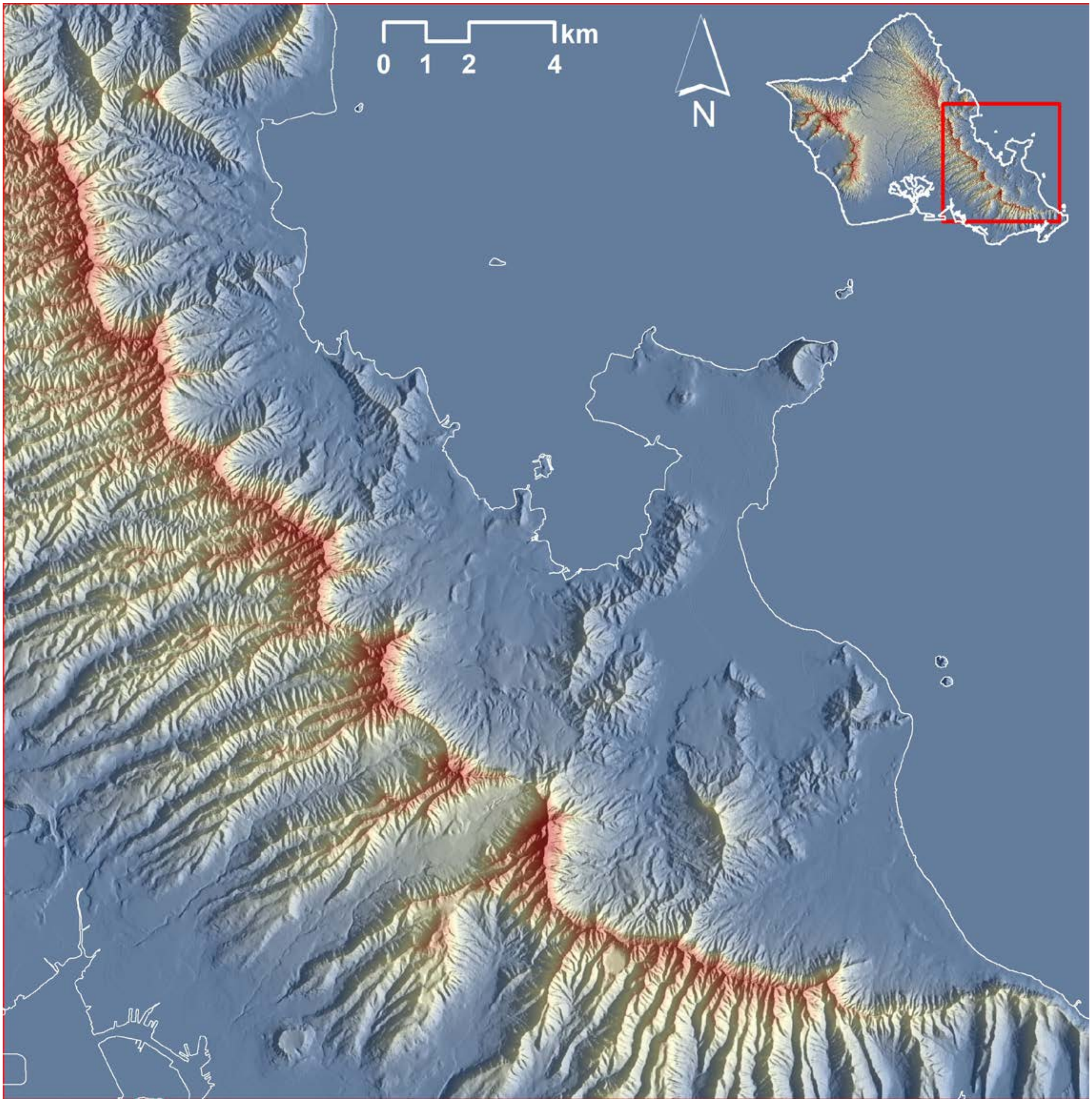
KO‘OLAUPOKO GEOLOGY FIELD TRIP GUIDE



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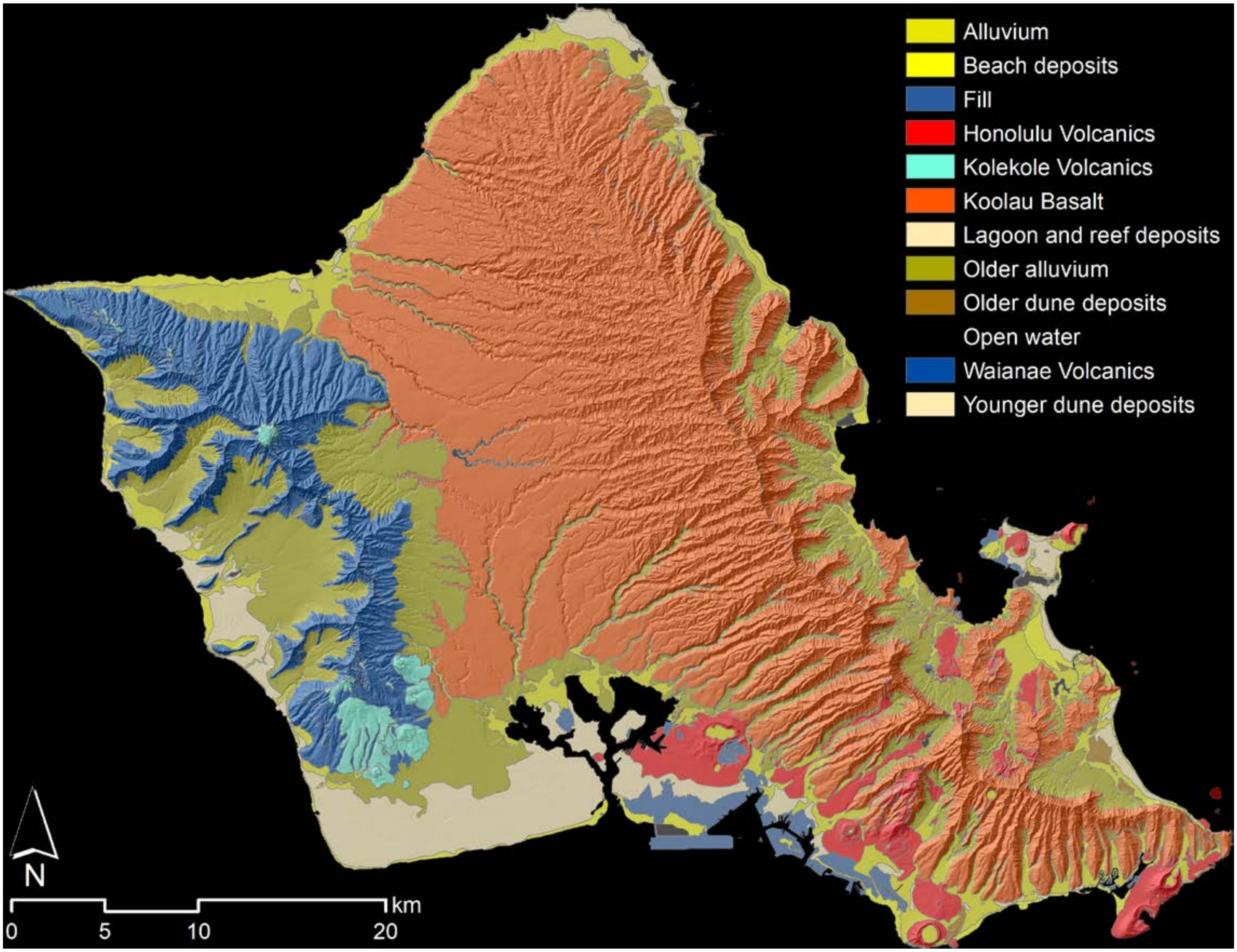

This guide borrows from previous guides written by George Walker, Ralph Moberly, and Steve Self

INTRODUCTION

This field trip will examine the geologic structure, history, and features of the southeastern part of Koʻolau Volcano. Many of the original literature sources are difficult to find so we have tended to cite more recent compilations such as <u>Volcanoes in the Sea</u> (Macdonald *et al*. 1983). The Island of Oʻahu is constructed from two shield volcanoes, Waiʻanae (*mullet water*) and Koʻolau (*windward*; front inside cover; Figure 1); a third shield volcano, Kaʻena (*the heat*), pre-dates and underlies Waiʻanae, but is now completely submerged (Sinton *et al*. 2014). Both Waiʻanae and Koʻolau were at one time at least the size that Kīlauea is today, and probably even larger (Figure 2). Waiʻanae is the older of the two (subaerial flows are ~3.9 to ~2.8 million years old; e.g., Presley *et al*. 1997) and makes up the western part of Oʻahu. Koʻolau is younger and makes up the eastern part. Its subaerial shield flows are ~3.3 million to ~1.8 million years old (Clague & Sherrod 2014), and as we will see later, after a million-year hiatus during which these shield flows were deeply weathered and eroded, rejuvenated activity began, lasting until perhaps as recently as 30 to 50 thousand years ago.

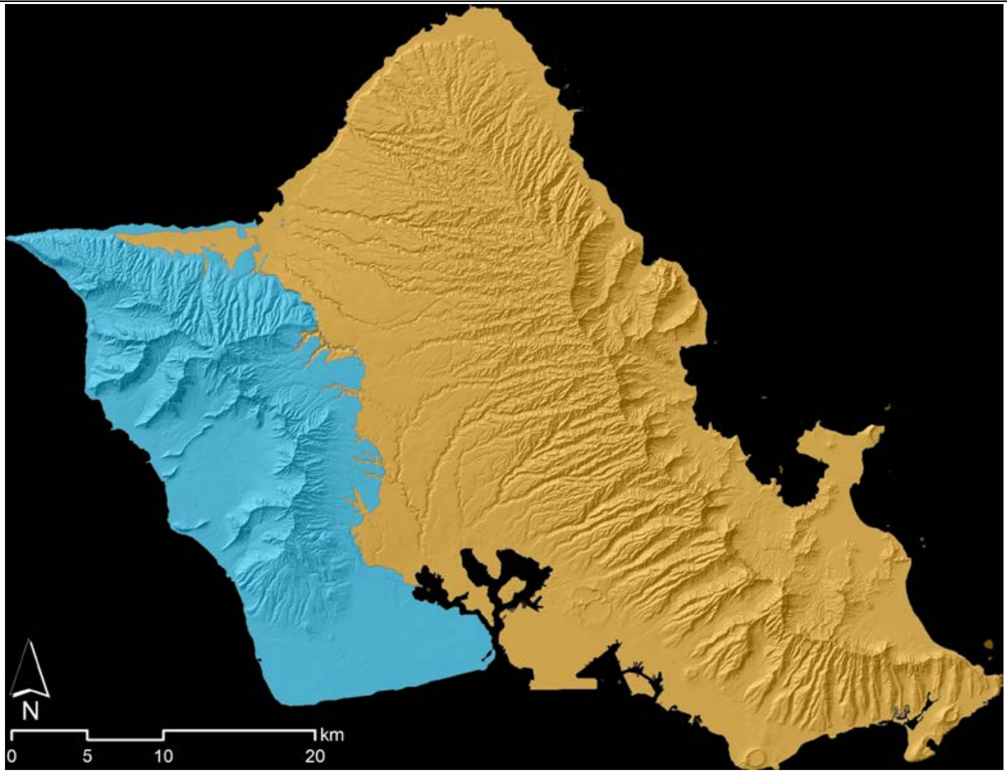

Figure 1. Shaded relief image of Oʻahu, showing Waiʻanae in *blue* and Koʻolau in *orange*.

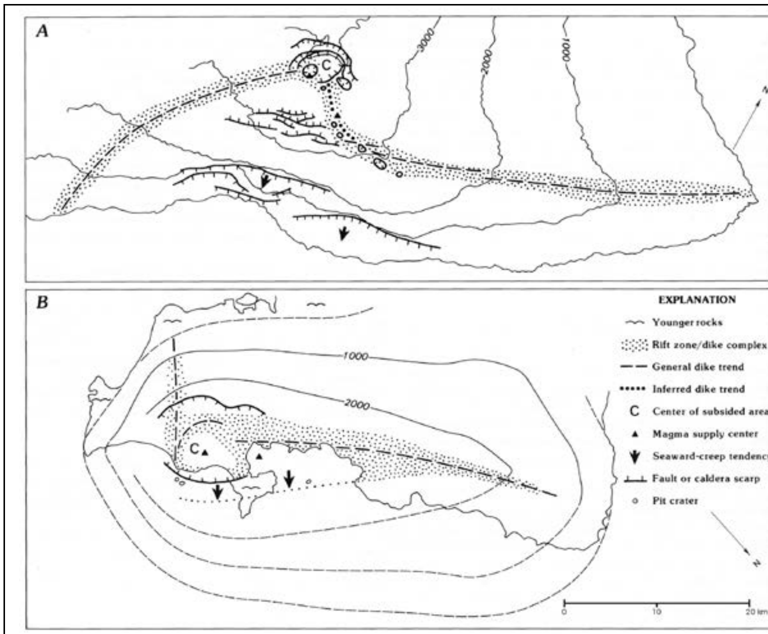

Figure 2: Kīlauea (A) and Koʻolau (B) volcanoes drawn at the same scale (from Walker 1987). Kīlauea contours are in feet, Koʻolau contours (also in feet) are generalized from present topography (solid) and inferred (dashed) to show the original form of the shield volcano. Note that Koʻolau has probably subsided by at least 1000 m since it moved off the hotspot.

