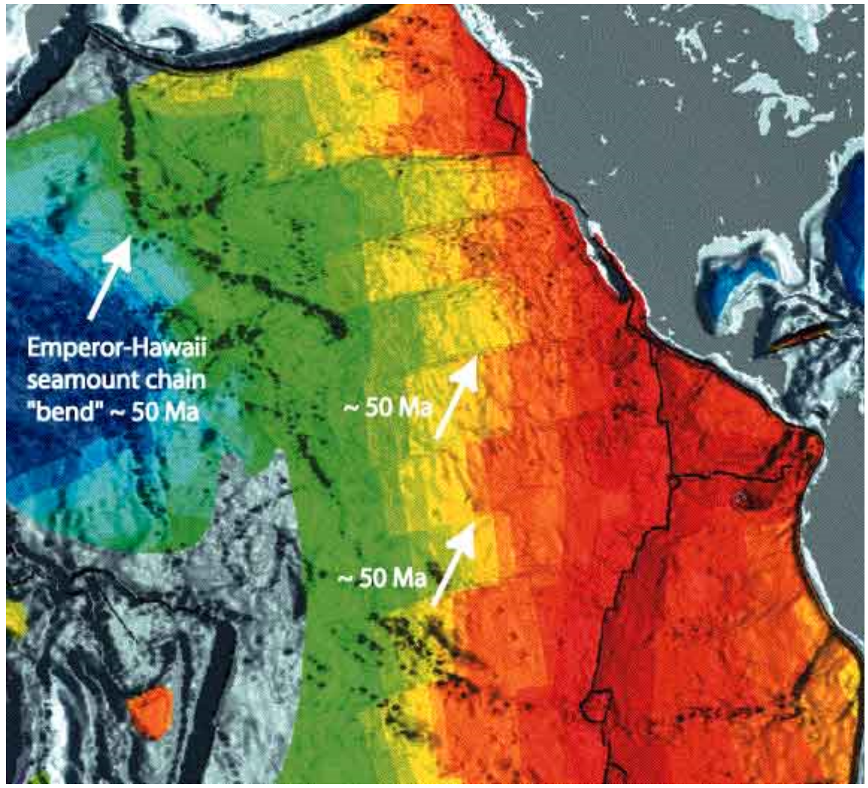

Figure 2. *The idea that the Hawaiian Ridge-Emperor Seamount bend is caused by an abrupt change in Pacific plate motion at 50 Ma is unsupported by fracture zone trends in the western Pacific (Foulger and Anderson, 2006).*

produced at the source should have formed at the same latitude as the present-day position of the hot spot, ~20°N. This is not the case. Paleolatitude data from the Emperor Seamounts indicate that the structures formed at paleolatitudes well north of the present-day hot spot position, and that the hot spot must have migrated southward between 81-47 Ma at a rate of 44 mm/year (Tarduno et. al, 2003).

The last problem emerges from the comparison of apparent polar wandering paths for the Pacific plate derived from plate rocks and hot spot rocks. If the Hawaiian hot spot has remained fixed, or nearly so, over the course if its 80+ Ma history, the apparent polar wandering path derived from sampling Pacific plate rocks should match (or nearly match) the one derived from hot spot rocks. Sager (2007) finds that the two paths are broadly similar from 49 Ma-present, but from 80-49 Ma the two paths are markedly different.

In more detail, the Pacific plate apparent polar wandering path shows southward movement of the Pacific plate in the Jurassic and Early Cretaceous, thereafter followed by northward movement, producing a J-shaped apparent polar wandering path (Figure 3). However, during the period from 80-49 Ma, the Pacific plate data shows negligible northward Pacific plate motion, interpreted by Sager (2007) to indicate motion along an east-west path and northward motion then resumed at 49 Ma. On the other hand, from 80-49 Ma, hot spot-derived data shows ~19° southward motion, which is inconsistent with the Pacific-derived data. Interestingly, the north-south linear trend of the Emperor Seamounts can be explained, in light of this data, by drift of the hot spot in a *southwesterly* direction, where the southward component of drift is ~19°, and the *westward* component is equal to the rate of westward drift of the Pacific plate. This would produce a southward-trending hot spot track on the Pacific plate.

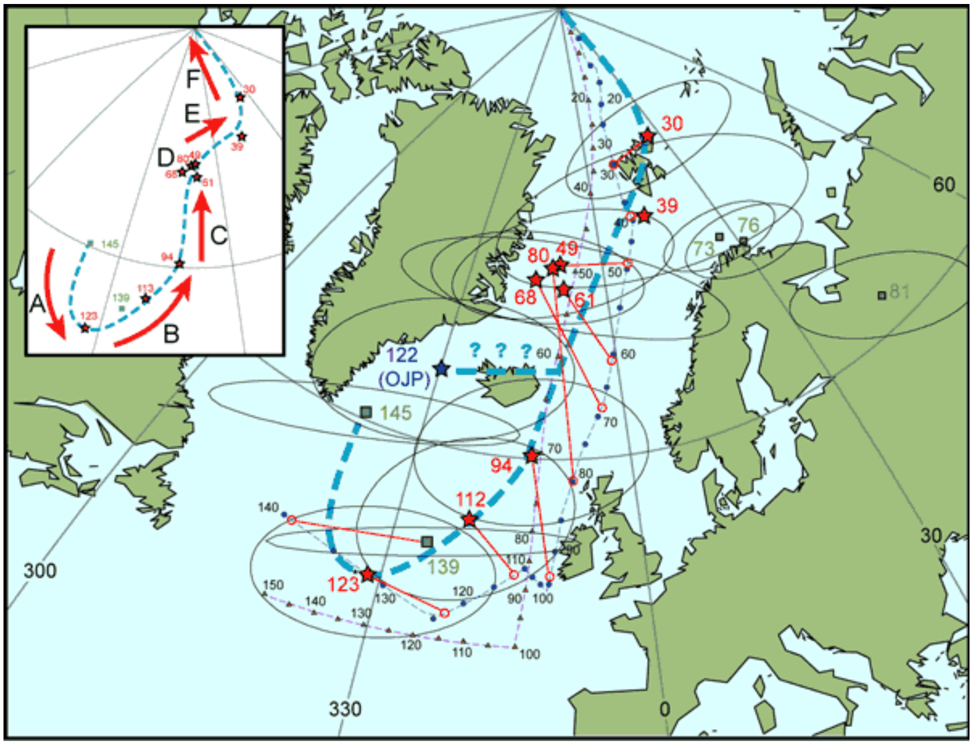

Figure 3. *Comparison of apparent polar wandering paths for the Pacific plate from the Jurassic to present as derived from Pacific plate rocks with that derived from hot spot rocks. If the Hawaiian hot spot has remained fixed through time, then the two paths should match. Although broadly similar, the hot spot path shows considerable southward movement from 80-49 Ma whereas the plate path does not, suggesting that the Hawaiian hot spot drifted south during that time. From Sager, 2007.*

The observations discussed above are clearly inconsistent with the decades-held belief that mantle plume-hot spot systems are fixed, or relatively so, in their positions.

The Big Island and Its Volcanoes

The island of Hawai‘i is composed of five overlapping shield volcanoes of varying ages (Map 3 and Figure 4). These include, from oldest to youngest, Kohala, Mauna Kea, Hualālai, Mauna Loa, and Kīlauea. A future sixth Hawaiian shield volcano lies about 30 km off the southeastern coast of the Big Island as the seamount Lo‘ihi, whose summit is still 969 m below sea level. Interestingly, the age of the most recent eruption of each of these shield volcanoes decreases roughly northwest to southeast, in accordance with the general decrease in age of the Hawaiian Islands to the southeast. See Table 2 below for details.

Basalts of the Hawaiian Islands (as well as other oceanic hot-spot archipelagos such as the Galapagos Islands) range between two compositions. Tholeiitic basalt (word origin from Tholay, Saarland, Germany (Bates and Jackson, 1984)) is by far the most abundant and is characterized by relatively low concentration of the alkali elements Na_2O + K_2O. It is generally erupted in large volumes during the main growth stage of a shield volcano’s history. Tholeiites usually contain phenocrysts of plagioclase and pyroxene. Conversely, alkali basalt tends to be richer in Na_2O + K_2O compared to tholeiitic basalt, and is present in much smaller volumes. Alkali basalts usually contain Na-rich pyroxenes and amphiboles, and may contain feldspathoid minerals.

These two types of basaltic lavas are erupted throughout four stages in the development of Hawaiian volcanoes (Wolfe and Morris, 1996). The first stage is the pre-shield-stage, during which time submarine eruptions of relatively small volumes of alkali basalts form a seamount. None of the Big Island volcanoes

Shield volcano or seamount (Hawaiian meaning, if known)	*Age of last eruption*	*Oldest Dated Rocks*	*Estimated Age of Earliest Subaerial Eruptions*	*Total Subaerial Area (% of Hawai'i)*	*Eruptive Stage*
Kohala	120 ka B.P.	460 ka	500 ka	606 km^2 (5.8%)	Post-shield (alkalic)
Mauna Kea ("White Mountain")	3.3 ka B.P.	237 ± 31 ka	(Age of volcano est. at 1 Ma)	2280 km^2 (22.8 %)	Post-shield (alkalic)
Hualālai	1800-1801 A.D.	128 ka	300 ka	751 km^2 (7.2%)	Post-shield (alkalic)
Mauna Loa ("Long Mountain")	1984 CE.	100-200 ka	~400 ka	5271 km^2 (50.5 %)	Tholeiitic shield-building
Kīlauea ("Spewing" or "Much Spreading")	Current eruption started in 1983 CE	23 ka	~50-100 ka	1430 km^2 (13.7%)	Tholeiitic shield-building
Lo'ihi Seamount ("Long")	1996 CE		(Not yet subaerial)	Submarine area 660 km^2 (0%)	Transitional between pre-shield and tholeiitic shield-building

Table 2. *The volcanoes and seamount of the Big Island (Hawaiian Volcano Observatory, 1998, 2000A, 2001, 2002, 2006C, 2009C; Rubin, 1998).*

have exposed pre-shield rocks, as they have been buried by large volumes of younger basalt, but Lo'ihi is near the end of this pre-shield building phase. It is difficult to estimate the duration of the pre-shield stage because of the lack of access to rocks that have been emplaced during this period.

The subsequent shield-stage is characterized by the eruption of large volumes of tholeiitic basalt and rapid shield volcano growth (Wolfe and Morris, 1996). Initially, submarine eruptions build the seamount to the sea surface, and subaerial eruptions then construct the shield volcano. Typically, 95-98% of the volume of the volcano forms during this phase (Wolfe and Morris, 1996; Eakins et al., 2007). The time span of this stage is not known because the oldest shield-building lavas are buried, but Wolfe and Morris (1996) estimate it to last ~500 ka. Kīlauea and Mauna Loa, the foci of the Big Island's most vigorous recent activity, are presently in this stage.

During the post-shield-stage, lava production drops and becomes more alkalic (Wolfe and Morris, 1996). These basalts can be transitional in composition between tholeiitic and alkalic basalt, but true alkalic basalts are also erupted. Some lavas contain even higher concentrations of alkalis such as hawaiite, mugearite, benmoreite, and trachyte (Wolfe and Morris, 1996). Because of the drastically reduced lava production and higher volatile content and viscosity of the lavas of this

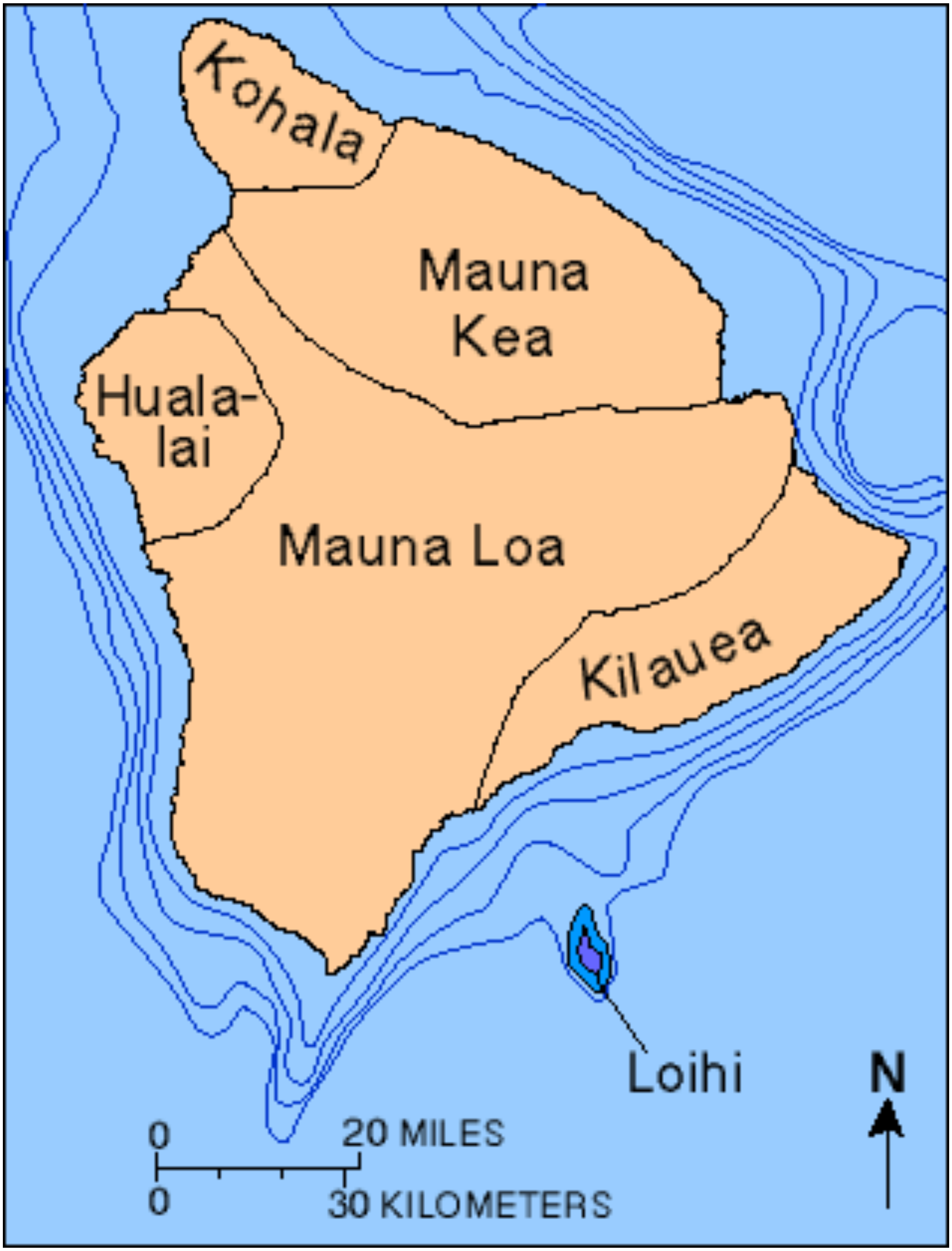

Figure 4. *Map of the Big Island showing its five overlapping shield volcanoes (Hawaiian Volcano Observatory, 2000).*

stage, the shield volcano morphology transitions from a relatively smoothly-shaped, convex-upward shield volcano to a more irregular profile with steeper flanks. The morphological transition is aided by the volatile-rich alkali lavas, which erupt more explosively and in much smaller volumes, resulting in the formation of numerous scoria cones. These features may be somewhat randomly distributed, such as on Mauna Kea, or distributed along previously existing rift zones, such as on Hualālai and Kohala (Wolfe and Morris, 1996); all three of these volcanoes are in the post-shield stage. Haleakalā on the nearby island of Maui (see STOP 4-5) is also in this stage (Hawaiian Volcano Observatory, 2003).

Finally, after as much as several million years of quiescence, the post-shield-stage may be followed by a rejuvenated stage, during which small volumes of low silica lavas are erupted (Wolfe and Morris, 1996). None of the volcanoes on the Big Island have yet reached this stage, but the tuff cones and craters of southeast Oʻahu (such as the popular snorkeling destination of Hanauma Bay, Koko Crater and Hawai'i's iconic Diamond Head) represent this stage (Zeigler, 2002).

The underlying principal for the transition through these stages occur is not completely clear, but generally, alkalic basalts are produced when the original mantle peridotite parent rock undergoes a lesser degree of partial melting than tholeiitic basalts. This leads to greater fractionation of alkali elements. The parent rock of both types of basalts is mantle peridotite, but with tholeiitic basalts, the degree of parental rock partial melting is greater than with alkalic basalts, leading to greater dilution of the alkali elements.

How does this relate to the eruptive stages of Hawaiian volcanoes? One idea is that these phases may reflect the tectonic passage of the volcano over the ~50 km-wide Hawaiian mantle plume at depth. When a Hawaiian volcano first makes its appearance as a submarine seamount, its eruptive center is on the up-drift edge of the mantle plume, where the degree of partial melting is relatively low, producing a small volume of alkalic basalt. The volcano is then tectonically rafted over the more vigorous main portion of the mantle plume, where it remains for ~500 ka, and a higher degree of partial melting of mantle peridotite produces a much larger volume (many orders of magnitude) of tholeiitic magma, forming the main, shield-building stage of the volcano's history. When the volcano is then tectonically carried to the down-drift edge of the mantle plume, again a much lower volume of alkalic basalt is produced due to less partial melting of mantle peridotite. The final rejuvenated stage may result from last-gasp eruptions that tap small volumes of long-stored magma imbedded within the plate beneath the volcano.

The Anatomy of a Shield Volcano

The edifices that comprise the Hawaiian islands are shield volcanoes, shaped like an inverted Greek warrior's shield. They typically have gently-sloping edifices as compared to their composite (stratovolcano) cousins such as those in the Cascade Mountains of the Pacific Northwest. For example, the slopes of Mauna Loa volcano on the Big Island are around 12°, and the angle shallows near the summit, forming a convex-upward shape. Shield volcanoes may reach immense heights and have large diameters, and therefore are highly voluminous volcanoes. For example, Mauna Loa is ~97 x 48 km as measured where its base rests on the Pacific Ocean floor. The gentle slopes and large diameters are a result of being primarily composed of low-viscosity, mafic lava flows with relatively little tephra. In comparison, composite volcanoes such as Mt. St. Helens or Mt. Rainier are composed of higher viscosity, more silica-rich lavas interlayered with tephra. The rather fluid nature of the mafic lavas that comprise shield volcanoes allows them to flow longer distances from the eruptive site (vent or fissure), thus contributing to their gentler slopes and greater diameters. As will be seen on this trip, mafic lava flows often form natural solidified lava levees along flow margins, creating a lava channel. Lava flowing down the channel may crust over, forming a lava tube. Lava flowing inside a tube is well insulated and is therefore able to flow long distances (up to several kilometers as the tube builds downslope) with very little heat loss, allowing for lateral widening of the volcanic edifice. For more, see STOP 1-5.

Mauna Loa volcano on the Big Island is Earth's most voluminous volcano, with a total estimated volume of about 75,000 km^3 (Kaye and Trusdell, 2002). In comparison, the Columbia River Basalt Group in the Pacific Northwest is estimated to have a total volume of 174,000 km^3 (Swanson et al., 1989). Although not Hawai'i's tallest mountain (this distinction belongs to Mauna Kea at 4,204 m), Mauna Loa's summit measures 4,169 m above sea level; however, its base lies on the surrounding relatively flat ocean floor at a depth of ~4,200 m below sea level. Simply adding these numbers does *not* yield Mauna Loa's true height, because the oceanic lithosphere upon which it sits is isostatically depressed an additional 8,000 m, thus making the true height of Mauna Loa's volcanic pile over 17,000 m, including its "root" system that lies beneath the level of the surrounding ocean floor. This is an astonishing height, double that of Mt. Everest above sea level!

As a typical Hawaiian shield volcano develops, it will inevitably lap onto the southeastern flank of the next older shield volcano to the northwest. Early in the tholeiitic shield-building stage, even while still a submarine seamount (such as Lo'ihi), the volcanic pile becomes gravitationally unstable, producing lateral spreading of the volcano's edifice. If not constrained by on-lap onto an adjacent, older shield volcano, three rifts zones may develop, symmetrically radiating from the summit or central summit caldera at angles of ~120° (Hazlett and Hyndman, 1996). However, as is more typical, Hawaiian volcanoes do lap onto older ones as they form. The older volcanoes then constrain the gravitational stress field acting upon the younger ones, disallowing symmetrical laterally spreading. Instead, two rift zones may develop, generally parallel or sub-parallel to the contact between the two volcanoes, extending outward in both directions from its summit or central summit caldera. Mauna Loa, Kīlauea, and Lo'ihi display this two-rift system.

Rift systems are important in the growth of Hawaiian shield volcanoes because they provide plumbing systems for magma movement away from a volcano's summit and toward its flanks. Magma may ascend toward the surface beneath the volcano's summit through a series of conduits and become stored near the surface (several kilometers under the volcano's summit) in a magma chamber. From there, it will follow the path of least resistance to the surface, which may be directly to the summit above the magma chamber, but may also be along a radiating rift zone, where it pierces the surface down the flank of the volcano from the summit. Because such rift zones are composed of a series of tensional fractures, faults, and small graben structures, eruptions often occur as fissure eruptions (hundreds to thousands of meters in length) rather than from a central vent. Flank eruptions may occur many kilometers downslope from the summit, thus contributing to lateral growth of the shield volcano morphology.

As previously mentioned, Mauna Loa and Kīlauea both have well-developed two-rift zone systems. Both have rift zones that extend to the southwest and northeast or east from their respective summit calderas. Each have had (and Kīlauea continues to have) significant eruptions from their rift zones during historical times.

The largest historical eruption from Mauna Loa's southwest rift zone occurred in 1950 (Hawaiian Volcano Observatory, 2004A). During the 23-day eruption, 376 million m^3 (0.376 km^3) of lava erupted along a 20-km-long fissure system. Lava flows reached the sea on the western shores of the Big Island in less than 4 hours (Figure 5), and the total volume of the eruption is equivalent to nearly 4 years of the total lava production from the 1983-present Puʻu ʻŌʻō-Kūpaianaha eruptions on Kīlauea's east rift zone (Hawaiian Volcano Observatory, 2004A). We will have an opportunity to view a 1907 lava flow erupted from Mauna Loa's southwest rift zone on DAY 3 of this trip (STOP 3-4).

Mauna Loa's northeast rift zone produced the volcano's most recent eruption in 1984 (Figure 6). A series of fountain events emanated from fissures, starting near the summit and continuing progressively down Mauna Loa's northeast flank about 2 km. Lava flows from this 22-day eruptive episode flowed eastward to within ~5 km of Hilo. The total volume of lava produced was about 220 m^3 (0.220 km^3) (Hawaiian Volcano Observatory, 2004B). Numerous other eruptions have originated from Mauna Loa's northeast rift zone during the 19^{th} and 20^{th} centuries, and several will be observed on DAY 4 of this trip (STOPS 4-4 and 4-5).

Kīlauea has also produced numerous rift zone eruptions during historical time. There were southwest rift zone eruptions in 1823, 1868, 1919, and 1974. All but the 1919 eruption were of short duration (<1 day to a few days), whereas the 1919 eruption lasted for 221 days and produced 45.3 million m^3 (0.453 km^3) of lava (Rubin, 2005).

