SOUTHEAST O‘AHU GEOLOGY FIELD TRIP GUIDE

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Above: Geologic map of O'ahu, from Macdonald et al. (1983)

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 Ko'olau Volcano. Many of the original literature sources are difficult to find so we have tended to cite more recent compilations such as Volcanoes in the Sea (Macdonald et al. 1983). The Island of O'ahu is constructed from two shield volcanoes, Wai'anae and Ko'olau (front inside cover; Figure 1). Both of these volcanoes were at one time at least the size that Kīlauea is today, and probably even larger (Figure 2). Wai'anae 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 O'ahu. Ko'olau is younger and makes up the eastern part. Its subaerial shield flows are ~2.9 million to 2.1 million years old, and as we will see later, after these shield flows had been eroded for a considerable time, rejuvenated activity occurred, lasting until perhaps as recently as 30 to 50 thousand years ago.

The life history of a Hawaiian volcano has been summarized by Macdonald et al. (1983) and Peterson & Moore (1987; Figure 3). In short, as the oceanic lithosphere passes over the upwelling mantle that is called the Hawaiian hotspot, it first encounters a region of low amounts of melting on the edge of the hotspot producing alkalic magma, then a region of high amounts of melting in the center of the hotspot producing tholeiite magma, and finally another region of low amounts of melting on the other side of the hotspot producing alkalic magma. The corresponding volcanic stages are the alkalic pre-shield stage (e.g., Lō'ihi), the tholeiite shield stage (e.g., Mauna Loa and Kīlauea), the post-shield alkalic stage (e.g., Hualalai and Mauna Kea), and finally an erosional stage (e.g., Kohala) once it has moved completely off the hotspot. Following extended periods of erosion, both gradual and catastrophic, some Hawaiian volcanoes undergo a period of rejuvenation. The lavas erupted during
this rather enigmatic stage are commonly strongly alkalic, occasionally contain mantle xenoliths, and the eruptions are spread far enough in 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 it began, as a seamount (Figure 3).

KO'OLAU VOLCANO
Ko'olau volcano started its life as a seamount above the Hawaiian hotspot ~4 million years ago. It broke sea level some time prior to 2.9 million years ago, the age of the oldest subaerial lavas (Haskins & Garcia 2004). During its tholeiite shield stage, Ko'olau volcano eventually reached an elevation of at least 2000 m (the current highest elevation is ~1100 m). Ko'olau does not have 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 be 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 or avalanched away.

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 gradual and catastrophic erosion have combined to produce the current, smaller edifice.

The main tholeiite shield-building stage of Ko'olau volcano ended somewhere around 2.1 million years ago (e.g. Langenheim & Clague 1987), 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 Kaua‘i to Hawai‘i (e.g. Westervelt 1963), and each of the places she is said to have rested turns out to be what modern geologists consider to be a site 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).

Presently, there are many competing ideas for the origin of rejuvenation-stage volcanism. One mechanism is related to the giant avalanches that have occurred on some of the Hawaiian volcanoes. The idea is that the removal of a large overburden by the avalanche causes the lithosphere and underlying mantle to rebound a little bit, accompanied by depressurization and partial melting. Although this mechanism has been shown to have occurred during the post-shield alkalic stage of Wai‘anae volcano (Presley et al. 1997), no studies have linked any specific giant avalanches to specific rejuvenation volcanic features. In particular, the Nu‘uanu landslide occurred well before the oldest known Honolulu Volcanic Series eruptions. Additionally, giant avalanches have occurred off Mauna Loa, which is still in its tholeiitic shield stage (e.g. Moore et al. 1989).

