LATE POSTSHIELD VOLCANISM ON WAIANAE VOLCANO OAHU, HAWAII

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSTY OF HAWAII IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

GEOLOGY

MAY, 1994

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ACKNOWLEDGEMENTS

I wish to thank all those that gave support and assistance with the field work, sample preparation, analytical techniques and the production of the draft. Special thanks to Malcolm Pringle, who without his energy the age dating work may not have been as successful; the illustration staff at SOEST for production of the map; to Michael Niederer for the production of the landslide illustration; and to my folks for their support. And finally, to the patience and help from John and JoAnn Sinton. Mahalo.

ABSTRACT

The 3.9-2.9 Ma Waianae Volcano is the older of two volcanoes making up the island of Oahu, Hawaii. A postshield alkalic cap of aphyric hawaiite, the Palehua Member of the Waianae Volcanics, is uncomformably overlain by small-volume, posterosional eruptions of alkalic basalt of the Kolekole Volcanics. Kolekole lavas occur in a variety of settings that mantle posterosional topography, including the uppermost slopes of the great Lualualei Valley on the lee side of the Waianae Range. Before this paper, the extent, age and geochemical characteristics of the Kolekole Volcanics were not fully defined. K-Ar analysis was conducted on 21 new samples of Palehua and Kolekole lavas. Despite the evidence of a distinct erosional contact, the determined ages of Palehua and Kolekole lavas are not statistically distinct. Based on the K/Ar work, magnetic polarity data, and geologic relationships, the eruptive ages of each unit are constrained to a period between 3.06 to 2.98 Ma for the Palehua Member, and 2.97 to 2.90 Ma for the Kolekole Volcanics. Palehua and Kolekole magmas have similar incompatible trace element ratios, and both suites show similar fractionation trends requiring early crystallization of clinopyroxene, consistent with evolution at elevated pressure. However, the Kolekole lavas are significantly less fractionated and appear to have formed at greater depths than the earlier Palehua hawaiites. Also, the extent of partial melting decreased within the eruption of Palehua hawaiites, but increased by 1-2% at the onset of Kolekole volcanism. Thus, the relatively short time period between the eruption of Palehua and Kolekole lavas appears to date the initial formation of Lualualei Valley and a marked change in magmatic conditions. We speculate that at least part of a large offshore submarine landslide deposit southwest of the Waianae Volcano occurred between the eruption of Palehua and Kolekole lavas. The association of an erosional event capable of altering lithospheric loading and petrologic

evidence of increased melting allows for a speculative model for the change of volcanism. The volume of material removed from the edifice could result in a depressurization capable of increasing partial melting by 1-4%, which is similar to the relative increase of melting between the youngest Palehua magmas and the Kolekole magmas. Other Hawaiian volcanoes have landslides and subsequent posterosional volcanism, suggesting that major catastrophic erosional events may elicit new volcanism.

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PREFACE

This thesis has been prepared as a manuscript for submittal to the Bulletin of Volcanology. The paper condenses the methods and results of the thesis work.

INTRODUCTION

The Waianae Volcano is the older of two shield volcanoes that make up the island of Oahu (Stearns and Vaksvik, 1935; Stearns, 1939, 1940 & 1946). Previous age determinations suggest that the subaerial portion of the edifice erupted between 3.69 and 2.70 Ma (Doell and Dalrymple, 1973; Mankinen and Dalrymple, 1979). The eroded Waianae Volcano is smaller in areal extent than its neighbor, the Koolau Volcano, yet it is taller of the two with the highest peak reaching 1226 meters.

Hawaiian volcano evolution is well defined by distinct growth stages (Clague and Dalrymple, 1987). The most voluminous stage, the shield-building stage, is dominated by the eruption of tholeiitic basalt. Eruptions are frequent, but diminish near the end of this stage. The subsequent yet nonubiquitous postshield stage forms a low volume veneer of alkalic lavas. The late postshield stage of many of the volcanoes consists of an "alkalic cap" of primarily differentiated alkalic lavas. Some Hawaiian volcanoes have a final stage of very low volume eruptions, the rejuvenated or posterosional stage, of undersaturated to extremely undersaturated alkalic lavas, that erupt after an hiatus of up to 2 million years.

Shield and postshield volcanic rocks are exposed on the Waianae Volcano. Postshield volcanism on Waianae Volcano includes an alkalic cap of aphyric hawaiite overlain by olivine phyric alkalic basalt, the youngest unit. These units are separated by an enigmatic erosional contact. This study concentrates on mapping and defining the postshield volcanism, and proposes an explanation for the results of our findings.

Geomorphology

The Waianae Range is the deeply eroded remnant of the Waianae Volcano. The volcano has been modified by subsidence from lithospheric isostasy (Moore, 1987), major submarine slumping to the west (Hussong et al., 1987; Moore et al., 1989) and significant subaerial erosion.

On both the windward (wet) side and leeward (dry) side of the range lie deep amphitheater headed valleys, separated by steep-sided ridges. Expansive, relatively unaltered lavas are well exposed on the cliffs and ridge crests. The orographic rain shadow of the Koolau Range shields much of the volcano from excessive amounts of rain. The yearly average rainfall is approximately 1000 mm along the Palehua ridgeline to below 600 mm at the lower elevations near Puu Makakilo and the Ewa Plain (Giambellucca, 1986).

The formation of large valleys on Hawaiian volcanoes usually can be attributed to the work of erosion on the wetter, windward sides. However, most of the largest and broadest valleys of the Waianae Range are on the leeward side. The most striking feature of the Waianae Range is the Lualualei Valley and adjacent Waianae Valley. The overall relief of this feature extends from the summit of Mt. Kaala (1224 meters) to a wide plain near sea level. Sediments and coralline reef deposits fill Lualualei Valley to approximately 370 meters below present sea level (Stearns and Vaksvik, 1935). The head of the valley is bounded by a ridge line in which the lowest point is Kolekole Pass (518 meters).

The overall outline of the Waianae Range is a crescent shape (Figure 1). This crescent shape and the steep cliffs set back from the coastline led Dana in 1842 to interpret these features to be created by large faults with up to 1000 meters of displacement (see Stearns and Vaksvik, 1935). A submarine slump deposit (Hussong et al., 1987; Moore et al., 1989) dominates the near shore region to the west. This deposit is classified as a slump, rather than a debris flow, due to the lack of an extensive deposition field and unattached blocks Figure 2).

The Waianae Volcano has two major rift zones: a prominent northwest rift zone, well defined by a complex of sub-parallel dikes trending approximately N52°W, and a more diffuse south rift zone, trending between S20°W to due south (Zbinden and Sinton, 1988). A minor rift zone trends to the northeast. There are more dikes in the caldera than in the rift zones (Zbinden and Sinton, 1988).

Stratigraphy

Waianae stratigraphy consists of two volcanic formations, the Waianae Volcanics and the Kolekole Volcanics (Stearns, 1946; Sinton, 1987). The Waianae Volcanics include flows, intrusions, pyroclastics and associated alluvium, and are divided into three members; the Lualualei member, the Kamaileunu Member, and the Palehua Member. The Lualualei Member is the oldest, shield-building member where flows are composed of mainly aphyric and olivine-phryic tholeiitic basalts. Shield-building lavas are exposed only at the bases of the ridges near the western shores. Overlying the Lualualei Member is the Kamaileunu Member which consists of tholeiitic, transitional and alkalic basalts that form

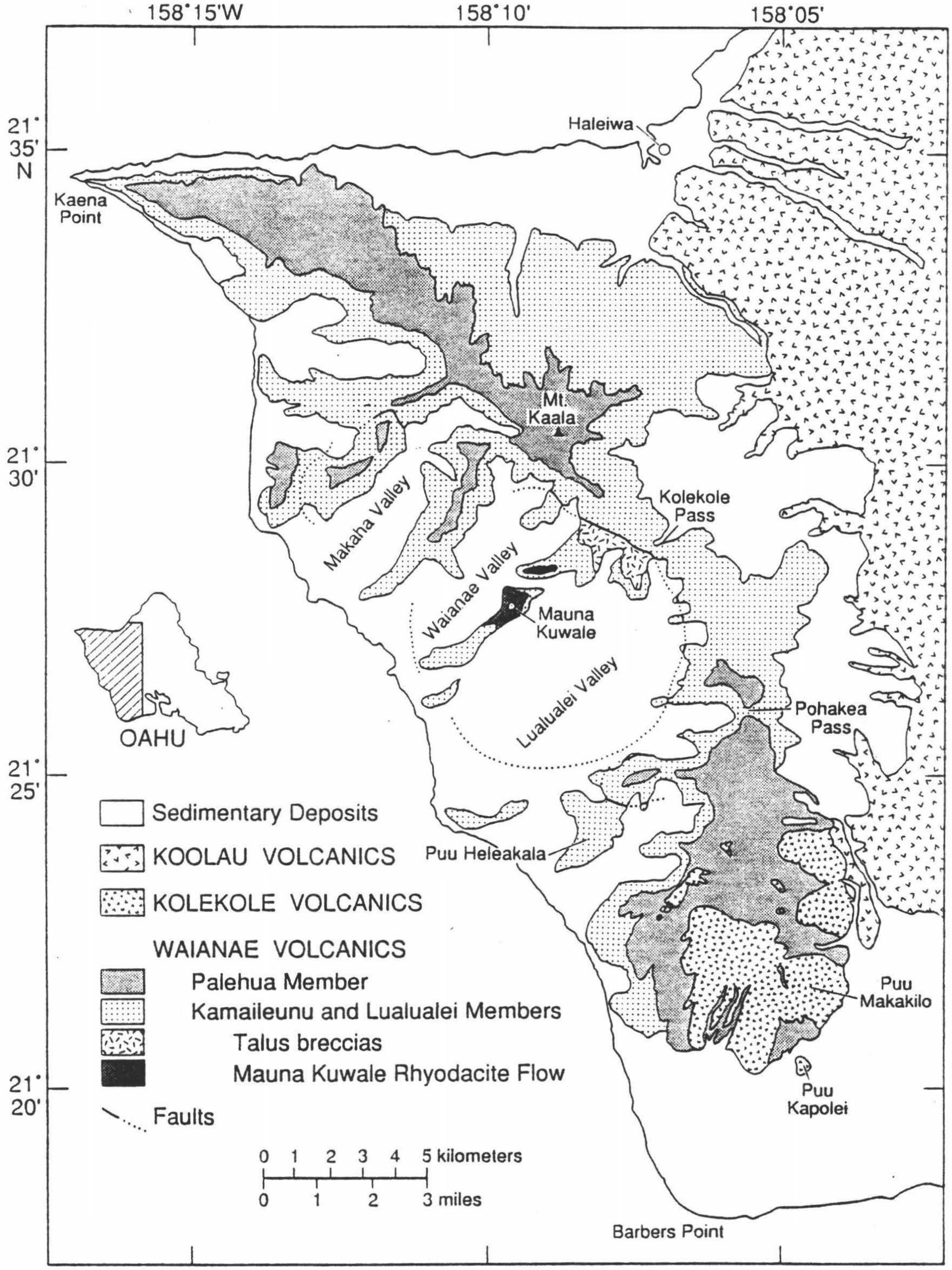


Figure 1. New geologic map of Waianae Volcano. Contributions to this map include Stearns (1939), Macdonald (1940), Sinton (1987), and the authors.

