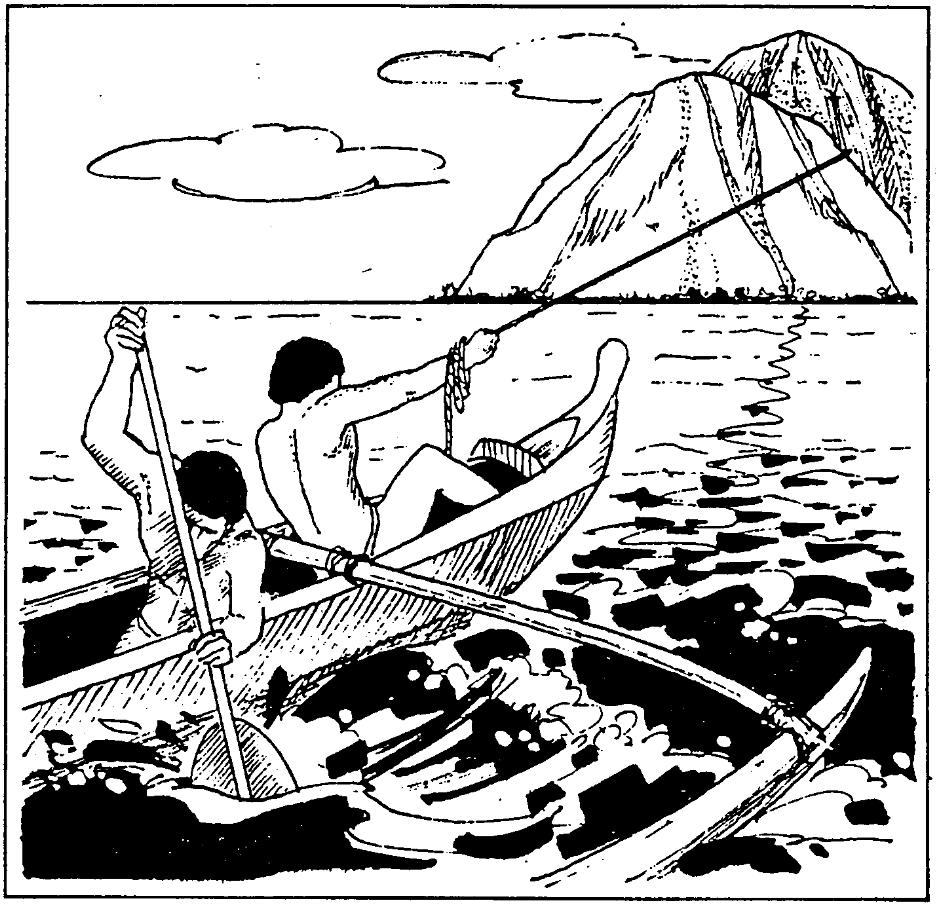
Structure and Geologic History of Wai‘anae Volcano



Māui often wondered why the islands of Hawai‘i nei were separated. After consulting with his mother, Hina, he decided to try to join them. He asked his brothers to help him and they made ready their fishing gear. Māui got his famous hook manaiakalani, and with his brothers, sailed to the middle of the sea off Ulehawa, between Nānākuli and Lualualei. He called to his brothers to paddle hard but not to look back. Finally becoming exhausted and thinking that it was not a fish they had hooked, they gave up and looked back. They saw the chain of islands following and were surprised. Māui was angry because they didn't reach shore and the islands were never quite joined. The hook was loosened and the islands separated and drifted back to their original positions.

Cover illustration from Roelofs [1992].

"Maui and Manaiakalani" abridged from T.G. Thrum, 1923, *More Hawaiian Folk Tales, Further Exploits of Maui*, p.248, as reproduced in Stirling and Summers, 1978, p.66.

INTRODUCTION

The Wai‘anae Volcano comprises the western and older part of the island of O‘ahu, Hawai‘i. Presently exposed lavas of Wai‘anae represent the subaerial shield and post-shield stages of Hawaiian volcanism, and range in age from about 3.9 to 2.8 Ma. This period of Earth history is one of relatively closely spaced magnetic polarity reversals, spanning the Gauss and Gilbert Chrons, as well as the Ka‘ena and Mammoth reversed "events" or Subchrons within the Gauss normal Chron (Figure 1). The rock units that make up the Wai‘anae Volcano are known as the Wai‘anae Volcanics, which has been divided into four sub-units or Members (Figures 1, 2).

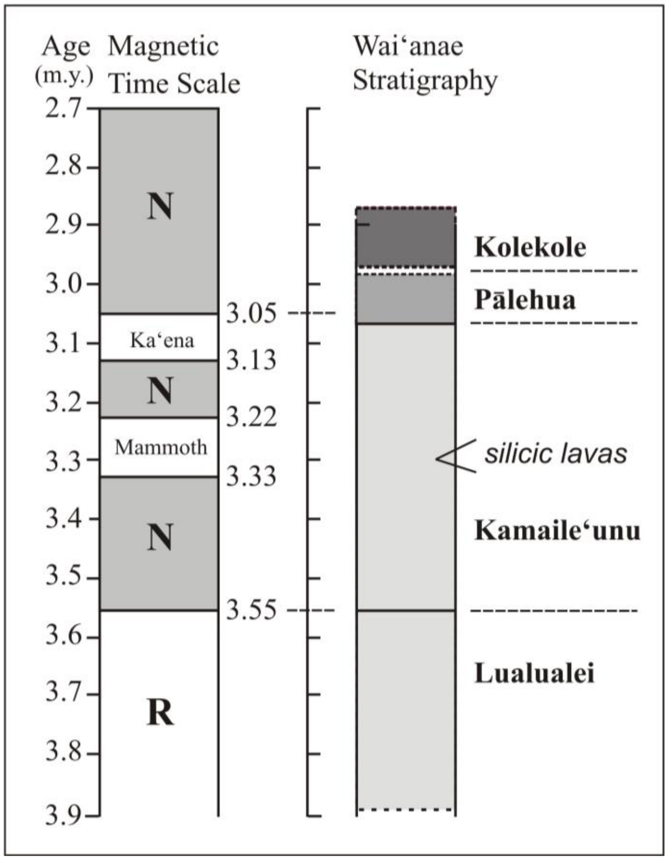


Figure 1. Wai‘anae stratigraphy, compared to the magnetic time scale of *Cande and Kent* [1992]. N and R denote "normal" and "reversed" magnetic polarity units.