The life history of a Hawaiian volcano has been summarized by Macdonald *et al*. (1983) and Peterson & Moore (1987; Figure 3). In short, there is a column of slightly warmer mantle material rising toward the surface, perhaps from as deep as the core-mantle boundary some 2900 km below the surface. Even though it is shaped like a column, it is called a "hotspot" because that's what it was named before we figured out its structure. This column is solid but slightly hotter than the surrounding mantle and this extra heat makes it buoyant. Once the column reaches to about 100 km beneath the surface it starts to melt via a process called decompression melting; the magma percolates to the surface, and builds Hawaiian volcanoes. The center of the column rises faster than the outer parts and this means the compositions of the magma at the center and edges are slightly different. As a point on the Pacific plate passes over the column, it first encounters the outer edge of the column, which is a region of low amounts of partial melting and the magma produced here (and erupted from the volcano) is called alkalic basalt. Later, it passes over the center of the column where there is a greater degree of partial melting, which produces what is called tholeiitic basalt. The greater degree of melting also means there is more of this tholeiitic magma, so this is the stage of life that accounts for ~90% of a Hawaiian volcano's total volume. Finally, the volcano moves over the downstream edge of the column, which is another region of low partial melting which therefore also produces alkalic magma. Lōʻihi has only recently started the transition from early alkalic basalt to tholeiite basalt, Mauna Loa and Kīlauea are both in the main tholeiite shield stage, Hualālai and Mauna Kea are both in the post-shield alkalic stage, and Kohala has moved far enough off the column so that it is no longer erupting at all. Following extended periods of erosion, both gradual and catastrophic, a few Hawaiian volcanoes went through a period of rejuvenation, meaning they erupted again even though they were way off the hotspot. The lavas erupted during this rather enigmatic stage are commonly strongly alkalic, occasionally contain mantle xenoliths, and the eruptions are spread far enough in both time and space that they result in individual monogenetic vents (tuff cones, scoria cones, and lava shields). The relationship between this activity and the hotspot is not yet fully understood. Eventually, 100,000 to ~2 million years later, even the rejuvenation activity ceases. The volcano is worn down by rain and waves, and subsides until only coral reefs remain above sea level. Because plate motion is to the northwest, into colder water, reef growth gets slower and slower and finally is unable to keep up with erosion and subsidence. The volcano ends its life as an old seamount (Figure 3).

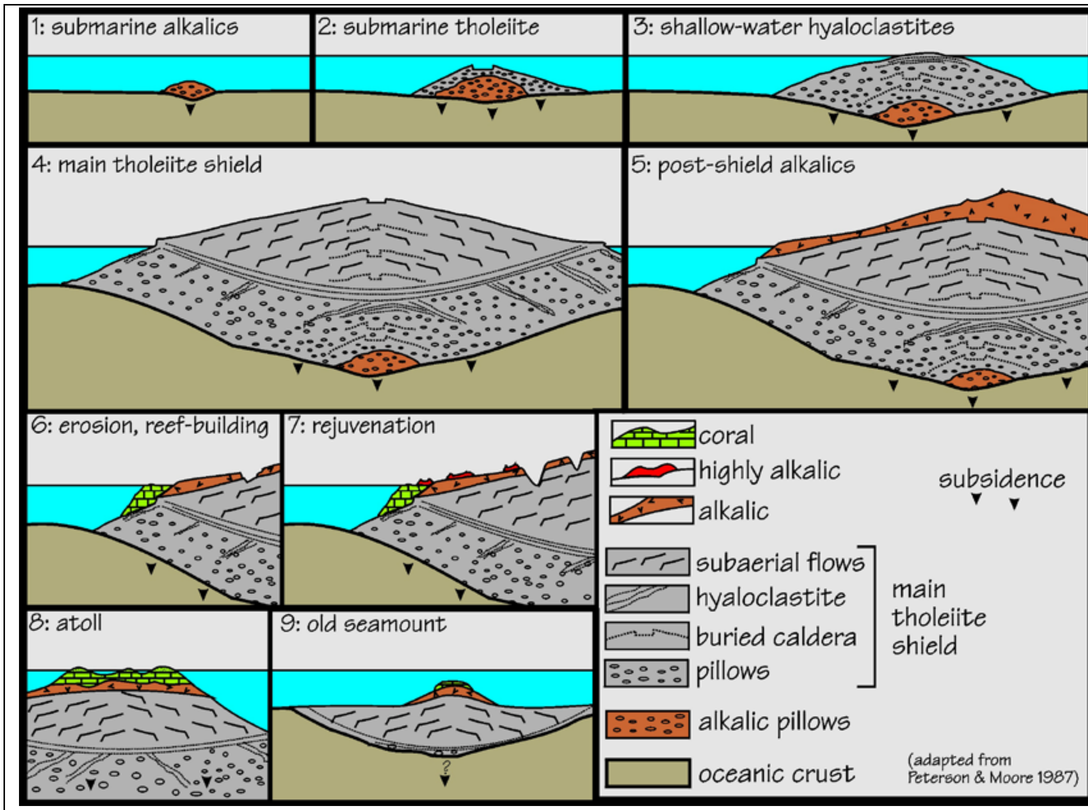

Figure 3: Sequence of diagrams illustrating the life history of Hawaiian volcanoes.

KOʻOLAU VOLCANO

Koʻolau volcano started its life as a seamount above the Hawaiian hotspot ~4 million years ago. It broke sea level some time prior to 3 million years ago, the age of the oldest subaerial lavas (Haskins & Garcia 2004; Clague & Sherrod 2014). During its tholeiite shield stage, Koʻolau eventually reached an elevation of at least 2000 m (Walker 1987; the current highest elevation is ~1100 m). Koʻolau does not have much evidence of having ever gone through the post-shield alkalic stage. Only 2-3 outcrops of alkalic basalt have been discovered near the top of the tholeiite section where the beginning of a transition to fully alkalic eruptions might be expected. Why this stage might have been skipped is not clear but it should be pointed out that the volume of post-shield volcanics on other Hawaiian volcanoes varies considerably from only a little (e.g.

Kaua‘i) to a lot (e.g. Mauna Kea). Therefore, it is entirely possible that there was a relatively small amount of post-shield alkalic lava erupted on Ko‘olau but that it has been eroded and/or avalanched away.

While active, Ko‘olau possessed the typical structural features of a Hawaiian volcano, specifically a caldera as well as two to three rift zones radiating away from the caldera (Figure 4). The rift zones are the cause of the northwest-southeast elongated plan view shape of Ko‘olau, and this shape was accentuated by catastrophic avalanching of the northeast side of the volcano. We will examine evidence for these major structural features as well as for the catastrophic avalanche during our field trip. Gradual subsidence combined with both slow and catastrophic erosion have combined to produce the current, smaller edifice.

The main tholeiite shield-building stage of Ko‘olau volcano ended somewhere around 1.8 million years ago (Clague & Sherrod 2014), and erosion took over as the dominant geologic process. As on other Hawaiian volcanoes, the northeast side of the volcano (facing the prevailing tradewinds) was eroded to a greater degree than the leeward side. As shown in Figure 5, there are very large rainfall gradients from northeast to southwest across the crest of Ko‘olau, with rainfall values climbing from ~50 to >300 and back to ~50 inches per year within only 25 km. This has led to very uneven degrees of erosion of the volcano. For example, there are remnants of the original shield surface along most of the southwest flank of Ko‘olau, but essentially none on the northeast flanks. Remnants of the old shield surface take the form of planezes between amphitheater-headed valleys, and many of them are highlighted today by expensive subdivisions.

REJUVENATED VOLCANISM

The rejuvenated stage of Hawaiian volcanism has produced dramatic scenery and has attracted attention for a long time. The Hawaiian stories of Pele, the goddess of volcanoes, has her stopping on each island as she journeyed from Ni‘ihau to Hawai‘i (e.g. Westervelt 1963), and many of the places she tried to build a home, but was fought off by her sister turn out to be what modern geologists have mapped as sites of rejuvenated volcanism. The rejuvenation-stage volcanism on Ko‘olau is called the Honolulu Volcanic Series. About 40 Honolulu Volcanic Series vents have been identified and they are all concentrated within the southeastern third of the elongate Ko‘olau edifice (Figure 4).

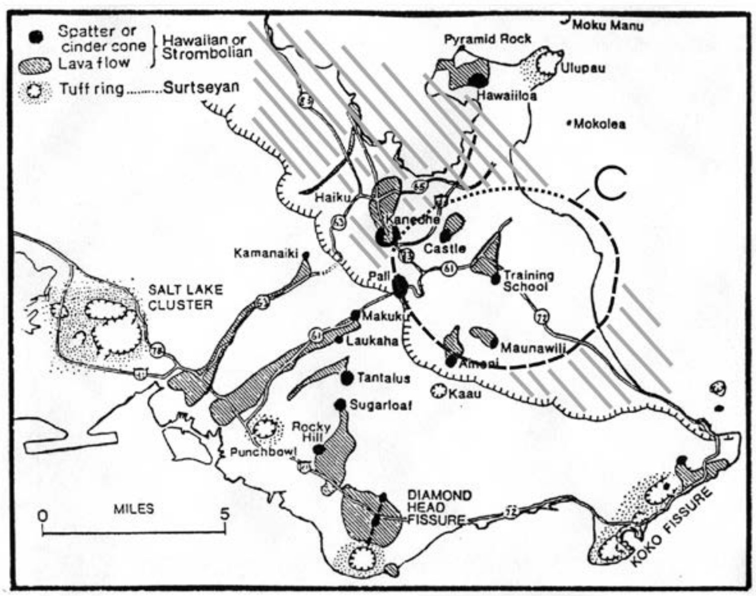

Figure 4. Geological/structural map of the southeast part of Ko‘olau volcano, showing the location of the old caldera (*C*), rift zones (*gray lines*), and rejuvenation-stage (Honolulu Volcanic Series) vents and lava flows. Adapted from a map by George Walker.

Presently, there are many competing ideas for the origin of rejuvenation-stage volcanism, and two main aspects need to be explained; 1) how to generate magma at a location far from the hotspot; and 2) why there is a gap in time, sometimes as long as 2 million years, before rejuvenation commences. It is also unclear why only 5 Hawaiian volcanoes (Ni‘ihau, Kaua‘I, Ko‘olau, E. Moloka‘I, and W. Maui) have undergone rejuvenation. One model proposes that northwestward movement of the lithosphere drags hotspot material along at the base of the lithosphere. The hotter hotspot material conducts heat to the overlying lithosphere and eventually, causes it to melt (Gurriet 1987). Because it takes a while for the lithosphere to be heated enough to start melting, there is a time gap between the end of the post-shield alkalic eruptions and the start of the rejuvenation-stage eruptions. And because it is lithosphere that is melting to produce the rejuvenation-stage magmas, their compositions are different from those produced by the hotspot (which is partially melted mantle).

Another model involves depressurization of the upper mantle due to flexure of the oceanic lithosphere. Essentially, the lithosphere can be thought of as a flexible lever that is being pushed downward at the hotspot end (due to the weight of the island of Hawai‘i). The downward motion at the SE end produces an upward motion ~300 km away. The upward motion depressurizes the underlying upper mantle, leading to small amounts of partial melting and the production of highly alkalic magmas. A third model (Ribe & Christensen 1999) proposes that as hotspot material is dragged “downstream” it also spreads laterally (i.e., to the NE and SW). This spreading causes the base of the material to move upward (to conserve volume), and any time that hot mantle material moves upward it has the possibility of undergoing decompression melting, in this case producing alkalic magmas 300-500 km downstream of the hotspot center. It is definitely possible that more than one mechanism is at work. Careful age dating by Ozawa *et al*. (2003) shows that within the Honolulu Volcanic Series there have been two pulses of magmatism separated by a hiatus of ~250,000 years. The earlier pulse, which lasted from 800,000 to 360,000 years ago, may have been due to one of the processes. The later pulse, from 100,000 to 30,000 years ago, may have been due to another.

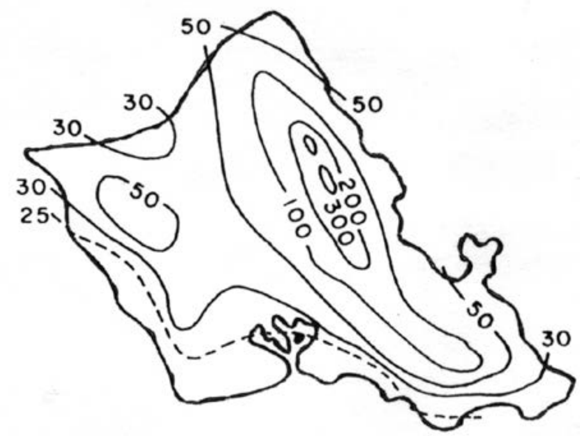

Figure 5. Rainfall map for O‘ahu (isohyets are in inches/year; from Macdonald *et al*. 1983). Note the great differences in rainfall over extremely short distances, particularly parallel to the direction of the prevailing tradewinds (northeast to southwest).