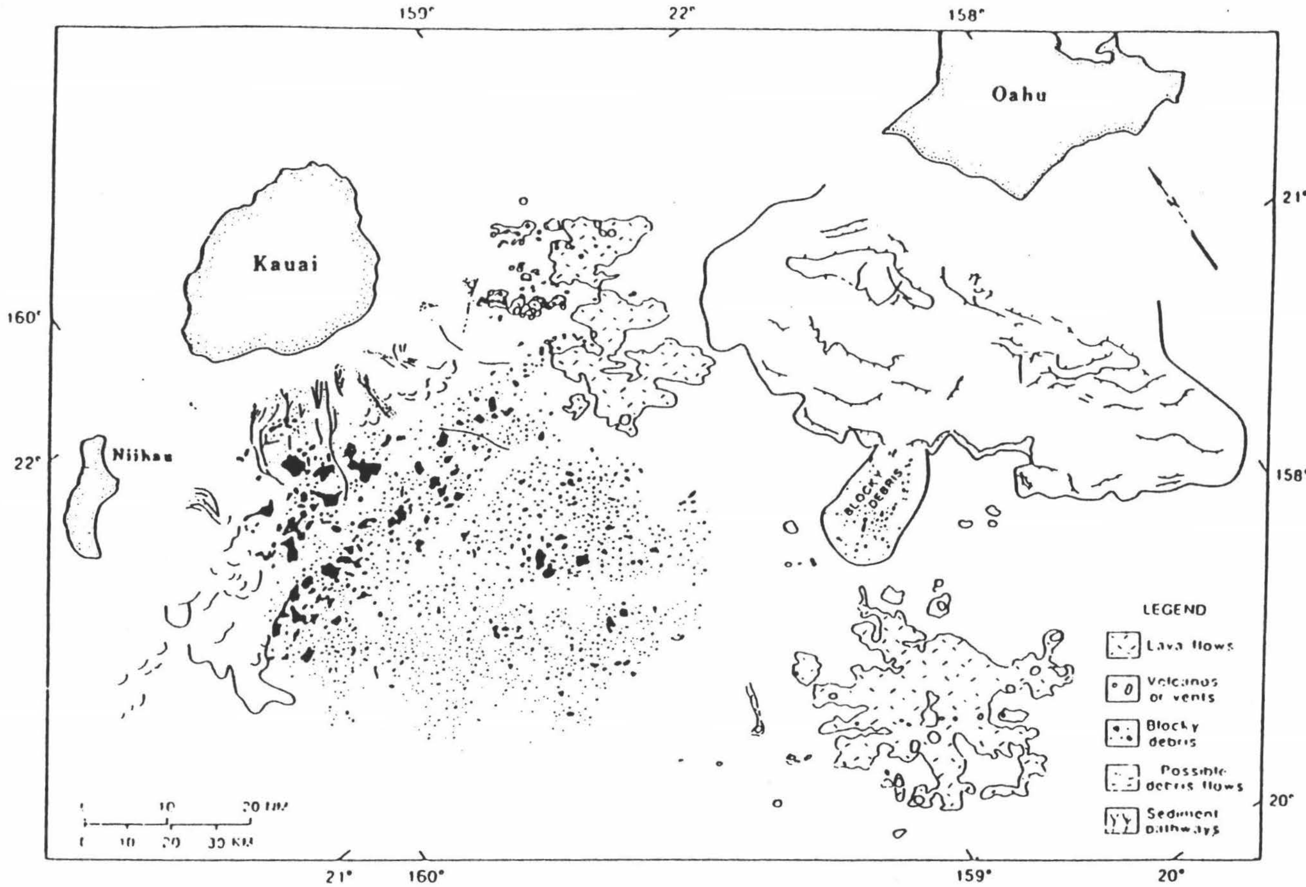


Figure 2. Map of submarine landslide and slump deposits from Kauai and Oahu. Figure from Moore et al., 1989.

late-shield, caldera-filling and early postshield lavas. The alkalic lavas tend to be olivine-phyric and plagioclase-phyric basalts and hawaiites. Also included in the lithology of the Kamaileunu member are several flows of atypical composition. An 80 m thick section of icelandite underlies a thick flow of rhyodacite, known as the Mauna Kuwale Rhyodacite Flow (Macdonald and Katsura, 1964; Bauer, 1979; Sinton, 1987). The rhyodacite flow is composed of hornblende, plagioclase, biotite and hypersthene in a glassy matrix. It is the most silicious lava found in the Hawaiian chain. The Palehua Member, the primary unit of the alkalic cap, consists almost entirely of aphyric hawaiite with minor local occurrences of plagioclase-phyric hawaiite, alkalic basalt and mugearite. (Sinton, 1987). The Palehua Member is generally conformable with the Kamaileunu member, yet in specific places, such as Pohakea Pass, the contact is disconformable.

The youngest unit in the Waianae Range is the Kolekole Volcanics, comprised of flows and vent deposits of a more mafic, olivine-phyric alkalic basalt. The basalts commonly contain xenoliths of pyroxenite, with lesser amounts of dunite and gabbro xenoliths and pyroxene xenocrysts. The type-section of the Kolekole Volcanics is located near the 520 meter Kolekole Pass. Other outcrops of Kolekole lavas exist at the summit of Mt. Kaala and in the southern part of the range where numerous cinder and spatter cones and flows are exposed.

Before this paper, the extent of the Kolekole Volcanics, the chemical relations to earlier Waianae lavas, and the age of this final eruptive activity were not well defined. Stearns and Macdonald (in Stearns, 1940) suspected a connection between the flow at Kolekole pass and "Laeloa Cones" at the southern part of the range. Later, the Kolekole Volcanics were designated as a separate unit by Stearns (1946). Sinton (1987) revised the Waianae stratigraphic nomenclature and found that the lavas from the cones in the southern part of the range were petrologically and geochemically similar to the flow at Kolekole Pass, thus extending the geographic range of the Kolekole Volcanics. The contact between the Kolekole Pass flow and the underlying geology shows that a great amount of erosional modification to the volcano occurred between the eruption of alkalic-capping lavas and the Kolekole Volcanics. However, Kolekole eruptive activity antedated the headward erosion of Nanakuli Valley (Stearns and Vaksvik, 1935) and is older than the abutting flows of the Koolau Volcano (Figure 1.). Furthermore, the contacts between the cones and the Palehua Member alkalic-capping lavas show only thin soil layers with minor erosion into underlying Palehua hawaiite flows.

In this paper, we report the results of new field mapping, petrographic analyses, chemical analyses by X-ray fluorescence (XRF), and potassium-argon age analyses. We concentrated our mapping efforts on the southern portion of the range where there is an abundance of Kolekole Volcanics (Figure 3). With these results, we interpret that the magmatic evolution may be linked to a major erosional event during the late postshield eruptive activity. We also compare Waianae petrology and evolution with that of other Hawaiian volcanoes with similar alkalic caps.

Analytical Techniques

Field mapping was focused on the southern part of the range to determine the extent of the Kolekole Volcanics and its relation to underlying strata. Besides the detailed mapping, the magnetic polarity of many outcrops (and samples) were tested in the field using a Meda μMAG digital flux gate magnetometer.

The samples studied also include rocks collected from various other workers. C-series samples were from early work by Macdonald (1968), OW- and WD- samples were collected by Sinton and Zbinden, respectively, and PW- samples were collected by the authors. All PW- samples are either Palehua Member lavas or Kolekole lavas with the exception of two Koolau Volcanics from the southeastern margin of the volcano. There is minor alteration of olivine phenocrysts on some of the samples but most of the samples are relatively unaltered. All the samples were studied in thin section to determine petrography and the extent of weathering for K-Ar dating.

Potassium-argon dating was performed at the U.S. Geological Survey in Menlo Park. Twenty-one samples of Palehua Member hawaiites and Kolekole Volcanics were chosen based on the extent of weathering, the occurrence of holocrystalline texture in the groundmass (after Mankinen and Dalrymple, 1972), and by their stratigraphical significance. All but three samples are part of stratigraphical sections in the southern Waianae field area (Figure 3).

For the dating work, rock samples were slabbed with a diamond saw and crushed with a roller mill down to a 18 to 35 interval sieve size. Each sample was cleaned with distilled water in an ultrasonic bath for over 20 minutes, dried, then split into four 10 to 15 gram aliquants (depending on rock type) and a reserve. Three of the splits were designated for argon analyses; the fourth was pulverized to a fine powder in a Spex steel shatter box for potassium analyses. At least two argon extractions and two potassium analyses were

U_c — **Consolidated calcareous sediments**
Includes consolidated beach sands, coral, coraline algae, and shells.

U_n — **Unconsolidated and consolidated noncalcareous sediments**
Includes unconsolidated and consolidated alluvium, colluvium, and soils.

T_k — KOOLAU VOLCANICS
Flows of oceanite and tholeiitic basalts.

KOLEKOLE VOLCANICS

Basalt aa flows, cinder and splatter cones, and cinder deposits. Lavas are olivine-phyric, commonly containing xenoliths of dunite, pyroxenite, and gabbro.

K_{ou}	K_{oku}
K_{op}	K_{om}
K_{oei}	K_{oai}

- K_{ou}: undifferentiated Kolekole flows, vents unknown;
- K_{oku}: Puu Kuua lavas;
- K_{om}: Puu Makakilo lavas;
- K_{op}: Puu Palailai lavas;
- K_{oei}: Puu Kapolai lavas;
- K_{oai}: Puu Kapuai lavas.

Stippled pattern signifies spatter and cinder deposits.


Contact in Kolekole Volcanics where Stratigraphy is known. Dots indicate the younger unit.

Erosional unconformity

WAIANAE VOLCANICS

W_p — **Palehua Member**
Predominantly aphyric hawaiite aa flows, rare plagioclase-phyric hawaiite aa flows and vent deposits. Stippled pattern signifies spatter and cinder deposits.

W_k — **Kamaileunu Member**
Late Shield tholeiite, transitional and alkalic basalts and hawaiites. Tholeiitic pahoehoe flows predominate in the lower sections. Upper sections include both plagioclase-phyric and aphyric hawaiite aa flows.

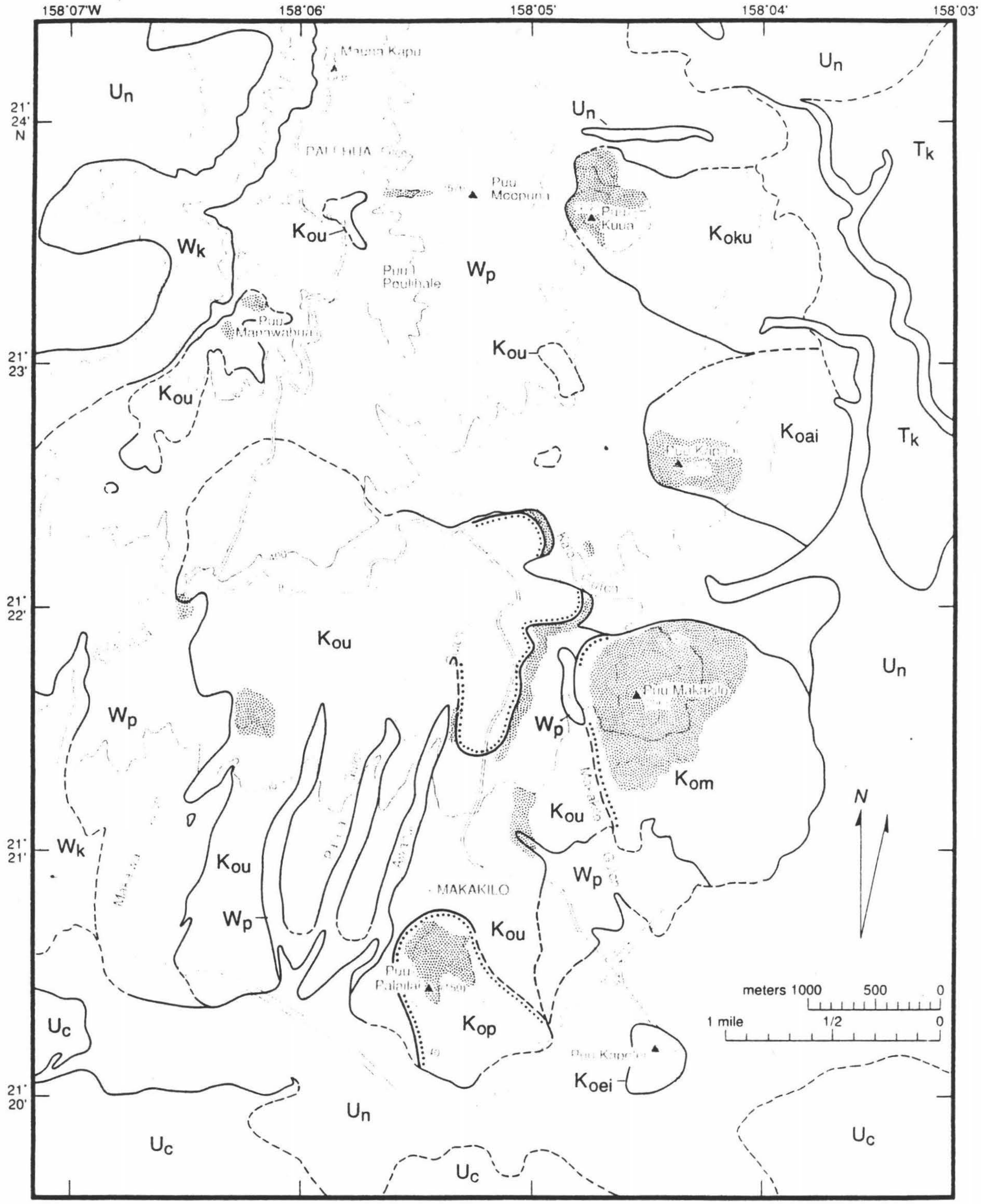


Figure 3. New geologic map of southern Waianae Volcano. The greatest abundance of Kolekole volcanics are preserved at the southern end of the volcano.

completed for each sample using techniques similar to those previously described by Dalrymple and Lanphere (1969) and Ingamells (1970). Argon ratio measurements were accomplished using an argon multi-collector mass spectrometer (Stacey et al. 1981).