The oldest exposed lavas of the Wai‘anae Volcano constitute a shield-building stage dominated by the eruption of tholeiitic olivine basalts. These lavas comprise the reversely magnetized, >3.9-3.55 m.y-old <u>Lualualei Member</u> of the Wai‘anae Volcanics. A well-developed caldera in the vicinity of Lualualei Valley was present throughout this stage, along with one, well-developed rift zone trending approximately N60°W from near Kolekole Pass. To the south, dike orientations are less parallel and more radial (Figure 3). A possible third, poorly developed rift zone has an orientation of approximately N65°E. Dikes of these three trends intersect near Pu’u Ka‘īlio near the back of Lualualei Valley. A reconstruction of Wai’anae Volcano during shield volcanism, consistent with the presently observed structures, is shown in Figure 4. Lualualei lavas are mainly exposed near Pu‘u Heleakalā and Pu‘u o Hulu on the south side of Lualualei Valley, outside of the caldera boundary fault.

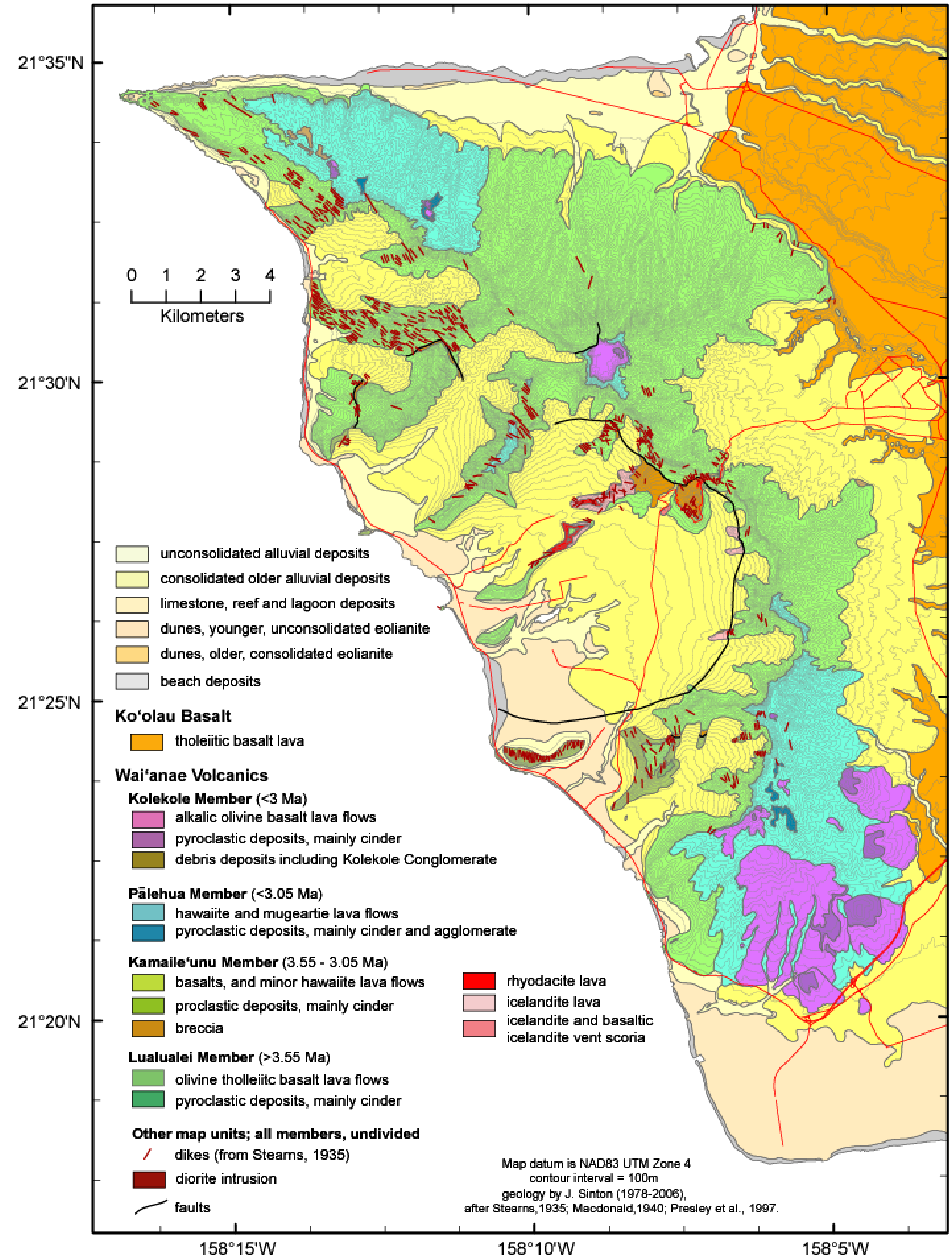


Figure 2. Geologic map of the Wai'anae Range, modified after *Stearns* [1939], *Macdonald* [1940], *Sinton* [1986] and *Presley et al*. [1997].