Kīlauea's east rift zone has been the site of mostly continuous eruptive activity since 1983. The eruption began mid-way down the east rift zone and eventually localized and formed Puʻu ʻŌʻō cone. Lava flowed downslope to the south and entered the ocean, destroying several structures in the process, including many homes in the Royal Gardens subdivision and a National Park Visitor Center. In 1986, the main vent shifted 3 km down rift and formed the Kūpaianaha lava shield, with lava also flowing to the southern coast. In 1992, the activity shifted back to Puʻu ʻŌʻō and erupted from this location until 2007 (Hawaiian Volcano Observatory, 2008). At the start of the summer of 2007, flows erupted from a series of fissures just east and down-rift of Puʻu ʻŌʻō on the east rift zone. These flows and the resulting lava tubes eventually reinvaded Royal Gardens, forcing final abandonment, and reached the sea to form new ocean entry points down slope from the subdivision (Figure 7). Details of these eruptions will be discussed in a later section of this field guide.

The relationship between rift zones and the movement of magma along them is important. One might argue that flank eruptions from rift zones occur because magma passively flows in the subsurface along rift structures until piercing the volcano's flank. However, Swanson et al. (1976) suggest that magma movement into the east rift zone of Kilauea is by forceful injection, *causing* rift widening, rather than passive movement *caused by* rift

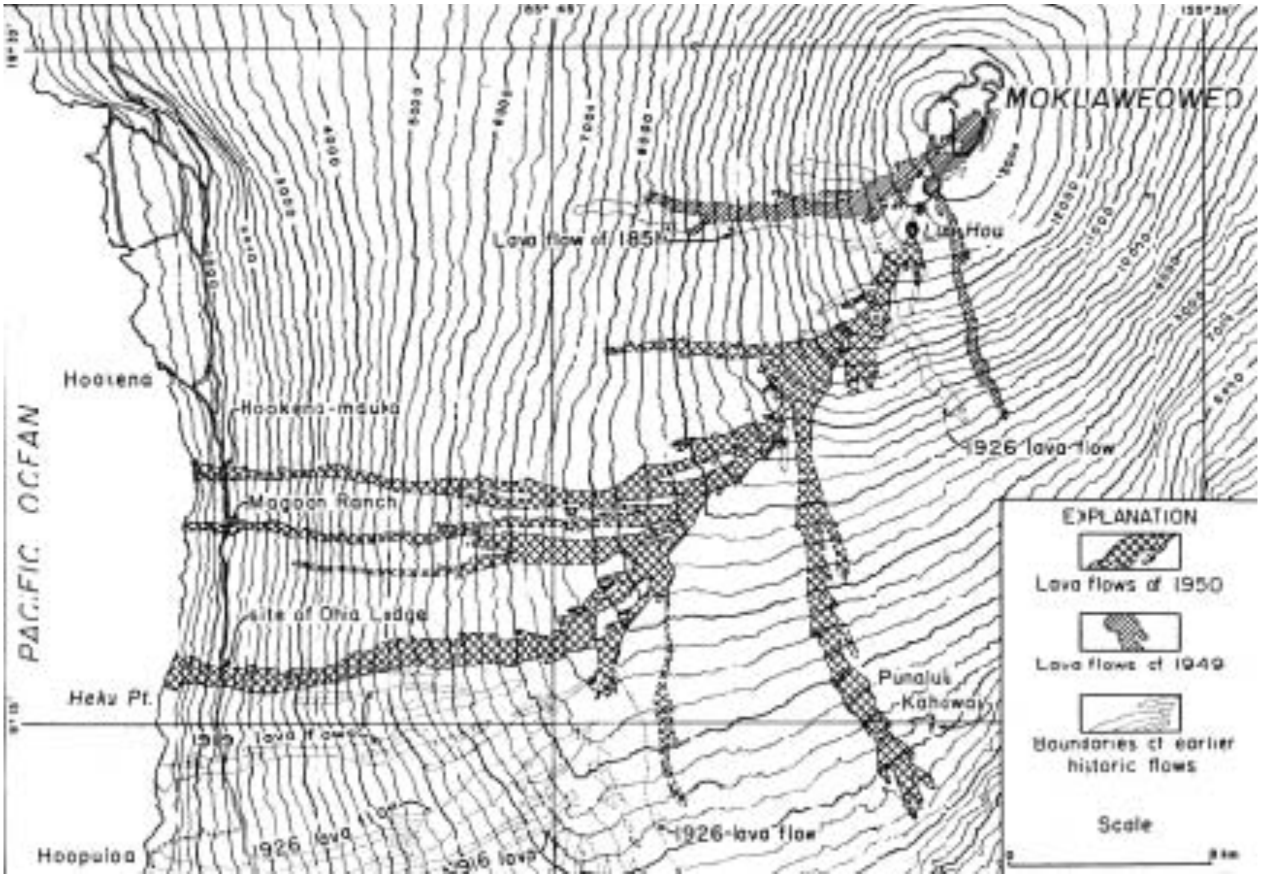

Figure 5. *Map showing the aerial extent of the 1950 lava flows from Mauna Loa's southwest rift zone (Hawaiian Volcano Observatory, 2004A).*

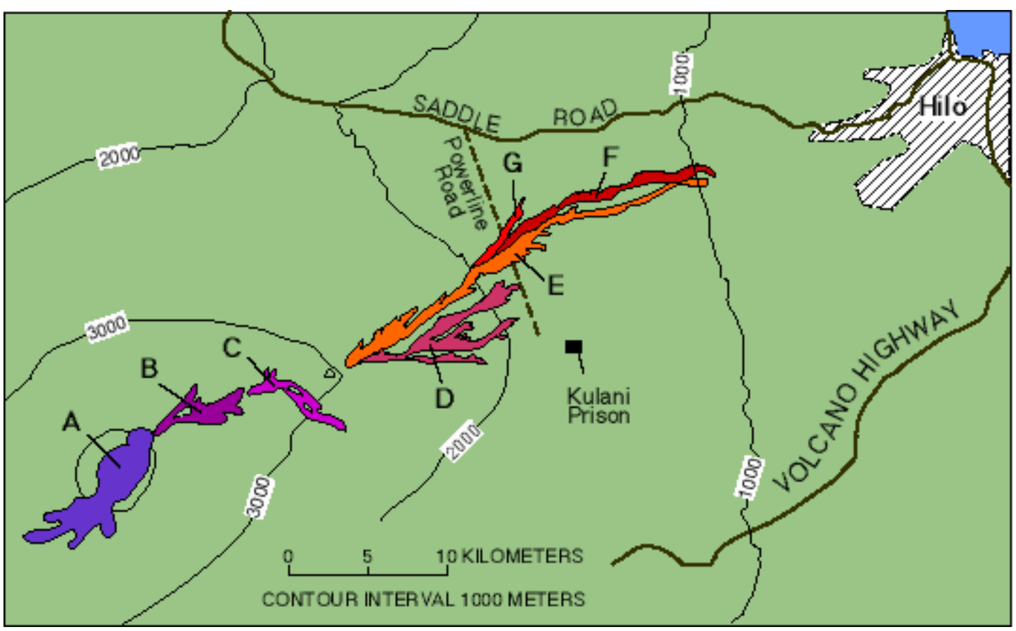

Figure 6. *Map showing aerial extent of 1984 lava flows from Mauna Loa's Northeast Rift Zone (Hawaiian Volcano Observatory, 2004B).*

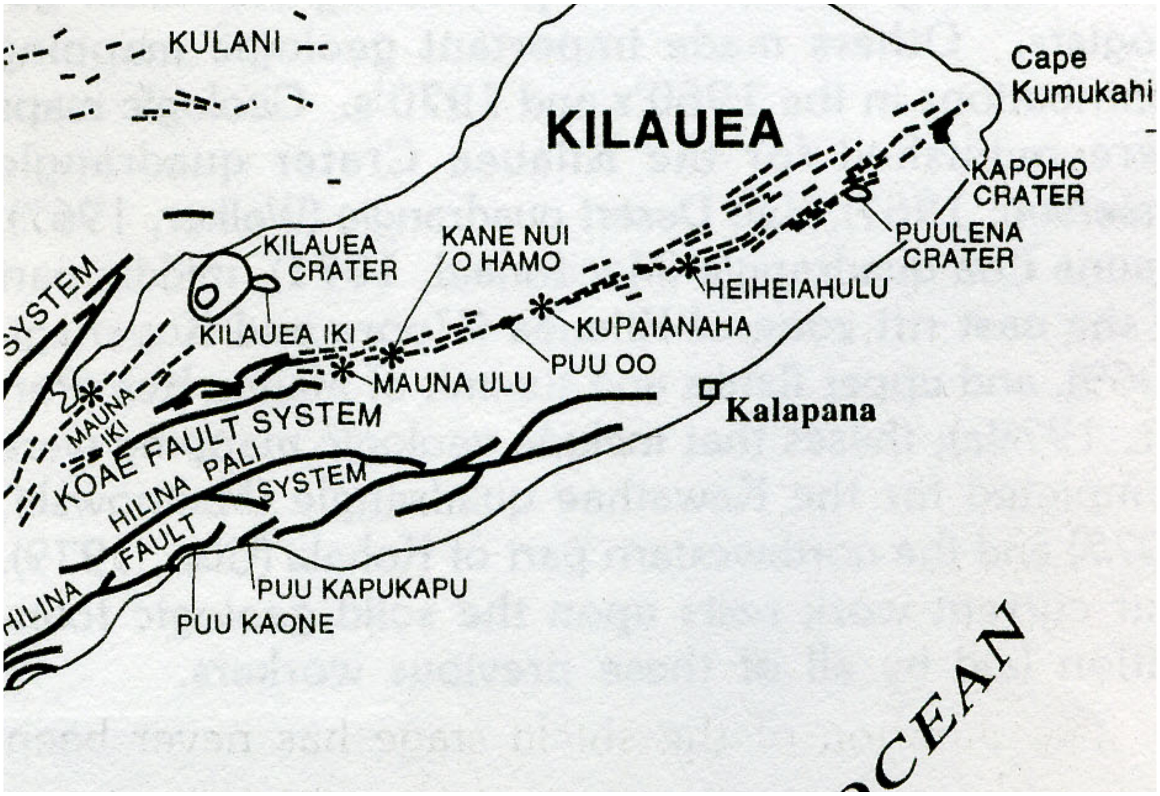

Figure 7. The Hilina fault system of the southern flank of Kilauea volcano (Wolfe and Morris, 1996).

opening. This theory is supported by seismic and geodetic evidence. Tectonic movement of the southern flank, accompanied by seismic events, occurs shortly *after* the intrusion of magma along rift structures, indicating that magma intrusion is forceful rather than passive (Swanson et al., 1976). In general, the southern flank of Kilauea has been displaced upward and away from the rift zones (southward) by several meters during the 20th century, while the north flank is unmoving, as it is buttressed by Mauna Loa. There are examples, however, in which magma may be passively injected. Apparently both forceful and passive injection are real processes; both are manifestations of the gravitational stress system that controls the development of the rift zones.

The Koaʻe fault system (Figure 7) is a very interesting series of east-west tensional structures extending across the southern flank of Kīlauea, connecting the southwest and east rift zones. The east rift zone extends from Kīlauea's summit caldera in a southeasterly direction for about 6 km to Pauahi Crater, where it bends eastward and continues down the flank of Kīlauea out to sea and still farther along the sea floor. The Koaʻe fault system joins Kīlauea's east rift zone at this bend, and is probably the result of the seaward displacement of the southern flank of Kilauea. We will visit the Koaʻe fault system on DAY 2 (STOP 2-4) of this field trip. Look for evidence that this has been one of the world's most active fault zones over the last several centuries.

The Hilina fault system is seaward of the Koaʻe and is an assemblage of gravity faults that downdrop the coastal region of Kīlauea. During major south flank earthquakes, such as the M 7.2 earthquake on November 27, 1975, faults in the Hilina system slipped and are at least partly responsible for subsidence of the coast line by several meters.

Stratigraphy of Kīlauea, Mauna Loa, and Mauna Kea

Throughout this trip, many of stratigraphic terms and geologic map rock units of Kīlauea, Mauna Loa, and Mauna Kea will be referenced. A synopsis for each volcano follows.

<u>Kīlauea</u>: Table 3 below summarizes the primary stratigraphic units of Kīlauea volcano. Kīlauea has three primary stratigraphic units. From oldest to youngest, these are the Pleistocene Hilina Basalt (>23 ka), the Pleistocene Pāhala Ash (estimated to be ~23 ka), and the Holocene and Pleistocene Puna Basalt (<10 ka B.P.) (Wolfe and Morris, 1994).

	Puna Basalt (Holocene & Pleistocene)	
Historic, C.E. 1790 our younger	p5	
200-400 yr B.P.*	p4	p4y
400-750 yr B.P.*		p4o
750-1,500 yr B.P.*	p3	
1,500-3,000 yr B.P.*	p2	
3,000-5,000 yr B.P.*	p1	p1y
5,000-10,000 yr B.P.*		p1o
23,000-30,000 yr B.P.*	**Pāhala Ash (Pleistocene)** Pha	
>23,000 yr B.P.*	**Hilina Basalt (Pleistocene)** hi	

*Ages in ^{14}C years

Table 3. *Summary of the stratigraphy of Kīlauea volcano (simplified from Wolfe and Morris, 1996). Letter and number symbols are geologic map units (y=younger, o=older).*

The Pleistocene Hilina Basalt consists of tholeiitic ‘a‘ā and pāhoehoe lava flows exposed mostly on the southern flank of Kīlauea in kīpuka (areas of land completely surrounded by younger lava flows). The basalt may be either aphanitic or porphyritic, with phenocrysts of olivine, plagioclase, or pyroxene. This unit also includes tephra layers up to 4 m thick, and palagonitic interflow soil horizons (Wolfe and Morris, 1996).

Stratigraphically complex, the Pleistocene Pāhala Ash unit is comprised of deeply-weathered primary and reworked tephra deposits found throughout the island. The deposits are thought to have erupted from Kohala, Mauna Kea, Mauna Loa, and Kīlauea, with the source determined by the relative geographic position downwind of these volcanoes. On Kīlauea, the unit separates the Hilina Basalt from Puna Basalt, and averages 15 m in thickness (Wolfe and Morris, 1996). The ash age for various localities around the island varies, but on Kīlauea, two charcoal samples from beneath it indicate a date of 23 ka.

Overlying the Pāhala Ash, the Holocene and Pleistocene Puna Basalt is comprised of ‘a‘ā and pahoehoe lava flows, tephra deposits, scoria, spatter, and littoral deposits. This unit includes all deposits on Kīlauea from 10 ka to present (Wolfe and Morris, 1996). Some lava flows have basalts with olivine phenocrysts up to 0.5 cm. The Puna Basalt accounts for a significant resurfacing of Kīlauea, more than 75 percent, and includes numerous historical flows from Kīlauea’s caldera and southwest and east rift zones.

Just this year, Fiske et al. (2009) introduced the Uwēkahuna Ash as a separate formation. It occurs primarily in the summit region of Kīlauea, where it is interbedded with the Puna Basalt.

Mauna Loa: Table 4 summarizes the stratigraphic relationships of Mauna Loa, which has four primary stratigraphic units. From oldest to youngest, these are the Pleistocene Nīnole Basalt (200-100 ka), the Pleistocene Kahuku Basalt (>30 ka), the Pleistocene Pāhala Ash (>30 ka), and the Holocene and Pleistocene Ka‘ū Basalt (Wolfe and Morris, 1996).

	Ka‘ū Basalt (Holocene & Pleistocene)	
Historic, C.d. 1790 our younger	k5	
200-400 yr B.P.*	k4	
400-750 yr B.P.*		
750-1,500 yr B.P.*	k3	
1,500-3,000 yr B.P.*	k2	
3,000-5,000 yr B.P.*	k1	k1y
5,000-10,000 yr B.P.*		k1o
> 10,000 yr B.P.*	k	
23,000-30,000 yr B.P.*	**Pāhala Ash (Pleistocene)** Pha	
>30,000 yr B.P.	**Kahuku Basalt (Pleistocene)** kh	
Prob. 200,000-300,000 yr B.P.*	**Nīnole Basalt (Pleistocene)** n	

*Ages in ^{14}C years

Table 4. *Summary of the stratigraphy of Mauna Loa volcano (simplified from Wolfe and Morris, 1996). Letter and number symbols are geologic map units (y=younger, o=older).*

The Nīnole Basalt consists of numerous tholeiitic ‘a‘ā and pāhoehoe basalt flows exposed on steep slopes on Mauna Loa’s southeastern flank. Age dates are not precise and range from 100-200 ka but may be as old as 300 ka (Wolfe and Morris, 1996).

Overlying the Nīnole Basalt is the Pleistocene Kahuku Basalt, which consists of tholeiitic lava flows older than 30 ka. It is generally exposed along steep slide and fault scarps, such as Pali Kapu o Keōua south of Kailua-Kona (pali "cliff"), and the Pali Ha‘uke‘uke near South Point, both of which will be seen on this trip (STOPS 3-5 and 3-7).

Pleistocene Pāhala Ash on Mauna Loa is typically exposed in kīpuka (an older land surface surrounded by younger lavas) on the southeastern flank of the volcano and overlies the Kahuku Basalt. It may be as thick as 10 m, and a radiocarbon age date near Na‘alehu indicates a minimum age of 30 ka in this area (Wolfe and Morris, 1996).

On Mauna Loa the Holocene and Pleistocene Ka‘ū Basalt overlies the Pāhala Ash. It consists of tholeiitic ‘a‘ā and pāhoehoe flows, scoria, spatter, littoral deposits, and tephra ranging in age from >10 ka to present. It accounts for a resurfacing of most of Mauna Loa volcano and includes historical flows at

Mauna Loa’s Moku’aweoweo summit caldera and southwest and northeast rift zones.

Mauna Kea: Table 5 summarizes the stratigraphy of Mauna Kea volcano, which has two major stratigraphic units. From oldest to youngest, these are the Pleistocene Hāmākua Volcanics (~250-200 ka to ~70-65 ka) and the Holocene to Pleistocene Laupāhoehoe Volcanics (~65-4 ka) (Wolfe and Morris, 1996).

	Laupāhoehoe Volcanics (Holocene and Pleistocene?)	
Possible age range 4-14 ka	Younger Volcanic Rocks Member	ly
~14-40 ka	Makanaka Glacial Member	lmt (till) lmo (outwash)
~14-65 ka	Older Volcanic Rocks Member	l
	Hāmākua Volcanics (Pleistocene)	
~70 ka	Waihū Glacial Member	hmw
65-70 to 200-250 ka	Basalt	hm

Table 5. *Summary of the stratigraphy of Mauna Kea volcano (modified from Wolfe and Morris, 1996). Lettered symbols are geologic map units.*

Two members are present in the Pleistocene Hāmākua Volcanics. The older Basalt member consists of basalt lava flows and scoria cones of alkalic and transitional composition, as well as an unmapped glacial till known as the Pōohakuloa Glacial Member (Wolfe and Morris, 1996). The Basalt member dates between ~250-200 ka to ~70-65 ka. The younger member of the Hāmākua Volcanics is the Waihū Glacial Member, which is composed of glacial drift found on the slopes of Mauna Kea between the elevations of ~3,240 and 2,720 m (~1,000-1,500 m downslope from the summit) (Wolfe and Morris, 1996). It consists of a massive to crudely stratified diamict composed of subangular to subrounded clasts of basalt from the Hāmākua Volcanics, and gravel, which is stratified and sorted and composed also of Hāmākua Volcanics basalt clasts.

The Holocene and Pleistocene Laupāhoehoe Volcanics has three members. The oldest is the Pleistocene Makanaka Glacial Member, dating between 40-14 ka (Wolfe and Morris, 1996). This member consists of a glacial till diamict with angular to sub-rounded hawaiite or mugearite clasts up to 2 m in diameter and glacial outwash deposits containing subrounded to rounded clasts of the same materials. The clasts originate from the Older Volcanic Rocks Member of the Laupāhoehoe Volcanics (Wolfe and Morris, 1996). The Makanaka deposits are found higher on the slopes of Mauna Loa than the Waihu Glacial Member, between ~4,000 and 3,200 m in elevation. The Holocene and Pleistocene Older Volcanic Rocks Member consists of hawaiite and mugearite lava flows, scoria cones, and tephra deposits, as well as benmoreite lava flows and scoria cones dating at between ~65-14 ka. The youngest member of the Laupāhoehoe Volcanic Rocks is the Younger Volcanic Rocks Member, which also consists of hawaiite and mugearite lavas, scoria cones, and tephra that are post-glacial and date between 14-4 ka.

Kīlauea Eruptive Activity—The past 1000 years

Volcanic activity on Kīlauea has been notable and diverse in the past 1000 years, which happens to be the time that people have been in this part of Hawai'i Island. Consequently, the interplay between volcanic activity and culture has led to a rich oral tradition appreciated today by many Hawaiians (Swanson, 2008).

At Kīlauea's summit, eruptions began in about 1000 CE that eventually filled an old caldera (the Powers' caldera) and built a shield (the Observatory shield). By about 1400 CE, the summit of the shield was probably 100-150 m higher than today's high point on the caldera rim. Lava flows spread into adjacent forest and were controlled by the deity 'Ailā'au ("forest eater"). In about 1410 CE, the eruption of the largest lava flow known on either Kīlauea or Mauna Loa began from a vent near Thurston lava tube.This eruption, termed the 'Ailā'au eruption, produced 5-6 km^3 of lava in about 60 years and covered most of Kīlauea north of the east rift zone (Clague et al., 1999). This eruption is remembered in chants as the result of Pele's anger at her sister Hi'iaka for taking too long to return from Kaua'ī with Pele's lover, Lohiau (Emerson, 1915; Swanson, 2008).

Kīlauea's modern caldera formed immediately following the 'Ailā'au eruption—and may have caused the end of the eruption. Geologic evidence (a pure reticulite deposit around the caldera and subsequent phreatomagmatic eruptions) further described at STOP 1-2 indicates that the caldera was very deep, perhaps more than 600 m, just after it formed. Hawaiian oral tradition supports this interpretation; as Hi'iaka dug the caldera to recover the body of Lohiau, who was killed by Pele for making love with Hi'iaka, she was warned not to dig too deeply or water could come in to put out Pele's fire. Today's water table is some 515 m below the current caldera floor, so Hi'iaka probably dug about that deeply.

Between 1500 and the early 1800s, most volcanic activity occurred in the caldera, but several small eruptions took place outside it, notably along the lower east rift zone. Most of the caldera eruptions during that time were explosive, mainly phreatomagmatic, producting the Keanakāko'i Tephra. At least three of these explosive eruptions were powerful enough to sent eruption columns into the jet stream. One of these events is remembered by a story about Pele throwing rocks to chase away an erstwhile suitor, Kamapua'a (Ellis, 1825). Another of these powerful explosive eruptions was associated with surges that killed scores of people in November 1790, decimating the forces of Keōua, a rival of Kamehameha, and leading to Kamehameha's ascendancy to king of all of Hawai'i—an event of extreme importance in subsequent dealings between the kingdom and western world.

The last explosive eruptions were in the early 1800s. Since then, the caldera has been filled by eruptions from several vents, chiefly Halema'uma'u. When first described in writing by Rev. William Ellis in 1823, the caldera floor was about 400-450 m below HVO; now it is 120 m. The filling was chiefly done before 1921, but flows as young as 1982 occur on the surface. During this time, relatively few eruptions took place along the rift zones. One notable one was from the Great Crack on the southwest rift zone just before Rev. Ellis' visit in 1823. Another large eruption occurred from the middle and lower east rift zone in 1840. Smaller eruptions were on the southwest rift zone in 1868 and the east rift zone in 1922 and 1923.