Another proposed mechanism involves northwestward movement of the lithosphere dragging hotspot material downstream. The hot mantle material conducts heat to the overlying lithosphere, causing it to melt (Gurriet 1987). One problem with this idea is it provides no explanation for the break in time between the end of the post-shield alkalic stage and the rejuvenation stage. One of the more popular models involves depressurization of the upper mantle due to flexure of the oceanic lithosphere. Essentially, the lithosphere is considered as a lever that is being pushed downward at the hotspot end (i.e., under the island of Hawai‘i), and moving upward ~300 km “downstream”. The upward motion depressurizes the underlying upper mantle, leading to small amounts of partial melting and the production of highly alkalic magmas. Most recently, numerical modeling by Ribe & Christensen (1999) predicts that there will be mantle upwelling and the production of alkalic magmas 300-500 km downstream of the hotspot center. It is definitely possible that more than one mechanism is at work. Perhaps the heating of the lithosphere model explains the early Honolulu...
Volcanic Series activity, and the lithospheric flexure model explains the later Honolulu Volcanic Series activity. Careful age dating by Ozawa et al. (2003) shows that within the Honolulu Volcanic Series there are 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 mantle upwelling. The later pulse, from 100,000 to 30,000 years ago, may have been due to lithospheric flexure. Downward flexure is still occurring under Hawai‘i and 30,000 years isn’t very long ago geologically - there is the possibility that rejuvenated volcanism could occur again on Ko‘olau!

STOP 1. NU‘UANU PALI OVERLOOK

After driving up Nu‘uanu valley you reach the pali overlook. Geomorphologically this location is a wind gap, where the heads of two oppositely-trending valleys intersect (Figure 6). On most days this geomorphic term is very appropriate. The view looks out to the windward side of O‘ahu, across what was the volcanic center of Ko‘olau volcano. In particular, the Kapa‘a area, the Ka‘iwa ridge, and Olomana all consist of thick lava flows that all dip very slightly towards a point centered in Kawainui 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 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 Nu‘uanu pali in the vicinity of the overlook.
In the far distance, the Mōkapu peninsula forms the northeastern-most point on O'ahu and the Kāne'ohe 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 Ko'olau slope. These north-dipping (to the right from this vantage point), red-colored scoria layers unconformably overlie south-dipping (to the left) 'aʻā 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 'aʻā 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 'aʻā 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 Ko'olau dike trend.

Nu'uanu pali is one of the most spectacular geological features on O'ahu (pali is the Hawaiian word for cliff). Many Hawaiian islands have pali but the Nu'uanu 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 Kaua'i and Moloka'i) and others are inland (e.g., on O'ahu and Ni'ihiwau). A wide range of suggestions have been offered to explain the origin of Nu'uanu (and other) pali:

1) Faulting - Dana (1891), the first geologist to visit Hawai'i, proposed that great fractures were responsible for these cliffs. Such a fault would have at least 1 km of offset to have created the Nu'uanu 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 Ko'olau volcano caldera boundary grazes the pali in a few places, as does the margin of a Ko'olau rift zone, just below the Nu'uanu pali overlook (Macdonald et al. 1983; Walker 1987).

5) Headwall of the Nu'uanu landslide (see next section) - Marine surveys north of O'ahu revealed that the northeast side of the Ko'olau 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 Ko'olau 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 Ko'olau volcano, extending from the pali. These include the Mokulua islands, Olomana, Kapa'a, 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 Ko'olau volcano was formed, it was never high enough on O'ahu to have eroded the base of the pali (except at the Makapu'u 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 Nu'uanu 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 Ko'olau volcano (as well as much of E. Moloka'i 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 O'ahu does indeed consist of Ko'olau 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 Ko'olau (named the Nu'uanu 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).

As we noted above, any avalanche scar must be seaward of the seaward-most remnant of the Ko'olau 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 Hawai'i, 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.

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 Nu‘uanu avalanche? After all, there are landslides that just creep slowly downslope. The best evidence for catastrophe is that the Nu‘uanu 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 Ko‘olau, 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 Hawai‘i (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 Lāna‘i was formed by a giant-avalanche-generated tsunami or by high sea level followed by tilting of the island.
STOP 2. H-3 DIKES

Exposed along a section of the H-3 freeway is the interior of the old Ko‘olau 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 Ko‘olau 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.

George Walker, during his tenure as Macdonald Professor of Volcanology at the University of Hawai‘i, conducted an exhaustive study of the Ko‘olau 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).