STOP 1. NU‘UANU PALI OVERLOOK

After driving up Nuʻuanu (*cool height*) valley you reach the pali overlook. Geomorphologically this location is what is called a wind gap, where the heads of two oppositely-eroding valleys intersect (Figure 6). On most days the “wind” portion of this geomorphologic term is very appropriate. The view looks out to the windward side of Oʻahu, across what was the volcanic center of Koʻolau volcano. In particular, the Kapaʻa (*the solid* or *the closing*) area, Kaʻiwa (*the frigate bird*) ridge, and Olomana (*forked hill*) all consist of thick lava flows that all dip very slightly towards a point centered in Kawainui (*the big water*) marsh. They therefore are intra-caldera lavas and the slight dips record inward sagging due to subsidence over the old magma chamber (Walker 1988). Kawainui marsh also corresponds to

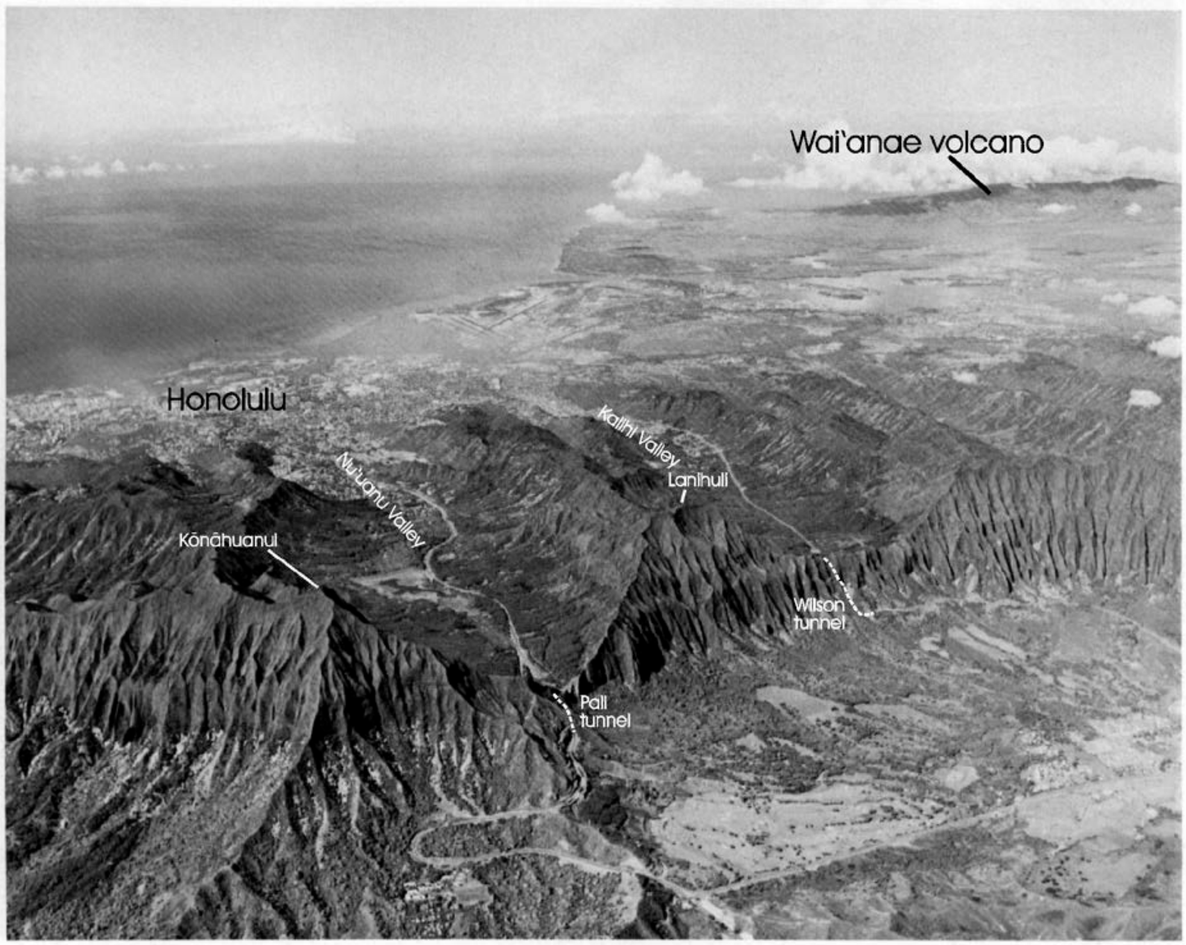

Figure 6. Air photo looking west, of the Nuʻuanu pali (from Macdonald *et al*. 1983). Valley erosion working northeast and ~parallel retreat working southwest has produced wind gaps at the heads of Nuʻuanu and Kalihi valleys, and it is through (actually just below) these wind gaps that the first two cross-Koʻolau tunnels (*dashed*) were built. Kōnāhuanui (918 m) and Lanihuli (803 m) are the two highest points on Koʻolau.

the center of a gravity high (Strange *et al*. 1965) and overlies a zone of high seismic-velocity rocks (Adams & Furumoto 1965). The boundary of thick, slightly inward-dipping lavas and thin, steeper outward-dipping lavas is therefore the caldera margin. It can be mapped to within a few hundred meters in some places but elsewhere is obscured by water or alluvium. It grazes the base of the Nuʻuanu pali in the vicinity of the overlook.

In the far distance, the Mōkapu peninsula forms the northeastern-most point on Oʻahu and the Kāneʻohe Marine Corps Air Station is located there. The peninsula is composed of at least six closely-spaced rejuvenation-stage volcanic vents and lava flows. If you look to the right (along the pali) from the lookout you can see steeply dipping scoria and ash deposits from another rejuvenation stage vent that was perched high on an eroded windward Koʻolau slope. These north-dipping (to the right from this vantage point), red-colored scoria layers unconformably overlie south-dipping (to the left) ʻaʻā and pāhoehoe flank lava flows. In places the contact between the flank flows and the rejuvenation-stage scoria and ash is sharp enough to put your finger on. This contact represents a time break of ~1.5 million years.

Walking down the old Pali Road allows good views of pāhoehoe and ʻaʻā flows (Figure 7) in cross-section perpendicular to the direction in which they were flowing. The first pāhoehoe flow you encounter consists of numerous lens- or lozenge-shaped flow units called "toes". Here they tend to be ~0.5 m wide and 20-30 cm high. The first ʻaʻā flow along the road is more difficult to examine because it is high in the section. However, it is possible to identify the basal clinker layer (with kind of a rubbly appearance), the central "core" (with steep, roughly vertical fractures), and the upper clinker layer (rubbly, with plants growing on it). There is also a dike cutting through these flows. This dike has a squiggly margin and is vesicular; both suggest that it was emplaced at a shallow depth. Also somewhat unusual is its orientation, striking ~north-south, which is roughly orthogonal to the typical Koʻolau dike trend.

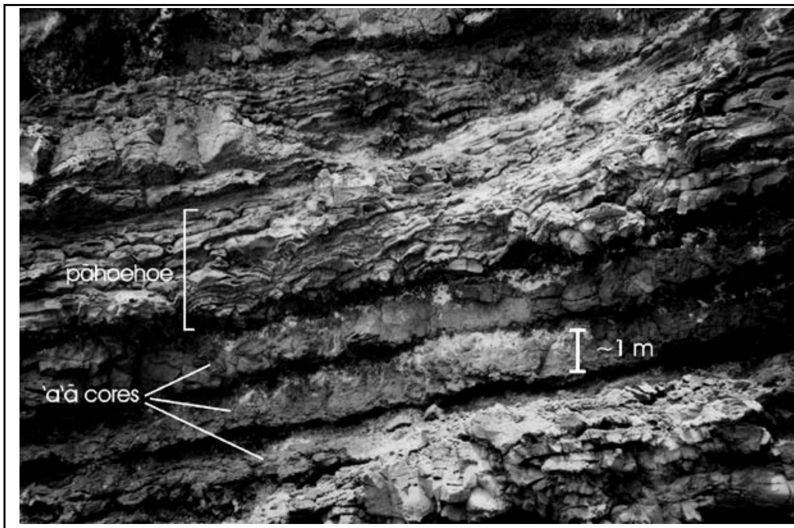

Figure 7. Photo showing the typical nature of ʻaʻā and pāhoehoe flows when viewed in cross-section. The cores of ʻaʻā flows are resistant relative to the top and bottom clinker layers. The pāhoehoe flows consist of innumerable toes and here differential erosion has accentuated vesicle-poor (resistant) and vesicle-rich (less resistant) flow-parallel sheaths in each toe. Note that this cross section (low on the cliff below Makapuʻu point) is oblique to the flow directions.

Nuʻuanu pali is one of the most spectacular geological features on Oʻahu (pali is the Hawaiian word for *cliff*). Many Hawaiian islands have pali but the Nuʻuanu pali is considered the classic example and is commonly just called "the Pali" (Stearns and Vaksvik 1935). Some pali are along the coast (e.g., north shores of Kauaʻi and Molokaʻi) and others are inland (e.g., on Oʻahu and Niʻihau). A wide range of suggestions have been offered to explain the origin of Nuʻuanu (and other) pali:

1) Faulting - Dana (1891), the first geologist to visit Hawaiʻi, proposed that great fractures were responsible for these cliffs. Such a fault would have at least 1 km of offset to have created the Nuʻuanu Pali.

2) Fluvial erosion - A young captain in the U.S. Army (George Dutton) visited Hawaii in the late 19th century. He was a keen observer and his observations led him to conclude that erosion was the main cause of the pali (Dutton, 1883).

3) Marine erosion - Some subsequent geologists combined marine erosion with faulting in explaining the pali's origin (e.g., Hinds, 1931).

4) Caldera rim - This idea has been at least informally discussed based on the fact that the Koʻolau volcano caldera boundary grazes the pali in a few places, as does the margin of a Koʻolau rift zone, just below the Nuʻuanu pali overlook (Macdonald *et al*. 1983; Walker 1987).

5) Headwall of the Nuʻuanu landslide (see next section) - Marine surveys north of Oʻahu revealed that the northeast side of the Koʻolau volcano collapsed into the ocean, removing ~40% of the old volcano (Moore and Clague, 2002; Satake *et al*., 2002). The location of the headwall for this landslide has been debated but some have suggested it is the pali (Carracedo 1999). Hydrothermal alteration in the rift zone was thought to weaken the rocks and make them more susceptible to failure (Carracedo 1999).

So we have many alternative models that can explain the formation of Pali. What key observations are needed to test these hypotheses?

A) The shape of the pali - it is not a linear feature. Instead, it is scalloped with many embayments. Thus, a pure fault origin is unlikely. Also, the numerous scalloped features make a pure avalanche scar explanation problematic.

B) Length of the pali - it extends well beyond the old Koʻolau caldera margins. It is not the remnants of an old caldera rim although locally it coincides with the rim.
C) Residual ridges, remnants of the old Koʻolau volcano, extending from the pali. These include the Mokulua islands, Olomana, Kapaʻa, and the Keolu hills. Any avalanche scarp must be oceanward of these remnants.
D) Former sea level stands were never high enough. Although sea level has fluctuation greatly over the last two million years since the Koʻolau volcano was formed, it was never high enough on Oʻahu to have eroded the base of the pali (except at the Makapuʻu end). Also, there are no relict marine features near the pali.

So what are we left with? As we explain below our current preferred model for the origin of the Nuʻuanu pali is a combination of a head start provided by the giant avalanche followed by the fluvial erosion idea proposed by Capt. Clarence Dutton in 1883.

GIANT AVALANCHES

Jim Moore provided evidence that much of the northeast flank of Koʻolau volcano (as well as much of E. Molokaʻi volcano; Figure 8) avalanched onto the ocean floor (Moore 1964). The idea was controversial at the time but recent sampling has shown that the hummocky material spread northeastward from Oʻahu does indeed consist of Koʻolau lavas. Additionally, side-scan sonar data collected around the eight main Hawaiian islands in the 1980s identified at least 17 additional deposits from giant avalanches (Moore *et al*. 1989; Figure 9). We now know that the avalanche associated with Koʻolau (named the Nuʻuanu avalanche) is one of the largest landslides on Earth, with blocks up to 40 km long and 2 km tall having slid as far as 100 km (Moore and Clague, 2002).

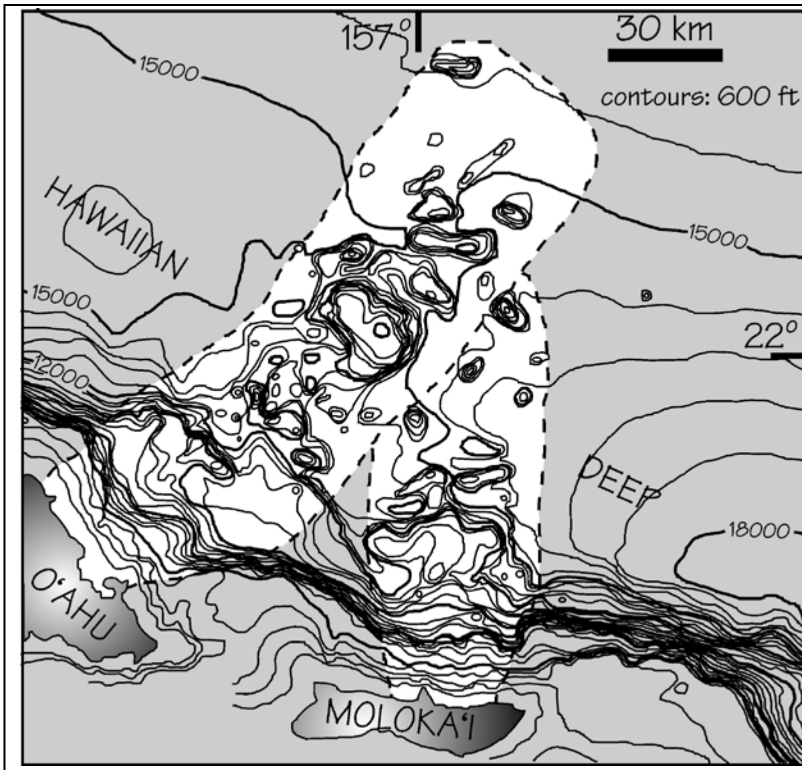

Figure 8. Map of bathymetry off the north coasts of Oʻahu and Molokaʻi first used by Moore (1964) to postulate and outline the deposits of giant avalanches. Adapted from Moore (1964).