In May 1924, phreatomagmatic explosions burst from Halema'uma'u, killing one observer and doubling the width of the crater to its current 1 km. The explosions were triggered by the disappearance of a lava lake in Halemaʻumaʻu, which had been a fixture of the crater for most of the time since at least 1823. Apparently the floor of Halemaʻumaʻu dropped to the water table or below, and groundwater poured into the emptied conduit, flashed to steam, and drove the explosive activity.

Kīlauea went into a lull thereafter, with only brief eruptions in Halemaʻumaʻu until 1952, when a lava lake formed in the caldera. Two pairs of summit-lower east rift zone eruptions followed, one in 1954-55 and another in 1959-60, the latter associated with 580-m fountains in Kīlauea Iki. Through the 1960s, eruption after eruption took place in Halemaumau and along the east rift zone, culminating in the Mauna Ulu eruption (1969-1974). Several smaller eruptions occurred along the upper east rift zone, in the caldera, and the upper southwest rift zone in 1973-74.

A M 7.2 earthquake beneath Kīlauea's south flank on November 27, 1975 was followed by a couple years of quiet before other east rift zone eruptions of 1977 and 1979. Two eruptions occurred in the caldera in 1982, and then the ongoing Puʻu ʻŌʻō-Kūpaianaha eruption started on January 3, 1983. This eruption, the longest and most voluminous since the ʻAilāʻau eruption in the 1400s, has dominated Kīlauea for almost 27 years (Heliker et al., 2003), and it continues to pour lava into the ocean at this writing. As of August 2009, flows have covered >120 km^2 with about 3.4 km^3 of lava, destroying 202 buildings (mostly houses) and adding about 195 hectares (481 acres) in the form of lava deltas extending the shoreline. The Puʻu ʻŌʻō-Kūpaianaha eruption has continued apace during the 2008-present eruption in Halemaʻumaʻu.

The Hawaiian Archipelago and Species Diversity

As stated in the introduction, the Hawai'ian Islands are one of the most isolated sets of islands in the world with respect to proximity (or lack thereof) to major continental land masses (Table 1). It is this geographic isolation that has lead to the development over time of numerous *endemic* species in the Hawaiian Islands, those found nowhere else in the world.

A detailed assessment of the number of species in the Hawaiian Islands by Eldredge and Evenhuis (2003) found that ~50% of the >20,000 non-extinct native marine and terrestrial species in Hawaiʻi are endemic. Geologic processes on a variety of scales (global to local) have greatly influenced species diversity and distribution within the Hawaiian Islands. As submarine volcanic processes build a seamount to form a subaerial volcano, the island soon becomes accidentally inhabited by *founder species*, those that arrive by "wind, wings, or water" from distant locations. Over time, these species evolve into new ones that are well adapted to their new island environment, thus forming numerous endemic species. However, the ~10 Ma time frame (based on the age of the oldest islands in the Hawaiian chain) for evolution to bring about the diversity of species in the Hawaiian Islands today is insufficient (Eldredge and Evenhuis, 2003), but the subaerial exposure of Hawaiian-Emperor volcanoes dates back at least 82 Ma, providing sufficient time. The influence of Hawaiian geologic processes on species diversity and distribution will be an interesting component of this field trip. This theme henceforth will be known simply as *geology rules!*

II. FIELD LOG

WEDNESDAY, SEPTEMBER 16
ARRIVAL IN HILO, HAWAI'I

Suggestion to participants: make every effort to get a window seat on the right side of your flight into Hilo, as this will afford an excellent view of four of the Big Island's five shield volcanoes during the approach (Map 3), as well as the heavily eroded northeastern slopes of Mauna Kea with its many waterfalls.

5:00 PM Meet trip leaders at Hilo airport baggage claim area. Aloha and E Komo Mai! Load into vans and depart airport.

6:00 PM Stop for dinner in Hilo.

8:00 PM Check into dormitories at Kīlauea Military Camp (KMC).

DAY 1: THURSDAY, SEPTEMBER 17
CRATER RIM DRIVE

7:00 AM Breakfast at the KMC cafeteria.

8:00 AM Morning briefing—KMC dormitory porch (30 minutes).

8:30 AM Depart for the field.

From KMC, proceed east (left) from KMC clockwise on Crater Rim Drive about 1.2 miles to Hawai'i Volcanoes National Park Visitor Center.

9:00 AM Hawai'i Volcanoes National Park Visitor Center (30 minutes).

Here we will spend a few minutes getting oriented and then move on to our geologic stops. This is an excellent opportunity to purchase relevant maps and literature. Below are suggested purchases.

Maps:

- Hawai'i Volcanoes National Park, Hawai'i
- Map of Hawai'i The Big Island

Literature:

- Hazlett, R.W., 2002, Geological Field Guide Kilauea Volcano, Hawai'i Natural History Association, 162 p.
- Eldredge, L. G., and Evenhuis, N. L., 2003. Hawaii's biodiversity: a detailed assessment of the numbers of species in the Hawaiian Islands, Bishop Museum Occasional Papers No. 76, p. 1–28.
- Ellis, William, 1825, Narrative of a tour through Hawaii, or Owhyhee. H. Fisher, Son, and P. Jackson, London, 264 p. Reprinted 2004 by Mutual Publishing, Honolulu. (*Highly recommended for its ethnography and colorful writing. Available in park bookstores for under 10 bucks.)*

Proceed back to the west (counterclockwise) along Crater Rim Drive towards KMC about 0.7 miles. Pull into the parking area on the south (left) at Steam Vents.

Note: each stop is numbered according to the Day number and the vehicle stop number for that day. Stops with letter designations (such as STOP 1-1A & STOP 1-1B) are separate localities at a given vehicle stop accessed by foot without returning to the vehicles and driving.

10:00 AM Steam Vents (10 minutes).

STOP 1-1A: VOLCANIC FUMEROLES

Observe the steaming ground cracks at the parking area. These fumaroles are spewing meteoric waters that have been heated by shallow magma under the caldera. These vents have not recently formed, but have existed for decades, an indication of their relative stability, at least within this time frame. What is the component of magmatic gases they are venting, and why are these vents found concentrated in this area?

Standing in the area of the vents, one may notice that the Hawaiian vegetation is sparser here than a short distance (a few hundred meters) away. This meadow is here because of the influence of hot, acidic groundwater on soil characteristics and vegetation, especially larger, deep-rooted trees and plants. This is our first example of "*geology rules*," as geologic processes of Kīlauea influence the distribution of life here.

From the parking area, walk along the path to the south a hundred meters or so to the bluff overlooking Kīlauea's caldera.

10:15 AM Kīlauea's caldera (20 minutes).

STOP 1-1B: OVERVIEW OF KĪLAUEA CALDERA (OPTIONAL)

From here, on a favorable day, we have an excellent view of Kīlauea's caldera and beyond. To the west (right), there may be a splendid view of the eastern edifice of Mauna Loa volcano, showing its "long mountain" profile, the English translation of its Hawaiian name.

To the southwest, Hawaiian Volcano Observatory (HVO) and Jaggar Museum on Uwēkahuna Bluff can be seen. This will be our next stop.

To the south, the crater of Halemaʻumaʻu may be visible within Kīlauea's caldera. A vent in its east wall began steaming in March of 2008; it has also produced several small explosions of steam and tephra. The thermal webcam on the rim of Halemaʻumaʻu has shown cycles of filling and drainback of a lava within the vent.

The southwest rift zone of Kīlauea may be visible in the distance beyond Halemaʻumaʻu. It extends from the southwest rim of Kīlauea's caldera for about a dozen kilometers to the southern shore of the Big Island and perhaps beyond. We will visit a portion of this rift zone on DAY 3 (STOP 3-1).

Kīlauea's southwest rift zone lies within an area known as the Kaʻū Desert. This is not a true desert as defined as area of low precipitation (it receives more annual rainfall than does Seattle), but is referred to as a desert because of its relative lack of vegetation as compared to other parts of Kīlauea. This is due, in part to the reduced amount of rainfall on the leeward side of Kīlauea relative to the northeast trade winds, and to the dispersal of volcanic fumes (VOG) downwind from Kīlauea's summit. We will discuss these factors further on DAY 3 (STOP 3-1).

To the southeast (left) is the crater of Kīlauea Iki and the cinder cone Puʻu Puaʻi, both of which will be observed from a closer vantage point later today (STOP 1-3). Kīlauea's east rift zone extends from about there to the southeast for about 6 km before bending eastward and continuing out to sea beyond Cape Kumukahi at the island's southeastern tip.

Directly to the east (left) is the historic Volcano House Hotel, perched on the rim of Kīlauea's caldera.

We are standing on the rim of Kīlauea's caldera, which is about 3 x 5 km in dimension and formed about 500 yr B.P. (to be discussed in detail at the STOP 1-2). Although similar in origin, a caldera by definition is greater than 1 mi in diameter, whereas a crater is smaller (we will visit several craters during DAY 1 and DAY 2 of this trip). The floor of Kīlauea's caldera is covered with numerous Puna Basalt lava flows erupted over the last centuries (Figure 8). The caldera is comprised of a series of circumferential ring faults that have produced a series of step-like half-graben benches extending down to the caldera floor. These are especially evident below HVO and Volcano House.

One important aspect of Kīlauea's caldera to ponder from this vantage point is the distinction between its *topographic* and the *structural* margins. Here, we are standing on the topographic caldera rim, but where is the structural margin of the caldera?

From here, walk back to the parking area, and then follow the path 0.4 miles to the east (right) to Sulphur Banks.

10:45 AM Sulphur Banks (30 minutes).

STOP 1-1C: FUMEROLES AT SULPHUR BANKS (OPTIONAL)

This appropriately named area is a further expression of the fracture system along the northern margin of Kīlauea's caldera. Obviously, we are no longer standing on the rim of the topographic caldera, but its structures are still evident here as sulfurous gases are emitted from ground cracks. This area was previously known as *North Sulfur Bank* as distinguished from *South Sulfur Bank* southeast of Halema'uma'u. The latter of these was covered with lava from Halemaumau by the late 1800s (Hawaiian Volcano Observatory, 2005C).

Careful close inspection of some of the vents reveals the presence of nice sulfur crystals that have precipitated directly from the sulfurous gases. Native sulfur deposits of volcanic origin have been commercially mined in Japan, New Zealand, and elsewhere (Kesler, 1994). Other mineral precipitates that may be found here include gypsum, opal, and hematite. Look closely for these.

Walk back to the vans at the parking area. Continue west (counterclockwise) around the caldera for 1.8 miles to Hawaiian Volcano Observatory.

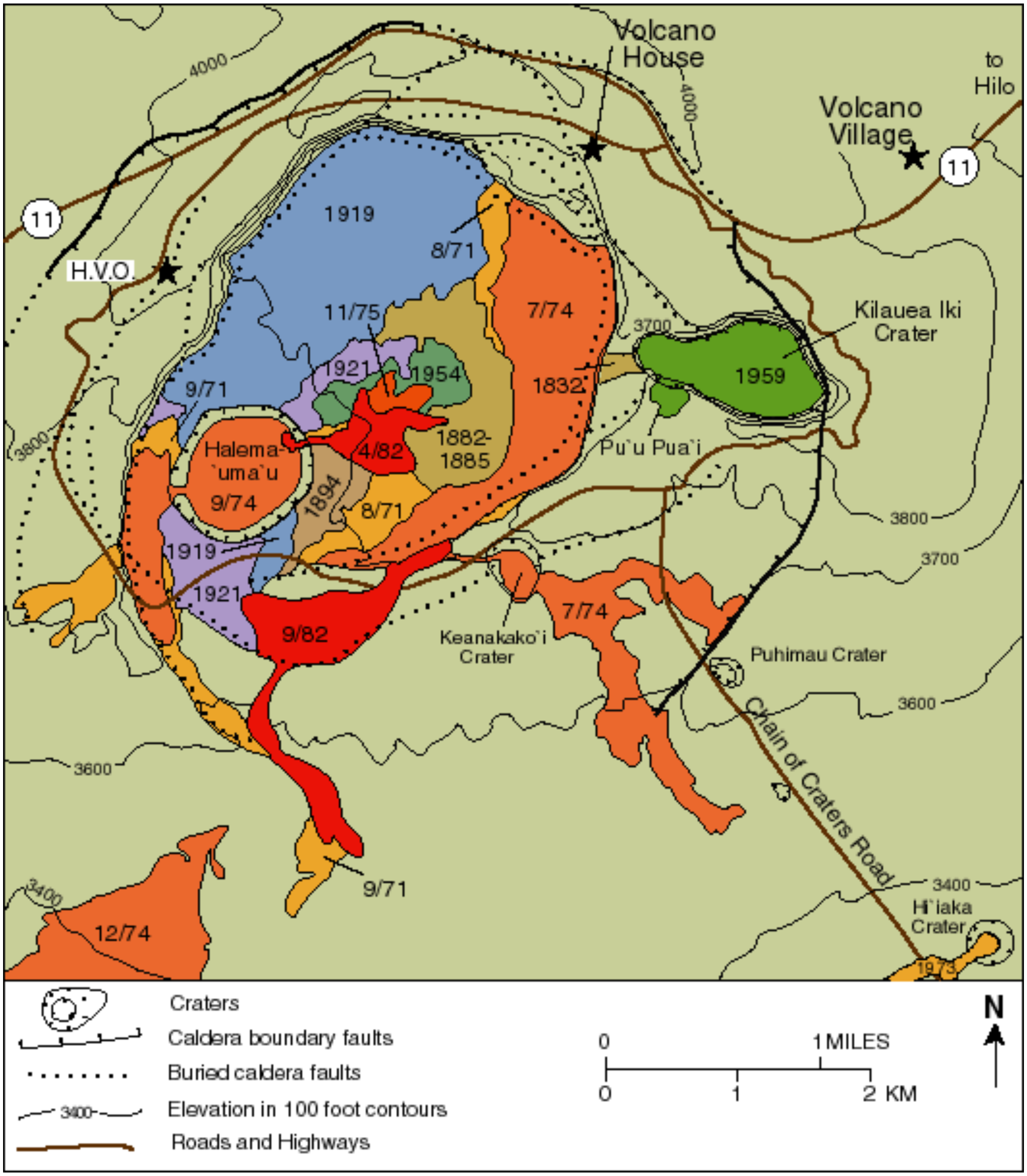

Figure 8. *Simplified geologic map of Kilauea caldera (Hawaiian Volcano Observatory, 2000B).*

11:30 AM USGS Hawaiian Volcano Observatory—Lunch (30 minutes).

12:00 PM USGS Hawaiian Volcano Observatory (60 minutes).

STOP 1-2: CALDERA VIEW FROM HAWAIIAN VOLCANO OBSERVATORY ON UWĒKAHUNA BLUFF

From Uwēkahuna Bluff, one can see most of the topographic expression of Kīlauea's caldera and its surroundings. The caldera floor today is about 120 m below HVO and is about 3 km wide. Halemaumau (or Halema'uma'u, depending on which Hawaiian oral tradition you accept), the home of the volcano deity, Pele, is the crater indenting the floor of the caldera and is about 1 km across.

A large pit crater, Kīlauea Iki, is directly across the caldera; the bare cone with an orange summit on its south side, Pu'u Pua'i, formed during a famous eruption in 1959 which created a lava lake in Kīlauea Iki. The horizon behind Kīlauea Iki shows the profile of the 'Ailā'au shield, which formed at the vent for Kīlauea's largest eruption, lasting about 60 years in the 15th century. We will visit these areas later today (STOP 1-4).

Across the caldera, just left of a line to Halemaumau, is Keanakāko'i Crater, and in the distance beyond Keanakāo'i is the bare lava shield of Mauna Ulu, built in 1969-74. Keanakāko'i can be thought of as the start of the east rift zone; Mauna Ulu is along the rift zone, at a big bend where it swings east-northeast and continues to and beyond the east tip of the island. The currently erupting area of Pu'u 'Ō'ō is 20 km from here beyond the 'Ailā'au shield, along the middle part of the east rift zone.

The southwest rift zone is poorly visible from our vantage point, but from the Jaggar Museum overlook several spatter and cinder cones are visible that trace the rift zone from near the caldera to the sea coast, visible on clear days. The most recent activity along the southwest rift zone was in 1974.

The caldera floor is underlain mainly by 20th-centuury lava flows; the youngest dates from September 1982 and is the gun-metal gray surface beyond the Halemaumau parking lot. Several patches of late 19th-century flows are preserved just east of Halemaumau. Pāhoehoe is the dominant flow type on the caldera floor, but patches of dark 'a'ā are present, particularly directly in front of us.

A "bath-tub" ring on the wall of Halemaumau denotes the high stand of a lava lake active in 1967-68. In September 1971, a fissure cut across the crater, and the still-molten part of the lake drained away, leaving a terrace. The white material below the terrace is mainly Ca and Mg sulfates precipitated as gas escaped along the contact of the lake and the crater wall before 1971. The crater floor visible today dates from 1974.

The fuming vent is the site of a small eruption that started on March 19, 2008 and continues to this writing (August 2009). This eruption, and the associated fume rich in SO_2, are the reasons that the national park had closed the road across the caldera.

William Ellis (1825), who made the first written account of the caldera on August 1, 1823, saw a vastly different scene, probably from about our vantage point. The caldera was about 450 m deep then, Halemaumau was filled with lava as were several other craters now buried, and lava was spilling from the lakes and spreading across the floor. Halemaumau became dominant in the late 1820s and thereafter erupted lava flows that largely filled the caldera in the late 19th and early 20th centuries. Technically, the caldera is full now, because lava flows in 1971 and 1982 spilled out of the caldera through a gap in the low south rim. However, lava isn't as fluid as water, and eruptions during the next few centuries or less will fill the depression below us and build a new summit shield that will eventually collapse to form a future caldera.

The modern caldera first formed about 500 years ago, as deduced from field work during the past decade; it was previously considered to have formed in 1790, the year of a large explosive eruption assumed to be related to caldera formation. However, tephra ^{14}C-dated at about 1,500 CE coats the wall of the caldera in a few places, and the wall cuts across the ‘Ailā‘au shield last active in about 1470 CE; thus the formation of the caldera is neatly placed in the ca. 1470-1500 CE period. This date is consistent with Hawaiian chants (Swanson, 2008). Since then, there could well have been periods when inner parts of the caldera dropped down—1790 may be such a time—but the main outline of the caldera was established about 500 years ago.

The caldera exists because it is directly above the magma conduit that carries magma up from the hot spot. The caldera apparently formed by collapse into an evacuated magma reservoir, doubtless complex, but the details are far from clear.

From HVO, walk to the Jaggar Museum.

1:00 PM Jagger Museum (30 minutes).

The patio outside the Jaggar Museum provides an excellent view of Kīlauea's caldera and Halema‘uma‘u crater, as already seen at STOP 1-2. The interpretive signs fall within the view of HVO's Halema‘uma‘u webcam, so if patient, your friends and relatives all around the world may see you on the internet.

From the patio viewing area, go inside the museum and take a few minutes to peruse the displays and make any desired purchases.

From HVO, drive clockwise back around the caldera to the Visitor Center and beyond. Turn south (right) just before the park entrance station to continue on Crater Rim Drive. Follow this for about 1.3 miles to Kīlauea Iki Overlook on the right and park.

1:45 PM Kīlauea Iki Overlook parking area (30 minutes).

STOP 1-3: KĪLAUEA IKI CRATER AND THE PU‘U PUAĪ ‘I LAVA FOUNTAIN OF 1959

The overlook here affords a nice view of Kīlauea Iki and Pu‘u Pua‘i. The age of Kīlauea Iki (Iki "small") is not known, though it was likely soon after the caldera collapsed. The floor of Kīlauea Iki lies about 120 m below the rim and is composed of lava erupted in 1959 from a vent below Pu'u Pua'i, the cinder cone visible on the southern rim of Kīlauea Iki. The 1959 eruption poured lava into the crater, forming a lake about 120 m deep. This lake was the site of extensive drilling programs, initially to track the cooling history of the lava (Helz, 2009) and then as part of Sandia's Hot Dry Rock project in the 1980s. The last liquid probably solidified in the latest 1980s. Look at the margins of the lava lake and note the system of circumferential fractures, indicating partial recession of the lava lake surface after it formed. This marginal subsidence terrace lies about 15 m above the crater floor.

<u>Suggested stay-over stop</u>: *the hike to the floor of Kīlauea Iki along Kīlauea Iki trial is highly recommended! The trailhead is across the*

road from Thurston Lava Tube and descends about 120 m to the floor.

Puīu Puaīʻi (“fountain hill”) cone (120 m in height) across Kīlauea Iki formed in 1959 as a result of spectacular lava fountains that at times reached 550 m or more in height, the highest eruption on record in Hawaiʻi (Richter et al., 1970). The eruption, which lasted about five weeks, originated from the reddish vent at its base near the crater floor, visible from here. The northeast trade winds carried pumice, spatter, and other airborne materials downwind to the southwest for up to 4 km, the coarsest of which accumulated on the SW rim of Kilauea Iki to form Puʻu Puaʻi. This fallout damaged the tropical forest in the area, and it has been allowed to recover naturally since the eruption.

Suggested stay-over stop*: a stroll along Devastation Trail south of Puʻu Puaʻi provides an opportunity to see the destruction and the natural recovery process.*

From here, continue clockwise on Crater Rim Drive another 0.3 miles to the Thurston Lava Tube area and park on the right.

2:30 PM Thurston Lava Tube (30 minutes).

STOP 1-4: LAVA TUBES AND THE CONSTRUCTION OF SHIELD VOLCANOES

Thurston lava tube formed during the 15th-century ʻAilāʻau eruption—the one that immediately preceded caldera collapse. The tube, also known at Nāhuku (“the protuberances,” from the stalactites and stalagmites that used to adorn the cave), is a good example of a tube formed by continued flow of lava for months or probably years.

Lava tubes result whenever crust develops on the surface of a flow and lava continues to move beneath the crust. Cooling against air forms crust on lava flowing in channels, just as ice develops on water rivers. The tubes are of various sizes, from a few centimeters to more than 10 m in diameter. Pāhoehoe toes are technically tubes, because lava moves through them under a crust. A collection of pāhoehoe toes forms a complex of small and, by coalescence, large tubes.

The main entrance to Thurston lava tube is in the wall of a small collapse crater that cut across the tube; the date of the collapse is not known. The lighted segment of the tube shows evidence of deepening caused by thermal erosion, a high stand of the last lava that flowed through it, accretionary coating of the walls by lava, and many other features.

Lava tubes are fundamental features in the construction of Hawaiian shields. They thermally insulate flowing lava, thereby allowing the lava to move long distances and hence to develop the shallow slopes characteristic of shields. During the Puʻu ʻŌʻō eruption, studies found that lava flowing in tubes cools only about 0.7°C per km of travel. Lava tubes are not curiosities but are instead integral parts of a shield.

Lava tubes are important culturally as well as geologically. They served as living quarters, burial grounds, water-catchment systems (from drips from the roof), and places of refuge during times of strife.

Lava tubes are also interesting Hawai’ian ecosystems, so once again, *geology rules*. At least 95 endemic species of invertebrates make Hawaiian lava tubes their homes (Zeigler, 2002). Such species, especially the 75 that live exclusively in lava tubes, must have evolved from species that lived close by on the surface or within the same lava tube. Once evolved, dispersal to other islands, or even distant lava tubes on the same island, would be impossible.