To study the geochemistry, 76 new samples were chosen for analysis and 56 samples from previous studies were chosen for reanalysis using a Siemens 303AS fully automated, wavelength-dispersive, x-ray fluorescence spectrometer at the University of Hawaii. Samples were analyzed for major and minor elements plus Sc, V, Cr, Ni, Co, Cu, Zn, Rb, Sr, Y, Zr, Nb, Ba, Pb, Th and U. Rock chips were cleaned in an ultrasonic bath of distilled and deionized water prior to crushing in Spex tungsten carbide or alumina swing mills. Samples were ignited for 8 hours at 900° C and a loss on ignition was determined. Two fused buttons and one pressed powder pellet were prepared for each sample following procedures modified slightly from Norrish and Hutton (1969) and Chappell (1991).

RESULTS

Field Relations

Postshield volcanism of the Waianae Volcano probably capped almost the entire subaerial portion of the edifice. Where stratigraphy is not deeply incised by erosion, Palehua Member hawaiite flows reach lower elevations and underlie subsequent Koolau Volcanics. The flows are mostly thick aa flows that result in a maximum thickness of the unit at 182 m below Mt. Kaala. In the southern end of the range, Palehua hawaiites are exposed to the east and west, and in gulches cutting through the veneering Kolekole Volcanics. Thicknesses vary at the southern part of the range. A 123 meter-thick section of Palehua hawaiite, beginning at 613 meter elevation, was collected by Macdonald (1968) along the ridge pointing WNW, 0.5 km north of Puu Manawahua (Figure 3). A recent drill core, located at an elevation of 98 meters near Puu Makakilo, recovered 61 meters of Palehua hawaiite before reaching plagioclase-phyric Kamaileunu Member lavas. The Palehua lavas thin towards the distal ends of the edifice. A possible Palehua rift zone trends north along the ridge containing Mauna Kapu and Palikea, where numerous vent deposits and breccias crop out. A small Palehua cinder cone also has been exhumed by erosion in a small gully between Puu Makakilo and Puu Kapuai.

Exposures of Kolekole lavas include a small flow at Kolekole pass, a small spatter cone near the summit of Mt. Kaala and numerous monogenetic cinder and spatter cones and associated flows at the southern part of the range. Other small outcrops may exist elsewhere on the volcanic edifice, yet erosion has probably removed most evidence of other Kolekole volcanism. The Kolekole Volcanics have a variety of contacts with the underlying members. At Kolekole Pass, a polymict conglomerate unconformably overlies weathered, plagioclase-phyric Kamaileunu lavas and dikes. This sequence is further unconformably overlain by an approximately 1 m thick flow of Kolekole basalt. The conglomerate, interpreted to be a mudflow deposit, contains matrix-supported clasts of a wide range of lithologies including Palehua hawaiites.

Exposures of the contact in road cuts and stream gulches locally include a 0.25 meter thick crystalline ash layer separating the Kolekole lavas from the Palehua lavas. The ash is extremely weathered but contains oxides, weathered plagioclase and other grains. The underlying Palehua hawaiite has a thick clinker and block zone above a massive core. The Palehua flows have only slight erosion with a few small gullies but no major, multiple flow incisions. The oldest Kolekole lavas in this region form numerous flows and small outcrops that veneer Palehua hawaiites. Some thin weathered zones exist between Kolekole veneer flows in road cuts along Farrington Highway. Sources for these flows, such as Puu Manawahua and two small topographical highs 0.2 km northeast and 0.7 km southwest of Puu Manawahua, are in a wetter and higher elevation region, and thus are deeply eroded and weathered. These cones erupted before the formation of the head of Nanakuli Valley (Stearns and Vaksvik, 1935). Other sources for the veneering lavas include two flat cinder-covered vents located 1 km south and 3 km south of Puu Manawahua. These vents are aligned along a north-trending rift zone of Palehua hawaiites seen at higher elevations along the Palehua area ridge line. The southwestern part of the volcano is eroded more extensively and no Kolekole lavas have been found there.

Other Kolekole eruptions occurred further down the flank forming the Laeloa Craters (Puu Kapolei, Puu Kapuai, Puu Kuua, Puu Makakilo and Puu Palailai), which appear to be among the last eruptive events of the Waianae Volcano except for a flow that overlies Puu Makakilo vent deposits. The cones have varied amounts of spatter and cinder and all but Puu Kapolei have extensive flows emanating from the bases of the cones. Drainage was diverted due to the formation of these vents, creating the gulches that surround the cones and removing most of the cinder originally deposited. Flows from Puu Makakilo and Puu Palailai have been extensively quarried. The thickest section (approx.

40 m) of Kolekole Volcanics surrounds Puu Makakilo, and includes six flows of veneering lava from sources higher in elevation. These flows underlie vent deposits of ash, cinder and spatter of the Puu Makakilo cone. Overlying an approximately 5 meter thick ash and cinder layer is a thin xenolith-bearing flow which probably erupted from the vent 1 km south of Puu Manawahua.

Other small outcrops exist at higher elevations. They include a small and extremely eroded outcrop, referred to as Building 203, which is unusually coarse grained and includes an intrusion of finer grained Kolekole basalt within the coarser rock.

Potassium-Argon Dating

The ages of the Palehua Member and the Kolekole Volcanics were poorly constrained by previous work. Doell and Dalrymple (1973) summarized existing Waianae potassium-argon data, but since then the decay constants of the isotopes and the stratigraphic nomenclature for the Waianae Volcano have changed (Mankinen and Dalrymple, 1979). Five previous dates for the Palehua have been recalculated using the revised decay constant (ranging from 3.18 ± 0.10 Ma to 2.87 ± 0.070 Ma). Three of the dates are from samples located very close to the Palehua Member-Kolekole Volcanics contact in the southern part of the range. The other two samples are from a massive flow of Palehua hawaiite in the northern part of the range. A thick, ponded Palehua flow with reversed magnetic polarity, is the type locality of the Kaena Reversed Polarity Subchron within the Gauss Normal Polarity Chron. This flow yielded a date of 2.94 ± 0.05 Ma (Doell and Dalrymple, 1973; Mankinen and Dalrymple, 1979). However, the Kaena event has been recently interpreted to have occurred between 3.054 and 3.127 Ma (Cande and Kent 1992). There is only one previous K-Ar age for a Kolekole sample, probably from Puu Palailai or nearby veneering lavas; it yielded an age of 3.38 ± 0.10 Ma (Doell and Dalrymple, 1973; Mankinen and Dalrymple, 1979).

We dated twenty new samples to constrain the age of Kolekole and Palehua lavas. We used conventional potassium-argon techniques which are best for young Hawaiian basalts. Recently developed methods using incremental heating $^{40}Ar/^{39}Ar$ or laser activated $^{40}Ar/^{39}Ar$ techniques require greater amounts of radiogenic ^{40}Ar from the young, relatively low potassium rocks of Hawaiian volcanoes.

Four stratigraphic sections were dated so that the reliability of the determined ages could be constrained by geological relationships. Four other localities were chosen for their significance but were not part of an analyzed section (OW-80, the Kolekole Pass flow; OW-128, the oldest Palehua hawaiite of Mt. Kaala; PW-43, a Palehua lava under Puu Kuua; and PW-47, a sample of the Building 203 outcrop). Locations of the samples are given in the appendix.

The new age determinations are given in Table 1 for each split, along with the standard deviation for analytical precision. In general, the analyses of the Palehua hawaiites yielded better age determinations statistically than the Kolekole basalts, primarily due to the higher potassium abundances, freshness and holocrystalline texture in the hawaiites. The weighted mean ages and errors for each sample are calculated by weighting the age value by the inverse of the variance (Taylor, 1982). This statistical technique allows data of poorer analytical quality to affect the average less. The table is arranged in stratigraphic order with the sample deepest in the section on the bottom. A comparison of the mean ages with the stratigraphy indicates that the real errors are greater than those estimated by analytical precision. Errors may arise from element migration due to weathering, incomplete extractions during analysis or from inherited ^{40}Ar from xenoliths in Kolekole lavas. The OW-118b and PW-29 sample outcrops contained xenoliths, as well as many of the other localities. Most of the Palehua sample sites were near the Palehua-Kolekole contact so they provide a best estimate of the youngest Palehua eruptions with the exception of OW-128, which was sampled from the bottom of the section exposed at Mt. Kaala.

Comparing the age determinations of the Palehua and the Kolekole samples shows that there is considerable overlap for the two volcanic units. Statistical tests show that only some of the ages for both the Palehua or the Kolekole lavas are distinct from each other based on a 95% confidence level. If the age determinations were all non-distinct, then a weighted mean of the age determinations would yield a more accurate value by weighting the better analyses. Since there are distinct age determinations, suggesting real differences in age between eruptive events, non-weighted means will give a more plausible result. The non-weighted mean for the samples of Palehua member is 2.983 ± 0.035 Ma. To calculate the non-weighted mean for the Kolekole Volcanics, samples OW-118b and PW-29 were omitted to reduce the error. Both of these samples were taken from the youngest lavas in the stratigraphical section, perhaps the youngest of the volcano, yet they yielded the oldest age determinations of the 20 samples dated. As stated above, the rock outcroppings that these samples came from contain xenoliths. The non-weighted mean for the Kolekole Volcanics is 2.961 ± 0.030 Ma. The mean difference between these two sample series

Table 1. Potassium - Argon ages of the Palehua Member and the Kolekole Volcanics, Oahu

SAMPLE NO.	UNIT	K2O			ARGON			AGE	S.D.	WEIGHTED MEAN	S.D.	MAGNETIC POLARITY
		VALUE	S.D.	NO. ANAL.	WEIGHT (gms)	Ar-40* (mol/gm)	Ar-40* (%)	(m.y.)	(m.y.)	(m.y.)	(m.y.)	(Flux Gate)
Kolekole Pass												
OW-80	KOLEKOLE	1.033	0.005	4	15.406	4.356E-12	60.9	2.928	0.038			
					14.626	4.301E-12	61.4	2.891	0.036			
					15.387	4.411E-12	63.4	2.965	0.036	2.928	0.021	NORMAL
Building 203												
PW-47	KOLEKOLE	0.810	0.001	4	14.763	3.426E-12	57.1	2.934	0.042			
					15.085	3.321E-12	47.0	2.844	0.042	2.889	0.030	NORMAL
Veneer Section 1, low elevation												
OW-123a	KOLEKOLE	0.851	0.002	4	14.830	3.608E-12	49.4	2.943	0.043			
					14.790	3.665E-12	61.5	2.989	0.040	2.968	0.029	NORMAL
PW-20	PALEHUA	1.734	0.006	4	10.146	7.557E-12	71.4	3.024	0.036			
					10.868	7.518E-12	67.0	3.008	0.032	3.015	0.024	NORMAL
Veneer Section 2, high elevation												
PW-29	KOLEKOLE	1.089	0.005	4	15.159	4.976E-12	54.9	3.172	0.040			
					15.390	4.603E-12	60.6	2.935	0.037	3.054	0.119	NORMAL
OW-122	PALEHUA	1.733	0.002	4	11.777	7.526E-12	45.9	3.013	0.035			
					11.848	7.275E-12	56.5	2.913	0.003	2.914	0.018	NORMAL
PW-32	PALEHUA	1.787	0.007	4	10.690	7.663E-12	72.2	2.976	0.032			
					9.991	7.711E-12	74.1	2.994	0.034	2.984	0.023	NORMAL
PW-32a	PALEHUA	1.689	0.005	4	11.260	6.984E-12	51.3	2.870	0.033			
					10.607	7.149E-12	58.1	2.938	0.034	2.903	0.024	NORMAL
Puu Kuua												
PW-43	PALEHUA	1.737	0.003	4	10.053	7.590E-12	51.7	3.032	0.035			
					10.255	7.615E-12	49.0	3.042	0.037	3.037	0.025	NORMAL
Mt. Kaala												
OW-128	PALEHUA	1.810	0.002	4	9.680	7.790E-12	59.6	2.987	0.032			
					9.680	7.790E-12	59.6	2.987	0.032	2.987	0.023	NORMAL

Table 1. Potassium - Argon ages of the Palehua Member and the Kolekole Volcanics, Oahu, cont.