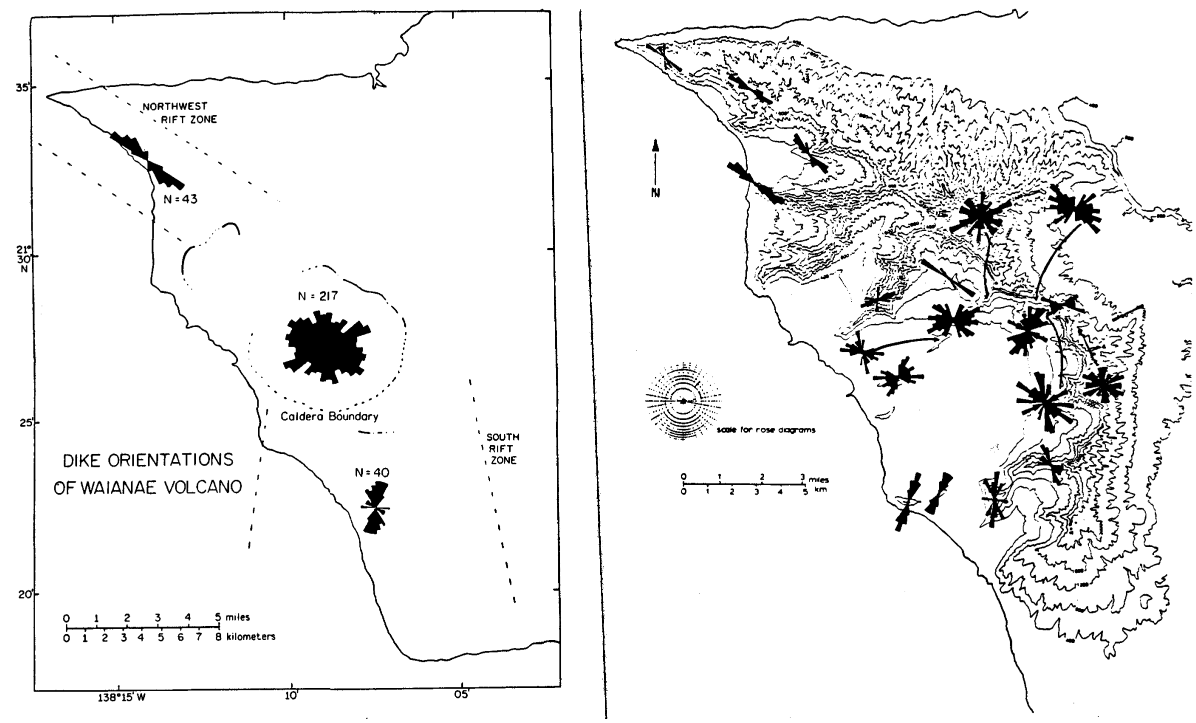


Figure 3. Dike orientations in Wai'anae Volcano [*Zbinden and Sinton*, 1988]. The figure on the right shows orientations in individual localities; the figure on the left shows integrated orientations for the northwest rift zone, caldera region, and south rift zone.

A later shield-building stage (~3.55-~3.06 Ma) is characterized by increasing variability of lava compositions, including plagioclase-bearing tholeiitic and alkalic basalts, and basaltic hawaiites of the Kamaileʻunu Member of the Wai'anae Volcanics. Eruptions of Kamaileʻunu lavas occurred within the caldera and along rift zones outside of the caldera. The caldera eventually was filled by Kamaileʻunu lavas, and this period can be viewed as a caldera-filling sequence. Kauaʻō puʻu, Mauna Kūwale, Pāheʻeheʻe, Māʻiliʻili and Kamaileʻunu ridges consist of lavas of this period. Near Mauna Kūwale and elsewhere toward the back of Lualualei Valley, silicic lavas are exposed as intracaldera dikes and flows, and constitute the only known silicic (icelandite and rhyodacite) lavas of the Hawaiian chain.

Post-Shield Volcanism

The post-shield "alkalic cap" of the Waiʻanae volcano includes alkalic hawaiites and rarer mugearites of the Pālehua Member of the Waiʻanae Volcanics. This sequence is exposed best on the NE and southern flanks of the volcano, particularly near Pālehua and above Mokulēʻia, and represents eruptions along NW- and SSE-trending rift zones. Most Pālehua lavas are normally magnetized but the type locality for the Kaʻena reversed event is a thick Pālehua hawaiite flow near Mokulēʻia. The age of Pālehua Member lavas is approximately 3.06-2.98 Ma.

A major unconformity locally separates Pālehua hawaiites from the "last gasp" of the Waiʻanae volcano, which marks a return to generally basaltic eruptions of the Kolekole Volcanics. These lavas commonly contain xenoliths of lower crustal dunites, pyroxenites and gabbros. Kolekole volcanism extended from the young cones and flows of Pu‘u Kapua‘i, Ku‘ua, Makakilo, Pālailai and Kapolei on the southern end of the Wai‘anae Range, a "post-erosional" flow at Kolekole Pass, the summit region of Mt. Ka‘ala (the highest point on O‘ahu), and Pahole and Kuaokalā regions in the northern part of the Wai‘anae Range. The age of Kolekole eruptions is barely distinguishable from the earlier Pā̲lehua lavas, with the transition occurring about 2.98 m.y. ago. Thus, although short-lived, the profound erosional event about 2.98 m.y. ago correlates with a significant change in the degree of differentiation of erupted lavas. These results suggest that a catastrophic erosional event at this time led to substantial changes in the plumbing system of the volcano; this event may be associated with the offshore submarine landslide deposit present on the south side of Wai‘anae Volcano (Figure 5).