What is the source of energy for the lava tube ecosystem? Some fungi act as decomposers and can thrive in complete darkness, and can then serve as food for others. Organic detritus blown in from skylights may provide some nutrients for inhabitants. On occasion, birds or animals may enter lava tubes and become trapped, and their remains after death provide a source of nutrients for the ecosystem. However, interestingly, *photosynthesis* is the primary energy input into the lava tube ecosystem, even in complete darkness! This occurs because tree roots, especially those of ōhiʻa lehua trees, may penetrate through as much as 10 m of roof, piercing the tube ceilings and providing a source of food for the subterranean dwellers (Zeigler, 2002).

Common lava tube inhabitants include various species of insects, spiders, centipedes, and millipedes (Zeigler, 2002). Adaptations to this dark, moist, and gaseous environment include blindness, highly sensitive vision, flightlessness, and pale colors.

As these lava tubes have created a unique ecosystem and influenced Hawaiian species evolution, herein lays another example of "*geology rules*!"

Continue clockwise on Crater Rim Drive. Proceed about 1.4 miles and turn left onto Chain of Craters Road. Proceed down this road for 0.4 miles to Lua Manu Crater. Park on the right.

3:30 PM Lua Manu Crater and the 1974 Lava Flow (90 minutes).

STOP 1-5: TREE MOLDS (LAVA TREES), PIT CRATER, AND SPATTER RAMPARTS NEAR LUA MANU CRATER

Note the young lava in the crater and the buried iron railing of a former overlook just below us. Then walk several tens of meters up the road and enter a narrow lava channel on the left. Follow a faint trail as far as the tree molds area.

An eruption in July 1974 took place from fissures in thick forest, mainly ʻōhiʻa lehua (*Metrosideros polymorpha*), a member of the myrtle family, the tree with the red, bottle-brush-like blossoms. Some of the lava cascaded from the fissure system into Lua Manu and buried the old overlook. Most of the lava, however, flowed westward, leaving hundreds of tree molds and lava trees when lava quenched against trees and then subsided or flowed away. The tree molds and lava trees are the best that can be easily reached in the park; they've been shown on a National Geographic special, so they must be good! The unburned trunk of an ʻōhiʻa lehua is preserved in one of the tree molds and provides clear evidence for how tree molds form. Inclined flanges on the sides of several molds indicate the direction that lava was flowing as it drained down slope, exposing the molds. We will also visit fissures and a spatter rampart or cone, the inner part of which slumped away either late in the eruption or just after its end.

Finally, we will observe the deleterious effect of the recently introduced faya (*myrica faya*) tree from the Azores on the native forest, particularly the ʻōhiʻa lehua. Sadly, future geologists will be able to date lava flows as pre- or post-faya by the nature of the tree molds.

Return to KMC by retracing the route to here.

6:00 PM Dinner at KMC cafeteria.

DAY 2: FRIDAY, SEPTEMBER 18
CHAIN OF CRATERS ROAD

7:00 AM Breakfast at the KMC cafeteria.

8:00 AM Morning briefing—KMC dormitory porch (15 minutes). Be sure to bring a headlamp or flashlight for possible lava ocean entry viewing after dark.

8:15 AM Depart for the field.

From KMC, turn east (left) and drive clockwise on Crater Rim Drive all the way to its intersection with Chain of Craters Road. Turn south (left) and proceed 1.0 mile down the road to Puhimau Crater. Park on the left.

8:45 AM Puhimau Crater (15 minutes).

STOP 2-1: ANOTHER PIT CRATER (OPTIONAL)

Just before arriving at Puhimau Crater, the road ascends a gentle bluff. This shows up on topographic maps and aerial photos as a linear feature trending northeast-southwest through this area. Farther northeast, the elevation change along this scarp is about 10 m. It is of interest because in May 2007, several small earthquakes occurred in this area. This escarpment is the outermost fault of Kilauea's caldera.

Puhimau Crater ("always steaming") is a fine example of a Hawaiian pit crater. Note that the walls are virtually vertical and that the floor is covered with talus. Numerous such craters define the Chain of Craters along this portion of Kilauea's east rift zone, as we saw yesterday at Lua Manu. All such craters are relatively young (<500 years old B.P.); all but one (Devil's Throat) were here when European explorers arrived in the mid-1800s.

Puhimau Crater is 160 m deep, and its walls show an excellent cross-section of the numerous lava flows that formed this part of Kīlauea. According to Wolfe and Morris (1996), the floor of Puhimau Crater is composed of p3 Puna Basalt (750-1,500 years B.P.). This and other pit craters form not by explosions but by collapse into a void, probably created by the withdrawal of magma at depth as it flowed down the east rift zone. Intersecting fractures may play a role in the positioning of such craters.

From here, continue down Chain of Craters Road 0.2 miles. Park on the side of Chain of Craters Road just before the cattle guard (actually a pig guard), walk to the end of a track road, and then follow a faint trail through forest to the edge of the thermal area. Do not walk beyond the grassy area for reasons given below.

9:15 AM Puhimau thermal area (45 minutes).

STOP 2-2: VOLCANIC THERMAL AREA (OPTIONAL)

The Puhimau thermal area was discovered in early May 1938 as a 15-acre tangle of dead and dying vegetation in otherwise healthy forest. Tree kill was because of heat, with soil temperature measured as high as 83°C, compared to 19 °C in forest outside the area. A shallow intrusion within the previous year or two was considered the best explanation, and two geophysical studies in the mid-1980s corroborated the presence of a hot, perhaps partly molten, magma body within a few hundred meters of the surface. Recent work shows that the amount of CO_2 and SO_2 emitted from the area is low.

The thermal area began expanding in the early or mid-1960s. The area grew as shown by vertical aerial photographs: 1945, 15 acres; 1961, 15.7 acres; 1976, 20.8 acres; 1985, 29 acres. The current area is about 37 acres. It became visible from the road in the late 1980s and crossed the road in the late 1990s. Its expansion is in an east-northeast direction, parallel to fracture trends in the east rift zone.

Such expansion is hard to explain by an intrusion in the 1930s, and it is not swelling as if the intrusion is growing. What does correlate with the expansion is the pick-up in eruptive activity along the east rift zone in the early 1960s, continuing to the present. This suggests that heat may be escaping from the conduit carrying magma from the summit to the east rift zone. But why here? That question has no good answer, unless it is somehow associated with the putative intrusion.

The thermal area hosts a vulnerable plant species (*Portulaca sclerocarpa*) that the park is trying to bring back. The largest steam vent is used by some Hawaiians taking part in a cleansing ritual. For these reasons the area is sensitive. HVO would like to establish cross-lines with permanent marks for leveling and temperature monitoring, because a pit crater is a possible outcome of the intense thermal activity. The area's sensitivity, however, makes such studies controversial, and the park has taken a very conservative stance about scientific work here.

Return to the vehicles and continue down Chain of Craters Road for 1.1 miles. Park in the pullout opposite the spatter cone down the Chain of Craters Road from the Hilina Pali Road. Walk back up road nearly to the road junction and then follow faint trail on north side of road.

10:15 AM Devil's Throat (15 minutes).

STOP 2-3: ANOTHER INTERESTING PIT CRATER

Please exercise caution as there is no safety railing at the crater rim here, and tensional fractures occur near the edge in places!

Devil's Throat is the youngest pit crater on the east rift zone. It was not mentioned in print until 1909, is not shown on any older maps, and is the only crater that lacks a Hawaiian name. Its rapid evolution in the early 20th century further suggests its youth, probably no older than the late 1800s. The old trail used to pass right by the crater before the Chain of Craters Road was completed in the 1930s.

Early observers said that the opening of the crater was so narrow that a horse could jump across it. The opening had grown to about 10 m wide in 1923, when William Sinclair was lowered into the throat on a rope. He found the crater to have the shape of an inverted funnel. Fumbling in the darkness, he measured a depth of 78.5 m to the top of a talus pile, which itself was estimated as 10-12 m high; the total depth was therefore about 90 m. The long diameter at that depth, parallel to the rift zone, was about 61 m.

The opening widened markedly through the next 2-3 decades, as noted in photographs and sketches. Once jumpable by a horse, it would take Pegasus now. In 2006, Swanson used a small electronic distance meter to measure the two diameters as 50 m along the rift zone and 42 m perpendicular to that. By tape measure, the deepest point on the floor near the rim is 49 m, though the center of the crater is probably a few meters lower.

The increased width and decreased depth since 1923 are consistent with simple collapse of the overhanging wall of the inverted funnel, not with fundamental enlargement of the crater. This information was given to the park for use in its assessment of visitor safety.

Devil’s Throat is an excellent place to demonstrate a crater that formed by collapse. There is no ejecta rim around it. The thin tephra on the ground surface is part of the Keanakāko‘i tephra erupted from the summit long before the crater formed. All of Kīlauea’s pit craters similarly formed by collapse; no explosion crater is known on the volcano.

The relative paucity of vegetation near the crater may indicate the former presence of a mild thermal area. This would not be surprising, for thermal areas are present near many if not all of the pit craters along the east rift zone.

Walk to the car, drive a short distance back up Chain of Craters Road for 0.1 miles, and turn west (left) onto Hilina Pali Road. Follow this for 2.5 miles. Park at the intersection of a small track road with the Hilina Pali Road

11:00 AM Hilina Pali Road (1 hour).

STOP 2-4: WHITE RABBIT AREA OF THE KOA’E FAULT SYSTEM

From the parking area, we will walk northwest cross-country. The stop will take about 1 hour, so be prepared. Bring your lunch, as we may eat in the field if the weather permits.

The Koa‘e fault system connects the east and southwest rift zones. It is about 9 km long and 2.5 km wide and is a zone of extension, with measured amounts of extension (crack opening) as high as 30 m on a flow 600-700 y old. Studies in the past 50 years show that most of the extension is coseismic but that some faults creep open, particularly those where the system merges into the east rift zone in the Devil’s Throat area. The latest major episode of faulting was on November 29, 1975, in sympathy with a M7.2 earthquake centered near the eastern end of the Hilina fault system. The largest recorded episode of faulting was on December 24-25, 1965, when thousands of earthquakes rocked the area (Fiske and Koyanagi, 1968). It was that event that triggered the establishment of monitoring networks in and spanning the Koa‘e.

The faults continue the trends of fissures in the east rift zone. A structure map of Kīlauea (Figure 7) shows a continuous fault and fracture system from the southwest rift zone through the Koa‘e and into the east rift zone to the east tip of the island. Fiske and Swanson (1992) interpret the Koa‘e as a breakaway zone separating the relatively stable part of the volcano to the north from the mobile south flank. Some others consider the Koa‘e to be a part of the south flank.

Several faults show substantial vertical displacement, more than 7 m, in the past 600-700 years. Most such faults face north (upslope) and bound asymmetric graben with widths of at least several tens of meters. A few faults with significant vertical offset face south, however.

The direction of extension can be easily measured by fitting sides of cracks together as in a jigsaw puzzle. By doing so, Duffield (1975) showed that the direction of opening is southeastward, parallel to the direction of displacement of Kīlauea’s south flank, and is independent of the local trend of the crack. This cleared up the confusion, which unfortunately still persists among some workers, that there is strike-slip motion in the Koa‘e. No evidence yet uncovered suggests anything but extension.

The youth of the Koa‘e, and the excellent exposure, has prompted recent studies of the mechanics of the faulting that, not surprisingly, are at odds with one another in some respects. See Parfitt and Peacock (2001), Peacock and Parfitt (2002), Martel and Langley (2006), and Podolsky and Roberts (2008) for the details.

We will visit one of the best-exposed and youthful areas of the Koaʻe, the White Rabbit area, which is where the Podolsky and Roberts paper focused. We will observe White Rabbit pali itself, which forms the southern boundary of a graben. We will observe its monoclinal ramp and evidence of thrusting of this ramp across the ground surface, creating an unexpected antiform in a zone of extension. With luck, we'll flush a barn owl from its perch deep in one of the cracks that creases the floor of White Rabbit graben. Finally, we'll observe the face of White Rabbit pali and discuss how many lava flows are exposed.

Return to the vehicle and drive 1.1 miles west along Hilina Pali road to the campground at Kulanaokuaiki. A brief rest stop may be made here if necessary. Proceed 0.2 miles further past where the road bends up a bluff and around to the south and southeast (left). Park on the right.

1:00 PM Hilina Pali road on top of Kulanaokuaiki Pali (1 hour).

STOP 2-5: TEPHRA DEPOSITS OF KĪLAUEA; KANE V. WAHINE CONTEST (OPTIONAL)

Time-permitting, we will examine the tephra deposits here with a contest between the Kane (men) and Wahine (women) to see who can find the largest lithic pyroclast on the surface. There is method to this madness, but this is not the place to give the method away.

Following this, back-track to the east along Hilina Pali road to Chain of Chain of Craters road. Turn south (right), drive 1.4 miles, turn left toward the Mauna Ulu parking lot, and park in the lot. This is the trailhead for the Napau Crater Trail to Mauna Ulu and beyond. A toilet is available here.

2:30 PM Initial fissure of Mauna Ulu eruption (30 minutes).

STOP 2-6: MAY 24, 1969, SPATTER RAMPART: EPISODE 1 OF THE MAUNA ULU ERUPTION

Walk to the end of the pavement (the pre-1969 Chain of Craters Road), veer right past the front of a thick ʻaʻā flow, and approach a line of spatter cones.

Kīlauea's largest lava outpouring since the 15th century began here, as a 3-km-long fissure system opened in the predawn hours of May 24, 1969. Lasting for 5 years, with a break of a few months halfway through, the eruption produced a vast array of activity that included the growth of Mauna Ulu (the 120-m-high lava shield in the distance), spouting of lava fountains to 540 m height, filling of two pit craters and partial filling of three others, destruction of 11.5 km of highway, and development of a broad flow field traversed by today's Chain of Craters Road for most of the way to the sea. Though later dwarfed by the ongoing Puʻu ʻŌʻō eruption, the Mauna Ulu eruption was more easily accessible and provided a richer diversity of activity than its upstart cousin (Swanson et al., 1979; Tilling et al., 1987).

This spatter rampart was constructed by low fountaining (less than 50 m high) along several segments of the fissure system, each segment no longer than 100-200 m. At Kīlauea, single fissures are rarely longer than that at the surface, ending in steps to the right or left as the next segment comes into play. Eruptions occur from fissure systems made of many such segments. Each is connected to the same dike at depth but diverges from the trend of the dike owing to rotation of the stress field near the ground surface.

We will walk along the fissure side of the rampart, observing the fluidal textures of the individual spatter clots. Note that each actual fissure segment—home for vegetation because of warm water vapor and seed traps—is separated from the rampart by several meters. Note also that the rampart is one-sided; there is no rampart on the south side of the fissure, except locally. We will discuss the reason for this on the outcrop.

In places there are rounded masses adjacent to the south side of the fissure. Farther south, stone "mushrooms" rise above the top of the lava flow. You will now recognize these features as tree molds or lava trees, having seen the beauties near Lua Manu. But why are they wider at the top? We will see why.

In this area you can see evidence of three different eruptive events, all part of the Mauna Ulu eruption. The stratigraphic relations indicate that the fissure opened first and erupted a lava flow and spatter. Then vitric tephra fell on top of the flow, dispersed here from tall fountains as Mauna Ulu began to grow in the final 7 months of 1969. Finally, a pāhoehoe flow covered the tephra, dating from 1972. The ʻaʻā flow that we saw before the rampart represents a still later, fourth eruptive event of the eruption.

<u>*Suggested stay-over stop*</u>*: although time constraints won't permit it, the short hike along Napau Crater Trail to Pu'u Huluhulu and Mauna Ulu is spectacular and highly recommended for those who may be staying over after this trip. The view from Pu'u Huluhulu is splendid in all directions, and weather-permitting, provides photo opportunities of Puʻu ʻŌʻō down the east rift zone, as well as Mauna Loa and Mauna Kea to the west and northwest, respectively. Continuing from there, the hike to the summit of Mauna Ulu is even more spectacular. Mauna Ulu, as mentioned above, is a lava shield that formed during the 1969-1974 eruption. An interesting levied lava channel occurs on the north face, along with a splendid example of a perched lava pond. From the summit, the view down the east rift zone toward Puʻu ʻŌʻō is worth the extra walk. (A National Park permit is required to go past Puʻu Huluhulu; obtain one at the Visitor Center in advance).*

Return to the vehicles along a new trail made by the park in spring 2009. From here, continue down Chain of Craters road for 7.4 miles. Note that as we drive down Chain of Craters Road, we soon start to cross lava flows erupted from the 1969-1974 Mauna Ulu eruption. The road has obviously been built since.

Park at the Kealakomo Picnic area.

4:00 PM Kealakomo Picnic area (30 minutes).

STOP 2-7: HOLEI PALI GRAVITY FAULT SCARPS AND MAUNA ULU LAVAS

<u>Holei Pali story</u>

This area provides a splendid view of the Holei Pali ("cliff, precipice, steep slope"). In fact, this must be one of the world's most prominent gravity fault scarps on the grandest of scales. As you stand at the picnic area and gaze to the west (right as you face the ocean), you are looking at a 300-400 m-high series of escarpments of the Holei Pali scarp system. They are the eastern expression of the Hilina fault system, which slice their way across the southern portion of Kīlauea west of here. Some interpret these faults to be listric in nature and down-to-the-south, whereas others interpret them to extend down to the old seafloor. Look for a series of benches stepping downward toward the coastal flat from the top of the pali. These are individual gravity faults within the Holei Pali fault system that have moved seaward in half-graben-like fashion.

The gravity fault interpretation of the step-like landscape visible from here is supported by seismic evidence, as this portion of the Big Island is seismically active. Numerous small-magnitude ($M<4$) earthquakes occur at relatively shallow depths (≤ a few km); however, in the last 25 years, 11 $M>4$ earthquakes have occurred, including three of $M>5$. The most recent (as of this writing) was a M5.0 on April 14, 2009.

Many researchers interpret a decollement or detachment fault to underlie the Hilina fault system and indeed all of Kilauea. This fault or fault zone dips gently northward under the volcano and is thought to separate the volcano from the old sea floor on which it is built. A M7.2 earthquake in 1975, which triggered substantial movement along faults in the Hilina fault system, was located along the decollement below Kalapana (Cannon et al., 2001). This earthquake and resulting activation of the Hilina produced about 3.5 m of coastal subsidence and about 8 m of horizontal displacement of much of Kilauea's south flank (Lipman et al., 1985). An earlier, even larger earthquake in 1868 (Hazlett, 2002), estimated at M7.9, caused similar coastal subsidence and presumably southeast displacement, even though the best location of the earthquake, based on damage reports, was near Pahala, far from the Hilina fault system. The relationship between the movement of the south flank during these events, and the earthquakes themselves, is problematic, though some workers believe that the Hilina faulting was a sympathetic response to the shaking caused by the main shock.

On a grander scale, the existence of the entire Koa‘e-Hilina-Holei fault system is due to gravitational instability of the southern sector of Kīlauea volcano. Forceful injection of magma into Kilauea's east rift zone over time has mobilized the entire southern sector of the volcano between it and the southwest rift zone. The fault systems have developed due to this mobilization, with the Koa'e faults farthest up the volcano's flank. This system is primarily a series of north-facing, down-to-the-north half-graben fault scarps, whereas the Hilina faults are south-facing down-to-the-south faults, as discussed above. In simple terms then, the crustal block between the Koa'e and Hilina fault systems can be thought of as a large horst, which itself is slowly moving southward.

The dips of all of these faults tend to shallow with depth, reaching a maximum depth of a few kilometers (within the listric model). However, movement along them may be facilitated by deeper motion of this entire sector of Kīlauea along a shallower-angle, gently-north-dipping thrust fault acting as a basal detachment at 8-10 km depth (Cannon, 2001).

Although movements along these systems of faults may produce earthquakes of moderate (and rarely large) magnitude, the mobility of Kīlauea's southern flank is of interest for another reason. GLORIA side-looking sonar studies of the Hawaiian exclusive economic zone have shown that the islands are surrounded by ~100,000 km^2 of slump and debris avalanche deposits, an area 5x greater than that of the islands themselves, with some individual debris avalanche deposits being >200 km long and >5,000 km^3 in volume (Moore et al., 1994). These mega-scale mass-wasting events commence during the seamount phase of the islands' histories, continue during the subaerial shield-building stages, and significantly contribute to their destruction afterwards. The implication, of course, is that such large-scale displacements into surrounding waters would induce mega-scale, ocean basin-wide tsunamis, and that the mobility of the southern flank of Kīlauea could result in such an event. Sector collapses have been documented elsewhere in the Hawaiian Islands and at other volcanic island archipelagos such as the Canary Islands. They occur on average every 10 ka worldwide (Stanford University, 2002).

Although such sector collapses in the Hawaiian Islands have not occurred during historical times, the 1958 landslide-induced tsunami in Lituya Bay, Alaska serves as a reminder of the tsunami-generating ability of large mass wasting events into standing bodies of water. Lituya Bay is located 819 km southeast of Anchorage and is one of the many fjords of this region. The head of the northeast-southwest-trending bay is transected by the northwest-trending Fairweather fault, which is part of the Queen Charlotte-Fairweather fault system.

At 10:16 p.m. on July 9, 1958, a M7.9 earthquake occurred 20.8 km southeast of the head of Lituya Bay along the Fairweather fault (Pararas-Carayannis, 1999). About 2.5 minutes after the start of the earthquake, two separate eyewitnesses reported that a landslide was initiated at the head of the bay, which slid into the water (Figure 9).

The resulting mega-tsunami propagated into the bay after overtopping a promontory in its path, washing across an island in the bay and the spit across the bay mouth, out into the Gulf of Alaska. As much as 61 million m^3 of debris was released during this event (Garrison, 1993), with a wave run-up on the

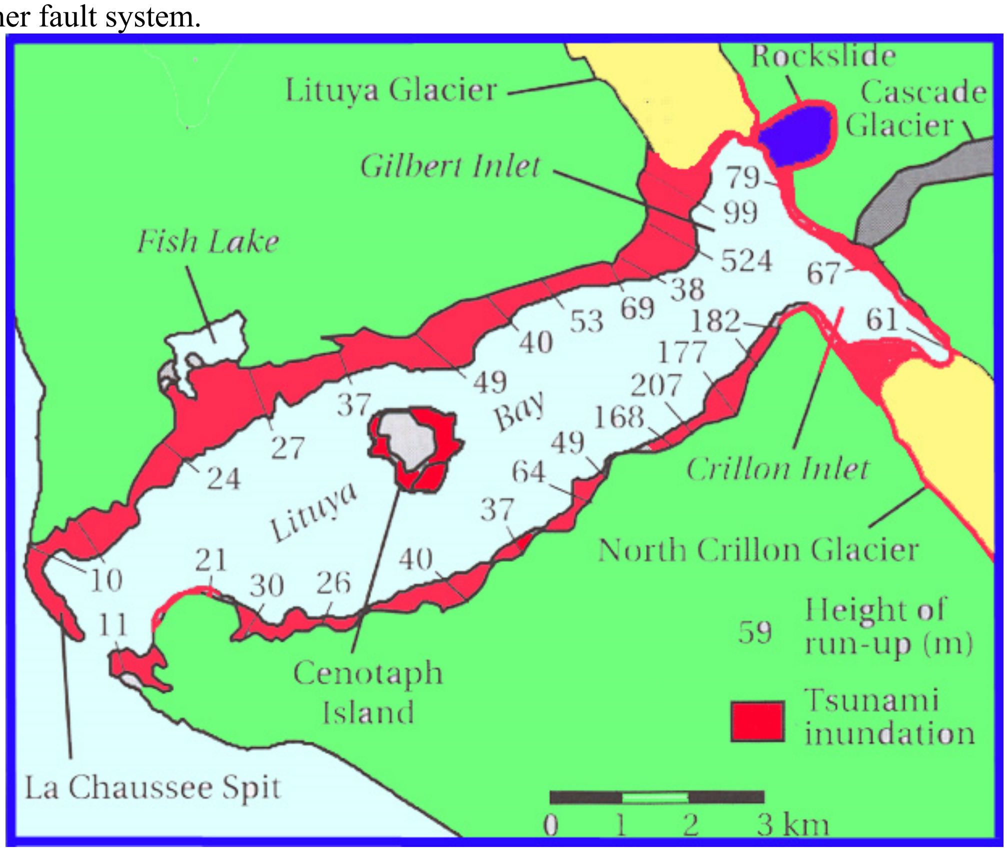

Figure 9. *Map showing areas of inundation of the 1958 Lituya Bay, Alaska tsunami and the record 524 m wave run-up on the shore opposite the mass wasting event that produced it (Pararas-Carayannis, 1999).*

promontory immediately opposite the input point of 524 m, the highest tsunami on record (Pararas-Carayannis, 1999). However, mechanism analysis of the mega-tsunami-inducing landslide has shown that it alone could not have been sufficient to produce the recorded wave run-up, and that other combined disturbances must have contributed, such as a component of upward vertical movement on the SW side of the Fairweather fault, movement of a tidal glacier front, and the sudden drainage of a subglacial lake (Pararas-Carayannis, 1999). Nonetheless, this event illustrates the point that mass movements can be a significant force in mega-tsunami generation.