SAMPLE NO.	UNIT	K2O			ARGON			AGE	S.D.	WEIGHTED MEAN	S.D.	MAGNETIC POLARTITY
		VALUE	S.D.	NO. ANAL.	WEIGHT (gms)	Ar-40* (mol/gm)	Ar-40* (%)	(m.y.)	(m.y.)	(m.y.)	(m.y.)	(Flux Gate)
OW-118b	KOLEKOLE	1.094	0.002	4	15.501	4.850E-12	48.8	3.076	0.037			
					15.180	4.824E-12	46.7	3.059	0.039	3.068	0.027	NORMAL
OW-76	KOLEKOLE	0.962	0.006	4	14.890	4.161E-12	59.6	3.003	0.041			
					15.136	4.053E-12	54.4	2.925	0.041	2.964	0.029	NORMAL
PW-69	KOLEKOLE	1.081	0.005	4	15.474	4.709E-12	39.0	3.023	0.041			
					14.781	4.607E-12	48.0	2.958	0.038	2.988	0.028	NORMAL
PW-81	KOLEKOLE	0.755	0.008	4	14.971	3.315E-12	17.6	3.049	0.078			
					15.058	3.257E-12	30.7	2.996	0.058	3.015	0.049	NORMAL
PW-78	PALEHUA	1.536	0.008	4	9.797	6.531E-12	39.1	2.951	0.041			
					10.274	6.706E-12	38.8	3.031	0.045	2.987	0.030	NORMAL
PW-85	PALEHUA	1.454	0.010	4	10.100	6.390E-12	39.0	3.050	0.047			
					9.983	6.221E-12	59.6	2.970	0.041	3.005	0.031	~
Puu Palailai Section												
PW-19	KOLEKOLE	1.220	0.002	4	16.650	5.364E-12	38.1	3.052	0.041			
					15.304	5.055E-12	18.2	2.877	0.061	2.998	0.037	NORMAL
PW-17	KOLEKOLE	0.600	0.002	4	15.466	2.531E-12	24.3	2.929	0.063			
					14.330	2.534E-12	43.0	2.932	0.057	2.931	0.042	NORMAL
PW-10	KOLEKOLE	1.111	0.002	4	14.822	4.757E-12	33.7	2.971	0.043	2.971	0.043	NORMAL
PW-6	PALEHUA	1.760	0.010	4	10.319	7.676E-12	52.4	3.026	0.038			
					12.203	7.646E-12	54.0	3.014	0.035	3.020	0.026	NORMAL

*Ar-40 is radiogenic Ar-40

Note: All age dating performed at the Branch of Isotope Geochemistry, U.S. Geological Survey, Menlo Park. Ages calculated using 1976 IUGS constants (Steiger & Jager, 1977): lambda B=4.962E-10/yr, lambda E=0.581E-10/yr, K-40/K-total=1.167E-4mol/mol. Errors are estimates of analytical precision at the 68% confidence level. Means are weighted by the inverse of the variances following Taylor (1982).

Within each section, samples are listed in stratigraphic sequence.

within a 95% confidence level is 22 ± 43 ky, suggesting a maximum average age difference of 65 ky.

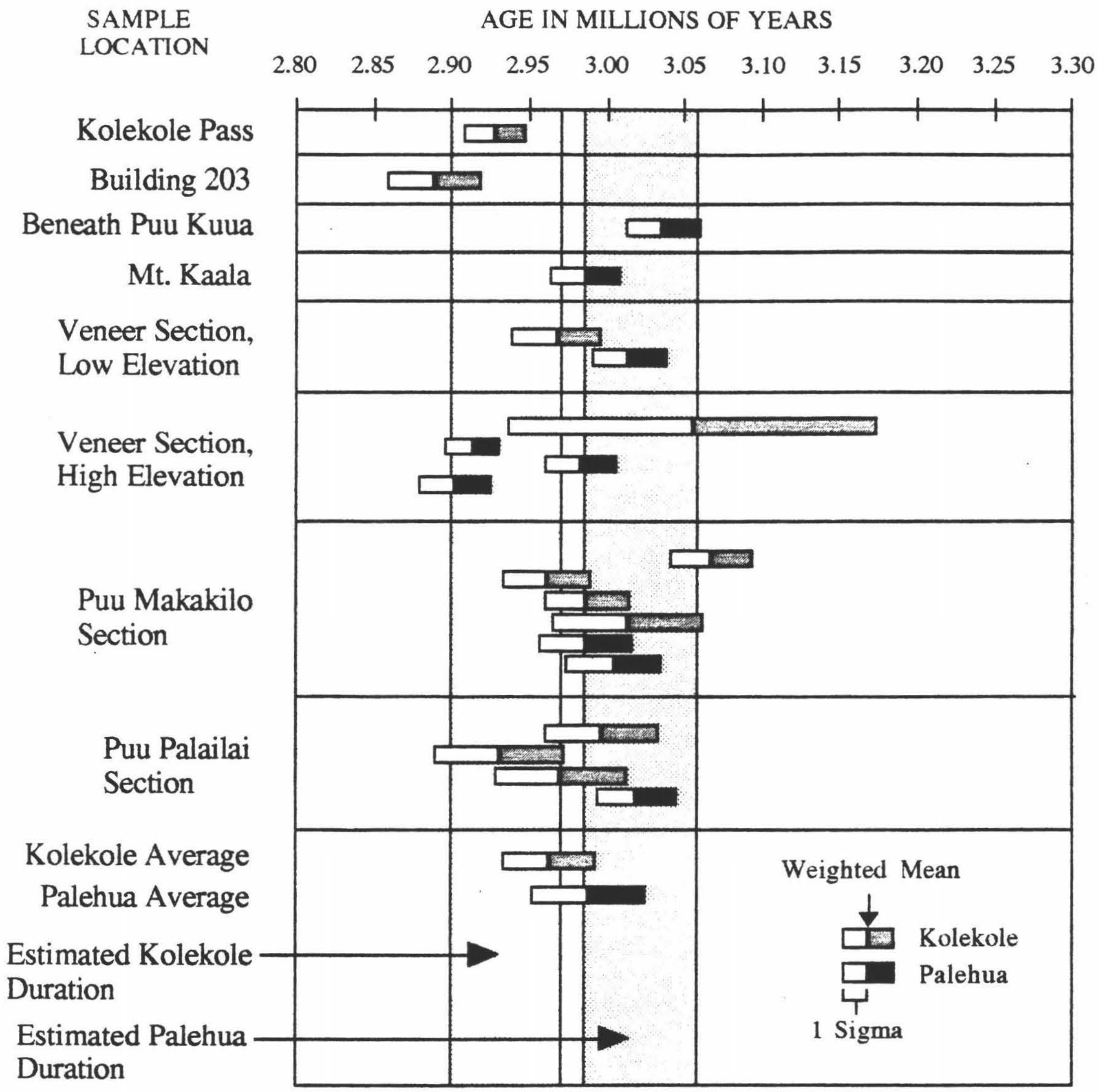
The maximum age difference calculation between the oldest Palehua sample and the youngest Kolekole sample yielded 148 ± 77 ky, suggesting an age range for the postshield volcanism. The analyses do not give distinct durations for each unit that sum to the value for postshield volcanism due to the overlap and error of the age determinations. The maximum age difference calculation, which would yield a duration of activity around the means for each unit, yielded a value of 134 ± 68 ky for the Palehua member and 126 ± 113 ky for the Kolekole Volcanics.

The age dating and statistical analyses cannot determine the exact timing of these events. Therefore, only speculative time durations for each unit can be assigned. If the age data are plotted for each section (Figure 4), then the time duration can be assigned for each unit by comparing data that fall within a reasonable pattern based on the geology, previous data (both potassium-argon and magnetic polarity data), and by considering the averages and maximum age differences. Thus, a possible eruptive sequence would be as follows: Palehua volcanism started at approximately 3.06 Ma yielding flows of reversed magnetic polarity in the northern extent of the range (due to the Kaena Reversed Polarity Subchron type locality) and ended at approximately 2.98 Ma with normal polarity flows. Normal polarity Kolekole volcanism started about 2.97 Ma and ended approximately 2.90 Ma. The duration of the hiatus between the Palehua and Kolekole is short or nonexistent (~10 ky, but maybe anywhere from 0 to 65 ky) in this scenario.

Many Palehua and Kolekole samples were tested for magnetic polarity in the field using a Meda μMAG digital flux gate magnetometer. All of the measureable samples in the field area and the flow at Kolekole pass are normally magnetized. The magnetic polarity of a few samples could not be determined due to lightning affects. If the outcrop had been struck by lightning, the compass needle was greatly deflected as the compass was brought within contact of the rock.

If these rocks are normally magnetized, then they must fall within normal polarity interval. The geomagnetic time scale rests without revision for only brief periods. However, the age determinations of this study agrees very well with a more recent revision by Cande and Kent (1992) (Figure 5). All of the age determinations except for the two Kolekole samples that yielded large errors (OW-118b and PW-29) fall after the Kaena Reversed Polarity Subchron within the Guass Normal Polarity Chron, which begins at 3.054 Ma.

Figure 4. Bar graph of potassium-argon age data. Each bar represents the weighted mean age (from Table 1) with one standard deviation (68% confidence level) around the mean. The data are plotted in the same order as in Table 1, which is the stratigraphic order by section. Two Kolekole samples yielded ages that are too old for their respective stratigraphic position and have not been included in the calculated Kolekole Volcanics "average". Statistical calculations for a mean difference between the two units (22 ± 43 ky), and for a maximum age difference between the youngest and oldest age determination of each unit (134 ± 68 ky for the Palehua member and 126 ± 113 ky for the Kolekole Volcanics) reveals that there is a distinct difference in ages for the two units, but the difference is too small compared to the errors of the analytical techniques to adequately determine the timing of the events. By incorporating geology and previous data (especially the Dillingham Quarry Palehua Member hawaiite of reversed magnetic polarity and the magnetic time scale of Cande and Kent, 1992), a good speculative fit for the timing of these events can be made. The stippled regions are the speculative fits for the postshield volcanism. Palehua eruptive activity may have occurred between 3.06 and 2.98 Ma (a duration of 80 ky) and Kolekole eruptive activity may have occurred between 2.97 and 2.90 Ma (a duration of 70 ky).


SAMPLE LOCATION
AGE IN MILLIONS OF YEARS
2.80
2.85
2.90
2.95
3.00
3.05
3.10
3.15
3.20
3.25
3.30
Kolekole Pass
Building 203
Beneath Puu Kuua
Mt. Kaala
Veneer Section, Low Elevation
Veneer Section, High Elevation
Puu Makakilo Section
Puu Palailai Section
Kolekole Average
Palehua Average
Estimated Kolekole Duration
Estimated Palehua Duration
Weighted Mean
Kolekole
Palehua
1 Sigma