Clastic Deposits

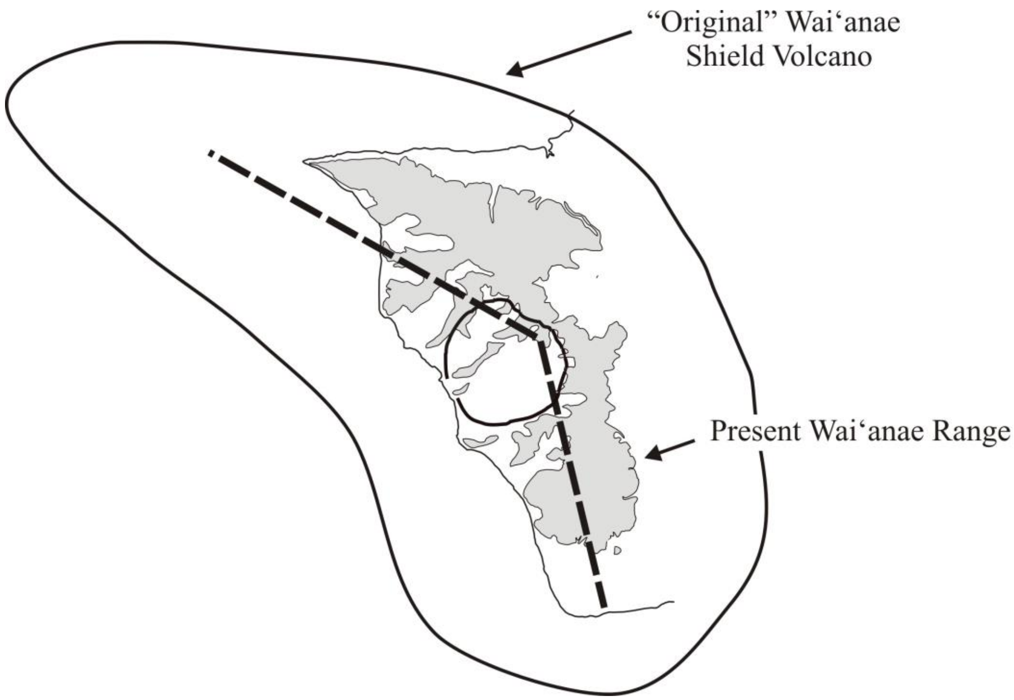


Figure 4. A possible reconstruction of the Wai‘anae Volcano based on observed caldera faults and dike abundances and orientations. Note that Ka‘ena Pt. is not along the rift zone axis.

In addition to the above lavas, some clastic deposits are locally exposed. These include fault breccias, best exposed at Pu‘u Ka‘īlio and in the saddle north of Pu‘u Heleakalā. These breccias apparently were shed off of faults along the caldera boundary, with caldera-filling lavas ponded against them. Mudflow deposits have been mapped in the saddle of Kolekole Pass and at the base of the ridge north of Kunia.

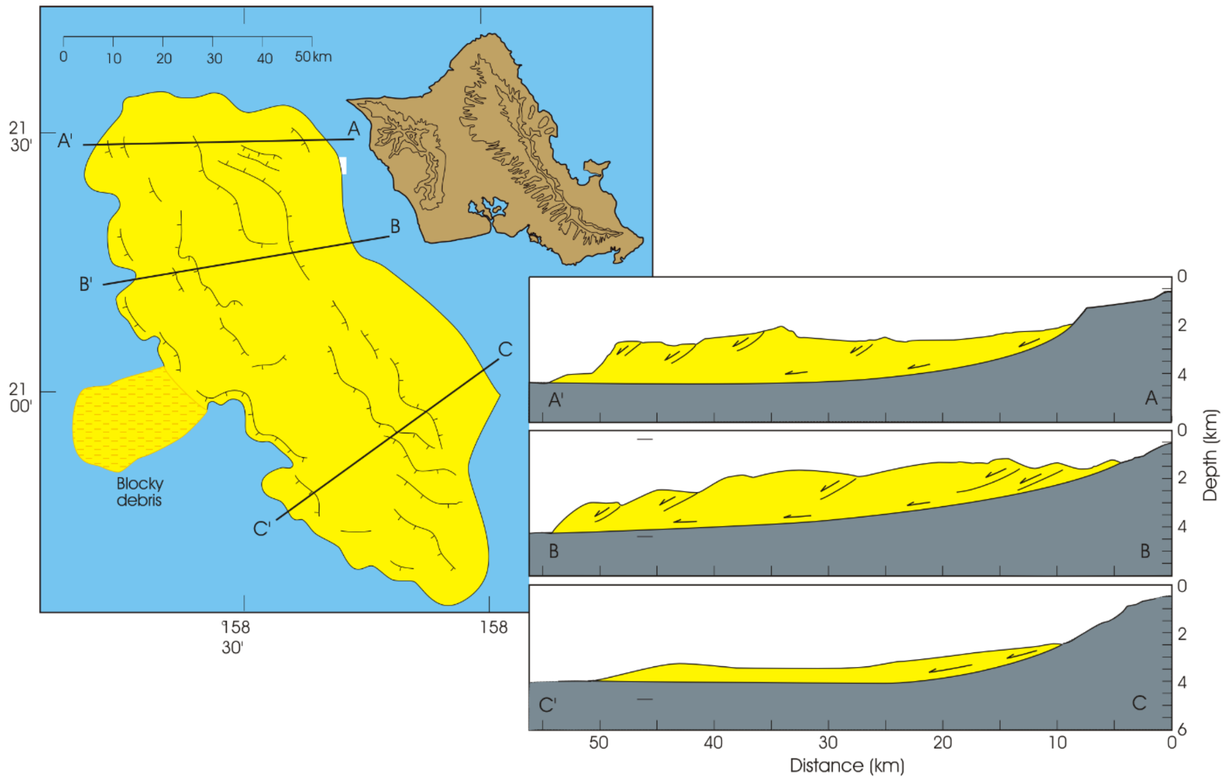


Figure 5. Map and cross-sections through the Wai‘anae slump [after Presley et al., 1997]