A sector collapse in the Hawaiian Islands could have far-reaching ramifications, as it might produce an ocean basin-wide tsunami wave train. The resulting waves could have a coastal run-up of hundreds of meters, with effects far exceeding that of the 2004 Indian Ocean tsunami. The threat to public safety from a Kīlauea sector collapse could be great; however, because the recurrence interval of such an event in the Hawaiian Islands may be ~250 ka, and because no event has occurred at Kīlauea, the chances of it occurring in a given year are very small. The topics of sector collapses and the resulting mega-tsunamis will be revisited at STOP 3-5.

Look to the southwest from here to the coast. You will see ʻĀpua Point, the location of a village that was destroyed by the subsidence and tsunami associated with the 1868 earthquake (Hazlett, 2002). Several other villages were also destroyed, and the subsidence associated with the M7.2 1975 earthquake drowned some still-existing ʻĀpua Point archaeological sites.

<u>Mauna Ulu story</u>

Gazing in the same direction, several dark gray and light gray Mauna Ulu lava flows that flowed over the pali stand out in relative contrast to the untouched grassy areas in between. Lava flows cascaded repeatedly over the pali during the~~se~~ eruptive episodes, and several reached the ocean. One such prominent ʻaʻā flow can be seen reaching to the shore just east of ʻĀpua Point (Figure 10). Unfortunately, a 1971 lava flow destroyed an archeological site at Kealakomo (Hazlett, 2002). Most of the flows visible from here are ʻaʻā (dark gray to black), but some are pahoehoe (light gray). Many of the ʻaʻā flows started at their source as pāhoehoe, but as they moved over the steeper pali slopes, the additional internal turbulence caused them to change to ʻaʻā lava. In fact, this illustrates a general principle regarding basaltic lava types: ʻaʻā tends to form from pāhoehoe either as the latter degasses, causing it to become more viscous, or as pāhoehoe flows from a gentle to a steep slope, causing increased turbulence and a change to a'a. However, once a flow changes to a'a, it cannot revert to pahoehoe.

Many of the lava flows from the Mauna Ulu eruption were able to flow long distances (up to 12 km to the shore) due to the development of a system of small lava tubes, illustrating the contribution that lava tubes make to shield construction.

The repeated cascading of Mauna Ulu lava flows over the pali during five years of eruptions from Mauna Ulu caused a significant resurfacing of Kilauea's flank in this area. The 340 million m^3 of lava erupted during this time period covered 45 km^2 of surface area, ranging in depth from 1 to100 m (Hazlett, 2002). However, several large areas of the volcano's flank were left untouched by these lava flows, sparing the native Hawaiian plant and animal communities that previously

Figure 10. *Photo showing Mauna Ulu lava flows on the coastal flat near ʻĀpua Point (T. Bush photo).*

developed on the older surfaces. The Hawaiian term *kīpuka* refers to something different than its surroundings. In geology, we use the term to denote an older land surface surrounded by younger lava flows. Sometimes, kīpuka have a well-developed community of plants, animals, and insects, whereas the surrounding areas have been destroyed and essentially sterilized by much younger lavas, left only to start anew.

Kīpuka play a significant role in the development of endemic species in Hawaiʻi. Because lava flows isolate a portion of an existing ecosystem, species are left to develop independently, especially those that cannot crawl, walk, fly, or be blown by wind to surrounding areas. Thus, kīpuka provide yet another example of how geologic processes influence species development in Hawaiʻi, or "*geology rules!*"

Here at the Kealakomo Picnic area, we are in one of these kīpuka, and others can be seen nearby.

From this locality, continue down Chain of Craters Road around the large switchback for about 2.9 miles to Alanui Kahiko. Park in the pull-out on the left.

4:30 PM Alanui Kahiko (15 minutes).

STOP 2-8: LAVA FLOWS AND FEATURES (OPTIONAL)

Here we are just about directly below the last stop and have another vantage point of the Mauna Ulu lava flows where they cascaded over Holei Pali. These flows covered many miles of Chain of Craters road, built in 1965, only four years before the eruption started. This locality not only provides an excellent view of lava flows on the pali, but also a salient example of a place where lava covered the old road. Numerous smaller-scale features of pāhoehoe can be observed here, including toes and tumuli. A tumulus develops when a small lava tube becomes blocked and continued injection of pressurized lava causes the roof to inflate. Tumuli often develop longitudinal rifts reminiscent of cracks in the crust of a rising loaf of bread. These cracks can provide an interesting cross-section of the roof's interior. The lava flows here were emplaced in 1972 by overflows from the ‘Alae lava shield, formed during the Mauna Ulu eruption.

Continue along Chain of Craters road in the same direction. In a couple miles we will pass the pull-out for the Pu‘u Loa Petroglyphs Trail.

<u>Suggested stay-over stop</u>: *the Pu'u Loa Petroglyphs area is a highly recommended stop for those staying over; they are easily accessed along a 1.4-mile round-trip trail from Chain of Craters Road.*

Continue ~5.8 miles to the end of Chain of Craters Road and park. Restrooms may be available here.

5:00 PM End of Chain of Craters Road (1-3 hours or more).

STOP 2-9: VIEW OF ACTIVE FLOW FIELD AND LAVA OCEAN ENTRY

<u>Holei Sea Arch</u>

Unless lava flows have inundated the area since this writing (unlikely), Holei Sea Arch lies along the coastal cliff directly across the road from the park's ranger station. It is worth a brief look, *but please be careful along the coastal cliff*, since live bodies going over the edge cannot be recovered, and even dead ones are difficult to retrieve.

<u>Current activity and the 1983-flow field</u>

After viewing Holei Sea Arch, walk past the ranger station along the closed and partially lava-covered portion of the end of Chain of Craters road onto the recent flow field. There may be a trail to a lava ocean-entry view point. If activity continues over the summer as it is at the time of this writing, a steam plume (or two or more) may mark the site(s) of lava entering the ocean and should be visible from here.

(Note for those staying over after this trip: at the time of this writing, Hawai'i Civil Defense has set up an ocean entry view point on the other side of the flow field to the east at the end of SR 130, but the ocean entries are about equidistance from that and this view point (about 7 km). However, this could change, so the interested visitor should check with HVO and Hawai'i Volcanoes National Park for an eruption update on the current activity to determine the best view point. (In fact, by the time of our visit, we may opt to view from the other side, necessitating a change in our schedule.)

From here, much of the 1983-present Pu‘u ‘Ō‘ō-Kūpaianaha flow field lies before us from the base of Hilina Pali to the north (left) and southward to the shore; the total area resurfaced during this eruptive phase of Kilauea's history is ~120 km^2, including the coastal flat between here and Kalapana to the east, a distance of about 7 km. Chain of Craters road used to extend all the way from here along this coastal flat to connect with HA 130 on the other side of the flow field, but no more. The average rate of lava production here since 1983 has been ~0.0003-0.0005 km^3/day (0.10-0.18 km^3/yr) (Swanson, 2009).

Numerous lava flows of this >26—year eruptive episode may be seen extending down

Holei Pali from here, as well as a number of kīpuka that were created. Here we are standing on lava flows emplaced in 2002-2004 (Figure 11) (Hawaiian Volcano Observatory, 2009B). As seen elsewhere on Kīlauea, the development of lava tubes here has been instrumental in the movement of lava down the pali system to the coast, and this process continues at the time of this writing. Occasionally, lava breaks out of the tubes and extrudes onto the surface. (Depending on the proximity of such break-outs to access roads, this may provide an opportunity to view lava close up. However, this often requires hiking some distance (up to several kilometers), across recently emplaced masses of very uneven pāhoehoe in the hot sun without vegetation to provide refuge; such access can be rewarding but grueling. Depending on the nature and location of activity at the time of our visit, we will not likely attempt such viewing.)

Where lava has spread across the coastal flat or broken out from lava tubes, many interesting features can be seen. Numerous tumuli often form in this environment, some of which are sizable (up to 15 m across and 3-4 m high), with fascinating longitudinal fractures along their crests as discussed at the previous stop. Pāhoehoe toes are common, and both shelly and ropy pāhoehoe can be observed. One can easily imagine lava toes forming as lava breaks out from small tubes or inflated, crusted-over lava masses. On the pali, small (<1 m in width) lava tubes and lava gutters (lava streams with self-made natural lava levees) can be seen along with entrail pahoehoe.

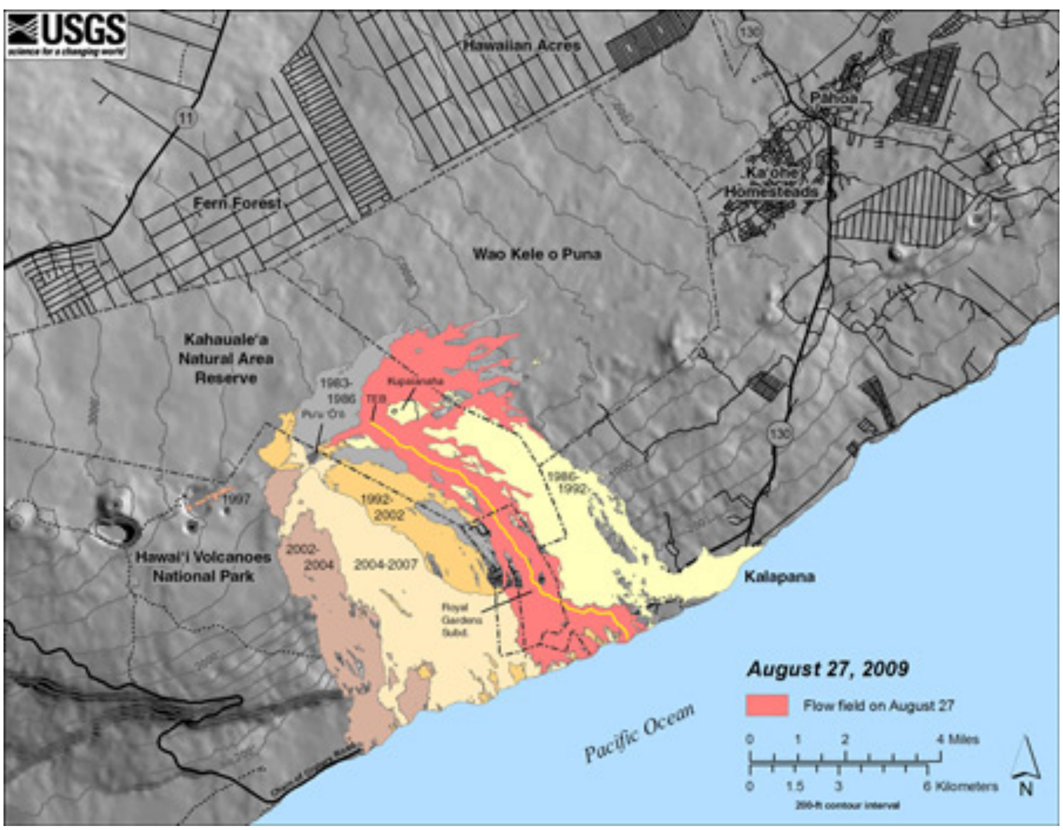

Figure 11. *Map showing flow field of the 1983-present Pu'u O'o-Kupaianaha eruption of Kilauea's East Rift Zone (Hawaiian Volcano Observatory, 2009B).*

Ecological functions of tumuli

Fractures in the tumuli serve an important ecological function: they not only collect water and wind-blown dirt, but also provide a stable environment for the accumulation of airborne seeds. As you look around, you will probably see native ferns colonizing in tumuli cracks, thus providing yet another example of "*geology rules!*" As vegetation becomes established, invertebrates will also soon start to re-colonize recent lava flows. Insects such as bees and crickets may fly into the area, and spiders or small non-flying insects may be blown onto the lava flows. Their food source might be the colonizing plants, seeds that have blown into cracks, or sometimes each other. Vertebrates also soon start to colonize or at least occasionally feed here. Birds land on newly formed lava and feed on the plants or insects. Intriguingly, in 2004, Bush's group hiked onto the flow field from here and, nearly 2 km from the edge of the flow field, observed a lone healthy mouse scurrying about!

Lava ocean entries and their hazards

When lava spills from the lava tubes into the ocean or spills over the coastal cliffs, the interaction of hot lava and relatively cold seawater causes intense steaming, occasional explosions, and eventually, accumulation of rubbly, glassy, fragmental material at the base of the coastal cliff just beneath wave base. Under the right conditions, a littoral cone of sand-sized volcanic glass, basalt fragments, and minerals such as olivine may accumulate at the ocean entry site. Otherwise, over time, if the supply of new lava to the area continues, the rubbly base material may build up above wave base, allowing accumulation of lava just above sea level, forming a lava delta. The lava delta may actually even have foreset "beds" of pillow basalts that form as blobs of lava accumulate on the shallow, sloping seafloor beneath the waves (Figure 12). Once this process has started, new land has essentially been added to the island. However, further accumulation of lava onto the fragmental pile may destabilize the rubble base, initiating collapse of the recently-formed coastal bench along shore-parallel tensional fractures. This process can occur with little or no warning, and obviously can be quite hazardous to unwary lava watchers. Delta collapses have resulted in one fatality during the current 26-year eruptive period, and three others have died from various other problems encountered on deltas. For this reason, visitor access to the ocean entry area is not permitted.

Other hazards created by lava ocean entries include airborne rocks, tephra, lava, and volcanic glass; acid fumes; and scalding waves (Johnson et al., 2004). Explosions are especially common when waves enter hot lava tubes and immediately flash to steam; such explosions can hurl rocks the size of basketballs as far as 100 m from the ocean entry point. Droplets of still molten lava or sharp fragments of volcanic glass can be ejected much further. Seawater chlorine can form hydrochloric acid in the steam plume, which can then be dispersed far downwind by the northeast trade winds. Closer to the ocean entry site, explosions can hurl scalding hot seawater onto the lava bench.

6:00 PM Sunset picnic dinner at ocean entry viewpoint.

As dusk approaches, we hopefully will reap the added benefits of lava viewing in darkness, enhancing the glow of the ocean entries. After a healthy episode of viewing, return to the vehicles, taking care along the way in the dark.

8:00 PM Return to KMC.

Figure 12. *Photo showing "foreset" beds of ancient pillow lava delta on the northeast shore of Santa Cruz Island, Galapagos Islands (T. Bush photo).*

DAY 3: SATURDAY, SEPTEMBER 19
KILAUEA SOUTHWEST RIFT ZONE AND SOUTHEAST SECTOR OF MAUNA LOA

7:00 AM Breakfast at the KMC cafeteria.

8:00 AM Morning briefing—KMC dormitory porch (15 minutes).

8:15 AM Depart for the field. Those who wish to partake in beach activities are advised to bring a swimming suit and towel today.

From KMC, turn east (left) onto Crater Rim Drive and drive clockwise to the Park's entrance station and out the park. Turn east (left) onto the Hawai‘i Belt Road (SR 11) toward Kailua-Kona. Drive for about 7 miles as this highway curves back around Kīlauea's caldera and descends its southwestern flank. Park on the left side at the Ka‘ū Desert Trail trailhead to Mauna Iki. We will be away from the vehicle here for more than an hour, so be prepared.

8:45 AM MP 37.7—Ka‘ū Desert Trail (75 minutes).

STOP 3-1: MAUNA LOA AND KĪLAUEA LAVA FLOWS AND THE KEANAKAKO‘I ASH AT THE KA‘Ū DESERT

Hike along the trail toward Mauna Iki. This stop is southwest of Kīlauea's summit in an area known as the Ka‘ū Desert. Notice the relative lack of vegetation as compared to the northern rim of Kīlauea's caldera or its northeastern flank (for example, between Kīlauea's summit and Hilo).

To be or not to be a true desert

A true desert, by definition, receives <25cm/year rainfall and has a high rate of evaporation. The Kaʻū Desert is not a true desert in this sense, in spite of its name. This area of Kīlauea receives ~125 cm/year rainfall, depending on the location (Zeigler, 2002). Although this is well above the maximum precipitation for the area to be considered a true desert, it is markedly lower than the northeastern flank of Kīlauea, which receives anywhere from 200 to 750 cm/year of rainfall (Zeigler, 2002). Here we are on the leeward side of Kīlauea relative to the northeast trade winds, and the reduction in annual precipitation here relative to the northeastern flank is, of course, due to the rain shadow effect of Kīlauea volcano acting on the northeast trade winds coming off the Pacific.

This reduction in annual precipitation on this side of Kīlauea does not completely explain the sparseness of the vegetation here. For example, the Seattle area receives about 75-100 cm/year of rainfall, comparable to this area. Another reason for the paucity of vegetation is acidic nature of rain, caused by the upwind emission of SO_2 from Kīlauea. As magma ascends beneath the caldera from depth it depressurizes and releases a variety of volcanic gases at the surface. In 2003-2007, Halemaʻumaʻu crater released an average of 400 tonnes/day of SO_2, but more recently, since the opening of a new vent in March 2008, these emissions have been greatly elevated to as much as 1700 tonnes/day. SO_2 and other volcanic gases are dispersed from the summit area downwind by the trade winds for many kilometers. The acidic volcanic fumes from the summit affect soil pH and the ability of plants to photosynthesize. The soil pH in the desert 1-2 km from Halemaʻumaʻu is about 3, and the pH of mist is about 2. Within 2-3 km of Halemaʻʻumau, acid groundwater dissolves silica and then precipiates it when the water reaches the surface. The result is a deposit of opal, which forms a hardpan not conducive to seed or spore germination.

Yet another factor influencing vegetation quantity in the Kaʻū Desert is the high porosity and permeability of the soil, a function of the tephra present. So for three reasons, *geology rules* here as well.

Geology

Hike from the trailhead across the older Keamoku ʻaʻā flow, ca. 600-700 years old. Note the abundant accretionary lava balls, which form by accretion and rolling along channel margins and then are carried by the flow beyond the channel. In about 800 m the trail descends from the flow onto older pāhoehoe, probably about 800 years old. Gray to tan lithic ash erupted in 1790 rests on the pāhoehoe, in places overlying windblown sand reworked from older Keanakākoʻi vitric ash. Hard to find are an older gray ash on which some dune sand has been deposited. Both gray ash beds contain accretionary lapilli, which are larger and more abundant in the upper bed. The accretionary lapilli indicate that the ash was wet when it was deposited. Embedded in the surface of the upper gray ash are small lithic ejecta, which fell while the gray ash was still wet. If you can distinguish these deposits, or for more fun, make a simple geologic sketch map and/or cross-section illustrating their relations as observed in this location. Space is provided below.

Hawaiian story

Continue along this same trail for another few hundred meters to a small shelter, which was constructed by CCC workers in the 1930s to protect human footprints in one of the gray ash beds. Unfortunately, the shelter was a magnet, and the footprints have been vandalized. After an orientation discussion at the shelter, we will walk for 10 minutes to an area with numerous footprnts still preserved.

The footprints occur in both gray ash beds but are far more abundant in the upper bed. Both beds are distal, downwind fall deposits from late Keanakākoʻi time. Earlier vitric ash, found around the caldera, occurs here only as windblown deposits in fossil and active dunes. The age of the older gray ash is not known except that it was probably erupted some time in the early or middle 18th century. The upper ash bed has been assumed to be of 1790 vintage, but this was only an assumption until recent work by Swanson and colleagues demonstrated it stratigraphically. The story is as follows.

A powerful series of explosive eruptions took place from the caldera in 1790, probably November. One of the eruption columns was observed by John Young, an English sailor, from Kawaihae near the north end of the island. The column towered over the summits of Mauna Loa and Mauna Kea and has been estimated to have been at least 10 km high, well into the jet stream. Ash of late 18th-century vintage occurring far east and southeast of the summit was probably produced from this high column. At the summit, rocks fell from this column, and from associated surges, into a wet accretionary lapilli ash, embedding themselves in the ash. Therefore, the ash must be 1790 in age. This is the upper footprints bed, in which hundreds of footprints have been found. Therefore the footprints also date from 1790.

Swanson and Rausch (2008) measured the sizes of more than 400 footprints (now more than 500) and found that most of them were probably made by women and children, not men. This conclusion was reached by measuring the heel-big toe length of prints and using the relation that a person's foot is 15 percent of her height. The average and mean height is about 152 cm (5'1"). Hawaiian men were tall; assuming only heights over 173 cm (5'8") were men, the ratio of men to women and children is about 4.5—a good family group. We measured the tracks of about 200-300 different people, we believe. About half were walking back toward Kīlauea's summit and about 35 percent away from the summit.