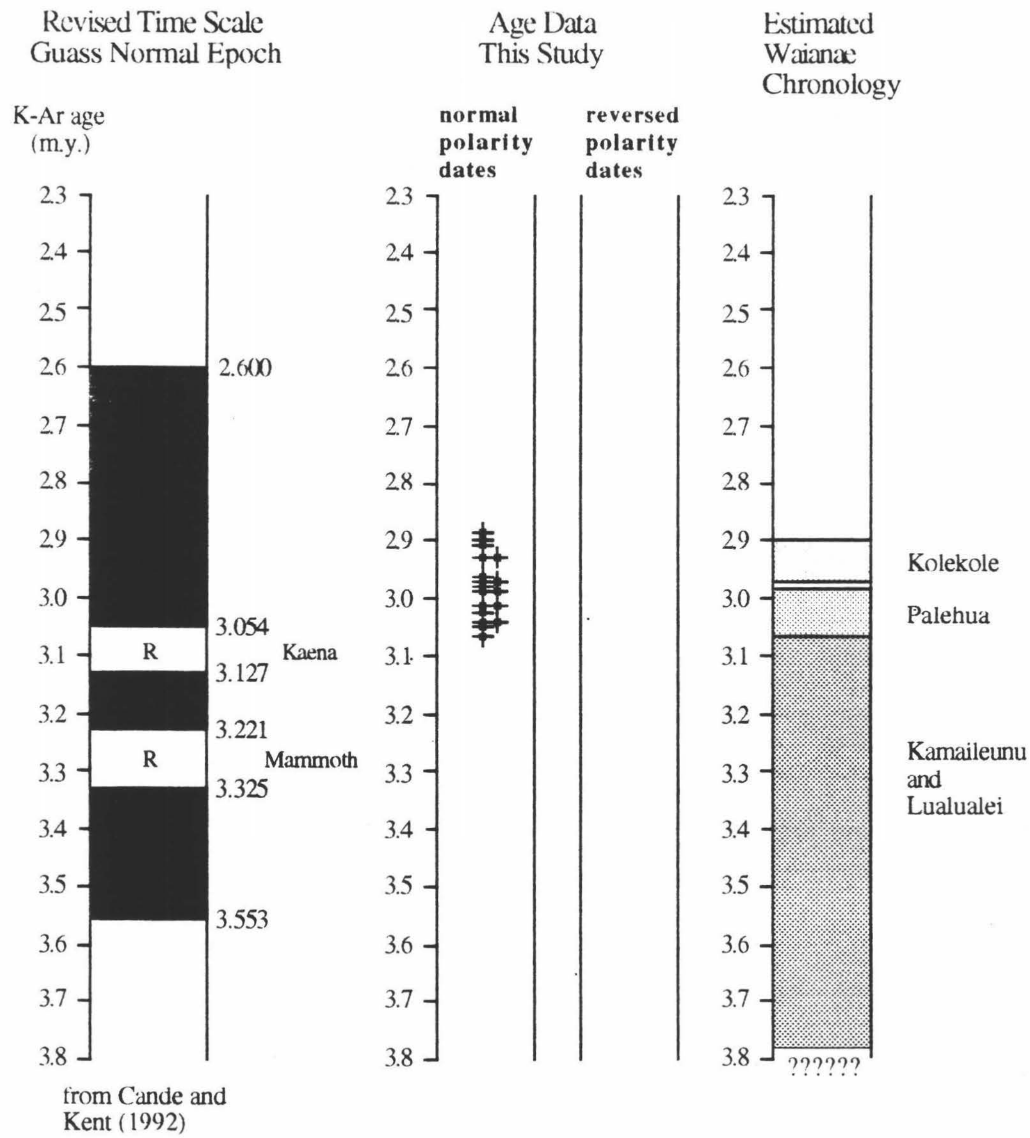


Figure 5. New Waianae age data and the magnetic time scale of Cande and Kent (1992). All of the dated samples have normally magnetic polarity, including the bottom of the Palehua section at Mt. Kaala. The data agree with the magnetic time scale. Estimated Waianae chronology is based on previous dates and the new data from this study.

Petrography

Palehua Member hawaiite is typically aphyric in hand specimen, with rare small olivine grains. The rock is generally blueish to light gray in color. Thin section analysis to estimate modal percentages revealed an average of 2 % olivine microphenocrysts smaller than 1 mm, 11% groundmass olivine, 6% clinopyroxene as small (.01 mm or smaller) grains, 48% plagioclase ranging from oligoclase to labradorite, rare (<1%) plagioclase phenocrysts, 16% groundmass oxides, 2% larger grains of oxides and an average of 14% microcrystalline material not resloved in thin section. Apatite is absent. Groundmass grain size averages approximately 0.03 mm. Olivine grains are commonly at least partially altered to iddingsite. The outlines of the olivine grains can be embayed but are mostly euhedral or skeletal. Two distinct sizes of oxides occur in most rocks, the larger having lower abundances but with distinct euhedral outlines. A few samples contained acicular oxide grains. Nearly half of the analyzed samples contained small flakes of biotite either in the groundmass or protruding into vesicles. Groundmass textures are predominantly trachytic. In the field, many outcrops exhibit a foliation due to preferential weathering of the trachytic groundmass. Other variations of Palehua hawaiite included a few samples that contained single, rare, small xenoliths or glomerocrysts of olivine and plagioclase, and an extremely plagioclase phyric rock from the Palehua ridge area that has over 50% large phenocrysts (1-2 cm) of andesine in a fine grained groundmass.

Kolekole Volcanics ubiquitously contain orange to greenish, 1 to 3 mm size phenocrysts of olivine. This diagnostic feature allows Kolekole basalts to be recognized in the field with great accuracy. It is blueish to dark gray in color, generally darker than the Palehua hawaiite. Kolekole lavas commonly contain small (1 cm or smaller) xenoliths and xenocrysts. Approximate modal percentages of the samples average to 10% olivine phenocrysts, 14% groundmass olivine, 13% groundmass clinopyroxene, 38% groundmass plagioclase, 12% groundmass oxides, 2% larger oxide microphenocrysts and 11% microcrystalline material. Apatite is absent. Samples from the Building 203 locality have much larger groundmass sizes, subophitic and ophitic textures, and greater abundances of groundmass clinopyroxene. Average groundmass size is approximately 0.04 mm. A majority of the samples exhibit olivines that have embayed or resorbed outlines, yet euhedral and skeletal outlines are also abundant. Olivines are partially altered to iddingsite in most samples. Small euhedral groundmass clinopyroxene grains are interdispersed with plagioclase laths and oxide grains. Over half of the samples contain microphenocryst oxides in the form of euhedral, resorbed or acicular grains, yet the characteristic of two oxide sizes is much less prevalent in Kolekole samples than in Palehua samples. Biotite also is less prevalent in Kolekole Volcanics; only a fourth of the samples contain biotite. Groundmass textures are felty or pilotaxitic yet a few samples exhibit trachytic textures.

The largest suite of xenoliths occur at the Puu Kapolei locality. Xenoliths and clinopyroxene xenocrysts as large as 4 cm are abundant in the outcrops of this vent. The xenoliths contain different abundances of orthopyroxene, clinopyroxene, olivine, oxide and plagioclase, with a predominance of cumulate olivine, clinopyroxenite and gabbro compositions. The grains within these inclusions are usually embayed and fractured.

Vesicles in Kolekole lavas often show fine grained crystalline material along their walls. A sample collected by GR Bauer during an excavation for a water reservoir contained 5 cm long needles of calcite in a large vesicle.

Chemical composition

Major and trace element data for a selected number of samples from the Palehua Member and the Kolekole Volcanics are presented in Table 2. The precision and accuracy of single analyses and averages of multiple analyses of the U.S. Geological Survey standards BHVO-1 and BCR-1 along with the accepted reference values from Govindaraju (1989) are given in Table 3. Data are available from the authors for all the rocks discussed.

Major and trace element analyses show that Waianae shield lavas are chemically distinct from the postshield Palehua and Kolekole lavas. Lavas of the Palehua Member are alkalic, and in general have greater alkali contents and higher silica contents than Kolekole Volcanics (Figure 6), whereas most Kolekole lavas are mildly alkalic and a few plot within the tholeiitic field (samples from Puu Kuua, Puu Kapuai, Puu Palailai, Building 203 and the uppermost veneering lavas).

CIPW norms were calculated for all of the analyzed samples. The total moles of iron for each sample were cast as 90% FeO and 10% Fe_2O_3. The normative calculations reveal that some, but not all, of the Kolekole samples that plot within the tholeiitic field are as high as 20% hypersthene normative (Puu Kuua, Building 203, and the uppermost veneering lava samples). Beeson (1976) showed that some whole rock analyses from East Molokai that are mildly tholeiitic based on the alkali silica diagram (Macdonald and

Table 2. Selected XRF Analyses of Palehua Member lavas and Kolekole Volcanics lavas.

Waianae Volcanics, Palehua Member

	OW-128	PW-6	PW-20	PW-32	PW-35a	PW-35b	PW-37	PW-38	PW-43	PW-52	PW-53a	PW-53b	PW-54	PW-78
SiO2	48.47	49.16	49.75	49.33	49.96	49.80	49.39	49.93	48.65	49.64	46.74	47.43	47.55	47.81
TiO2	3.23	3.37	3.47	3.32	3.78	3.68	3.45	3.51	3.75	3.29	4.27	4.13	4.15	4.04
Al2O3	15.48	15.30	15.45	15.38	17.03	16.66	15.68	15.84	16.16	15.97	15.23	15.48	15.55	15.18
Fe2O3*	12.44	13.30	12.74	12.54	14.23	13.78	13.14	13.10	13.94	12.67	14.78	14.52	14.46	14.60
MnO	0.15	0.17	0.13	0.14	0.18	0.18	0.18	0.18	0.16	0.17	0.17	0.17	0.18	0.17
MgO	4.19	3.86	3.97	4.18	2.39	3.08	3.92	3.55	3.28	3.55	4.71	4.39	4.23	4.07
CaO	6.84	6.60	7.04	7.27	4.82	5.25	6.92	6.33	6.11	6.82	7.64	6.99	7.09	7.23
Na2O	4.19	3.81	4.37	4.40	4.00	3.93	3.67	3.76	3.46	4.00	2.97	3.13	3.23	4.28
K2O	1.80	1.78	1.76	1.79	2.00	1.95	1.83	1.87	1.75	1.87	1.42	1.51	1.50	1.53
P2O5	0.92	0.91	0.71	0.94	0.70	0.64	0.89	0.64	0.77	0.99	0.72	0.63	0.63	0.79
LOI §	2.27	1.26	0.75	0.77	2.22	1.27	0.36	0.57	1.79	0.50	0.69	0.81	0.80	0.99
TOTAL	99.97	99.51	100.14	100.06	101.31	100.22	99.43	99.28	99.82	99.47	99.34	99.20	99.37	100.68
Sc	15	16	14	13	18	17	17	15	19	15	19	19	18	19
V	180	227	214	186	192	191	193	207	263	205	281	250	251	327
Cr	6	8	6	5	6	7	5	7	<2	5	4	5	6	11
Ni	11	38	<3	<3	<3	<3	<3	<3	6	<3	12	4	6	25
Co	33	44	36	29	25	26	26	26	27	24	40	33	34	36
Cu	11	16	9	8	7	9	8	8	15	9	17	15	15	23
Zn	135	135	147	145	158	157	142	154	135	160	143	140	137	140
Rb	35	35	31	33	38	39	36	36	35	34	23	26	26	30
Sr	919	815	873	914	950	940	913	913	810	927	912	922	944	857
Y	55	98	36	45	32	35	72	38	96	54	46	37	36	52
Zr	385	347	366	373	384	383	355	369	358	399	306	325	324	311
Nb	45	45	43	44	49	49	45	48	46	44	35	37	37	40
Ba	741	1111	457	480	621	597	539	548	576	516	467	459	484	664
Pb	<2	3	4	4	4	4	4	3	3	4	2	4	3	3
Th	3	3	2	3	4	4	5	3	3	4	2	3	3	2

* Total iron is listed as Fe2O3.
§LOI listed as total loss on ignition. Condition for ingnition was 900° C for eight hours.

Table 2. Selected XRF Analyses of Palehua Member lavas and Kolekole Volcanics lavas, cont.

Waianae Volcanics, Palehua Member, cont.

	PW-85	C-170	C-171	C-172	C-173	C-174	C-175	C-176	C-177	C-178	C-179	C-180	C-181
SiO2	47.64	46.96	47.82	47.35	47.45	47.89	47.36	47.38	47.16	49.59	49.60	49.30	50.25
TiO2	4.06	4.17	3.73	4.03	4.04	3.79	4.00	4.06	4.09	3.24	3.29	3.35	3.06
Al2O3	14.90	15.00	15.64	15.22	15.10	15.19	15.01	15.06	15.01	15.93	15.86	15.84	16.36
Fe2O3*	14.49	14.60	13.71	14.35	14.30	13.94	14.44	14.49	14.65	12.72	12.83	13.01	12.23
MnO	0.16	0.17	0.18	0.17	0.18	0.18	0.18	0.18	0.18	0.17	0.17	0.19	0.18
MgO	4.63	5.11	4.61	4.60	4.87	4.15	4.57	4.55	4.67	3.61	3.46	3.77	3.45
CaO	7.89	8.13	7.30	7.75	8.01	7.56	7.73	7.74	7.71	6.57	6.79	6.31	6.26
Na2O	3.91	3.71	3.92	4.06	3.99	4.04	3.87	3.99	3.89	4.49	4.52	4.43	4.61
K2O	1.44	1.38	1.59	1.45	1.44	1.57	1.49	1.47	1.45	1.92	1.89	1.90	2.12
P2O5	0.73	0.73	0.84	0.75	0.76	0.82	0.77	0.75	0.75	0.95	0.93	0.94	1.08
LOI §	0.37	0.18	0.96	0.71	0.22	1.10	0.91	0.72	0.66	1.49	0.81	0.92	0.95
TOTAL	100.21	100.14	100.29	100.45	100.37	100.23	100.36	100.39	100.24	100.67	100.14	99.95	100.54
Sc	19	15	15	17	15	16	17	17	17	15	13	15	12
V	309	270	223	269	249	234	269	273	271	173	187	193	178
Cr	17	6	5	6	4	6	7	6	8	6	6	6	6
Ni	36	7	7	<3	5	5	4	4	3	<3	<3	<3	<3
Co	36	37	31	35	34	31	36	34	36	22	25	26	19
Cu	32	15	14	14	14	11	13	12	11	7	8	9	7
Zn	127	138	142	144	138	154	150	144	144	141	144	153	149
Rb	30	23	27	24	24	28	27	26	24	37	36	35	39
Sr	842	915	885	923	932	877	861	872	874	882	875	886	869
Y	52	41	47	47	49	107	62	48	45	78	50	84	62
Zr	291	312	357	318	315	351	327	323	320	391	382	380	429
Nb	37	35	40	36	36	40	37	37	37	49	48	48	55
Ba	672	427	487	416	415	461	426	413	420	575	545	582	650
Pb	3	3	3	3	2	4	3	3	3	4	5	3	3
Th	3	3	3	3	3	3	3	3	3	3	4	3	4

* Total iron is listed as Fe2O3.