Magmatic Evolution

As in all Hawaiian volcanoes, the shield stage is dominated by high magma supply to magma chambers lying only a few km below the summit. By the end of Kamaile‘unu time Wai‘anae Volcano was no longer centered over the hotspot. Magmas became more alkalic as extent of mantle melting and the supply of magma into the volcano both decreased. Infrequently-fed, shallow magma chambers crystallized and disappeared, and were replaced by deeper magma storage areas, perhaps near the base of the crust. Eruption of magma from deep reservoirs was inhibited so that only differentiated magmas (hawaiites) were buoyant enough to find their way to the surface, a situation that apparently persisted throughout Pālehua time.

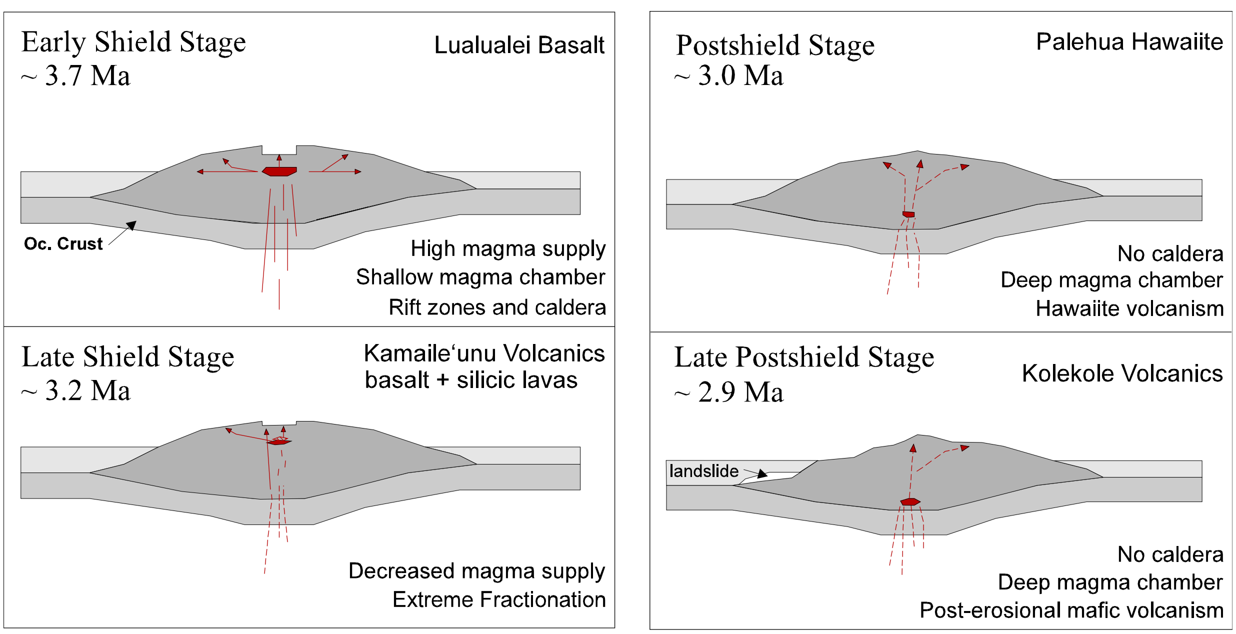
The end of Pālehua volcanism marks a catastrophic event in the evolution of Wai‘anae Volcano. At this time, a major erosional event occurred, possibly the great offshore, submarine Wai‘anae slump. Following this event the plumbing system was changed so that more mafic magmas from deep in the crust (Kolekole magmas) were erupted, carrying with them wall-rock fragments (xenoliths) of the deep crustal magma chamber.

Pleistocene “Fossil” Reefs

Reef deposits and associated shoreline features, suggestive of prior “high stands” of sea level, are widespread on O‘ahu. Variations in sea level are mainly attributed to fluctuations in global climate. In the northern hemisphere continental ice sheets have repeatedly expanded and contracted during the last 2.5 million years. During the last 1 million years these glacial-interglacial periods have occurred on fairly regular, ~100,000-year, cycles. When large ice sheets grow water is removed from the global ocean to lower sea level. During the last glacial maximum ~20,000 years ago global sea level was between 120 – 125 meters lower than today. Likewise, when ice sheets shrink, sea level rises. Today we live in what climate scientists call an interglacial – a time of relatively small ice sheets and relatively high global sea level. We now know, however, that the natural cycles have been greatly perturbed in the last few hundred years by rapidly rising anthropogenic carbon dioxide in the atmosphere and consequent increases in average global temperatures and the rate of global sea level rise.

The most common features indicative of former sea level high stands were formed during the last major interglacial period ~125,000 years ago; deposits of this age on O‘ahu are collectively referred to as the “Waimānalo stand” which is typically found ~ 5-10 m (~25 ft) above present sea level. Most of the leeward beach parks and almost the entire ‘Ewa Plain are deposits from this period. Some deposits closer to Ka‘ena Point occur more than 25 m above present sea level, and probably were formed ~400,000 years ago.

It has long been noted that so-called “raised reefs” are much more prevalent on O‘ahu than on any other island. Some cite this observation as evidence that O‘ahu has been experiencing uplift, possibly as a result of lithospheric flexure due to plate loading near the Big Island. If this is so it complicates the interpretation of exposed shoreline deposits in terms of variations in global climate and glacial-interglacial cycles.