The year 1790 was a time of conflict on Hawaiʻi as different groups attempted to gain control following the 1782 death of Kalaniopu'u, Hawaiʻi's Aliʻi Nui (prime chief) (Moniz-Nakamura, 2007). His son, Kiwala'o, was appointed as the new aliʻi in accordance with his father's pre-death wishes. This, however, enraged Kalaniopuʻu's nephew, Kamehameha, Kiwalaʻo's cousin, who wished to rule the islands himself. In Kamehameha's attempts to overthrow his cousin, Keōua, Kalaniopu'u's half-brother and loyal supporter, escaped. Later, the armies of Kamehameha and Keōua battled in the Hilo area, but both retreated from the indecisive confrontation. As Keōua's armies (family groups, not just warriors, constituted Hawaiian forces) were returning to their home district of Kaʻū, to the south, their route took them past the summit area of Kīlauea. The volcano was exploding, and Keōua feared that he and his armies had offended Pele, so they paused for several days to attempt to appease her. One story, reported by a missionary decades later, is that, upon departure, Keōua divided his troops into three companies which departed the summit area at different times. The first group got through unscathed, but the second and most of the third were annihilated. One missionary story is that when the bodies were discovered, they were coated with little ash, not broken by falling rocks, and looked from a distance is if they were only resting. One romantic missionary reported that family members were grasping one another "as if taking final leave." More likely, they were holding on to keep from being swept away by a surge of hot ash and gas. The number of fatalities ranges from "about 80" to "about 400" to "about 800" to 5405. No matter what the correct tally, more people were killed than during the Mount St. Helens 1980 eruption, so that, of all the volcanoes now in the U.S., Kīlauea has the dubious distinction of being the most lethal. With Keōua's strength weakened, and many of the populace believing that Pele disfavored him, it was only a matter of time before Kamehameha was able to establish himself as ruler of all of the Hawai'ian Islands, thus providing a prime example of "*geology rules!*"

Did Keōua's forces leave the footprints? Perhaps they were made by the first party, who weathered the fall of wet ash (they must have had trouble breathing) in the desert and then started walking once the sky had cleared. About the half the party went back to investigate what had happened. But this is only supposition. Park archaeologists (Moniz-Nakamura, 2007) have found many worksites in the desert (including several near here) for chipping glass to make tools. Perhaps people were doing this when the wet ash fell. Without more oral history than is presently available, we may never know whose feet made the indentations in the mud.

Then, we must remember that there are footprints in the older ash, separated from the younger by as much as 90 cm of dune sand. The older prints cannot date from 1790 and cannot be from Keōua's party.

As we walk to the footprints from the shelter, the shield of Mauna Iki appears straight ahead. It formed during an eruption in 1919-1920 (Rowland and Munro, 1993). This eruption was almost entirely effusive. Observers at the time could see lava flowing through cracks in several places between Kīlauea's summit and the main eruption site at Mauna Iki.

<u>Suggested stay-over stop</u>*: continue along this same trail to Mauna Iki along Kīlauea's southwest rift zone.*

From the shelter, hike back to the vans along the same trail and load into the vehicles. Proceed down SR 11 toward Kailua-Kona as before. Drive for about 20 miles, passing by the small town of Pāhala (note the town's name for later geologic reference). As we drive to the next stop, the highway generally follows the swale where Kīlauea and Mauna Loa lava flows intersect. Turn left to Punalu'u Harbor and proceed down the road past the golf course on the right. To park, drive past the black sand beach and turn left into the parking area near the grassy area and the restrooms.

10:30 AM MP 55.6—Punalu'u Harbor (60 minutes).

STOP 3-2: BLACK SAND BEACH

(Please note that it is illegal to collect sand from this locality.)

Punalu'u ("immersed in springs" as the tide pools here reportedly fill with spring water at low tide) Harbor is one of the nicer and more popular black sand beaches on Hawai'i Island. At this site, we have crossed the boundary from Kīlauea lava flows to those of Mauna Loa, but the harbor itself is formed at the junction of two sets of Mauna Loa lava flows. The west side of the harbor is formed in Ka'ū Basalt unit k1y, dating between 3,000-5,000 y BP (Table 4), whereas the northeast side of the harbor is formed in Ka'ū Basalt unit k2, dating between 1,500-3,000 y BP (Table 4) (Wolfe et al., 1996).

Inspect the black beach sand with a hand lens and determine its composition (see Appendix to estimate proportions of various materials present). You should see that it is mostly composed of black basaltic glass fragments, with a small fraction of white shell or coral fragments and olivine crystals. Such black sands form from the explosive interaction of lava and seawater, producing finely-commutated fragments of basalt glass and minerals. Three tsunamis in historical times have ravaged this beach over the last 141 years (1868, 1960, and 1975), each of which caused a significant reduction in the beach size here.

Once again, *geology rules*: the beach provides an ideal nesting habitat for the threatened Green Sea Turtles (*Chelonia mydas* or Honu), which can commonly be seen at Punalu‘u in the shallow waters or even basking in the sun on the beach. After mating in the sea, the female lays between 100-200 eggs in a hole she digs in the sand above high-tide line and buries them. After 45-75 days, the eggs hatch at night under the cover of darkness, and the hatchlings instinctively scurry to the water, as they are quite vulnerable to predators such as gulls or crabs until they reach the waves. If they happen to emerge from their nest during daylight hours, they are quite vulnerable to predators (Figure 13).

From here, we will split into two groups. OPTION 1 is for those wishing to go to STOP 3-3 and OPTION 2 is for those wishing to go to STOPS 3-4, 3-5, and 3-6. You cannot do all of these stops. The two groups will then reconvene at STOP 3-7. STOP 3-3 involves a wind-blown and dusty 5.2-mile, round-trip hike in the hot sun to Mahana Bay and

Figure 13. *Photo of Frigate Birds preying upon Green Sea Turtle hatchlings who happened to have emerged from their nest during daylight hours, Bachas Beach, Santa Cruz Island, Galapagos Islands (T. Bush photo).*

Green Sand Beach where there will be an opportunity to cool off in the waves–before heading back to the vehicles. If you feel this hike is beyond your abilities, or you prefer not to do it, you should opt to do STOPS 3-4, 3-5, and 3-6 instead. There is an excellent snorkeling opportunity at STOP 3-6.

Lunch today will be eaten en route to the next stop.

OPTION 1: For those traveling to STOP 3-3, follow these directions: return to SR 11 and turn south (left), continuing towards Kailua-Kona. At MP 69.6, turn south (left) onto South Point Road. Continue almost to the end, and a short distance from South Point, take the left fork and drive back toward the north about 0.3 miles. Park in the primitive dirt parking lot a few hundred yards up from the boat launch. **NOTE: DON'T LEAVE VALUABLES IN THE VEHICLES.**

For those traveling directly to STOPS 3-4, 3-5, and 3-6, skip STOP 3-3 and follow the directions thereafter.

1:00 PM	Arrive Ka Lae National Historical District (South Point). Park and prepare for hike to Pu'u Mahana (Green Sand Beach).
1:45 PM	Trail to Puʻu Mahana (15 minutes).

STOP 3-3A: PAHALA ASH (OPTIONAL—participants doing this stop CANNOT go to stops 3-4, 3-5, and 3-6)

From here we will hike 2.7 miles (one way) along the anastomosing jeep trails to Green Sand Beach. Expect hot, dusty, and windy conditions along the way, and be sure to wear boots or at least good walking shoes. Bring (or wear) your swimming suit and towel if you wish.

As we hike toward Mahana Bay, the trail crosses several ʻaʻā lava flows from Mauna Loa. These are Kaʻū Basalts of geologic map unit k1o dating between 5,000-10,000 y B.P.

Many of the anastomosing jeep trails en route to Puʻu Mahana (Hawaiian: "warm hill") are carved into Pleistocene Pāhala Ash, named after exposures on the southeastern slope of Mauna Loa near Pāhala (Easton, 1987). The use of this stratigraphic term is complex, and some workers use it to refer to older, regional ash units throughout the entire island originating from Kīlauea, Mauna Loa, Mauna Kea, and Kohala, the specific volcanic source at a given locality being determined by its position from these sites relative to the northeast trade winds (Wolfe and Morris, 1996).

The Pāhala Ash deposits are typically yellowish-orange to reddish-brown and consist of a mixture of clay minerals and hydrated oxides (Wolfe and Morris, 1996). The ash is basaltic in composition, may reach a thickness of 10 m on the southern slopes of Mauna Loa, and is deeply weathered. Its distribution on the 1:100,000 geologic map of the Big Island (Wolfe and Morris, 1996) shows that it is found only on Mauna Loa's southeastern slopes, not the northwestern ones, and forming kīpuka between younger lava flows, such as here. It occurs interlayered with and overlain by the oldest flows of the Kaʻū Basalt of Mauna Loa. Near Naʻalehu (between South Point and Punalu'u Harbor), Wolfe and Morris (1996) report that a radiocarbon date from a lava flow directly overlying the Pāhala Ash is dated at 31,100 ±900 years B.P.

It is valuable to ponder the source of the Pāhala Ash in this area. Previous workers have presumed that the ash source was Kīlauea because of its southeasterly position relative to the volcano's summit, placing it downwind relative to the northeast trade winds. However, the ash thickness (2-5 m in this area, but up to 16 m on the SW slope of Mauna Loa) is too great to have been brought this far (40 km) from the summit of Kilauea. So what is the source of the Pāhala Ash in this area, and how did it get here?

Recent studies (for example, Hawaiian Volcano Observatory, 2005A) have shown that Kīlauea is an explosive volcano, with explosions occurring about as often as at Mt. St. Helens (every few decades to centuries). However, the magnitude of an explosive eruption has a profound effect on the downwind distribution of its ash. Eruptions expelling ash into the northeast trade winds will be dispersed downwind from Kīlauea to the southwest, or, when the southerly Kona winds blow, to the north. These patterns will occur from Kīlauea if eruption columns do not exceed 4 km in height, the base of the jet stream and above the influence of these near-surface winds.

However, Kīlauea has produced tephra that has been dispersed downwind in other directions, ranging from east-southeast to south-southeast and as far as 20 km from Kīlauea's summit (Hawaiian Volcano Observatory, 2005A). These dispersal patterns could only be produced by more powerful eruptions that produce eruption columns greater than 4 km, penetrating above the surface wind patterns into the jet stream, distributing debris in a variety of directions from Kīlauea's summit.

In light of this new information about Kīlauea's darker, more powerful side, certainly other Big Island volcanoes could produce jet-stream-penetrating explosive eruptions as well. Although the Pāhala Ash in this area is too thick to have been dispersed to this region by northeast trade winds from Kīlauea, the distribution and thickness here fit with a more powerful, jet-stream-penetrating explosion from Mauna Loa.

Here is one environmental geology note: the deep incisions into the Pāhala Ash here illustrate the deleterious effects that off-road vehicle use can have on accelerating soil erosion.

2:30 PM Pu‘u Mahana (Green Sand Beach) overlook (15 minutes).

STOP 3-3B: A LITTORAL CONE? (OPTIONAL—participants doing this stop CANNOT go to stops 3-4, 3-5, and 3-6)

Upon arriving at Pu‘u Mahana, the trails culminate at a splendid overlook of Mahana Bay. From this location, several important depositional units may be observed. Straight ahead are stratified ash deposits that make up the heavily eroded cone of Pu‘u Mahana, which dates at >49 ka (Hawaiian Volcano Observatory, 2005B) and compose the northern portion of Mahana Bay. Overlying these deposits at the top of the bluff are brownish-orange Pāhala Ash deposits. The ‘a‘ā flow to the west (left) is Ka‘ū Basalt map unit k of Mauna Loa (>10 ka.) (Wolfe and Morris, 1996), which composes the southern margin of Mahana Bay.

The origin of Pu‘u Mahana may initially seem obvious: a littoral cone formed from the prolonged effect of lava explosively interacting with seawater at its point of entry. This conclusion seems straightforward because of Pu‘u Mahana's position along the shore, its volcaniclastic composition, and its morphological similarity to known littoral cones (such as Sand Hills at Nānāwale) (Hawaiian Volcano Observatory, 2005B). However, there is a problem with this interpretation: Pu‘u Mahana could not have formed along the shore. This is because the Big Island is isostatically sinking at a rate of 2.4 mm/year, and with a radiocarbon age of

49 ka, Pu‘u Mahana would have been about 118 m above sea level at the time it formed. Furthermore, sea level was 70 m lower at that time due to glaciation, which means that Pu‘u Mahana would have been actually ~188 m above the shore when it formed. This means that it could not have formed as a littoral cone.

An alternative explanation is that Pu‘u Mahana formed over a primary vent rather than as a rootless cone, and that the accumulation of the debris that formed the cone is the result of the interaction of ascending magma and ground water. Therefore, the present position of Pu’u Mahana along the shore is simply an artifact of isostatic island sinking and eustatic sea level rise, and it is a mere coincidence that it occurs in the littoral zone at this time.

3:00 PM Pu‘u Mahana (Green Sand Beach) (15 minutes).

STOP 3-3C: A GREEN SAND BEACH (OPTIONAL—participants doing this stop CANNOT go to stops 3-4, 3-5, and 3-6)
From the overlook we will scramble down to Green Sand Beach for a closer look. The greenish tint of the beach is the result of the accumulation of olivine sand within the protected confines of Mahana Bay. Wave action has winnowed out lower density detritus, leaving behind a residual of denser olivine grains in the beach sand. Look at the sand with your hand lens and see if you can estimate the percentage of olivine crystals in the sand using the chart in the Appendix. Compare this with the detritus from the back-beach bluff of Pu‘u Mahana and see if the olivine content is similar.

Hike back to the vehicles by the same route.

<u>To travel to STOP 3-7 from STOP 3-3</u>: drive back along the dirt road for a half mile and turn south (left) on a road that leads out to South Point. Drive almost all the way to the end, stopping near the fishing cliffs. Park and meet the other participants there. Turn to STOP 3-7 in this field guide.

<u>OPTION 2: for those traveling directly to STOPS 3-4, 3-5, and 3-6, from STOP 3-2, follow these directions</u>: Return to SR 11 from Punalu‘u Harbor and turn south (left) toward Kailua-Kona. Drive about 17 miles to a lookout on the left at MP 75.0. Park there. This will be a roadside stop.

Lunch today will be eaten en route to the next stop.

1:00 PM Scenic Overlook SR 11, MP 75.0 (15 minutes).

STOP 3-4: 1907 MAUNA LAVA FLOW AND SLIDE SCARP OF MAUNA LOA’S SOUTHWEST RIFT ZONE (OPTIONAL—participants doing this stop CANNOT go to stop 3-3)
At this locality, we are on the southwest rift zone of Mauna Loa. Inspection of the Geologic Map of the Island of Hawai‘i (Wolfe and Morris, 1996) reveals numerous, east-stepping en echelon fissure vents extending down the southern slope of Mauna Loa in this direction. The view upslope from here may reveal lava flows associated with the rift zone. In the last few miles before arriving here, we crossed the historical flows of 1868 and 1887 that erupted from southwest rift zone fissures upslope of this location.

The lava flow exposed in the road cut across the highway and beneath the overlook is an ‘a‘ā flow erupted in 1907 from Mauna Loa’s southwest rift zone. The flow originated from fissures on the southern slopes of Mauna Loa at an elevation of about 6,000 m and flowed downslope in two main branches, ~~a~~ western and eastern. This flow is the eastern of the two, and it extended farther down slope to within about 1 km from the sea. The total volume of this flow is 0.121 km^3 and it covered an area of 28 km^2 (Hawaiian Volcano Observatory, 2006A). In the outcrop across the highway, note the dense, massive, jointed flow interior, overlain and underlain by oxidized rubbly ‘a‘ā breccia. This structure is typical of ‘a‘ā flows in cross-section. Close inspection of this flow will reveal the presence of olivine phenocrysts.

Note the lack of re-vegetation here in spite of over a century of time since the end of the eruption, in part due to the rubbly nature of the flow surface, and to some extent due to the rain shadow effect formed by Kīlauea and Mauna Loa. *Geology rules* once again.

Now look south-southeastward toward the prominent west-facing pali standing approximately 200 m above the sea. This is Pali o Mamalu, which is a massive slump scarp extending out to sea from this part of the island. This slump scarp exposes flows of the Kahuku Basalt (unit kh) of Mauna Loa, which underlies the Pāhala Ash and the Ka‘ū Basalt, and dates at >30 ka. This slump scarp is a southern expression of Mauna Loa’s southwest rift zone (Map 3). We will discuss this further at STOP 3-7.

From the scenic overlook, continue along SR 11 toward Kona for about 24 miles.

At MP 103.95 (*just before* MP 104 and Keokea), turn left onto SR 160 toward Kealakekuea Bay. Follow this road down a couple of switchbacks, descending the flank of Mauna Loa for 2.7 miles. At MP 2.7, just after the second switchback, stop at the lookout on the left.

1:45 PM MP 2.7—Lookout above Pu‘uhonua O Honaunau National Historical Park (20 minutes).

STOP 3-5: PALI KAPU O KEŌUA SLIDE SCARP (OPTIONAL—participants doing this stop CANNOT go to stop 3-3)

Here we are standing on Mauna Loa's western flank far below its caldera and summit. The lava flows around us are Ka‘ū Basalt unit k3 dating between 750-1500 y B.P. (Wolfe and Morris, 1996). As we drove down the switchbacks along SR 160 from SR 11, we crossed a large (~7.5 km long x 1.5 km wide) kipuka of Ka‘ū Basalt unit k1y lava flows (dating between 3-5 ka), but because the lava flows surrounding the kīpuka are not recent, the vegetation difference is unnoticeable between the two units.

To the north, the edifice of Hualālai, the Big Island's third oldest volcano, is visible. It last erupted in 1800-1801 A.D., sending lava flows down its western face to the sea. Some of these flows contain interesting dunite and gabbro xenoliths.

<u>Suggested stay-over stop</u>: *an excellent outcrop containing dunite and gabbro xenoliths in the 1800-1801 A.D. lava flows of Hualālai may be found at MP 27.6 on SR 190.*

Beyond Hualālai lies Kohala, Hawai‘i Island's oldest volcano (which is not visible from here). On Kohala, an interesting marine conglomerate consisting of broken coral and other marine shell fragments and angular basalt clasts cemented with coralline sand is found on its flanks up to an elevation of 61 m (McMurtry et al., 2004A). This deposit has been dated at 110 ± 10 ka. Similar deposits of comparable ages have been found on Lana‘i, Moloka‘i, and Maui at roughly the same elevation (McMurtry et al., 2004A). Initially, the origin of these deposits was unclear as the subsidence history of Lanai, Molokai, and

Maui was not well constrained. Were these littoral deposits formed at a time of interglacial eustatic sea level high-stand, or were they deposited by some other mechanism above the present shoreline? This question can be resolved by examining the subsidence history of Kohala volcano, which is well-documented to be subsiding at a rate of about 1 inch per decade (0.25 cm/year) over the last 5 Ma (McMurtry et al., 2004A). A drowned coral terrace lies below the western shores of Kohala at a depth of 396 m and dates at 120 ka, close to the age of the marine conglomerates (Figure 14), constraining the position of sea level on the flanks of Kohola to around the time of deposition of the coralline conglomerate. So these deposits must have been formed at an elevation of about 457 m above the paleo-shoreline, ruling out an origin as coastal gravels.

Bathymetric studies of the seafloor off the west coast of the Big Island by long-range side-looking sonar have revealed the presence of a 4,000-km^2 area of hummocky seafloor topography interpreted to be lobes of two separate phases of a giant landslide known as the ʻAlika 2 landslide, which originated from the western slopes of Mauna Loa (Lipman et al., 1988, Moore et al., 1994). Such landslides may have volumes of several thousand km^3 and extend for 200 km along the seafloor (Moore et al., 1994). The two lobes of the ʻAlika 2 landslide deposit have a volume of about 200-600 km^3 (Figure 15), with a total combined volume of 1,500-2,000 km^3 extending into the Kahoʻolawe Deep to a depth of 4,800 m (Lipman et al., 1988). Sediments on top of this deposit date at 120 ka (McMurtry et al., 2004B). This date correlates relatively well with the age of the stranded marine conglomerates on Kohala and elsewhere in the eastern Hawaiian Islands. As a result, these conglomerates are now interpreted to have been produced by the run-up of a mega-tsunami produced by the giant ʻAlika 2 landslide approximately 110-120 ka. Computer modeling has demonstrated that it is plausible for the ʻAlika 2 landslide to produce a mega-tsunami with a run-up >400 m extending inland >6 km (McMurtry et al., 2004A, McMurtry et al., 2004B).

As discussed previously on this trip, the implication is that a similar island sector collapse in the future could produce a mega-tsunami throughout the islands (as well as basin-wide) resulting in a similar wave run-up. Obviously, such an event would have grave and entirely catastrophic consequences not only for Hawaiian residences but also for those living throughout the Pacific basin, so although rare (recurrence interval of ~100-250 ka?), these types of events are worth studying further.

Look to the north across Honaunau Bay to a west-northwest-trending cliff. This is Pali Kapu o Keōua, a fault scarp which extends inland to the east-southeast and curves to the southeast. It lies 176 m above Kealakekua Bay and Cook Point, the location of the Captain Cook Monument, memorializing Captain Cook's 1779 C.E. death at this locality, when he violated a Hawaiian cultural taboo. The pali exposes a unit k Kaʻū Basalt (age >10 ka), and is surrounded and overlain by younger Kaʻū Basalt, ranging from unit k1o (age 5-10 ka B.P.) to unit k4 (age 200-750 y B.P.). This fault was the source of a M6.9 earthquake on August 21, 1951, which did considerable damage throughout this part of the island (Earthquake Hazard Program, 2009). Pali Kapu o Keōua is the head scarp of the ʻAlika landslide, which is curvilinear and concave to the southwest, trending up Mauna Loa's flank, inland, and southeastward from the Cook Point, crossing SR 11 about 6 km northeast of here. At this locality, we are

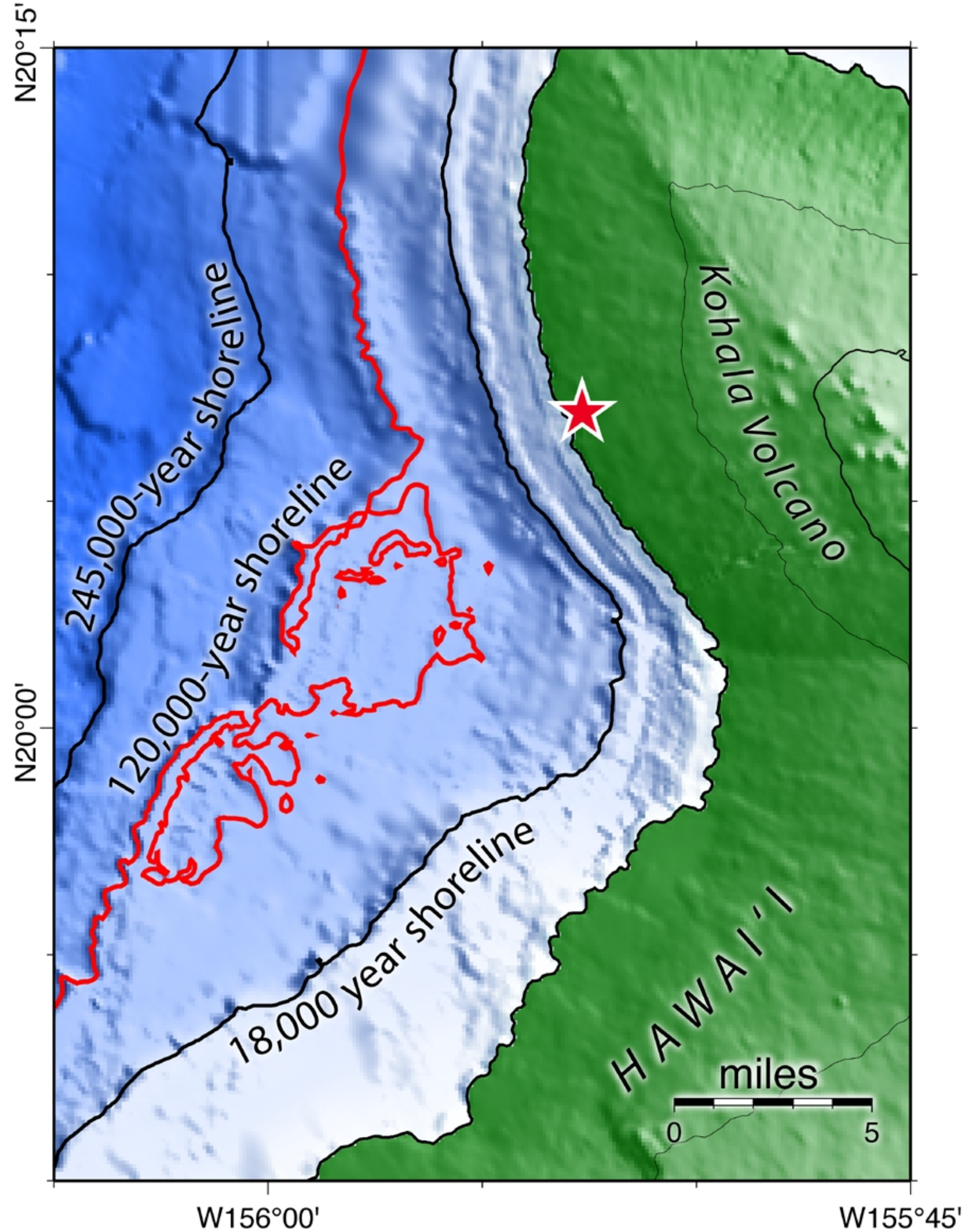

Figure 14. *Map showing the location (star) of marine coralline conglomerates on the western slope of Kohala. The red line shows the position of the shoreline at the time of its formation, indicating deposition at the time at an elevation 457 m above sea level (from McMurtry et al., 2004).*