As we noted above, any avalanche scar must be seaward of the seaward-most remnant of the Koʻolau volcano (Figure 10). This puts it at least a kilometer or so oceanward of the current coastline (i.e., just northeast of the Mokulua islands. Immediately after the avalanche there would have been a cliff perhaps 2000 m high, which obviously would have been very unstable. Smaller avalanches and rapid marine and stream erosion would have caused this cliff to be eroded back (southwest). This process of "parallel retreat" has been documented at a number of locations on Earth, including along the northwest part of India (Widdowson & Cox 1996). Basically it states that if a cliff is produced (e.g., by an avalanche), it will persist as a cliff as it is eroded landward. If the rocks involved are basalt lavas such as in Hawaiʻi, the process is aided by the fact that almost all such flows posses roughly vertical cooling joints, that are continually exposed by erosion and weathering.

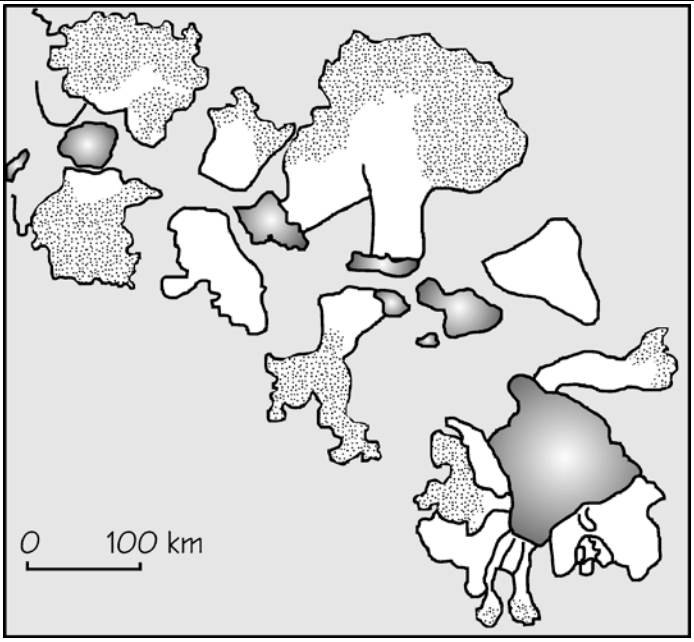

Figure 9. Map showing the locations of giant avalanche and slump deposits off the 8 main Hawaiian islands (adapted from Moore *et al*. 1989). The distal ends of some of the deposits are characterized by hummocky terrain (*stippled*).

Not all the retreat was parallel, however. As we noted above there is evidence that fluvial erosion resulted in the formation of amphitheater-headed valleys (Figures 5, 9), giving the pali its scalloped form. These scallops are the coalesced heads of these valleys. The northeast-trending ridges are remnants of the ridges that once separated the valleys. Olomana, for example, is a high point on the ridge that separates Maunawili and Waimānalo valleys (Figure 10).

How catastrophic was the Nuʻuanu avalanche? After all, there are landslides that just creep slowly downslope. The best evidence for catastrophe is that the Nuʻuanu avalanche deposit had enough momentum to flow uphill on the ocean floor. Figure 8 shows that the avalanche material flowed down off the flank of Koʻolau, crossed the Hawaiian Deep (a moat-like depression due to the weight of the island), and managed to lap up the other side of the Hawaiian Deep. This required a climb of roughly 300 m, and remember this was against water resistance. A creeping landslide could not have achieved this. An inevitable question is how big of a tsunami would such a catastrophic avalanche cause? The answer is that it would be devastating within Hawaiʻi (i.e., >200 m high; Satake *et al*. 2002) but opinions vary about whether or not it could also devastate other places such as the west coast of North America. There is currently considerable debate about whether a particular deposit on the south flank of Lānaʻi was formed by a giant-avalanche-generated tsunami or by high sea level followed by tilting of the island.

Figure 10. Air photo of the southeast end of the pali (view is to the West; from Macdonald *et al*. 1983). The view is to the northwest and was taken from above Makapuʻu. All flows to the left of the crest dip to the southwest. The plain northeast of the crest (occupied by houses and agricultural fields) consists of coral reef and beach sand deposits formed during the +3 m Waimānalo stand of the sea 143,000-106,000 years ago. The approximate boundary of the caldera is indicated by a *dashed line*. Olomana (444 m), under the cloud shadow, is the highest remnant of the pre-avalanche Koʻolau volcano seaward of the pali. Other pre-avalanche remnants are indicated with *R*.

STOP 2. H-3 DIKES

Exposed along a section of the H-3 freeway is the interior of the old Koʻolau northwest rift zone (Figure 11). This is identified by the high concentration of 0.5-1.5 m-thick dikes, almost all of which strike northwest (e.g. Walker 1987; Figure 12). Dikes are the mechanism by which magma propagates within a volcano from the magma chamber to the point of eruption. They essentially slice through the pre-existing rock like knives. Indeed, the dimensions of dikes are similar to those of knives. Studies on Kīlauea and here on Koʻolau show that typical dike dimensions are as follows: Length (measured on a map from a point above the magma chamber to the eruption site) can be as much as a few 10s of km. Height (measured during dike propagation by locating the shallowest and deepest earthquakes along the dike trace) is typically 1-2 km. And thickness (measured in locations such as this outcrop at H-3) is <1 m. Dikes are therefore much much thinner than they are tall or long.

Figure 11. Photograph of Koʻolau dikes exposed in a roadcut along the Pali Highway. Guardrail is ~1 m high for scale.

George Walker, during his tenure as Macdonald Professor of Volcanology at the University of Hawaiʻi, conducted an exhaustive study of the Koʻolau dike swarm, measuring and mapping thousands of dikes. One of his observations was that dike intensity drops considerably in the areas corresponding to thick, caldera-filling lavas. He considered that there was no reason to expect that dikes avoid intruding within the caldera. Instead, he considered that subsidence within the caldera carried lavas downward (along with any dikes that intruded into them) below the level of the current erosional surface (Walker 1987; 1988).

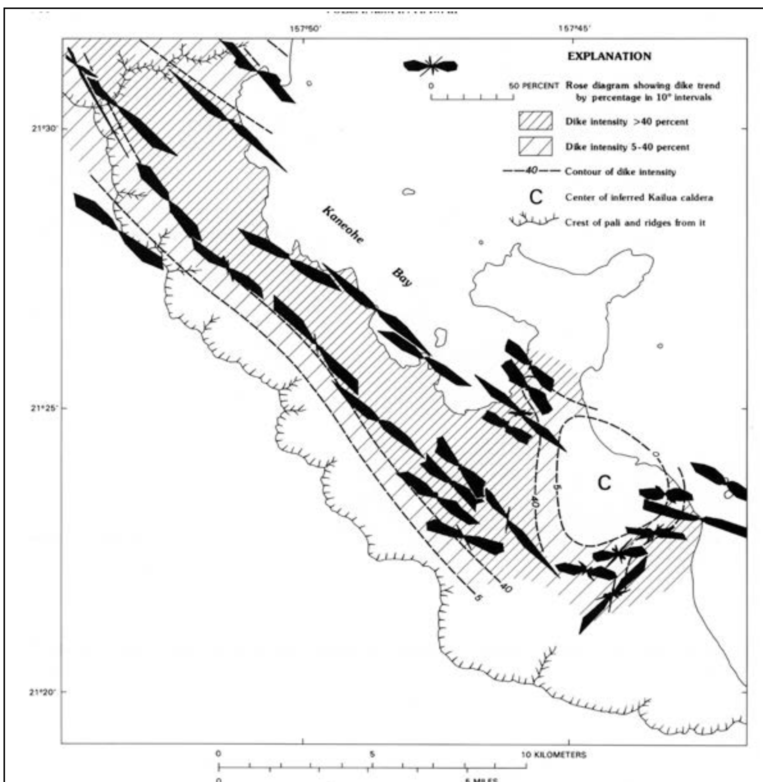

Figure 12. Map of part of Koʻolau volcano showing the locations and trends of dikes (from Walker 1987). Note that dike intensity drops off markedly in the region of the caldera *C*.

Walker (1987) also pointed out that most of the Koʻolau dikes have a relatively consistent northwest strike but they dip to both the northeast and southwest. In many locations, in a traverse perpendicular to strike the dip will swing back and forth from predominantly southwest to predominantly northeast. In other places most dikes will have one of these dips but there will be a few with the other so that they produce a braided pattern. Most of the dikes show prominent cooling fractures that grade from closely spaced at the dike margin to farther spaced at their centers. Many also have glassy margins. Some show flow-differentiation-induced concentrations of vesicles, and many of these vesicles have been filled with zeolites and other secondary minerals.

KĀNEʻOHE BAY

A scenic overlook gives us a good view of Kāneʻohe Bay and beyond (Figure 13). A fringing reef extends across almost the whole of the bay, from Mōkapu (to our right) to Kualoa off in the distance. Sand bars have developed in a few locations. Kapapa island, on the outer edge of the reef, is ~5 m high and preserves a fossil beach from a slightly higher stand of sea level 3-4000 years ago. Patch reefs dot the inner waters of the bay. The island near the center is Moku o Loʻe (Coconut Island) and it has been augmented artificially. It is home to the Hawaiʻi Institute of Marine Biology, part of the University of Hawaiʻi.

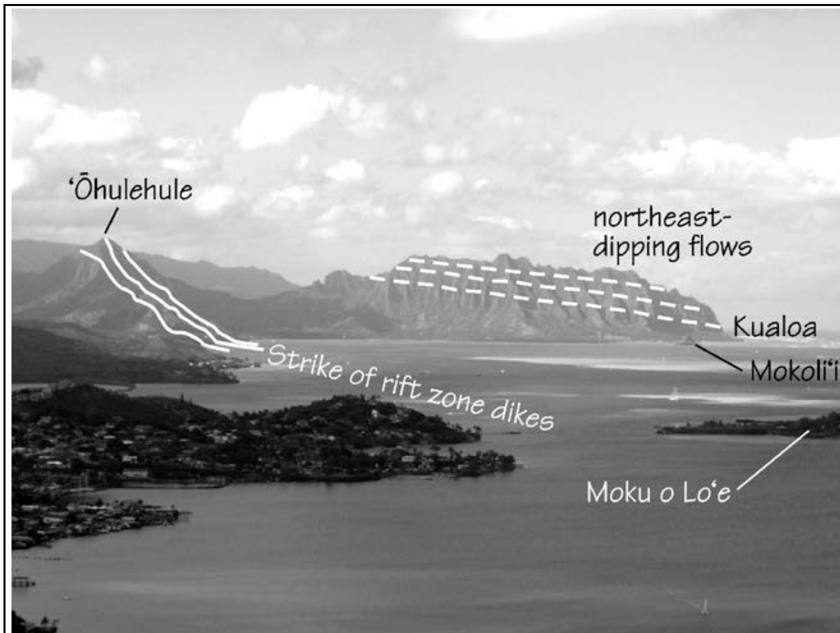

Figure 13. Photo across Kāneʻohe bay looking along the axis of the Koʻolau rift zone.

In the late 1960s and early 1970s Kāneʻohe Bay was an environmental disaster. Careless development caused huge volumes of mud to be washed into the bay whenever it rained (which is often here). Eventually much of the coral and most of the fish were dead or nearly dead and the influx of terrestrial nutrients spawned blooms of algae and exotic invertebrates. Public outcry led to stronger environmental laws regarding development and runoff control and today the bay is considerably healthier.

In the distance is a triangular peak, ʻŌhulehule. It is a resistant peak partially because it has a high concentration of relatively resistant dikes in it. Additionally, from this viewpoint, the lavas in the hills to the right dip to the right (northeast) whereas the lavas in the hills to the left dip to the left (southwest). It is pretty clear therefore, that ʻŌhulehule represents the axis of the rift zone.

STOP 3. WAIMĀNALO

We will next drive through the towns of Kailua and Waimānalo. These towns mostly overlie ancient coral reefs, and in places and calcareous sand dunes. Recent drill-hole studies in Kailua record higher and lower stands of sea level and their associated migration of the coastline. That same high stand of the sea recorded by the fossil beach on Kapapa island, for example, was associated with most of what is now Kailua town being under water. Semi-lithified dunes are exposed along the main highway just southeast of the Waimānalo shopping area (Figure 14). The dunes and reef in Waimānalo correspond to an older episode of higher sea level, the 106,000-136,000 year-old +3 m Waimānalo stand. The record of changing sea level on Oʻahu is very complex (Figure 15), and is currently being unraveled by the Coastal Geology group in UH Mānoa's Dept. of Geology & Geophysics, headed by Chip Fletcher.

Figure 14. Photo of semi-lithified sand dunes along Kalanianaʻole hwy., in the town of Waimānalo.

The back of Waimānalo is bounded by an extension of the Nuʻuanu pali, and is spectacularly fluted. During heavy rains each of these flutes contains a succession of water falls and plunge pools, and they contribute to the parallel retreat of the pali.