ITINERARY

From Honolulu we will travel over shield lavas of the younger (2-3 Ma) Ko‘olau Volcano. Even younger (<~0.7 Ma) lavas of the rejuvenation stage Honolulu Volcanics are exposed near Middle Street (Kalihi flow) and Āliamanu in Honolulu.

Pearl Harbor is a drowned river valley (estuary). The valleys were cut into coastal sediments during lower stands of the sea (or before O‘ahu subsided to its present level).

Ko‘olau lavas are exposed all the way to Honouliuli. The lavas presently lie more than 20 km from the rift zone of Ko‘olau Volcano, from which they presumably were erupted. Most of these Ko‘olau lavas are dense pāhoehoe, similar to that emerging from lava tubes on the south flank of Kīlauea today. Lava tubes are an excellent way to insulate lava, thereby allowing it to travel great distances at high temperature. Many of the residual boulders exposed along Kunia Road are extremely olivine-rich Ko‘olau basalts or picrites.

Late Wai‘anae (Kolekole) vents of Pu‘u Makakilo, Pu‘u Ku‘ua and Pu‘u Kapua‘i are exposed to the west of Kunia Road.

‘Ewa Plain, Kahe and Nānākuli Beach Parks

The entire ‘Ewa Plain is a “raised reef” with associated eolian deposits (wind-deposited dunes) that can be traced around much of the Wai‘anae coastline, including the beach parks at Kahe and Nānākuli, where excellent exposures of the fossiliferous reef complexes are best seen. These are all part of the so-called Waimanalo stand of the sea, dating to the last major inter-glacial period ~125,000 yrs ago.

Slightly acidic rainwater has dissolved out sinkholes in the ‘Ewa plain. Recently, bones of many species of prehistoric birds and shells of tree snails have been found in sinkholes at Barber’s Point. There is evidence for forty-five or more species, including ibises, two or three species of huge flightless geese, small or medium size flightless rails, the long-legged O‘ahu owl, crows similar to the severely endangered ‘alala, an eagle, ravens, and a plethora of songbirds including o‘o and numerous finches, many of which vanished just prior to Polynesian colonization, apparently in response to rapid climate change.

Stop 1. Nanaikeola Road, Nānākuli

Nānākuli is the southernmost ahupua‘a of the Wai‘anae district, one of the original *moku* (districts) established by Ma‘ilikukahi, ruler of O‘ahu in the 1500’s.

This location affords a view at the section of lava flows that make up Pu‘u Heleakalā, the large mountain off to the south and east. Lualualei lavas at the base of Pu‘u Heleakalā have been dated at ~3.7 Ma.

1. Determine the general direction of dip of lava flows making up Pu‘u Heleakalā. Where is this section with respect to “original” Wai‘anae Volcano structure, i.e., are we on the north, east, south or west flank of Wai‘anae?

Stop 2. Kaukama Road

Lava flows from here have been dated at ~3.5 Ma [Guillou et al., 2000], but they have reversed magnetic polarity so they much be at least 3.55 Ma.

1. What type of lava flows are exposed in the hillside here? Are they pāhoehoe or ‘a‘ā lavas? Explain why you answer the way you did, i.e., what properties of these flow units can you recognize that help you answer this question

2. Are all the rocks here lava flows? Do you see any other kinds of rock units?

3. Across the valley is the low hill of Puʻu Māʻiliʻili. What is the orientation of the flow units in this hill? Explain why they have the orientation (dip) they do?

Māʻili

The double bump hill (Puʻu o Hulu) between Māʻili and Nānākuli is composed of Lualualei Member olivine basalts and dikes. This fellow *Hulu* (for whom the hill is named) was in love with *Mā'ili'ili*, who was one of twin sisters; because he could not tell the sisters apart, a *mo'o* changed them all to mountains, and he still looks at them. The erosional remnant of Puʻu Māʻiliʻili is intracaldera Kamaileʻunu lavas, as are also exposed on Puʻu Pāheʻeheʻe separating Lualualei and Waiʻanae Valleys.

The old name for the region between Nānākuli and Lualualei is Ulehawa, said to be the birthplace of Māui. The name ("filthy penis") derives from the old Hawaiian practice of assigning unpleasant nicknames to newborns of high rank. It is said that this name was given to a king, as a means of providing protection.

Lualualei Valley

A prominent saddle in the ridge north of Puʻu Heleakalā marks the boundary between Lualualei lavas to the south (right) and Kamaileʻunu lavas to the north (Fig. 7). Farther along this road are exposures of limestone, not coincidentally near the Kaiser cement plant. Stearns [1975] assigned these outcrops to what he called the PCA +25 foot stand of the sea, which he thought was an old stand predating the Kaʻena stand. However, they are more likely vestiges of the Stage 5e, ~125 ka, +6m Waimānalo stand.

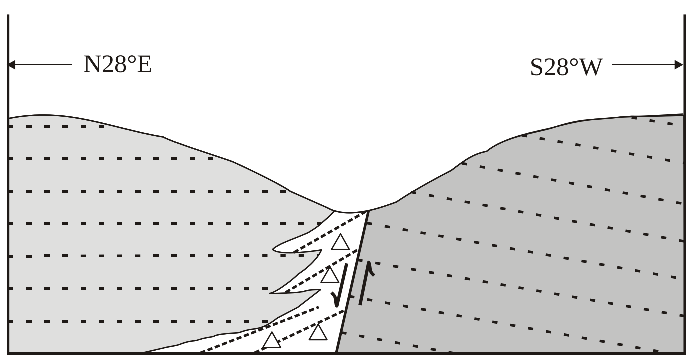


Figure 7. Cross section through the saddle north of Puʻu Heleakalā. The fault marks the boundary between Lualualei lavas to the south (right) and Kamaileʻunu lavas to the north. Here the boundary is a normal fault, down to the north, with talus breccias and Kamaileʻunu lavas ponded against the fault scarp (Figure 11). Lavas on either side of this fault have been dated. A Lualualei lava on the south side of the fault is 3.62 $\pm$ 0.09 Ma; a Kamaileʻunu lava on the north is 3.11 $\pm$ 0.04 Ma [Guillou et al., 2000].