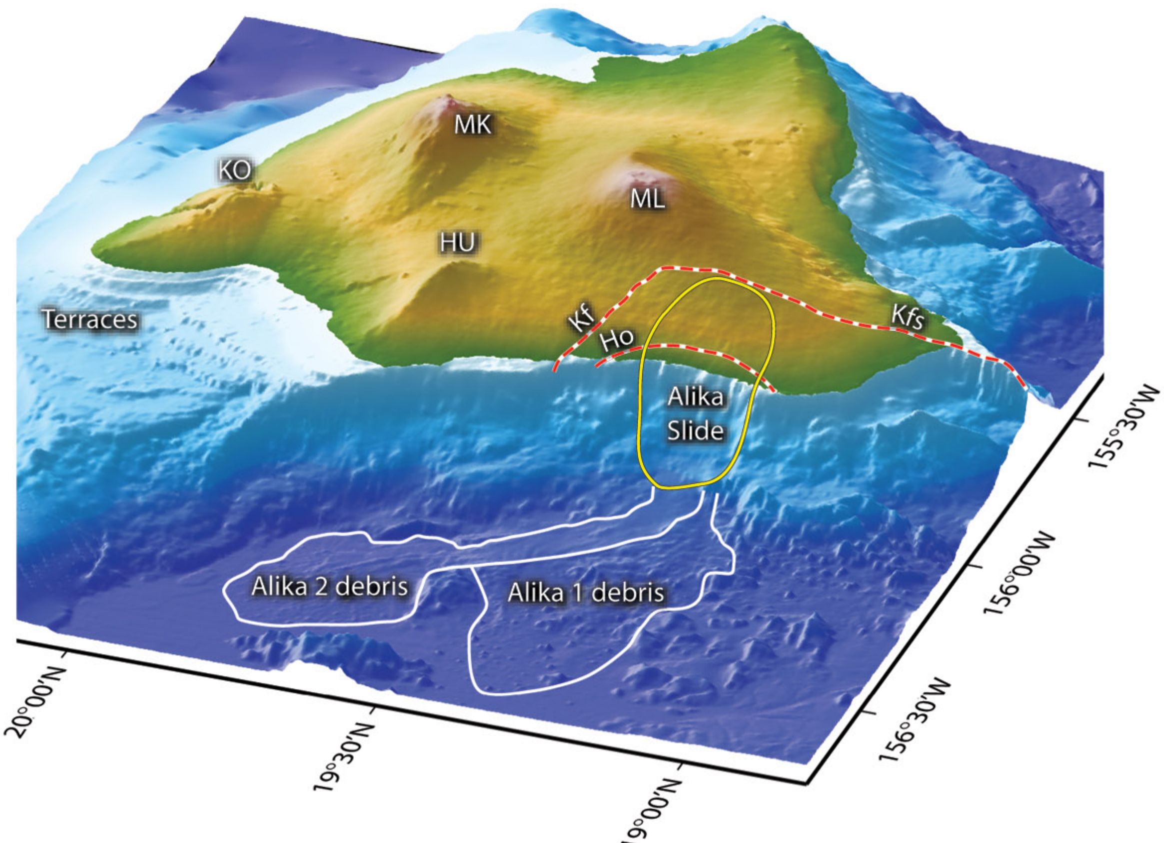

Figure 15. *Block diagram showing two lobes of the 'Alika landslide on the in the Kaho'olawe Deep west of the Big Island, and its source area on the western flank of Mauna Loa (McMurtry et al., 2004A).*

standing at "ground zero" of this giant landslide!

There is more to the story. The 110-120 ka age of the marine conglomerates and the 'Alika 2 landslide coincides with an interglacial episode. During such a time, the Hawaiian climate would have been warmer and wetter, similar to the present day. The higher level of precipitation as compared to a glacial age would increase water infiltration into the subsurface and underground water storage, as well as surface water impoundments within craters and calderas. As a result, explosive phreatomagmatic eruptions might be more likely during an interglacial episode. This raises the question, could these violent eruptions serve as triggering mechanisms for giant landslides during interglacial episodes? This is a very interesting question in light of the fact that Earth is now in a time of glacial retreat, particularly when considering the movement presently occurring in Kīlauea's south flank.

From here, continue down SR 160 for about another 0.7 miles. Turn west (left) into Pu'uhonua O Honaunau National Historical Park.

2:00 PM Pu‘uhonua O Honaunau National Historical Park (City of Refuge) (2.5 hours).

STOP 3-6: WHITE SAND BEACH AND HAWAIIAN CULTURE (OPTIONAL—participants doing this stop CANNOT go to stop 3-3)

This stop combines geology with Hawaiian culture. It is definitely worth taking some time to peruse the displays in the park conveying the significance of this locality in Hawaiian history as a *pu'uhonua o honaunau* (a city of refuge) for those that violated Hawaiian kapu (taboo).

The scenic white sand beach is one interesting geologic feature found at this spot, an ancient royal canoe landing site. Look at the beach material with a hand lens (<u>but please don't collect any</u>), referring to the charts in the Appendix for estimating percentages. You will find that it is composed mostly of pulverized coral and shell fragments with lesser basalt clasts. There may be occasional grains of olivine as well. (Green sea turtles may be seen basking here in the shallow waters next to the beach.)

White sand beaches are more common on the western shores of Hawai'i Island due to the greater number of coral reefs on this side of the island. These reef structures, as they are broken by wave activity, form the sediment source for the beaches. Reefs are more common on the western shores of the island because they are in the rain shadow produced by Mauna Loa and Mauna Kea, and therefore the annual precipitation is lower on this side of the island (20-50 in/year on the Kona side as compared to as much as 300 in/year on the Hilo side). The reduced annual precipitation on the leeward side of the island results in lower runoff, which, in turn, means lower turbidity coastal waters and greater infiltration of sunlight. This is important for coral reef productivity because of the symbiotic relationship between the corals and a type of photosynthetic dinoflagellate known as *zooxanthellae*, which lives within the coral structures. Through photosynthesis, *zooxanthellae* provide the reef organisms with dissolved oxygen and help recycle nutrients in the generally nutrient-poor tropical waters (Garrison, 2009). As a result, brightly lighted, clear waters are important for zooxanthellae photosynthesis. So the distribution of white sand beaches is controlled by a biological factor: the distribution of coral reefs. But coral reef distribution in the rain shadow of the volcanoes is yet another example of a geologic control on the distribution of Hawaiian life, so once again, *geology rules*.

While at this locality, it is worth taking a few minutes to examine the lava flows in this area. Just beyond the white sand beach is Pu‘uhonua Point, which is composed of k3 unit flows of Ka‘ū Basalt dating between 750-1,500 y B.P. (Wolfe and Morris, 1996) and containing an abundance of olivine phenocrysts. Again (as at STOP 3-5), we are directly west and downslope from Mauna Loa's summit caldera, and the flows found here form a wide swath (up 5 km).

At this point, you are encouraged to take some time to enjoy the interpretive displays of this monument. Also, those who wish may take advantage of the excellent snorkeling/swimming site just north of here at Honaunau Bay, which may be accessed via a residential street just outside the park entrance station.

From here, return up SR 160 to SR 11 the way we came earlier. Turn south (right) and drive ~32 miles. AT MP 69.6, Turn south (right) onto South Point Road. Continue to the end to South Point, stopping close to the end near the fishing cliffs. Meet the other participants here.

5:30 PM South Point (Ka Lae) (30 minutes).

STOP 3-7: SEA CLIFFS AND MAUNA LOA SOUTHWEST RIFT SLIDE SCARP (all participants regroup here)

The Hawaiian name for this locality, Ka Lae, means "the point." Located at a latitude of 18°54'39" N, this is not only the most southerly point on the Big Island and in the state of Hawai'i, it is also the most southerly point in the 50 United States (Florida's Key West is located at 24°N). Some may enjoy knowing that, of all the people in the entire United States, there is nobody who is further south than we are here. This is probably where the first Polynesians made landfall as they arrived in Hawai'i about 800 CE. (Masse and Tuggle, 1998; Tuggle and Spriggs, 2001). As you look directly south from here, the next continental landfall is on Antarctica, a distance of about 10,300 km, or about 2.5 times the air distance from Seattle to Boston. That would be a very long swim if you were to be swept out to sea by waves from here.

Just off shore are two converging ocean currents. This has two effects, the first an upwelling of deeper, nutrient waters, which fosters biological productivity in the vicinity of South Point. As a result, this is a popular fishing location for locals, as you may notice.

The second effect in this area is the accumulation of an abundance of marine debris along the shore, which was also evident on the hike to STOP 3-3. Combined with the remote location and difficulty in accessing the shore, this debris is difficult to clean up, despite the efforts of the Hawai'i Wildlife Fund.

As is probably obvious, the area of South Point is underlain by Pāhala Ash (for those doing STOPS 3-4 through 3-6, see the Pāhala Ash discussion under STOP 3-3) (Wolfe and Morris, 1996). To the north the ash is overlain by tongues of unit k1o Ka'ū Basalt lava flows (age 5-10 ka B.P.), exposed near the boat launch along the hike to STOP 3-3 (Wolfe and Morris, 1996). These lava flows protrude out from under the Pāhala Ash in the littoral zone at the very tip of South Point and form the rocky shore, near where we will have our sunset picnic dinner shortly.

Carefully go to the edge of the west-facing cliff above the crashing waves. Please don't fall over the edge, as this would create an inconvenience for the group, but look to the north along the cliff toward the gentlysloping flank of Mauna Loa. This west-facing, north-south-trending cliff is Pali Ha'uke'uke, an escarpment of basalt flows utilized for fishing by the local fishers. Its northward extension is Pali o Kulani and further north, Pali o Mamalu (briefly discussed at STOP 3-4). This system of cliffs, standing approximately 200 m high to the north, exposes Kahuku Basalt (unit kh) of Mauna Loa, a series of flows underlying and older than the Pāhala Ash in the vicinity, dating >30 ka (Wolfe and Morris, 1996). These cliffs are a massive slump scarp extending out to sea from this part of the island and are the southern extension of the southwest rift zone of Mauna Loa.

Now look to the shore at the base of the pali system at a distance of about 2-3 km from here, and then along the shore from there to the northwest (you may need binoculars). The ocean entry points of three tongues of unit k5 Ka'ū Basalt should be visible. These flows erupted in 1868 and originated from the lower portion of Mauna Loa's southwest rift zone at an elevation of 960 m on its flank, 20 km up rift from where they entered the ocean (Wolfe and Morris, 1996). One arm moved downslope to the south-southeast above the pali system for about 10 km, and another flowed south 20 km to the sea below the pali system. The arm that reached the sea split into the three tongues as mentioned above. A littoral cone called Pu‘u Hou, formed where the most northwestward tongue made its ocean entry, may be visible with binoculars. It has been heavily dissected by wave erosion since its formation.

Next we will board the vehicles and drive the short distance to the very southern tip of South Point.

6:00 PM Sunset picnic dinner (if timed properly) at Ka Lae (South Point).

9:00 PM Return to KMC.

DAY 4: SUNDAY, SEPTEMBER 20 SADDLE ROAD, MAUNA KEA, AND MAUNA LOA

7:00 AM Breakfast at the KMC cafeteria.

8:00 AM Morning briefing—KMC Dormitory porch (15 minutes).

8:15 AM Depart for the field.

Turn east (left) out of KMC onto Crater Rim Drive and proceed clockwise to the Park entrance station and out of the park. Turn south (right) onto SR 11 toward Hilo. Upon entering the outskirts of Hilo, turn east (left) onto Puainako St. Follow this through Hilo for a couple miles until it becomes the upper portion of Kaūmana Dr. and Saddle Rd. About 23 miles from downtown Hilo, pull off on the left (south) side of Saddle Road.

10:15 AM MP 21.7 View Point on Saddle Road (15 minutes).

STOP 4-1: BOMBING OF 1935-36 LAVA FLOW (OPTIONAL)

As we drove up Saddle Road from Hilo, the route follows several unit k5 historical lava flows from Mauna Loa (Wolfe and Morris, 1996). Just at the outskirts of Hilo, we crossed onto a flow that erupted in 1880-81, the terminus of which now lies in the central part of Hilo <2 km southwest of the waterfront. This flow originated from the upper portion of Mauna Loa’s northeast rift zone. The last 2 km of this flow sits atop a unit k3 flow that terminated <1 km from Hilo Bay, well within the present-day city limits of Hilo. Obviously, if either of these flows were to erupt today instead of when they did, they would cause a great deal of damage and property loss in the Hilo area.

About 2 km east and uphill from Kaūmana Caves County Park (another lava tube), Saddle Road crosses onto a unit k5 lava flow erupted from the upper portion of Mauna Loa’s Northeast Rift in 1855. This flow terminated about 6-7 km above what is now the outskirts of Hilo, and about 9.5 km from the Hilo waterfront. Saddle Road follows this lava flow for ~19 km before crossing a narrow (<0.5 km) band of unit k4 lava and then onto a narrow (~0.2 km) finger of a 1935 lava flow. This lava flow, like the others discussed here, originated from fissures in the upper portion of the Northeast Rift.

Because lava flows from Mauna Loa’s northeast rift zone have repeatedly flowed down its flanks toward the present-day site of Hilo, both in recent geologic time and during historical times, future eruptions from Mauna Loa’s northeast rift zone represent a significant hazard to Hilo. The Big Island has been divided into 9 lava-flow hazard zones (Figure 16), with 1 being the most hazardous and 9 the least (Hawaiian Volcano Observatory, 2006B). Hilo lies within zone 3, which includes areas downslope from active rift zones but at a greater distance than zone 2, so lava flows inundating Hilo would have to travel a considerable distance (kilometers). Nevertheless, it is a real possibility in the long term.

The best way to mitigate lava flow hazards is through wise land-use planning in areas that are likely to be inundated by lava. However, this strategy only applies to future construction, not existing development. Obviously, once lava is moving toward a developed area, it is nearly impossible to control its path. Efforts to retard flow movement or change its direction have been attempted on several occasions in the 20th century, and, to some degree, have been successful. For example, Icelanders prevented the fishing village of Vestmanneayjar on the island of Heimaey from being inundated by a basaltic lava flow from Eldfell volcano in

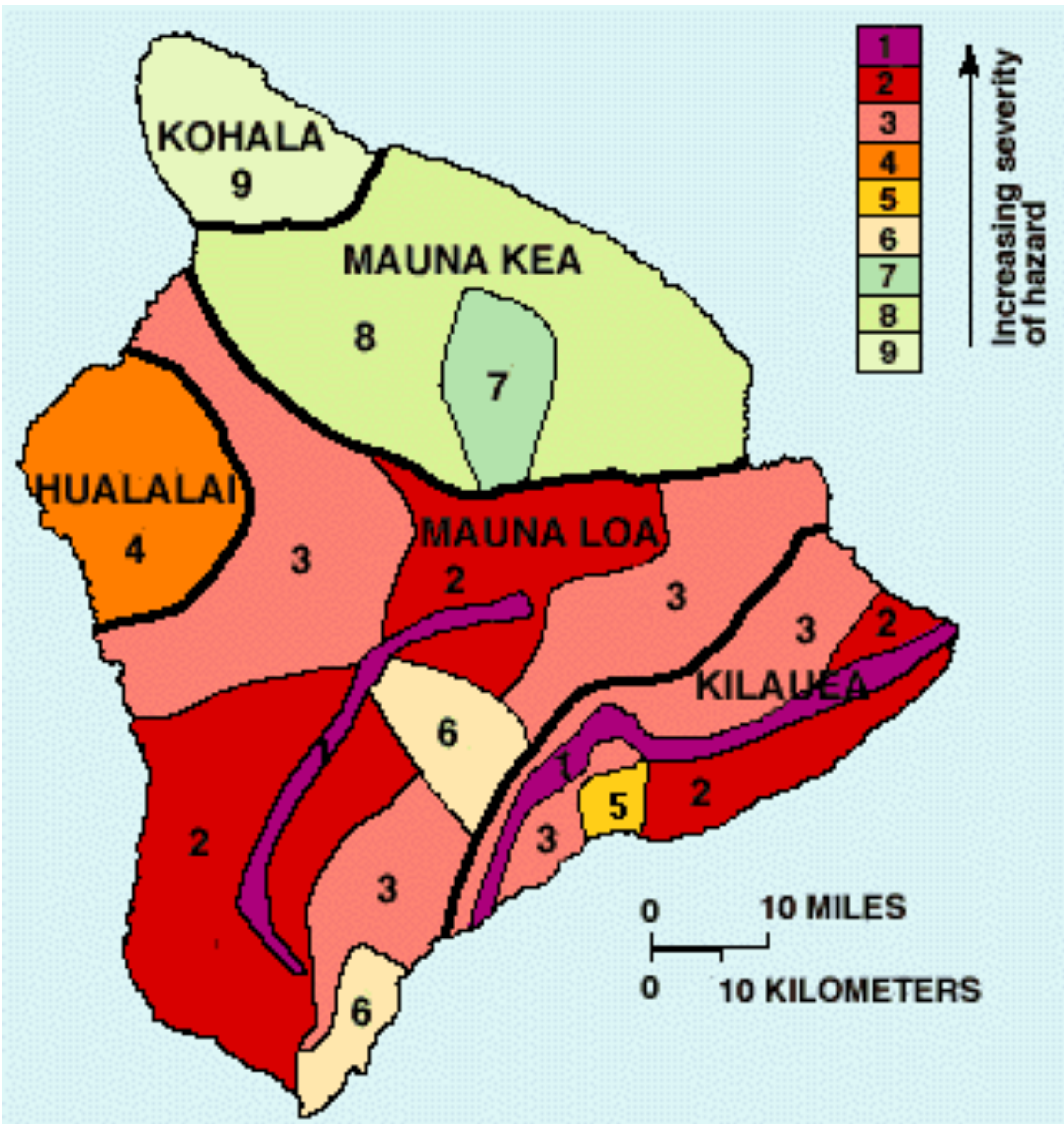

Figure 16. *Map showing lava-flow hazard zones of Hawai'i (Hawaiian Volcano Observatory, 2006B).*

1973 by cooling it with water for several weeks (Williams and Moore, 1983).

As previously discussed on DAY 2, naturally-formed lava tubes (and channels) are an efficient mechanism for the transport of lava over long distances down the flanks of Hawai'i Island's shield volcanoes and are an integral part of the morphological construction of such volcanoes. However, these processes also increase the likelihood of lava inundating populated locations far from eruptive sites. If such tube or channel systems can be disrupted, then it may be possible to reduce the supply of lava to the advancing flow front and decrease the hazard to downslope localities such as Hilo (Lockwood and Torgerson, 1980). The first attempt to divert a lava flow by bombing was employed on the lava flow we are now on. In 1935, the U.S. Army Air Corps dropped a series of bombs on the active pāhoehoe channel and tube system near here, but the effort was unsuccessful, since most bombs missed their targets and others didn't explode. Unsuccessful attempts were made again in 1942, and three days after the bombing, the spatter cone surrounding the vent partially collapsed, cutting off the flow of lava (Lockwood and Torgerson, 1980). In the 1970s, the U.S. Air Force carried out bombing experiments on prehistoric lava flows on Mauna Loa, using more modern aerial bombing techniques and concluded that bombing active lava flows now has a much higher probability of success for diversion (Lockwood and Torgerson, 1980).

Discussion of lava diversion has met with considerable skepticism and opposition on the island. Who would build a facility assuming that an upstream diversion barrier or bombing would work? Who wants lava diverted onto their land, even if it is unsettled ranch land? Moreover, the increasingly influential Hawaiian cultural community views lava diversion as inimical to Pele, who controls volcanic activity. Pele gets what she wants, according to Hawaiian culture. Currently there is little chance that diversion will be attempted by the state or county, unless a particularly favorable circumstance to save a particularly important facility should arise. A barrier to divert lava around a hospital might be acceptable under the appropriate conditions, to be determined at the time. A barrier to protect McDonald's, Starbucks, or even Walmart would not be.

From this locality, continue west up Saddle Road for ~5.5 miles. Along the way, Saddle Road continues to follow the 1935 lava flow discussed above; watch for the location at which pahoehoe transitioned to ‘a‘ā.

At the junction of Saddle Road with John A. Burns Way, park on the left side of Saddle Road in the small bird hunters parking area near Pu‘u Huluhulu (“shaggy hill”). Primitive restrooms are available here. Walk through the gate and out onto the lava flows to the southwest, immediately west of Pu‘u Huluhulu.

10:45 AM MP 29.95—Humu‘ula Saddle and Pu‘u Huluhulu Nene Sanctuary (45 minutes).

STOP 4-2: MAUNA LOA LAVA FLOWS AND MAUNA KEA ALKALIC CINDER CONES

Here we are in Humu‘ula Saddle, the saddle formed by the onlap of Mauna Loa lava flows onto flows and tephra deposits of Mauna Kea, so some interesting features are observable from here. We are at an elevation of 2,000 m; some people may have minor difficulty breathing here. This is a good place to start our acclimation process to the higher elevations we will encounter today, so we'll take our time.

Mauna Kea and Mauna Loa morphologies

Look to the north. Depending on the weather, parts or much of the edifice of Mauna Kea will be visible; it displays the typical convex-up shield volcano morphology, with some differences to be discussed below. Notice the numerous cinder cones dotting the southeastern flank (one of the differences). Other outstanding cinder cones are visible to the northwest, to be discussed at the next stop.

To the south, weather-permitting, the northern slopes of Mauna Loa volcano may be visible, along with its shield volcano morphology. From this vantage, the NOAA Mauna Loa Observatory buildings are visible (on a clear day), (STOP 4-5 this afternoon). The volcanic edifice is covered with numerous historical black lava flows, testimony to Mauna Loa's activity. On a clear day, a series of cinder cones dots Mauna Loa's eastern horizon along its northeast rift zone.