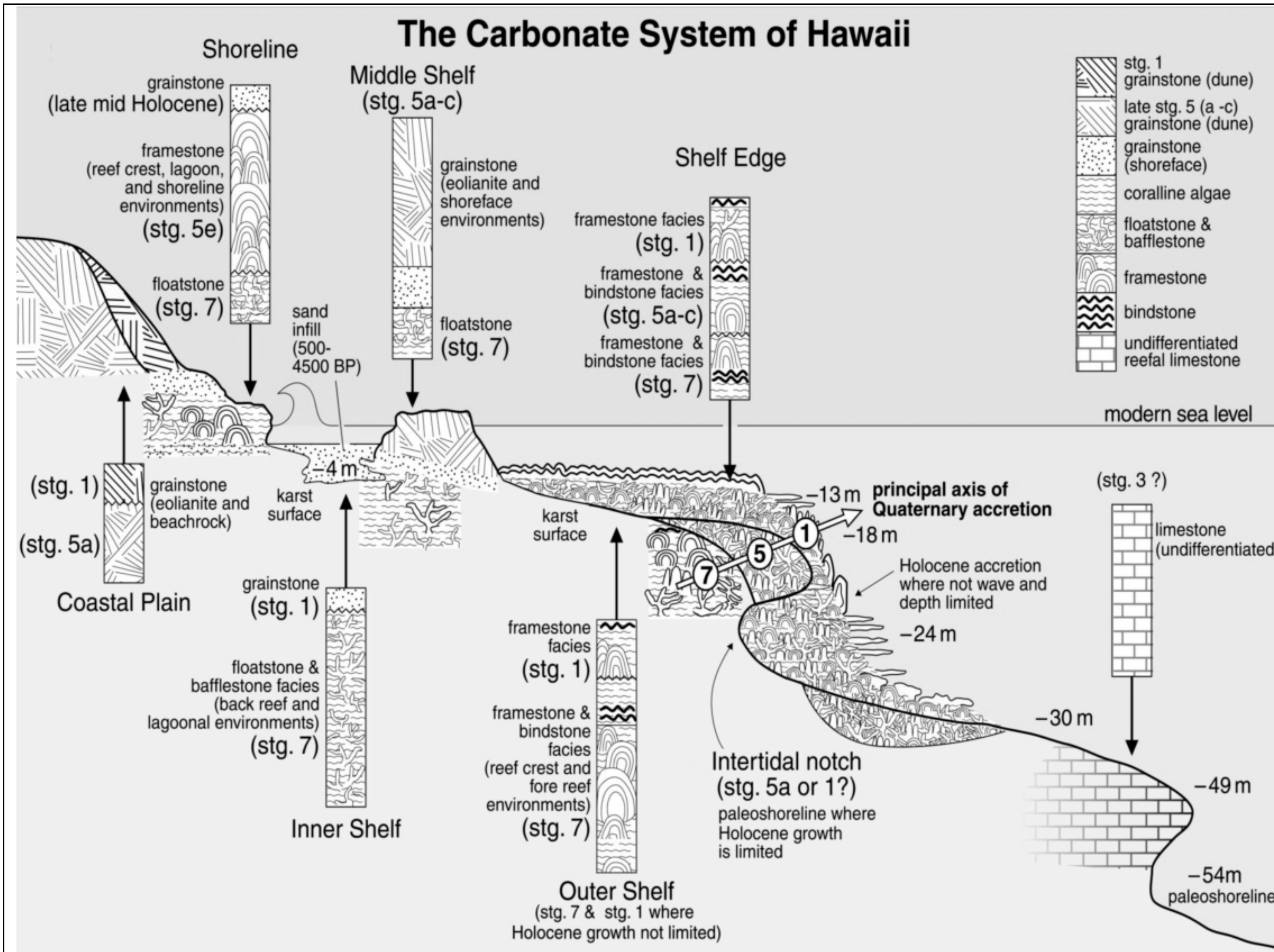

Figure 15. Composite diagram of the different facies, ages, and profiles of limestone found both above and below sea level on Oʻahu (by Chip Fletcher and the University of Hawaiʻi Coastal Geology Group: **http://www.soest.hawaii.edu/coasts/cgg_main.html**).

STOP 4. MAKAPUʻU LOOKOUT

From the Makapuʻu lookout we can look back along the windward side of southeastern Koʻolau volcano (Figure 16). All the shield stage lava flows in this area are truncated at their upslope ends, and slope uphill toward their sources, now gone, to the north. The cliffs behind Sea Life Park are an extension of the same pali that we first observed at the Pali Lookout. Here, however, because of the proximity of the ocean, marine erosion has contributed to development of the pali.

The lookout sits in a natural pass formed by an old valley. The rounded boulders just east of the parking area are reminders that a stream once flowed down this valley. As with the lava flows making up the pali, the head of the valley has been truncated by erosion.

The northernmost vents of the Koko fissure, part of the Honolulu Volcanic Series rejuvenation stage, lie just offshore from the Makapuʻu lookout (Figure 17). The most prominent, light-toned island is Mānana (also called Rabbit Island), a tuff cone containing melilite nephelenite clasts with sodalite crystals. Palagonitization of the fine-grained tuff has produced its light tan color. Inland from Mānana is Moku Hope, the remnant of a scoria cone and small lava flow. It is interesting that there were such different styles of volcanism from these two locations so close to each other, with Mānana showing strong interaction with external water and Moku Hope showing none. However, geochemically Mānana is different from all other vents along the Koko Rift and therefore probably erupted at a different time (technically separating it from the Koko Rift proper). There is some debate about island names. Most maps give the name of Moku Hope as Kāʻohikaipu. According to Pukuʻi *et al*. (1974) Kāʻohikaipu, in olden days, instead referred to a small rock in the mouth of a small inlet on the south coastline of Moku Hope.

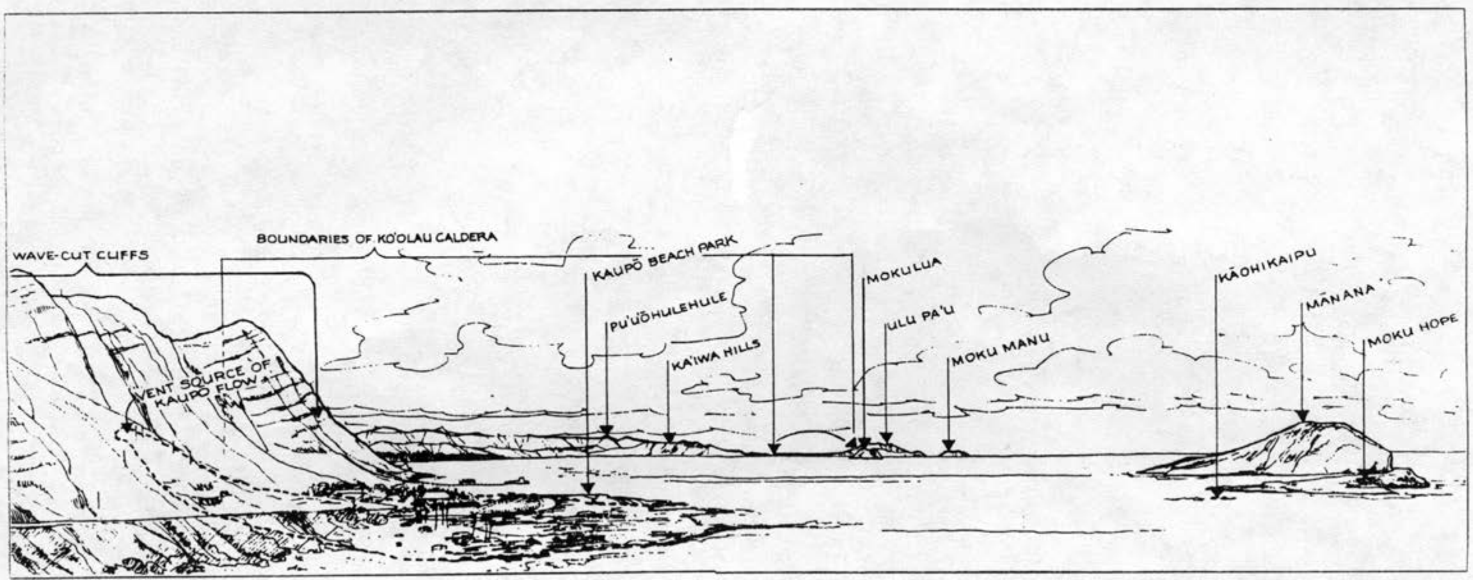

Figure 16. View plane diagram looking northwest from Makapuʻu lookout (by Lorin T. Gill, Moanalua Gardens Foundation).

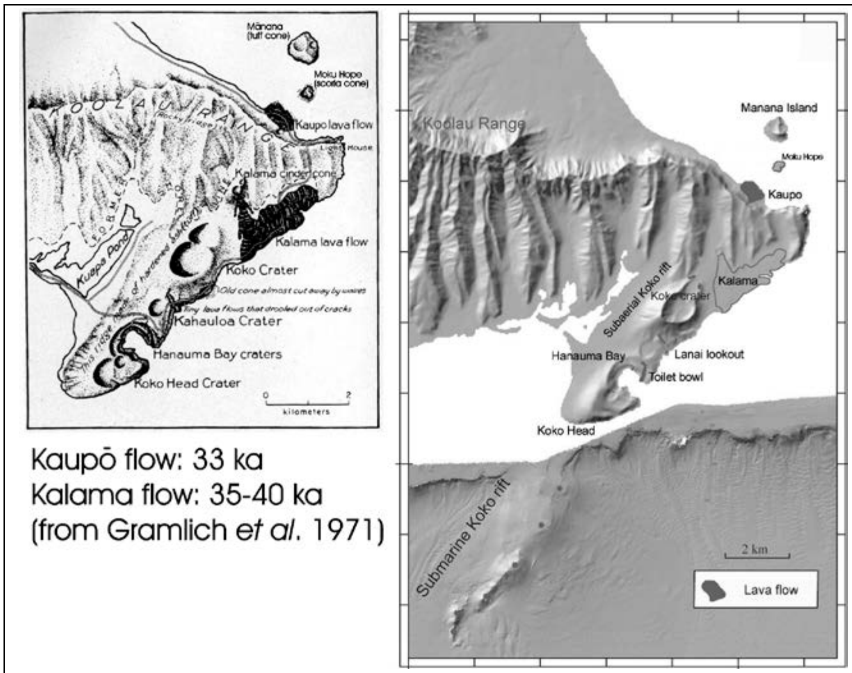

Figure 17. Schematic sketch map of the Koko rift (by H. Stearns; from Macdonald *et al*. 1983). The dashed line indicates the presumed shoreline prior to the eruptions. Note that Mānana (Rabbit island) lies northwest of the trend of the rest of the vents, which is remarkably linear. Age dates are from Gramlich *et al*. (1971).

An additional Koko Rift vent opened against the pali, just this side of the large wedding chapel (green roof). Very little vent structure was produced but lava, known as the Kaupō flow, flowed oceanward to form the peninsula on which Sea Life Park is built. This same lava is exposed as the black rock outcrops adjacent to Makapuʻu beach. The Kaupō flow is alkali olivine basalt and has been dated at ~32,000 to 100,000 years old (Gramlich *et al*. 1971; Ozawa *et al*. 2003).

Most of the Koʻolau lavas near Makapuʻu lookout are aphyric but a few are very rich in olivines (≥20 volume %). An example is the oceanite flow about 100 meters east of the parking lot. The olivines within this flow settled before the flow completely solidified (Figure 18). The distributions of the olivines have been used to calculate lava viscosities, and lavas such as these at Makapuʻu yield values of 10^3-10^4 Pa s.

After leaving the lookout we will drive down the beheaded valley. The slope is steeper than the dips of the Koʻolau flows so we are driving down-section. On either side of the valley the shield-building flows are clearly evident. An old road to a lighthouse offers a very pleasant hike (~1 hour round trip) to a spectacular overlook that offers fine 360º views of the eastern end of O‘ahu. This is also a prime whale-watching location between November and April. At the bottom of the hill the highway turns sharply to the right (southwest). The flat area on the ocean side of the road will some day hopefully be a state park. Prior to 1946 the area was a ranch but most of it was inundated by the 1946 tsunami. Run-up heights were >20 feet in this area (Macdonald *et al*. 1983; Figure 19), and water reached inland essentially to where the highway is today.

STOP 5. KALAMA LAVA FLOW AND SANDY BEACH

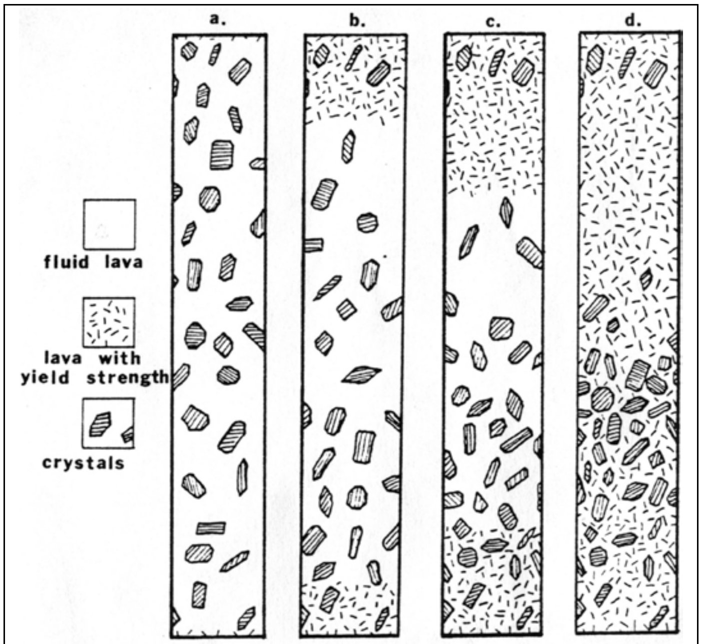

Figure 18. “Ideal” sinking process that causes concentration of olivine phenocrysts near (but not at) the bottom of a lava flow. Sections a, b, c, and d are arranged in order of increasing time. Note how the crystals sink (if not caught by a solidification front moving down from above) until they land on the more slowly-moving solidification front moving up from below. Modeling of this process allows an estimate of the viscosity (from Rowland & Walker 1988).