Walker (1987) also pointed out that most of the Ko‘olau 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.

KĂNE’OHE BAY
A scenic overlook gives us a good view of Kāne’ohe 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 Lo’e (Coconut Island) and it has been augmented artificially. It is home to the Hawai‘i Institute of Marine Biology, part of the University of Hawai‘i.

In the late 1960s and early 1970s Kāne‘ohe 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, ‘Ōhulehole. 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 ‘Ōhulehole represents the axis of the rift zone.

STOP 3. WAIMĀNALO
We will next drive through the towns of Kailua and Waimānalō. 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 Waimānalō shopping area (Figure 14). The dunes and reef in Waimānalō correspond to an older episode of higher sea level, the 106,000-136,000 year-old +3 m Waimānalō stand. The record of changing sea level on O‘ahu 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.
The back of Waimānalo is bounded by an extension of the Nu'uanu 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.

STOP 4. MAKAPU’U LOOKOUT

From the Makapu'u 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 Makapu‘u lookout (Figure 17). The most prominent, light-toned island is Mānana (also called Rabbit Island), a tuff cone containing melilitic nephelinite 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 Kā'ohikaipu. According to Puku'i et al. (1974) Kā'ohikaipu, in olden days, instead referred to a small rock in the mouth of a small inlet on the south coastline of Moku Hope.

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 Makapu'u 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 Ko'olau lavas near Makapu'u 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 Makapu'u 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 Ko'olau flows so we are driving down-section.
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 360° 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

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.

Between Sandy Beach and Lānaʻi 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.

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.

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 <100° 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 Ko‘olau 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.

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 O‘ahu. 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.

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.

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 whose 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.

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

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 Hawai‘i Kai, built since the early 1960s by Henry

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

Figure 26. Air photo of Hanauma Bay (by Eva Ng and Donielle Chittenden).
Kaiser. The area originally was marshy wetlands that were dredged to produce dry land and boat passages.

STOP 8. KAIMUKĪ

From Kaimukī (sometimes called Pu’u o Kaimukī) on exceptionally clear days, it is sometimes possible to see 7 Hawaiian shield volcanoes (Ko‘olau, Wai‘anae, West Moloka‘i, East Moloka‘i, Lāna‘i, 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 Pu‘u ‘Ō‘ō 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.

It is possible to include Kaimukī in a sort-of straight line that extends from Lē‘ahi 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 “Ka‘au rift”, named for Ka‘au 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. Lē‘ahi (Diamond Head) is a tuff cone, formed by hydromagmatic activity. Mau‘umae 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 Mau‘umae first, Lē‘ahi second, and Kaimukī third (Figure 32). All three of them overlie sediments that in turn, unconformably overlie shield-stage Ko‘olau 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 Ko‘olau 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.

The valleys cut into Ko‘olau 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 Ko‘olau 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.

Most of the sediment that eroded out of these valleys worked its way oceanward and was deposited along the south coast of O‘ahu. 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.
Lē‘ahi is ~2 km southwest of the summit of Kaimuki, 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 Lē‘ahi 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 Kaimuki it is clear that the far (southwest) rim of Lē‘ahi 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 Lē‘ahi, Kaimuki, Mau‘umae, and the underlying Ko‘olau basalts (after Wentworth 1951). Note the 10x vertical exaggeration.

**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 Kaimuki shield and have an interval of 40 feet.

**Figure 33.** Sketch of the view east from the highest point on Lē‘ahi (by George Walker). Note the profile of the Koko Rift, as well as the valleys (separated by planezes) cut into the Ko‘olau shield. KH = Koko Head, HB = Hanauma Bay, KC = Koko Crater.
Figure 34. Air photo of the southeast flank of Ko'olau 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 Kaimuki. Stage D corresponds to the vicinity of the Nu'uanu 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)

‘aʻā 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’a’u 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)
Kaliihi 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‘umaʻe 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
Wai‘ula kite water
Waimānalo potable water
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