The caldera boundary lies within Lualualei Valley. Lavas of Puʻu Heleakalā and Puʻu o Hulu, on the south side of Lualualei Valley dip to the south, whereas those of Puʻu Māʻiliʻili and Puʻu Paheʻeheʻe are flat lying, apparently erupted inside the caldera.

Turn right onto Waiʻanae Valley Road.

Stop 3. Mauna Kūwale (mountain standing alone)

The section at Mauna Kūwale consists, from the base, of Kamaile‘unu basalts overlain by augite-hypersthene tholeiitic andesite, which is in turn overlain by at least two flow lobes of hornblende-biotite-hypersthene rhyodacite. This sequence of Kamaile‘unu intracaldera eruption products is overlain by a thin flow of basaltic pāhoehoe, and mildly alkalic, very plagioclase-rich basaltic hawaiites that form the capping peak of Mauna Kūwale. The section above the now-defunct dairy starts in icelandite; the lower basalts are exposed in outcrops near the end of the Mauna Kūwale ridge. Several dikes and sills cut this sequence. The contact between the icelandite and rhyodacite is difficult to discern precisely in the field; apparently these two units were erupted in rapid succession. The overlying units are clearly much later, as a thin soil horizon occurs between the rhyodacite and overlying basalts.

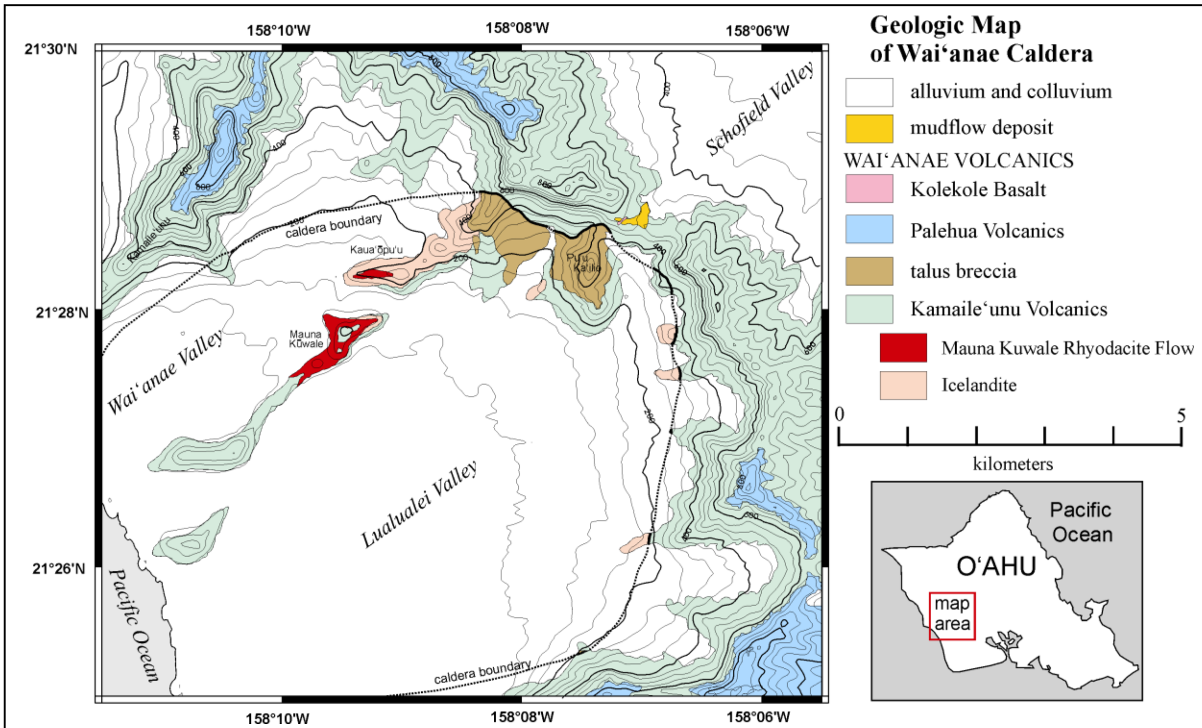


Figure 8. Geologic map of the caldera region. The caldera boundary fault is shown (dotted where covered).

The "best" age for the rhyodacite, consistent with the stratigraphic relations and age data on surrounding flows, is about 3.3 m.y. [*Guillou et al.*, 2000]. Some of the enigmatic features of these remarkable rocks include dunite and gabbroic xenoliths and Ti-rich clinopyroxene xenocrysts in the rhyodacite, and a variety of disequilibrium, mixing textures in the rhyodacite and many (but not all) of the icelandites. The xenoliths presumably represent either early crystallization products of mantle-derived basaltic magmas or random, disaggregated wall rock fragments entrained during ascent. Scattered tuff clasts in the rhyodacite, and local, ~1 m thick tuff deposits indicate that the eruption s producing this this sequence were, at least intermittently, pyroclastic.