§LOI listed as total loss on ignition. Condition for ingnition was 900° C for eight hours.

Table 2. Selected XRF Analyses of Palehua Member lavas and Kolekole Volcanics lavas, cont.

Kolekole Volcanics

	OW-80x	PW-47	OW-123a	PW-29	PW-61	PW-89	PW-39	PW-42	OW-76	PW-81	PW-69	OW-118a	PW-17	PW-19
SiO2	46.80	48.11	47.37	47.04	46.61	46.43	47.22	47.23	46.09	48.68	46.33	48.55	48.28	47.82
TiO2	2.89	2.41	2.97	3.14	2.81	2.38	3.02	2.98	3.24	2.67	3.14	2.03	2.32	2.81
Al2O3	13.34	13.45	12.70	13.66	13.10	12.22	14.73	14.12	13.50	14.33	13.62	14.63	13.33	13.76
Fe2O3*	13.50	13.33	13.87	13.98	14.55	13.98	13.58	13.47	13.96	13.02	14.13	13.79	13.77	13.27
MnO	0.16	0.16	0.17	0.17	0.15	0.15	0.14	0.15	0.16	0.16	0.17	0.14	0.15	0.19
MgO	9.70	9.85	9.23	8.90	9.32	12.02	7.65	7.67	8.61	7.37	8.93	7.14	8.57	7.77
CaO	9.39	8.65	9.59	8.97	8.41	8.96	8.31	9.10	9.08	9.15	9.20	8.15	9.34	8.67
Na2O	3.08	2.16	2.65	2.53	2.76	2.50	2.19	2.29	3.34	3.24	2.95	2.80	2.72	3.12
K2O	1.12	0.81	0.82	1.13	0.95	0.74	1.03	1.01	0.98	0.74	1.08	0.66	0.57	1.16
P2O5	0.52	0.29	0.46	0.49	0.51	0.28	0.41	0.50	0.57	0.42	0.58	0.35	0.34	0.61
LOI §	-0.01	0.77	0.74	0.19	1.35	0.39	1.30	0.94	0.60	0.83	0.28	2.51	1.25	0.73
TOTAL	100.50	99.99	100.56	100.21	100.51	100.04	99.59	99.45	100.13	100.61	100.40	100.75	100.64	99.90
Sc	22	20	25	20	22	25	20	21	23	21	19	27	25	21
V	305	244	276	270	268	300	279	276	290	256	270	274	260	255
Cr	453	409	401	319	498	630	305	286	328	293	314	517	393	328
Ni	348	313	341	260	962	574	225	244	305	246	269	468	304	490
Co	61	56	74	55	64	68	61	52	65	51	58	70	63	69
Cu	77	62	75	69	378	59	79	65	62	66	67	103	82	75
Zn	226	113	117	113	119	136	179	107	126	114	115	340	118	315
Rb	21	16	14	22	19	14	19	20	17	12	19	10	9	24
Sr	656	523	643	743	637	521	641	719	695	577	761	436	484	816
Y	293	41	27	29	32	28	256	31	27	30	32	31	25	44
Zr	213	169	186	235	202	150	206	203	207	171	229	139	135	220
Nb	27	18	21	29	23	19	23	23	22	19	28	16	15	26
Ba	336	241	244	343	338	244	297	310	268	285	356	185	174	2604
Pb	2	<2	<2	<2	2	2	3	<2	<2	<2	3	<2	<2	<2
Th	<2	<2	<2	3	2	<2	2	2	<2	<2	3	<2	<2	<2

* Total iron is listed as Fe2O3.

§LOI listed as total loss on ignition. Condition for ingnition was 900° C for eight hours.

Table 3. XRF Precision and Accuracy

	SINGLE RUNS		ACCEPTED, AVERAGE, STD. DEV., AND ERROR					
			BHVO-1			BCR-1		
	BHVO-1	BCR-1	ACCEPTED	AVERAGE	ERROR	ACCEPTED	AVERAGE	ERROR
SiO2	49.79	53.91	49.59	49.76 ± 0.20	0.17	54.39	54.66 ± 0.17	0.27
TiO2	2.71	2.21	2.69	2.74 ± 0.03	0.05	2.25	2.25 ± 0.02	0.00
Al2O3	13.51	13.41	13.70	13.64 ± 0.27	0.06	13.72	13.66 ± 0.27	0.06
Fe2O3*	12.31	13.37	12.39	12.41 ± 0.06	0.02	13.67	13.63 ± 0.04	0.04
MnO	0.16	0.18	0.17	0.16 ± 0.00	0.01	0.18	0.18 ± 0.00	0.00
MgO	8.00	3.51	7.22	7.14 ± 0.36	0.08	3.50	3.53 ± 0.06	0.03
CaO	11.22	6.99	11.32	11.38 ± 0.09	0.06	6.99	7.06 ± 0.07	0.07
Na2O	2.28	3.30	2.24	2.31 ± 0.28	0.07	3.29	3.47 ± 0.38	0.18
K2O	0.51	1.69	0.52	0.51 ± 0.01	0.01	1.70	1.72 ± 0.02	0.02
P2O5	0.27	0.36	0.27	0.28 ± 0.04	0.01	0.36	0.37 ± 0.03	0.01
LOI §	0.25	1.59						
TOTAL	101.01	100.53						
Sc	33	32	31.8	31 ± 2	1	32.6	30 ± 1	3
V	313	404	317	315 ± 4	2	407	407 ± 4	0
Cr	299	15	289	298 ± 6	9	16	15 ± 1	1
Ni	124	10	121	124 ± 2	3	13	10 ± 2	3
Co	47	38	45	45 ± 1	0	37	35 ± 1	2
Cu	139	19	136	139 ± 1	3	19	19 ± 1	0
Zn	104	127	105	105 ± 1	0	129.5	126 ± 1	4
Rb	9	48	9.5	9 ± 0	1	47.2	48 ± 0	0
Sr	390	327	390	389 ± 1	1	330	329 ± 2	1
Y	28	38	27.6	27 ± 0	0	38	38 ± 0	0
Zr	176	192	179	176 ± 1	3	190	193 ± 1	3
Nb	19	12	19	18 ± 0	1	14	12 ± 0	2
Ba	120	714	139	109 ± 12	30	681	712 ± 6	31
Pb	3	14	2.6	1 ± 1	1	13.6	14 ± 0	1
Th	2	6	1.08	1 ± 1	0	5.98	6 ± 1	0

Single Runs were run along with unknowns.

Accepted values are those listed in Govindaraju (1989), with the exception of a few adjusted values for certain elements (B. Chappell, pers. comm.).

Averages are of multiple runs for the UH lab from 12-89 to 5-91. 52 analyses are averaged for major elements, 5 analyses for trace elements. Standard deviations are ± 1 sigma.

Errors are listed as the difference between the accepted value and the average of all the analyses.

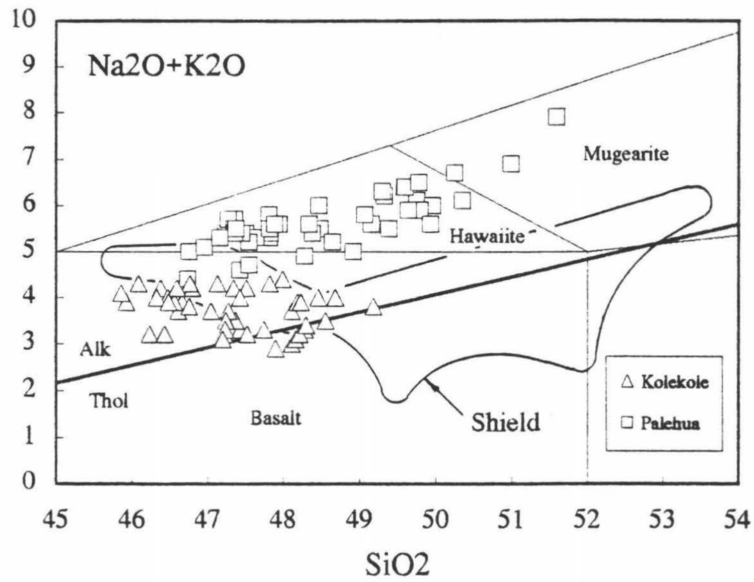


Figure 6. Total alkalis versus SiO_2 (all in wt.%) for all Waianae lavas studied. Shield lavas include the tholeiitic shield-building Lualualei lavas and the transitional Kamaileunu lavas. Kolekole lavas are more mafic than Palehua lavas and closer to the Macdonald-Katsura (M-K) line. Adopting the classification from Le Bas et al. (1986), Kolekole lavas are alkalic basalts and Palehua lavas are mostly hawaiites.

Katsura, 1964) will plot as alkalic when phenocryst-free compositions are calculated. However, these alkalic rocks from East Molokai were clinopyroxene-phyric whereas Kolekole rocks only rarely contain clinopyroxene.

Based on the classification schemes of Coombs and Wilkinson (1969) and Le Bas et al. (1986), almost all Palehua Member rocks are hawaiites (normative plagioclase ranging between An_{30-50}), and are sodic [(Na_2O-2 wt%)>K_2O], with a few samples plotting in the alkalic basalt field and two samples plotting within the mugearite field (WD-222, a dike, and OW-55, a flow near Pohakea Pass). Kolekole Volcanics, however, fall in different fields for the two different classification schemes. Using the method of Le Bas et al. (1986), the sample field lies almost completely within the alkalic basalt field with a few samples plotting as tholeiitic (Figure 6). Using the scheme of Coombs and Wilkinson (1969), Kolekole rocks range from alkali-olivine basalt to hawaiite with normative plagioclase compositions falling between An_{43} and An_{60}. Sinton (1987) classified Kolekole lavas that have normative andesine as mafic hawaiites to distinguish them from the less mafic Palehua hawaiites. To clearly distinguish the more mafic Kolekole rocks from Palehua hawaiites, the scheme of Le Bas et al. (1986) is adopted, thus Kolekole Volcanics are simply referred to as alkali basalts.

MgO variation diagrams clearly define the role of fractional crystallization of magmas and also clearly distinguish the shield lavas, the Palehua lavas and the Kolekole lavas from one another (Figures 7, 8). Palehua and Kolekole lavas tend to define nearly colinear trends. Relative to shield lavas, these Waianae postshield lavas tend to have lower SiO_2, CaO, Sc and Cr, and higher Al_2O_3, K_2O, P_2O_5, Nb, Zr, Rb, Sr and Ni at a given MgO content. Palehua lavas have oxide microphenocrysts and the variations of TiO_2 and V show that oxide saturation occurs at about 5 wt.% MgO in these magmas. In contrast, the TiO_2 variation in Waianae shield lavas indicates that these magmas did not fractionate an oxide phase, consistent with the lack of observed oxide phenocrysts in the samples.