This is a good location for comparing the morphologies of these two enormous and classic shield volcanoes. Mauna Loa displays the typical convex-upward shape that is characteristic of such volcanoes in the shield stage. As previously discussed, this morphology is a function of efficient lava transport downslope from eruptive vents, as the low viscosity lavas move easily through gutters, channels, and tubes long distances, promoting lateral development of the edifice. However, the morphology of Mauna Kea is more rugged, dotted with more cinder cones, its upper reaches are steeper, and its summit lacks a large caldera. These differences can be attributed to Mauna Kea's post-shield stage, during which much smaller volumes of slightly higher viscosity and volatile-rich alkalic basaltic lavas are erupted from scoria cones. The differences in the physical properties and volume of the lava in the post-shield stage promotes the modification of the volcanic edifice in a manner consistent with what we see on Mauna Kea.

Lava flows at this locality

Now let's focus our attention to the geology afoot. As we walk out onto the lava flows west of Puʻu Huluhulu, you will see a pāhoehoe flow overlying an ʻaʻā flow. The pāhoehoe flow is a part of the 1935 flow discussed at the previous stop, where it was ʻaʻā. This illustrates that lava flows can solidify as pāhoehoe in their upper reaches but as ʻaʻā further along. Notice that this flow has partially covered and surrounded a stone wall. The surface of the flow near the wall is fractured and convex upward towards the wall, indicating inflation of the surface crust by injection of lava beneath the crust.

At this location, the 1935 pāhoehoe flow overlies and forms several small kīpuka in a highly oxidized Mauna Loa unit k2 ʻaʻā flow. The margins of the 1935 flow form many interesting fingers, protrusions, and embayments onto the ʻaʻā flow. A radiocarbon date from the ʻaʻā flow on the western edge of Puʻu Huluhulu yielded an age of 1,580 years B.P. (Wolfe and Morris, 1996). Obviously, the principle of superposition allows for determination of relative age of these two flows, but what two other methods could be employed to determine their relative age?

Puʻu Huluhulu

We will now turn our attention to Puʻu Huluhulu. It is probably obvious that it is a cinder cone standing about 60 m above Humuʻula Saddle. But from which of the two shield volcanoes here, Mauna Loa or Mauna Kea, did it originate? Puʻu Huluhulu is composed of alkalic material, and since Mauna Kea, not Mauna Loa, is in the post-shield alkalic stage, it must belong to Mauna Kea. In fact, it does, as well as all the other symmetrical cinder cones visible from here. They belong to Mauna Kea's Laupāhoehoe

Volcanics (Holocene and Pleistocene hawaiitic volcanic rocks and associated glacial deposits between 65 and 4 ka in age) (Wolfe and Morris, 1996). The Laupāhoehoe Volcanics consist of a younger volcanic rocks member (age range 14-4 ka), and an older volcanic rocks member (age range 65-14 ka). All the cinder cones on Mauna Kea are of the older Laupāhoehoe Volcanics (Wolfe and Morris, 1996).

Pu‘u Huluhulu is surrounded by the much younger Mauna Loa lava flows discussed above; therefore it is itself an excellent example of a kīpuka. Notice the contrast in vegetation between the cone and the surrounding flows. The forest is a remnant of a dry montane koa forest that was once common at mid-elevations on the Big Island, but has been reduced to 10% of its original range by logging, fire, and cattle ranching. The habitat is ideal for rare forest birds, including the ‘akiapōlā‘au and ‘ākepa, as well as nēnē. Once again, *geology rules*.

Now look more closely at the small quarry on the near (southwest) side of Pu‘u Huluhulu, which nicely exposes the interior of this interesting cinder cone. Notice the narrow, vertical, highly oxidized zone near the margin of the quarry. This is actually a dike of tholeiitic basalt that intruded into Pu‘u Huluhulu. Because of its tholeiitic chemistry, its source must have been from Mauna Loa. This dike formed when a pāhoehoe lava flow engulfed Pu‘u Huluhulu, and pressurized lava under the flow crust was forcefully injected upward into the cone, forming this remarkable dike.

Mauna Kea’s glacial deposits

Finally, turning our attention back to Mauna Kea, look toward the summit. Binoculars will help. The summit, at an elevation of 4205 m, is high enough to receive a mantle of snow lasting several days to weeks in the winter months. But during the Pleistocene glacial episodes, the combination of average annual temperature and precipitation was conducive to the formation of glacial ice, even at this tropical latitude (“altitude offsets latitude”). The result, of course, is the accumulation of typical glacial deposits near the summit. The Pleistocene till and outwash deposits on Mauna Kea are grouped with the Laupāhoehoe Volcanics, and are designated as the Pleistocene Makanaka Glacial Member (40-14 ka) (Wolfe and Morris, 1996). These consist of both glacial till (unit lmt) and outwash (unit lmo), and, weather-permitting, may be visible near the summit from here. They roughly form a ring around the summit between about 4,000 and 3,200 m in elevation.

There are older glacial deposits on Mauna Kea as well. These are grouped with the Pleistocene Hāmākua Volcanics (age 250-200 ka to 70-65 ka) and are named the Waihū Glacial Member (unit hmw, age ~70 ka) (Wolfe and Morris, 1996). These deposits may be difficult to impossible to see from here, even with binoculars, but interestingly, they are found at lower elevations than the Makanaka Glacial Member on Mauna Kea’s southwest slope between 3,240 and 2,720 m. Why would the deposits from the older episode of glaciation be found at a lower elevation than the younger ones?

Glacial activity occurred on Mauna Kea during times of volcanic activity, producing fascinating interactions of lava and ice. There were probably six subglacial eruptions that produced small outburst floods whose deposits are preserved in deep canyons downslope (Wolf and Morris, 1996).

Ponder this question: the summit of Mauna Loa is only 36 m lower than that of Mauna Kea, yet no glaciers formed on Mauna Loa. Why not?

Walk back to the vehicles and proceed across Saddle Road up John A. Burns Way. Go 6.2 miles to the Onizuka Center for International Astronomy and park. Drivers: be cautioned to watch for *invisible cows* en route!

12:00 PM Onizuka Center for International Astronomy. Lunch (30 minutes).

12:30 PM Onizuka Center for International Astronomy (30 minutes).

STOP 4-3: MAUNA KEA GEOLOGY

The main goal for this stop is to take some more time to acclimate to the higher elevation before proceeding up the slopes of Mauna Loa (the elevation here is about 3,050 m). However, there is some geology to see here, as well.

The Onizuka Center is surrounded by an army of Mauna Kea alkalic cinder cones. Lava flows and cinder cones in this area include the older volcanic rocks member of the Laupāhoehoe Volcanics (65-14 ka, units l (flows) and lc (cones)), as well as younger volcanic rocks member of the Lapāhoehoe Volcanics (14-4 ka, units ly (younger flows) and lyc (younger cones)). The Center rests on a younger flow member of the Laupāhoehoe Volcanics (ly) which extends downslope from a younger volcanic member cinder cone (lyc), Pu‘u Keonehehe‘e. This flow covers and is surrounded by the older member Laupāhoehoe Volcanics (unit l).

Mauna Kea is in the post-shielding-building alkalic stage, where small volumes of alkalic lava flows and tephra erupted from vents, forming lava flows and cinder cones. Mauna Kea has >300 cinder cones dotting its flanks and summit, the youngest of which is about 3.3 ka in age. In fact, the summit itself is a cinder cone, Pu‘u Wēkiu. Look to the northeast and note the chain of cinder cones extending downslope from the summit on the eastern skyline of Mauna Kea. These are formed along Mauna Kea’s east rift zone. Unlike Kīlauea and Mauna Loa, Mauna Kea has three rift zones: West, East, and South. Our route to the Onizuka Center after leaving Saddle Road, and traveling along John A. Burns Way, followed the south rift zone and weaved through its cinder cones.

<u>Suggested stay-over stop</u>: *from the Onizuka Center, drive from here to the summit of Mauna Kea. (But be advised that rental car agencies have restrictions about driving up here-a 4WD vehicle is not only highly desirable but required but the rental car agencies.)*

From the Onizuka Center, proceed back down John A. Burns Way to Saddle Road. Turn east (left) toward Hilo. Drive for about ¼ mile and turn south (right) onto Mauna Loa Observatory Road just east of our friend, Pu‘u Huluhulu. Drive exactly 7.5 miles and pull over on the south (right) side of the road across from the “sink hole.”

1:30 PM Road to Mauna Loa Observatory (NOAA), 7.5 miles from Saddle Road (30 minutes).

STOP 4-4: RELATIVE AGES OF MAUNA LOA LAVA FLOWS

Walk back down Mauna Loa Observatory Road from here and observe the lava flows. Numerous flows of a variety of ages are exposed here, and our task is to decipher their relative ages using whatever criteria we can. Obviously, superposition will be one criterion, but what others are applicable? Fill in the table below. We will observe at least three different flows, but maybe as many as five, depending on how much walking we choose to do.

Continue up Mauna Loa Observatory Road to its end and park.

Flow	Flow type—A'a or Pahoehoe	Weathering Characteristics	Other Comments

Table 6. *Comparison of flow characteristics at STOP 4-4 (to be filled in by trip participants).*

2:30 PM Mauna Loa Observatory at 3,399 m (NOAA) (90 minutes).

STOP 4-5: VIEW OF SHIELD VOLCANOES; INDUSTRIAL-AGE ATMOSPHERIC CARBON DIOXIDE

Walk several hundred meters up to the Mauna Loa Observatory facilities (closed to the public). Because of the altitude here of about 3,400 m (11,000 ft), we should walk slowly and take our time to avoid the effects of the thin air. Also, the sun is harsh at this altitude, so a good slathering of sunscreen is advised at this time (but be careful when opening the container to avoid rapid depressurization and subsequent sunscreen eruption!). Pit toilet rest rooms are located at the end of the boardwalk at the western end of the facilities.

For the most part, the spectacular panoramic view from here makes this is an arm-waving stop, and an excellent one at that, if the weather is cooperative. On a clear day, *five* shield volcanoes are observable from here!

<u>Mauna Kea</u>

Start by looking directly north at Mauna Kea. Its profile stands out against the skyline, with its numerous cinder cones jutting up along its east and west rift zones. With binoculars, the astronomy observatories may be observed from here. These include the famous W. M. Keck Observatory, the NASA Infrared Telescope Facility (IRTF), the Subaru Telescope, two University of Hawai‘i telescopes, and others. Note the deeply-incised valleys extending down the south face. Are these a testimony to Mauna Kea's age, the result of glacial runoff, or both?

<u>Kohala</u>

Looking slightly to the west (left) of Mauna Kea, Kohala may be visible, weather-permitting. This is the Big Island's oldest and therefore least hazardous volcano (lava-hazard zone 9, Figure 15), not having erupted for 120 ka (Table 2). All of Kohala's flanks are incised by stream erosion, but especially the northeast flank. Why is this side more heavily eroded than the southwest face? The northeast shore has a pronounced indentation from Pololū Valley on the northwest to the famous and scenic Waipiʻo Valley on the southeast. What might be the origin of this indentation? (Hint: hummocky debris is found on the seafloor to the northeast for 120 km out into the Hawaiian Deep.)

Suggested stay-over stop: Pololū and Waipiʻo valleys are well worth visiting not only because of their geology but because they are also extremely scenic. Both afford splendid hikes down to isolated beaches. These valleys are experiencing significant infilling with alluvium as Kohala sinks, and the deep, wide shape of Waipiʻo valley makes it an excellent tsunami funnel.

Heleakalā on the island of Maui

Looking slightly to the west (left) of Kohala, Haleakalā (House of the Sun) volcano on the island of Maui may be visible (Map 2). Haleakalā is a typical Hawaiian shield volcano, but, of course, is older than the volcanoes on the Big Island, having breached the ocean surface about 900 ka (Hazlett and Hyndman, 1996). It is composed of three basalt formations. The Honomanū Basalt (>700 ka) represents Haleakalā's tholeiitic main stage, whereas the Kula Volcanic Formation (700-350 ka) represents the alkalic phase. The Hāna Volcanic Formation (<100 ka) represents Haleakalā's rejuvenated stage (Hazlett and Hyndman, 1996), and includes its most recent activity, a coastal eruption from its southwest rift zone probably dating from about the 15^{th}-16^{th} centuries (Sherrod, 2002). A crescent-shaped islet, the popular snorkel and scuba destination of Molokini, about 5 km off of Maui's southern shore, is a partially eroded and submerged cinder cone formed along this rift zone before the last ice age. Molokini's submerged slopes are excellent habitat for coral reefs, so once again, *geology rules*.

Hualālai

Now look to the west-northwest where the summit of Hualālai volcano may be visible. This is the Big Island's middle child, younger than Kohala and Mauna Kea, and older than Mauna Loa and Kilauea (with Lo'ihi Seamount still "in the oven"). Hualālai breached the ocean surface about 300 ka B.P., but its last eruption was in 1800-1801 A.D. (Wolfe and Morris, 1996). Lava erupted from the summit and two places on its western flank. Two major historic ocean entry points occurred, one on its northern shores just west of Kiholo Bay, and another on its western flank just north of Keahole Point (Wolfe and Morris, 1996). The Holocene and Pleistocene Hualālai Volcanics commonly contain mafic and ultramafic xenoliths.

Suggested stay-over stop: an excellent locality to observe dunite and gabbro xenoliths in an 1800-1801 A.D. flow is at MP 27.6 on SR 190, about 6 miles north of Kailua-Kona. This outcrop is well worth the visit!

Mauna Loa

The fifth shield volcano visible from here is Mauna Loa under our feet. A small unit k5 lava flow (historic Kaʻū Basalt A.D. 1790 A.D. or younger) erupted from a small fissure upslope from the Mauna Loa Observatory in 1852 and flowed through this area. The last ~8 miles of the road (since the last major switchback) crossed numerous similar k5 lava flows (historic Kaʻū Basalt, age 1790 A.D. or younger) erupted in the nineteenth century. Here, the 1852 flow sits on and partially covers k4 flows (Kaʻū Basalt 200-400 years B.P.). These, in turn, rest on and partially cover k3 flows (Kaʻū Basalt 400-750 years B.P.), which form kipuka on k2 flows (Kaʻū Basalt 1,500-3,000 years B.P.). Obviously, this area has been repeatedly inundated by lava flows over the last several thousand years. Eruptions of such lava flows today would pose a significant hazard to the NOAA Mauna Loa Observatory facilities here. To reduce this risk, lava flow diversion structures have been placed uphill from these facilities, but fortunately they have yet to be tested.

Lava erupted from a series of fissures 4 km west of the Observatory at this same elevation in 1859, as well as nearby fissures about 800 m downslope. These flows made their way all the way down to the sea, following the saddle between Mauna Loa and Hualālai in its lower reaches.

Suggested stay-over stop: *return to the Mauna Loa Observatory and hike to the summit of Mauna Loa, if your physical conditioning, equipment preparation, and weather allow it. The 6.4 mile rount-trip hike ascends 2,600 ft from here to the summit at the western rim of Moku'āweoweo caldera, and the geologic features along the way are spectacular, not to mention the view from the top. Be cautioned that this is a very arduous hike due to the altitude! It is advised that you be here by 9:00 a.m. and allow an hour to acclimate while snacking and preparing your pack. Have at least 3 liters of water and plenty of food for the trail. Those who are prepared and in good shape should be able to just barely make the round trip hike in 8 hours, so starting at 10:00 a.m. puts you back here at 6:00 p.m., just in time for sunset and to avoid hiking in the dark. Bring a GPS, to find your way back down if necessary. Clouds and fog may roll into Humu'ula Saddle below you while you hike near the summit under blue skies, obscured by Mauna Loa's convexity and unbeknownst to you. If this happens, once you partially descend, it is impossible to find your way from one trail cairn to the next in fog (or darkness if your hike is protracted), so a GPS with a back-track function is an important piece of equipment to have along.*

Geology rules

This location is a prime example of *geology rules* on a grand scale. The windward orographic effect of these large volcanoes causes variations in annual precipitation as a function of elevation, which in turn affects weathering rates, soil development, and ultimately, creates vertically zoned vegetation. From sea level to summit on the windward side, the Strand, Mesic Forest, Lowland Rain Forest, Montane Rain Forest, Cool Dry Forest, Alpine Scrub, and Aeolian Zones are encountered (Zeigler, 2002). Moving around a volcano's edifice to its leeward side, the Mesic Forest, Lowland Rain Forest, Montane Forest, and Cool Dry Forest Zones slope upward, and the Desert-Grassland and Dry Forest Zones develop between the Strand and Mesic Forest Zones in the rain shadow. At this elevation of about 3,400 m on the north slope of Mauna Loa, in which vegetation zone are we here?

Atmospheric CO_2

The NOAA facilities here started measuring atmospheric CO_2 in 1957; the measurements have shown a steady increase since then. These data formed the foundation for early discussions on global warming, and a plaque commemorating these measurements may be found on one of the buildings here.

From the Mauna Loa Observatory, return to the vehicles and drive back down Mauna Loa Observatory Road to Saddle Road, and then down to the outskirts of Hilo. Saddle Road becomes Kaūmana Drive and passes Kaūmana Caves.

Suggested stay-over stop: *visit Kaūmana Caves County Park, another fine lava tube (but much more primitive than Thurston Lava Tube, for the adventurous); this lava tube was formed in the 1880-81 Mauna Loa lava flow field.*

Where Kaūmana Drive joins Waiānuenue Avenue, turn west (left). After about 0.2 miles (just past Hilo Memorial Hospital), take the right fork that leads to Rainbow Falls Park on the right. Park and walk to the falls view point.

5:30 PM Rainbow Falls (15 minutes).

STOP 4-6: MAUNA LOA VALLEY-FILL LAVA FLOW (OPTIONAL)

This final stop of our trip is chosen primarily for its scenic value, but of course, there is geology to be discussed, as well.

The Wailuku River headwaters are high on the eastern slopes of Mauna Kea at an elevation of ~3,240 m. From there, the river flows southeast for about 15 km, but then turns eastward, where it follows the swale between Mauna Loa and Mauna Kea, downcutting a valley along the way (Hilo Bay and the city of Hilo are also at the junction of these volcanoes). This swale has also been exploited over many millennia by lava flows from both volcanoes, refilling the valley with basalt in the process.

Although it may not be particularly obvious from the viewpoint, Rainbow Falls appears to have formed at the contact between Kaʻū Basalt unit k lava flow of Mauna Loa and a Hāmākua Volcanics unit hm lava flow of Mauna Kea (Wolfe and Morris, 1996). A ^{14}C sample taken very close to here yielded a date of 10,610 y B.P. for the Kaʻū Basalt flow (Wolfe and Morris, 1996). The modern day Wailuku River valley carves a new course along the margins of valley-fill lava flows each time its valley is re-occupied by lava. In places, the new channel then downcuts across the course of its older, filled channel, exposing a cross-section of an older valley-fill lava flow. Such a cross-section can be seen from here if the lighting is conducive.

<u>Suggested stay-over stop</u>: *visit the scenic Boiling Pots, a series of plunge pools eroded into the Wailuku River valley, ~1.5 miles upstream from here.*

<u>Suggested stay-over stop</u>: *visit the Lyman Museum in downtown Hilo, located at 276 Haili St, Hilo (808-935-5021). Along with its diverse and interesting displays on Hawaiian culture, history, and geology, it sports an outstanding mineral collection.*

<u>Suggested stay-over stop</u>: *visit the Pacific Tsunami Museum located in downtown on the waterfront at 130 Kamehameha Ave (808-935-0926).*

Return to the vehicles and proceed into the downtown Hilo area for dinner.

6:00 PM Dinner in Hilo.

9:00 PM Return to KMC.

MONDAY, SEPTEMBER 21
FIELD TRIP CONCLUSION

5:30 AM Load vans in preparation for departure.

6:00 AM Check out of dorms and depart KMC for Hilo.

7:00 AM Participants are dropped at Hilo airport.

End of field trip. Mahalo nui loa!

APPENDIX

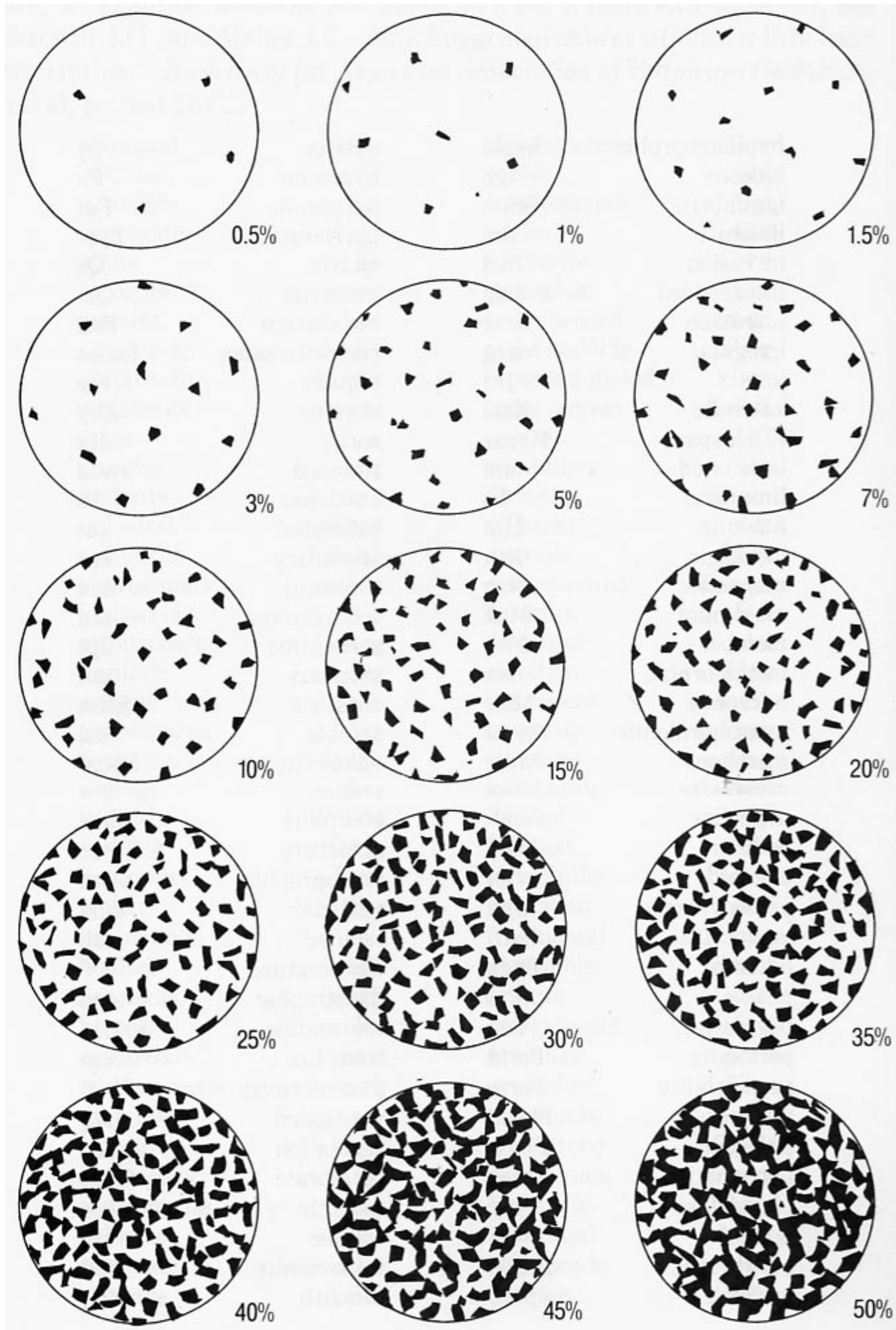

Chart for estimating the percentage of one material within another (Compton, 1985).

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