We will stop near a surface outcrop of another Koko Rift lava flow. This alkali olivine basalt flow was erupted from a scoria cone in Kalama Valley 35,000 to 80,000 years ago (Gramlich *et al* 1971), and it flowed out the valley (south) and was diverted northeastward along the coastline by the flank of Koko Crater (Figure 17). Most of the flow is today obscured by houses and a golf course. On the coastline, wave action has worn away the top parts of the flow to expose the interior. This flow has characteristics of both pāhoehoe and ‘a‘ā, and was probably transitional between the two. Crude columnar cooling joints are evident around some of the tidepools.

This stop also affords a good view of the southeast flank of Koko Crater, by far the tallest tuff cone along the Koko Rift. Koko Crater is actually two coalesced craters, both of which are higher on their southwest (downwind) sides. The elevation difference is so great that access into the crater is easy via the upwind end. Erosional gullies are prominent on the flanks (and inner walls) of Koko Crater. Additionally, it is clear that the topmost few meters of tuff are more resistant to weathering than the layers beneath this. This relationship has produced significant undercutting of the crater rim and some of the ridges between gullies (Figure 20). There is at least one ridge that locally forms a natural bridge due to this undercutting. Along the crater rim are exposures that illustrate how the ash layers of a tuff cone bank up the inner walls, over the rim, and down the flanks. The City & County of Honolulu maintains a dryland botanical garden inside Koko Crater.

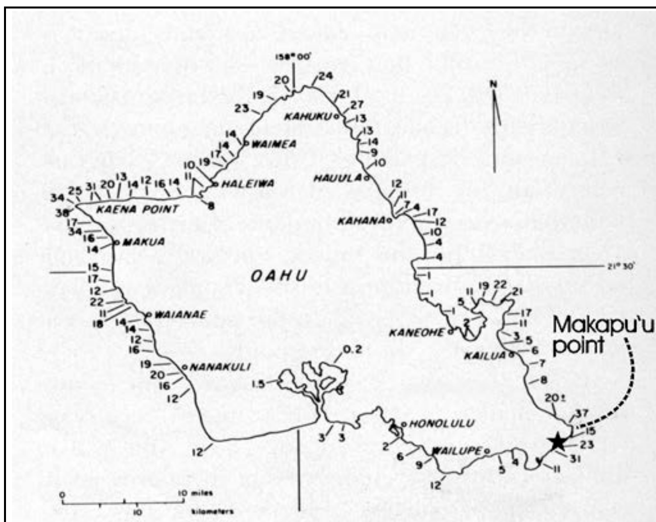

Figure 19. Map showing tsunami run-up (in feet) on O‘ahu during the April 1, 1946 tsunami (from Macdonald *et al*. 1983). *Star* indicates locatin of ranch abandandoned after tsunami. The waves approached Hawai‘i from the north, having been generated from the Aleutian subduction zone.

Between Sandy Beach and Lāna‘i Lookout (our next stop) is Hālona (“the blowhole”), a spouting horn. There are fractures within the Koko Crater tuff that extend from near sea level to the top of a wave-cut platform. Waves crashing against the coastline force a strong spray through the fractures and up into the air. The coastal shelf here is dangerous because it is often washed by large waves.

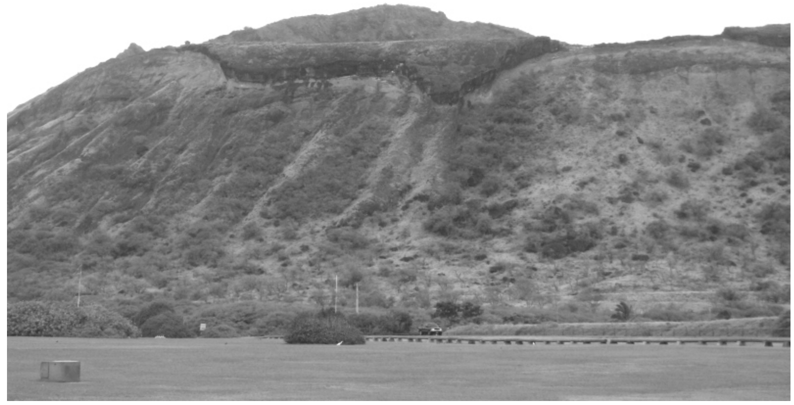

Figure 20. Photograph of the Koko Crater rim showing the undercutting caused by greater lithification of the outermost layers. Note that numerous rain gullies cut into the flanks.

STOP 6. LĀNAʻI LOOKOUT

Even though the island of Molokaʻi is much more obvious from here, this location is named Lānaʻi lookout. It sits on the lower flanks of Koko and Kahauloa craters and probably includes material from both vents. Except for a few small lava flows, almost all of the erupted material in this area is hydromagmatic ash. In the wave-cut sections there is abundant evidence of the nature of hydromagmatic (sometimes called "Surtseyan") eruptions. Observed eruptions of other oceanic volcanoes such as Capelinhos, Surtsey, and Taal (Machado *et al*. 1967; Moore *et al*. 1966; Thorarinsson 1967; Figure 21) were characterized by discrete explosions, each a few seconds to a few minutes apart. Each explosion is steam-driven and strong enough to fragment the erupting magma into sand-sized particles.

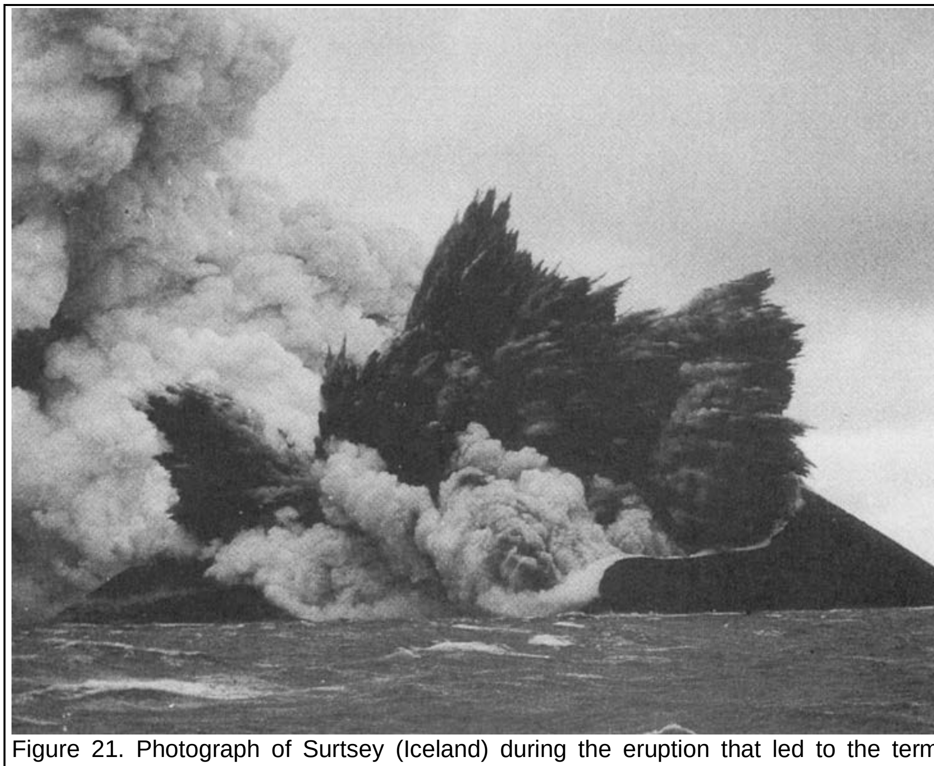

Figure 21. Photograph of Surtsey (Iceland) during the eruption that led to the term "Surtseyan" (often used interchangeably with hydromagmatic). Note the multiple blasts, both dark (sediment-laden) and light (mostly steam), each of which deposits a single layer of ash. Photo by T. Einarsson, from Decker & Decker (1998).

So-called "base surges" are commonly associated with hydromagmatic eruptions, and from the parking lot there is a nice view back across the highway of dune bedding in the ash layers, giving good evidence of lateral deposition in this particular location (Figure 22). You can see in the sections below the parking lot that there is also ample evidence of more vertical (i.e., airfall) deposition also having taken place during the eruption.

At Lānaʻi lookout, hundreds of layers are exposed in the outcrops, each was deposited by a discrete explosion during the eruption. Most of the ash (now lithified to tuff) making up these layers is sand-sized, attesting to the power of the steam explosions during the eruption. A few layers also contain accretionary lapilli (Figure 23, balls of mud that form as fine ash particles adhere to a nucleus of some sort (usually a slightly larger fragment). Individual accretionary lapilli are crudely layered and are important because they indicate the presence of liquid water in the eruption cloud (and therefore temperatures of <100º C).

Xenoliths of the underlying rocks are common. These xenoliths were ripped from the conduit as the violent steam explosions took place. Here, the xenoliths consist mainly of Koʻolau shield-stage basalts and reef limestone. Occasional xenoliths of earlier Koko rift tuff can sometimes be found. There are also juvenile fragments, usually with a fluid or ragged appearance. The largest of the xenoliths and juvenile bombs depressed, compacted, and/or disrupted the ash beds on which they landed to form “bomb sags” (Figure 24). Three-dimensional analysis of these bomb sags can be used to determine the direction (and thus the vent) from which the particular bomb came.

Figure 22. Photo of dune bedding in the wall of the next gully north of the cove below Lānaʻi lookout.

About 1 m above mean sea level is a shelf on which we will walk. *Make sure you don't turn your back on the ocean!!* One explanation of this shelf is that it was cut by a slightly higher stand of sea level. However, evidence for this particular sea level cannot be found elsewhere on Oʻahu. Additionally, in Hanauma Bay the shelf is conspicuously non-horizontal, being a few cm above sea level in the back of the bay and 1-2 m above sea level near the bay mouth. An alternative explanation, given by Wentworth (1938), is that the shelf indicates the level of water-saturated tuff. Where the waves are high (such as along the exposed coastline) the tuff is saturated 1-2 m above sea level but where the waves are small (such as at the back of Hanauma Bay) it is saturated only slightly above sea level. Because wet tuff is more resistant to erosion than dry tuff, the dry tuff just above the level of saturation is preferentially eroded (by current sea level), forming the tuff.

Figure 23. Photo of accretionary lapilli.

Exposed under a wave-cut overhang are two large exposures of limestone (Figure 25). They are composed mostly of coral branch fragments with a few shells. On the top of the larger exposure is ~0.5 m of poorly-developed limey soil. This strongly suggests that the limestone is in place, as opposed to having been ripped out of a vent wall and deposited here. It also indicates that this particular location was subaerial at the time of the eruption, consisting of reef material from a high stand of the ocean.

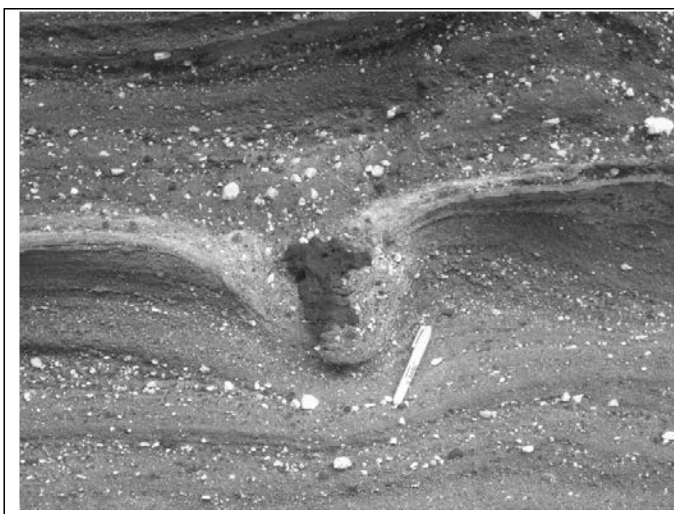

Figure 24. Photo of bomb sag (*marking pen* for scale).

One of the small Koko rift lava flows is exposed on a high point below and in front of the parking area. On close examination this lava is at least partially composed of large lumps of spatter which must have been accumulating rapidly enough to form a flow. The source of the flow is on the uphill side of the highway and it flowed down the valley formed by the flanks of Koko and Kahauloa craters (Figure 17). This flow has been dated at 40,000 years (Gramlich *et al*. 1971).

STOP 7. HANAUMA BAY

Hanauma Bay (Figure 26) is a world famous snorkeling destination that has almost become too popular for its own good. The bay sits within the crest of two closely-spaced tuff cones who's seaward rims were breached by the ocean. A reef developed within the bay and between this reef and the beach the water is calm, shallow, and clear. This is ideal for tourists to go snorkeling in as long as there aren't too many of them. Dating of the reef shows that the ocean gained entrance to the craters ~7000 years ago (e.g., Kelly 1980) Evidence for two craters forming the bay comes from its plan-view shape as well as from exposures along the northern shelf around the bay's periphery. Here it is clear that an older sequence of ash layers was cut by gullies prior to deposition of a younger sequence (Figure 27). The time interval indicated by these gullies almost certainly is not significant - no soil is present - and might represent as little as a few hours.