Within the postshield lavas, Palehua and Kolekole samples can be distinguished on the basis of their MgO contents and the behavior of CaO and CaO/Al_2O_3 on MgO variation diagrams. Analyzed Palehua samples have less than ~5.5 wt.% MgO, whereas Kolekole lavas have > 5.5 wt.% MgO. The CaO/Al_2O_3 ratio is particularly sensitive to clinopyroxene fractionation and the variation evident on Figure 9 suggests that the shield lavas, Palehua and Kolekole magmas became saturated with clinopyroxene at different MgO contents. Shield lavas are dominated by olivine and plagioclase fractionation until

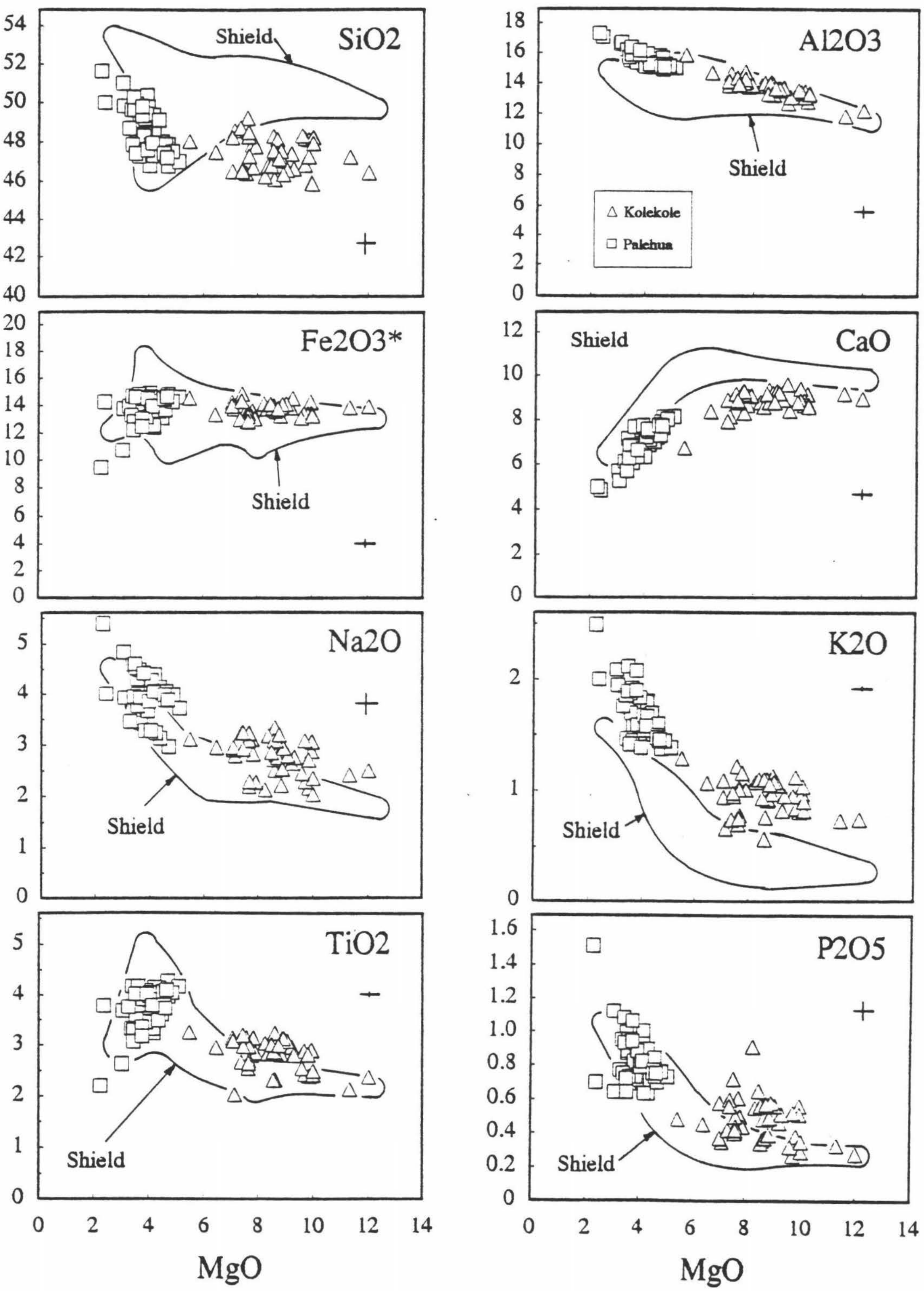


Figure 7. MgO variation diagrams of major oxides (wt. %) for all of the Waianae lavas studied. Shield lavas are shown as a field. Crosses indicate analytical uncertanties (2 σ).

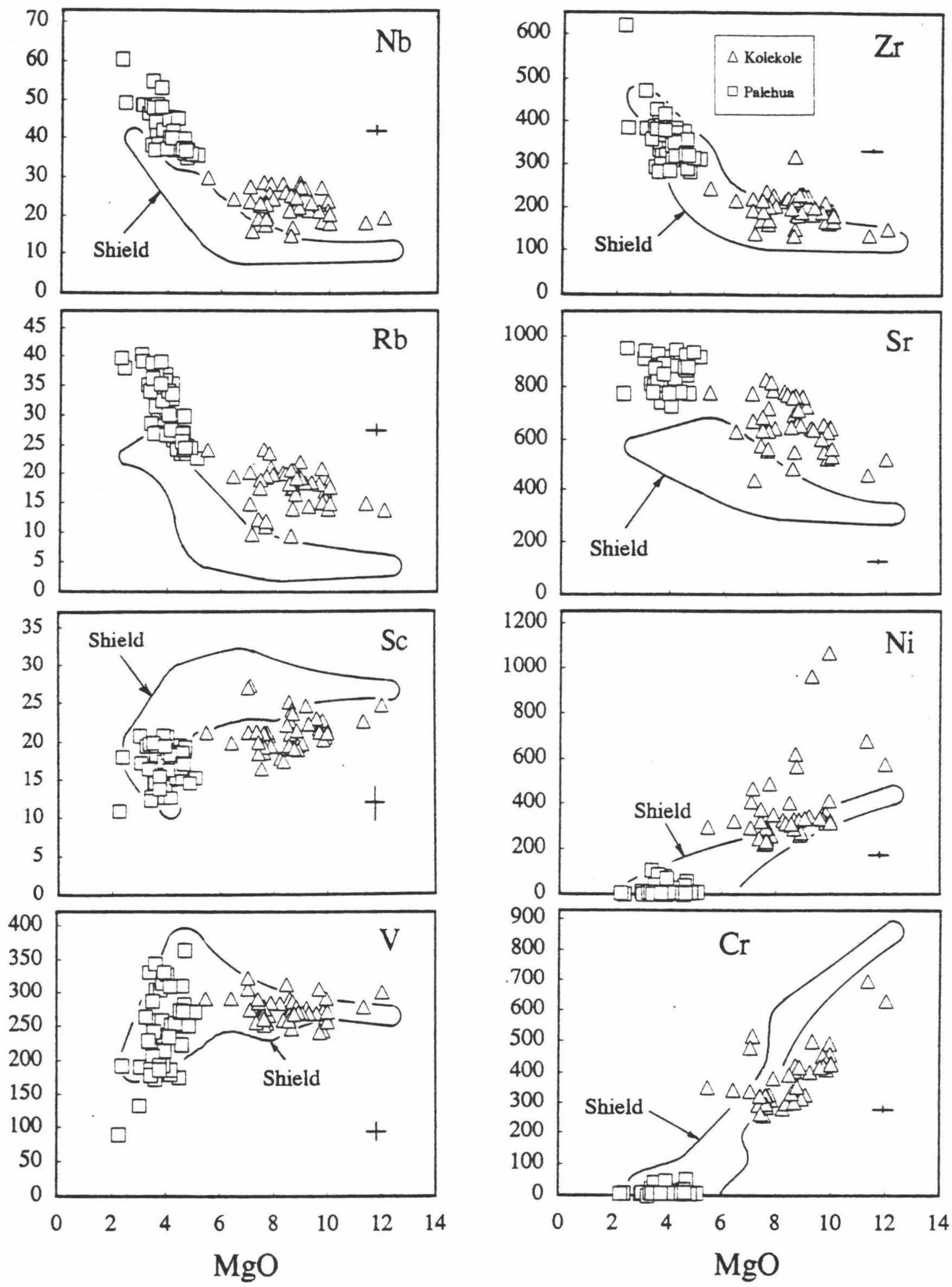


Figure 8. MgO variation diagrams for selected trace elements (ppm). Crosses indicate analytical uncertanties (2 σ).

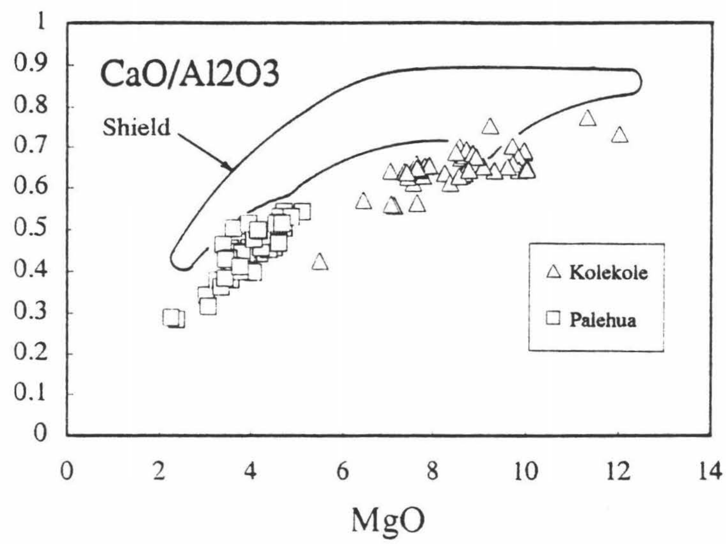


Figure 9. CaO/Al_2O_3 vs. MgO (wt%) for Waianae lavas. The difference between shield, Palehua and Kolekole fractionation trends are most evident in this plot. The more fractionated Kamaileunu lavas in the "shield" field are part of a different trend with higher CaO/Al_2O_3 ratios than Palehua lavas. Shield lavas start fractionating clinopyroxene at approximately 6 % MgO, whereas Palehua and Kolekole lavas fractionate clinopyroxene at approximately 7% and 9% MgO, respectively. This can be interpreted as a deepening of the magmatic systems as the volcano passes from shield stage to postshield and late postshield stages.

about 6 wt.% MgO where clinopyroxene removal produces a decrease in CaO/Al_2O_3. Palehua lavas appear to have fractionated clinopyroxene at slightly higher MgO contents (about 7% MgO if the Palehua data are projected back to CaO/Al_2O_3 =0.7), and Kolekole lavas show a decrease in CaO/Al_2O_3 at values less than about 8.5-9.0 wt.% MgO. Since clinopyroxene saturation is strongly influenced by pressure (Cohen et al., 1967; Thompson,1972b; Arculus, 1975; Bender et al., 1978; Mahood and Baker, 1986), this result suggests progressively deeper environments of fractionation for shield, Palehua and Kolekole magmas, respectively.

As noted above, Waianae postshield lavas tend to have higher abundances of incompatible elements than shield lavas. Compared to the moderately incompatible element Zr, highly incompatible elements such as Nb, Rb and K (Figure 10) are all enriched in postshield lavas. It is notable that Palehua and Kolekole magmas define collinear trends on such plots, suggesting that they were derived from parental magmas with similar highly incompatible to moderately incompatible ratios.

Within the Palehua data there is a suggestion of multiple trends with slightly different Nb/Zr ratios (Figure 10). This variation has time/stratigraphic significance as shown in Figure 11. The data shown in Figure 11 are on a suite of Palehua hawaiites collected by Macdonald (1968) above Nanakuli Valley. Mg# is an index of magmatic differentiation, whereas Nb/Zr is relatively insensitive to fractionation but can indicate the extent of melting of a source with a constant Nb/Zr ratio or different source compositions. Two distinct trends emerge: the older, less fractionated part of the section has lower Nb/Zr ratios and higher Ca/Al_2O_3 ratios, and the younger, more fractionated lavas have the inverse. Macdonald (1968) was first to see the increase in fractionation with time of the Palehua. The older Palehua flows exhibit lower abundances of most incompatible elements. MgO variation diagrams also show the double trend with respect to Na_2O. (Figures 7). Other sampled partial sections in the southern portion of the range plot within one or the other population. OW-128, a sample taken from the lowest elevation aphyric hawaiite at the base of Mt. Kaala, plots with the older samples of the C-section. OW-55, a mugearite sample taken from the first flow above an unconformity and overlying plagioclase-phyric hawaiites of the Kamaileunu member, and WD-222, a Palehua Member mugearite dike, do not plot in the same trend as the older C-section lavas.