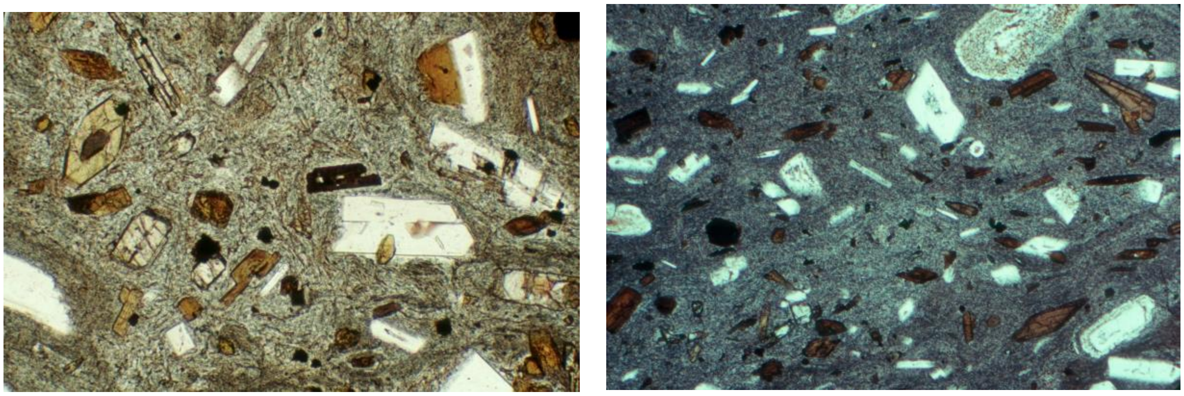


Figure 9. Photomicrographs of Mauna Kuwale rhyodacite. Each section ~2.5 mm across. Left hand slide contains conspicuous brown hornblende, very dark brown biotite, slightly pink hypersthene and colorless plagioclase. Right hand slide shows sieve-textured plagioclase crystals, indicating partial melting of the crystal following mixing between different magmas.

Highly silicic magma can form by two possible mechanisms: (1) by differentiation of basaltic magma, and (2) by partial melting of altered crustal rocks. According to van der Zander et al. [2010] some icelandite dikes appear to be the result of extreme differentiation of shallow-level magmas, whereas others, including the Mauna Kūwale Rhyodacite Flow, probably formed by direct melting of altered lower crust. Crustal melts later mixed with both shallow-level basalts and icelandites formed by differentiation. This scenario can explain the eruptive sequence of early formed icelandite followed by later eruptions of rhyodacite formed by melting of the lower crust. It also is notable that transitional shield volcanism continued in Wai‘anae for another ~200,000 years after the eruption of the Mauna Kūwale rhyodacite, before it finally turned into a postshield volcano with a much deeper magma reservoir.

1. Describe the contact between the lower, rubbly icelandite and the overlying rhyodacite. Is there evidence for a time break (soil, change in color, etc.)?

2. Notice the flow layering in the rhyodacite and how it changes orientation as we walk up through the flow. What explanation can you offer for this interesting variation?

3. A sequence of plagioclase-phyric basaltic lavas overlie the rhyodacite. Notice how the crystal size and content varies up-section to the top of Mauna Kuwale. Describe it in the space below.

Return to Farrington Hwy and turn right (north)

Wai‘anae to Mākua

The ridge separating Wai‘anae and Mākaha valleys is Kamaile‘unu Ridge, the type locality for this member of the Wai‘anae Volcanics. The Kamaile Heiau, said to be a luakini-class heiau where ruling chiefs prayed and human sacrifices were offered, is on Kamaile’unu Ridge at an elevation of about 400’.

Mākaha (lit. "fierce") is named for the gangs of bandits who once hid in caves as they waited to rob travelers. ʻŌhikilolo, a district just beyond Mākaha, means "prying out of brains" which may have been the unfortunate fate of travelers in this region. However, when the bandits met ʻolohe men from Kauaʻi, who were trained in the art of breaking bones, their days of ambush were ended.

Stop 4. Kāneana (the cave of Kāne)

Do not leave valuables in the car; this place is frequented by thieves.

There are many stories about this place, including that it is the place where Pele emerged on Oʻahu, from Kauaʻi; where Māui and his grandmother lived; and a place where a shark man lived (and probably still does!).

1. Why do you think this cave exists? Is it a lava tube? Is there a better explanation?

2. What is the orientation of the many dikes at Kāneana? Describe this location in terms of the structural elements of the Waiʻanae Volcano.

3. Look up at the the inside walls of the cave, ~20-25 ft above the floor. Do you see any rocks that look out of place? Describe these rounded rocks and provide an interpretation of what they might represent?

Stop 5. Roadcuts just south of Mākua Valley

Here there is an excellent section of carbonate sands and coral overlying late shield (Kamaileʻunu) lavas. The carbonate deposits have variably been described as eolianite (dunes from wind deposition) or inter-tidal lagoon deposits.

Inspect the exposures here and think about how they might have formed. Are there any fossils present? Could such fossils be preserved in dune deposits? How many different stragigraphic horizons can you recognize? Describe your observations and interpretations.

Keawaʻula (Optional stop)

The Oʻahu narrow gauge railway used to stop here to let off fishermen, many of which were of Japanese descent. Thus arose the slightly pejorative common reference of this place as Yokohama Bay; a summer surfing site here is called Yokohamas. Keawaʻula (lit. red harbor) refers to the large number of cuttlefish that colored the water red.

Lavas making up the ridges to the north dip consistently north, indicating that Kaʻena Pt is an erosional remnant of the north flank of the ancient Waiʻanae Volcano. A few dikes can be seen in the outcrops to the north, but not nearly as many as on the south side of Mākua Valley, near Kāneana.

Return south on Farrington Highway. On the way we will pass through the various regions of the Waiʻanae coast.

The sun is warm
At Mākua,
Then at Kū‘ano and Kea‘au ,
A breath of air stirs,
A soft breeze touches Kamalama.
Night overtakes one at Pīka‘i
A little dew from Ka‘ala ,
There is Hale‘au‘au and Kauna,
Then Pule‘e and now the sea of ‘Ewa,
‘Ewa is reached!

John Ii
in Stirling and Summers

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