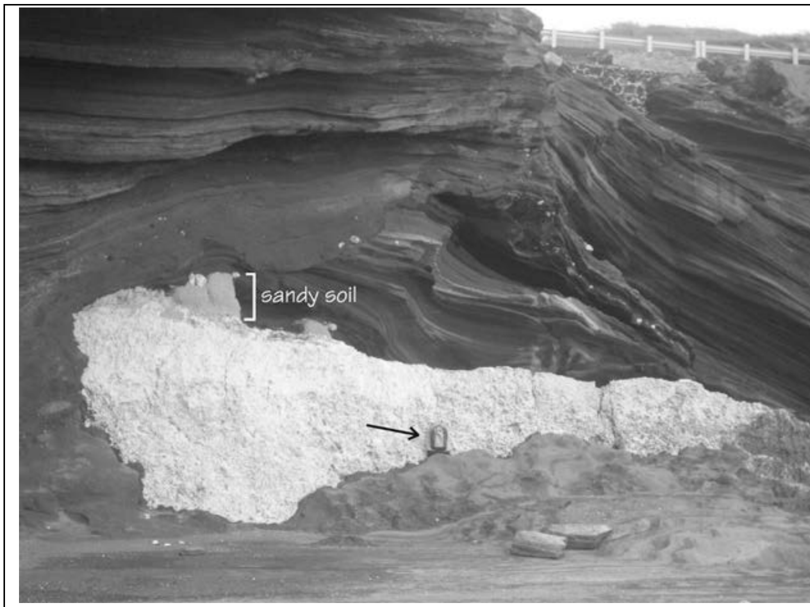

Figure 25. Photo of large reef fragment exposed by wave erosion below the Lānaʻi lookout. Note the poorly-developed soil on the top, strongly suggesting that these fragments are in their natural position. Backpack (*arrow*) gives scale.

Just outside the entrance to Hanauma Bay is a scenic stop that allows you to view the less-eroded south flank of Koʻolau volcano (Figure 28). Here, planezes (approximating the old shield surface) alternate with deep valleys. Exposed in the walls of these valleys are many Koʻolau lava flows. Most of the prominent, dark layers are the dense "core" of ʻaʻā lava flows, which are cliff-formers relative to clinker layers and pāhoehoe flows that tend to be slope-formers.


Figure 26. Air photo of Hanauma Bay (by Eva Ng and Donielle Chittenden).

The dips of some lava flows are slightly greater than those of the planezes, and this has been used as evidence that the planezes are not the original shield surface. Instead, they may have been lowered (and steepened somewhat) by sheet wash that removed chemically altered rock without incising gullies or valleys (Macdonald *et al*. 1983). In some instances, however, the dips of the flows and the planezes are the same, and elsewhere the flow dips are actually steeper. The downslope ends of all the ridges have been steepened by marine erosion during higher stands of the ocean. Immediately below the scenic stop is the sprawling suburb of

Hawaiʻi Kai, built since the early 1960s by Henry Kaiser. The area originally was marshy wetlands that were dredged to produce dry land and boat passages.

STOP 8. KAIMUKĪ

From Kaimukī (sometimes called Puʻu o Kaimukī) on exceptionally clear days, it is sometimes possible to see 7 Hawaiian shield volcanoes (Koʻolau, Waiʻanae, West Molokaʻi, East Molokaʻi, Lānaʻi, West Maui, and East Maui). Kaimukī is a Honolulu volcanic series (rejuvenation stage) vent that was produced by dry, as opposed to hydromagmatic, activity. Instead of shallow, steam-driven explosions, the lava welled peacefully out of the ground and flowed away in all directions. The result was a shallow-sloped "satellitic" shield with a crater at its summit. the total thickness of lava is probably around 60 m (Macdonald *et al*. 1983). Satellitic shields are a common type of vent on Hawaiian volcanoes and form when the erupting magma has a low amount of gas bubbles. They have formed on Kīlauea in 1920 (Mauna Iki; Figure 29), 1969-1974 (Mauna Ulu), 1986-1992 (Kūpaianaha), and 1992 to today (part of the Puʻu ʻŌʻō vent complex). While active, these Kīlauea satellitic shields had lava ponds at their summits and lava both overflowed the rims of the ponds and fed out the walls through lava tubes. The crater at Kaimukī is still obvious, although filled with houses.

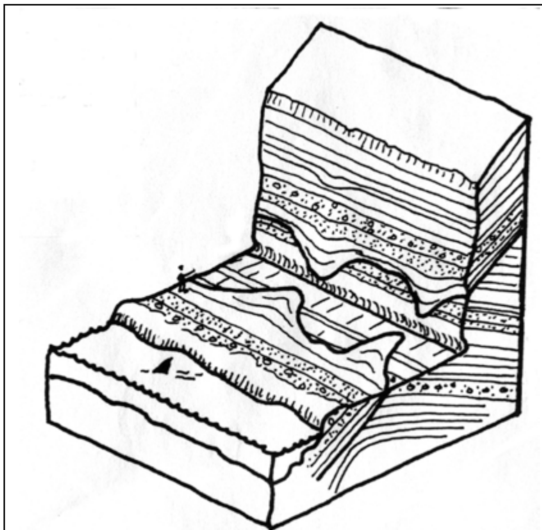

Figure 27. Block diagram (by George Walker) to illustrate the gullied discordances that are found at many points in the walls around Hanauma Bay. These discordances mark the contact between older and younger tuff cones. The waviness of the contact is due to gullies cut in the older cone, probably by running water.

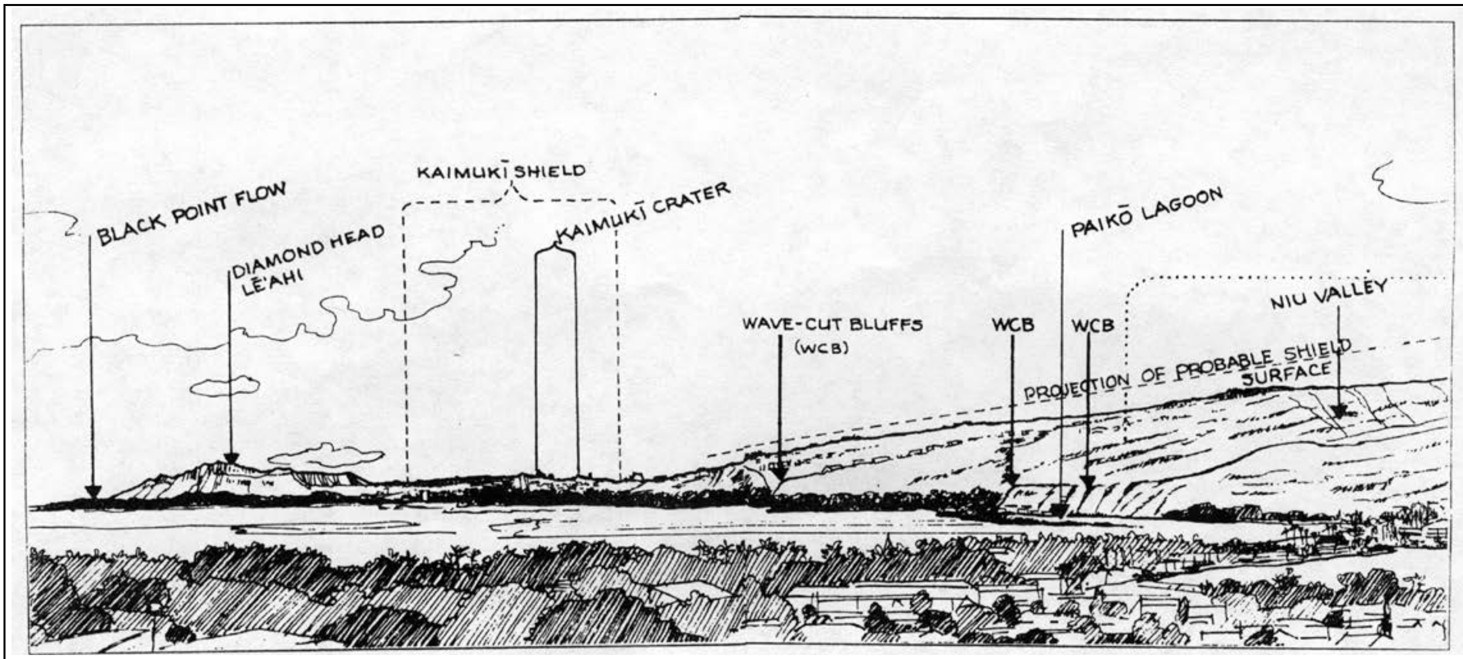

Figure 28. View plane diagram looking northwest from the Hawaiʻi Kai overlook (by Lorin T. Gill, Moanalua Gardens Foundation).

It is possible to include Kaimukī in a sort-of straight line that extends from Lēʻahi at its south end to the "Training School" vent on its north end. Early workers (e.g. Winchell 1947; Stearns 1985) as well as some modern geologists have included Kaimukī with some other Honolulu Series vents as part of the "Kaʻau rift", named for Kaʻau Crater, a maar in the back of Pālolo valley (Figure 30). However, unlike the Koko Rift, there is little to no geological (or geochemical) evidence that these vents are related. Together, Kaimukī and its immediate neighbors to the north and south (Figure 31) do provide excellent examples of the vents produced by the three most common eruptive styles on Hawaiian shield volcanoes. Lēʻahi (Diamond Head) is a tuff cone, formed by hydromagmatic activity. Mauʻumae is a scoria cone, formed by "dry" lava fountaining. Based partially on water-well drill logs and an exposure in an old quarry, Wentworth (1951) and Macdonald *et al*. (1983) determined the sequence of these three vents to be Mauʻumae first, Lēʻahi second, and Kaimukī third (Figure 32). All three of them overlie sediments that in turn, unconformably overlie shield-stage Koʻolau basalts.

Kaimukī is an excellent place for a long-distance look at the profile of the Koko Rift (Figure 33). Additionally, there are good views of the planezes that perhaps preserve the old Koʻolau shield surface (Figure 34; the planezes in this area correlate very strongly with expensive house prices). Hawaiian erosional valleys typically have an amphitheater shape, with heads that are wider than their mouths. Figure 35 (Macdonald *et al*. 1983) shows how a greater degree of erosion in the uplands produces these valleys. Figure 35 is presented as an evolutionary sequence of valley development. The different stages, however, can occur on the same volcano if there is a large range in rainfall amounts.

Figure 29. Photo of Mauna Iki (the gently sloping mound on the horizon), a satellitic shield on the southwest rift zone of Kīlauea that formed between January and August of 1920.

The valleys cut into Koʻolau are quite impressive, and they have U-shaped profiles unlike the V-shape typical of stream-cut valleys. The relatively flat floors of the valleys indicate infilling by sediments and to a limited extent, rejuvenation-stage lavas and pyroclastics, and extending the valley walls downward until they merge gives an impression of how much material has been eroded (Figure 36). A water well drilled near the middle of Mānoa valley passed through ~360 m of sediment (including limestone) before hitting Koʻolau basalt. This contact is ~300 m below present sea level and indicates that at least this amount of subsidence has occurred since the valley was initially cut.

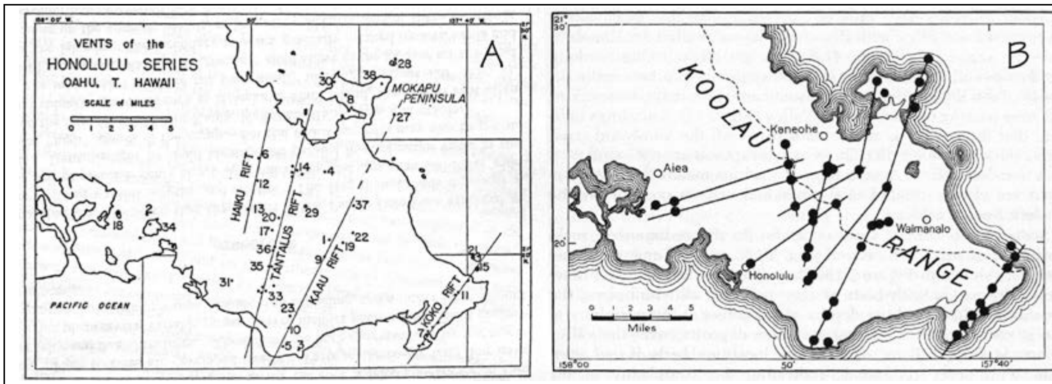

Figure 30. Map showing purported "rifts" derived by connecting locations of Honolulu Volcanic Series vents from Winchell (1947; A) and Stearns (1985; B). In B, note that one of these rifts has only two points(!) and some have only three or four.

Most of the sediment that eroded out of these valleys worked its way oceanward and was deposited along the south coast of Oʻahu. Here it is intercalated with buried reef limestone and occasional rejuvenation-stage lavas and tephra. Metropolitan Honolulu (including Waikīkī; Figure 37) is built on these sediments. The sediments have very little bearing strength and high-rise buildings in Honolulu are therefore built on concrete piles driven through the soft sediment until they bottom out on either a limestone or rejuvenation-stage lava layer. Some buildings are built on >1000 piles that may be up to 60 m long.

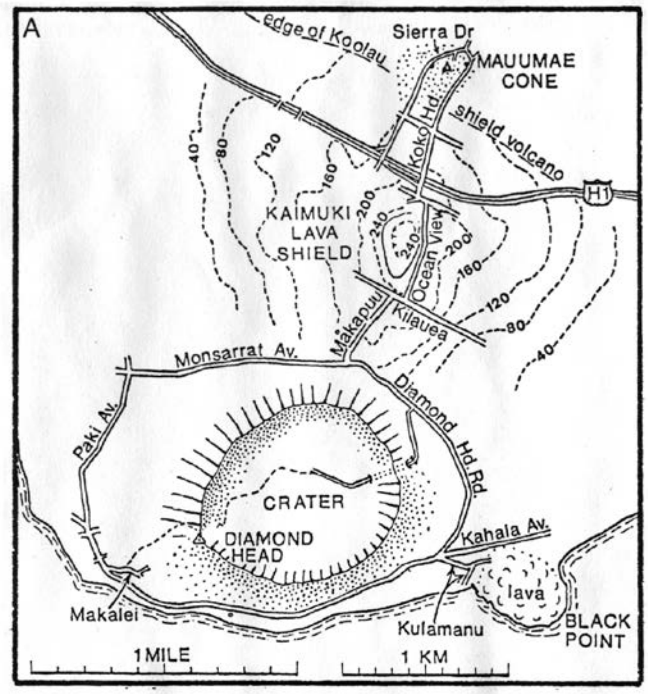

Figure 31. Map showing detail of the southern end of the so-called "Diamond Head Rift" (by George Walker). The *dashed contours* give the shape of the Kaimukī shield and have an interval of 40 feet.

Lēʻahi is ~2 km southwest of the summit of Kaimukī, and is probably Honolulu's most famous landmark. As noted above it is a tuff cone, produced by hydromagmatic eruptions. Growth-position tree molds have been found in the lowest layers of Lēʻahi ash indicating that at least part of the eruption occurred on land (Macdonald *et al*. 1983). The "diamonds" for which Diamond Head is named, were actually calcite crystals. The calcite was precipitated in fractures and between ash layers having originally dissolved out of coral xenoliths included in the ash. Some of the calcite may also derive from weathering of the ash. From Kaimukī it is clear that the far (southwest) rim of Lēʻahi is higher than the near rim, and the dips of the layers at the highest point indicate that it was once even higher. This view direction is essentially the same as the prevailing trade winds and undoubtedly this difference in height is due to more material having been deposited on the downwind side of the vent.

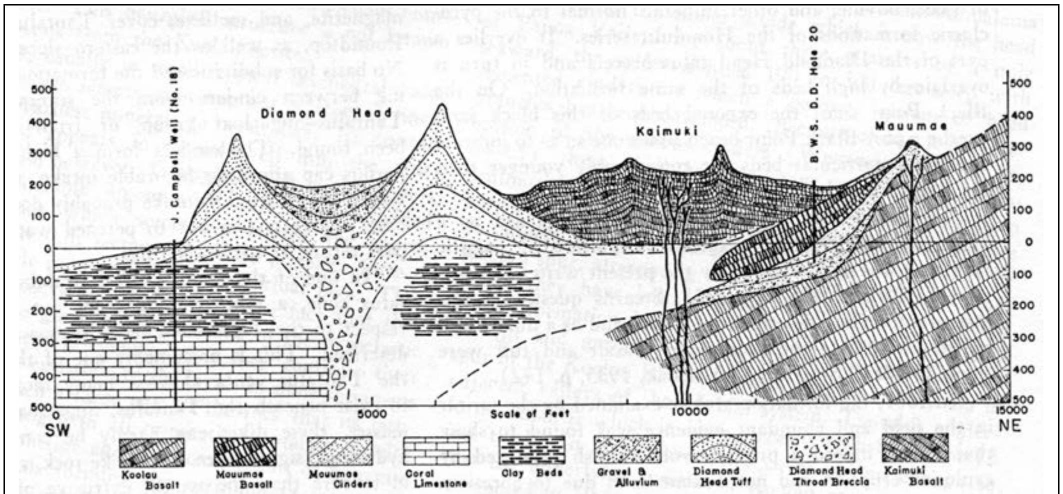

Figure 32. Cross section along the "Diamond Head Rift" showing the age relationships between Lēʻahi, Kaimukī, Mauʻumae, and the underlying Koʻolau basalts (after Wentworth 1951). Note the 10x vertical exaggeration.

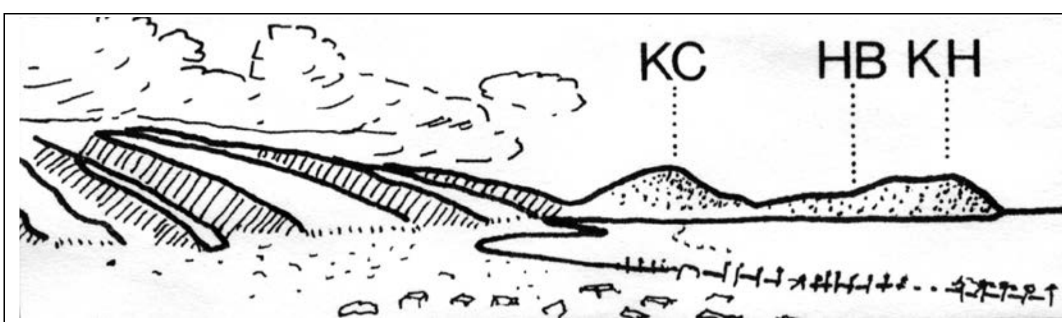

Figure 33. Sketch of the view east from the highest point on Lēʻahi (by George Walker). Note the profile of the Koko Rift, as well as the valleys (separated by planezes) cut into the Koʻolau shield. KH = Koko Head, HB = Hanauma Bay, KC = Koko Crater.

Figure 34. Air photo of the southeast flank of Koʻolau volcano. Note the planezes, that mimic the original surface of the shield. Wailupe peninsula is an old Hawaiian fishpond that was filled in so that houses could be built on it.

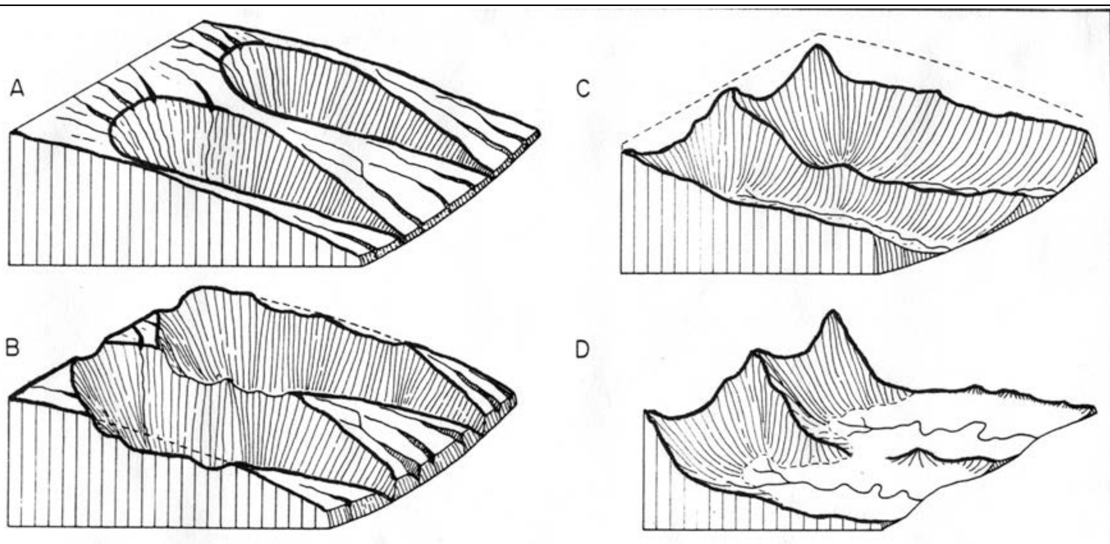

Figure 35. Diagrams of stages in the development of streams on Hawaiian volcanoes (Macdonald *et al*. 1983). Note that these can either be steps in time of the same flank on a volcano or they can be simultaneous on different parts of a volcano that is subject to different climates. Stage B corresponds to the southern flank of the Ko'olau shield as viewed from Kaimukī. Stage D corresponds to the vicinity of the Nuʻuanu pali (compare to Figure 10).

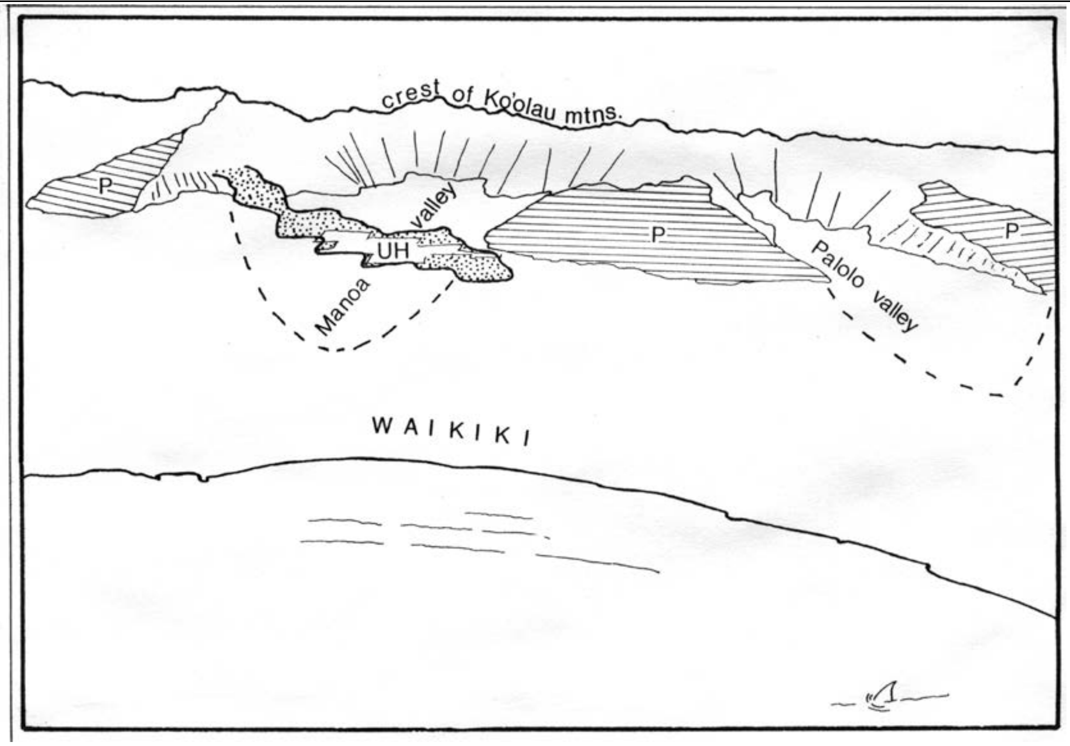

Figure 36. Sketch of the view looking northward from off Waikīkī beach. Note the large amphitheater valleys of Mānoa and Pālolo and the planezes (P) between them. The dashed lines show the extensions of the valley walls beneath the present fill of alluvium. A Honolulu Volcanic Series flow, on which main University of Hawai'i Mānoa campus sits, is shown (schematically) with the dotted pattern.

Figure 37. Photograph of Waikīkī and downtown Honolulu from the highest point on Lē'ahi. The flat land on which these buildings are built consists almost entirely of sediments washed out of the valleys being cut into the Ko'olau shield, as well as carbonate material and rejuvenation-stage pyroclastics and lavas. Note Wai'anae volcano in the distance.

THE MEANINGS OF SOME HAWAIIAN PLACE NAMES AND WORDS
(from Puku‘i *et al*. 1974; Puku‘i and Elbert 1986)

‘a‘ā	glowing, fiery (*as with fiery eyes*)
Hālona	peering place
Hanauma	curved bay, *or* hand-wrestling bay
Hawai‘i	(*no known meaning*)
Hilo (town)	first night of new moon, *or* a Polynesian voyager (*unclear which, if either*)
Honolulu	protected bay
Ka‘au	forty
Kahauloa	the tall hau tree
Ka‘iwa	the ‘iwa (*frigate bird*)
Kailua	two currents, *or* 2 bays
Kaimukī	ki (ti) oven (*a place for cooking ti roots*)
Kalaniana‘ole	a Hawaiian prince (*lit. the chief without measure*)
Kalihi	the edge
Kāne‘ohe	bamboo husband (*a particular husband was cruel like a bamboo knife*)
Kā‘ohikaipu	hold back the container (*blocking an inlet of debris*)
Kapa‘a	solid, *or* the closing
Kapapa	the flat surface
Kawainui	the big water
Kīlauea	spewing
Koko	blood
Kōnāhuanui	large fat innards
Ko‘olau	windward
Kualoa	long back
Lāna‘i	conquest day
Lanihuli	turning royal chief
Lē‘ahi	the brow of an ‘ahi (tuna)
Makapu‘u	hill beginning, *or* bulging eye
Mānana	buoyant
Mānoa	vast
Mauna Kea	white mountain
Mauna Loa	long mountain
Maunawili	twisted mountain
Mau‘umae	wilted grass
Mōkapu	kapu (*taboo*) district
Mokoli‘i	little lizard
Moku Hope	island behind
Mokulua	two islands
Moku o Lo‘e	island of Lo‘e (*a person*)
Moloka‘i	(*no known meaning*)
Nu‘uanu	cool height
O‘ahu	(*no known meaning*)
‘Ōhulehule	joining of waves
Olomana	forked hill
pāhoehoe	satin, *perhaps* paddle-like
pali	cliff
Paikō	Pico (*the name of a Portuguese resident here*)
Pālolo	clay
Wai‘anae	mullet water (*a place to catch mullet*)
Waikīkī	spouting water
Wailupe	kite water
Waimānalo	potable water

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