Only partial sections of the Kolekole Volcanics exist; the scattered and limited outcrops do not allow for investigation of temporal variation. There are no temporal trends in the short sections that do exist, thus the variation suggests that the evolution of Kolekole

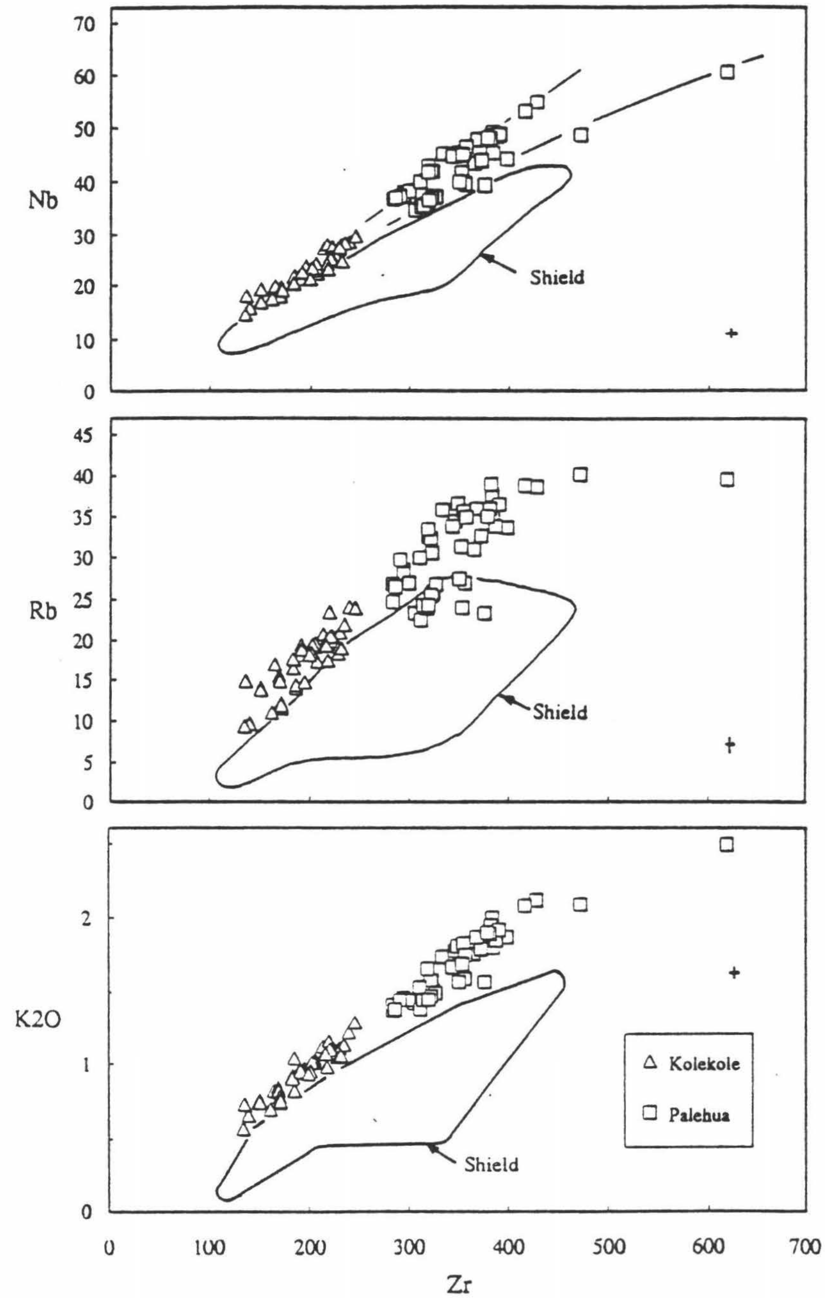


Figure 10. Nb (ppm) , Rb (ppm) and K_2O (wt%) versus Zr (ppm) for Waianae lavas. Postshield lavas show well-defined trends with higher Nb/Zr, Rb/Zr and K2O/Zr ratios than shield lavas. Also, within the Nb vs Zr plot, Palehua lavas show two sub trends of different Nb/Zr ratio (inferred with lines). Crosses indicate analytical uncertanties (2 σ).

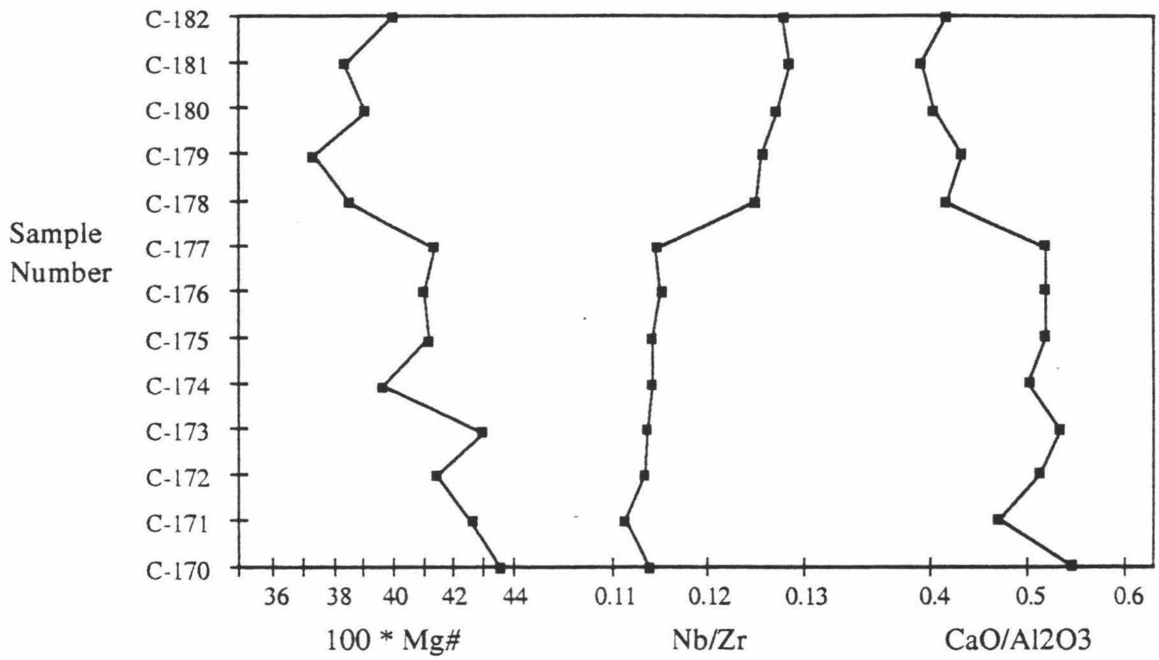


Figure 11. Temporal variation of the "C-Section" (Macdonald, 1968) of Palehua Member hawaiite using Mg#, Nb/Zr and CaO/Al_2O_3. The patterns are repeated for other smaller sections in the southern Waianae area. Younger Palehua lavas show an increase in fractionation and also higher Nb/Zr ratios.

magmas was quite varied. Samples collected from the youngest veneering flow in Makakilo town, the Building 203 outcrop, Puu Kuua and Puu Palailai all are hypersthene normative, contain less TiO_2 with the exception of Puu Kuua samples, and generally have higher SiO_2 concentrations than other analyzed Kolekole lavas.

Y and Ba concentrations for fifteen Kolekole and twelve Palehua samples are anomalously high compared to an overall incompatible element trend. Ow-80, a sample from Kolekole Pass, has 1800 ppm Y, yet a sample taken less than a meter away in the same lava flow, Ow-80X, contains only 293 ppm. Both these values are much higher than the common trend for Y in Kolekole lavas ranging from 25 to 40 ppm. A Palehua sample taken near Puu Makakilo has a concentration of 1662 ppm Ba, whereas most Palehua samples fall between 413 to 690 ppm. Five Kolekole and three Palehua samples have exceptional enrichments in Ba, yet only three Kolekole samples and two Palehua samples have enrichment in both Y and Ba. Fodor et al. (1987) described samples having anomalous Y, Ba and REE enrichments from the island of Kahoolawe and other authors have found such enrichments in other parts of the world (e.g. Price, 1991). Fodor et al. (1987) concluded that secondary and possibly deuteric phases, such as the hydrous Y-bearing phosphate rhabdophane, a Ba-Mn oxide, barite and iddingsite are responsible for the enrichments. Void spaces in some of the samples contain mineralizations of magmatic and secondary minerals such as biotite and calcite, respectively. Biotite presence does not correlate well with samples that have anomalously high Y and Ba values, yet the presence of secondary mineralizations suggests that a similar enrichment process might have occurred in the rocks of the Waianae Volcano.

DISCUSSION

Depth of Magma Evolution

An objective of this study is to determine the geochemical and petrogenic relation between the Kolekole Volcanics and the Palehua Member and to a lesser extent, the relation of the postshield lavas to the shield building lavas. Studies of other Hawaiian volcanoes with alkalic caps have found that the evolved lavas are the result of 1) fractional crystallization processes utilizing an assemblage of phases different than that of the shield building lavas and 2) different parental magma compositions than the shield lavas due to different extents of melting and/or different source compositions. It is, therefore, important to understand the role of both fractional crystallization and fractional melting when determining mechanisms for the variation of the postshield Waianae magmas.

Major and trace element trends in the variation plots suggest that fractionation of different mineral assemblages occurred for the shield, Palehua and Kolekole magmas. Shield magmas likely fractionated olivine+plagioclase±clinopyroxene± orthopyroxene. Palehua magmas likely fractionated olivine+plagioclase+clinopyroxene+ oxide, and Kolekole magmas likely fractionated olivine±clinopyroxene. The studies of Mauna Kea (Frey et al., 1990, 1991), Kohala (Fiegenson 1983, Lanphere and Frey 1987, Spengler and Garcia, 1988), Molokai (Beeson, 1976) and Kahoolawe (Fodor et al., 1992) all have concluded that the differentiated alkalic postshield lavas have fractionated clinopyroxene as a major constituent to the fractionating assemblage, possibly as a near liquidus phase.

The variations in CaO/Al_2O_3 versus MgO for the various units of the Waianae Volcano suggest progressively earlier (higher MgO) fractionation of clinopyroxene, consistent with an evolution of increasing depths of fractionation with time. The suggestion that postshield alkalic cap lavas fractionated at greater depths in the volcanic edifice than shield lavas has also been found from studies of Mauna Kea (West and Leeman, 1987; Frey et al., 1990, 1991), Hualalai (Clague 1987), Kohala (Spengler and Garcia, 1988), Kahoolawe (Fodor et al., 1992), and E. Molokai (Beeson, 1976). Thus, a general trend of high pressure fractionation giving rise to postshield, differentiated alkalic magmas has emerged for Hawaiian magmatic evolution.

Within the Waianae postshield, Palehua and Kolekole samples define distinctly different fields in normative projections involving olivine, clinopyroxene, plagioclase, quartz or nepheline. Unfortunately, no single projection scheme is fully adequate for displaying the Waianae variations because the constituent lavas straddle the critical plane (Ol-Cpx in the projections). Nevertheless, a common set of results emerges from such plots. In all cases the data are consistent with an increasing depth of fractionation from shield to Palehua and Kolekole magmas.

The clustering of the Waianae data into moderately well-defined fields in Figures 12a, 12b, and 13a (diagrams based on Grove et al., 1992, and Sack et al., 1987) suggests that these fields approximate cotectics for the pressures and compositions involved. However, the lack of systematic variation between indices of fractionation and normative components (e.g. Figure 14) indicates that the clusters did not arise from simple fractionation of single parental magma compositions. If a single parental magma compostion produced the Palehua or the Kolekole lavas, then a diagonal trend should

Figure 12a and 12b. Ternary projections following the conventions of Grove et al., (1992). (a) In the clinopyroxene-olivine-quartz projection, postshield lavas do not plot along cotectics plotted from experimental data from Serocki Volcano (arrows, Grove et al. 1992), but they do form general trends lying between the 2 and 8 kbar cotectics. Most Kolekole lavas plot closer to the olivine apex than do Palehua lavas, suggesting either that the Kolekole samples have fractionated at greater depths or that many of the Kolekole lavas have not reached the clinopryoxene-saturated cotectic. (b) Shield and postshield lavas cluster into trends in the plagioclase-olivine-quartz projection (projected from clinopyroxene). Kolekole lavas show a similar pattern to the data in the cpx-ol-qtz projection (12a). Some Kolekole lavas may not have reached a cotectic involving plagioclase.

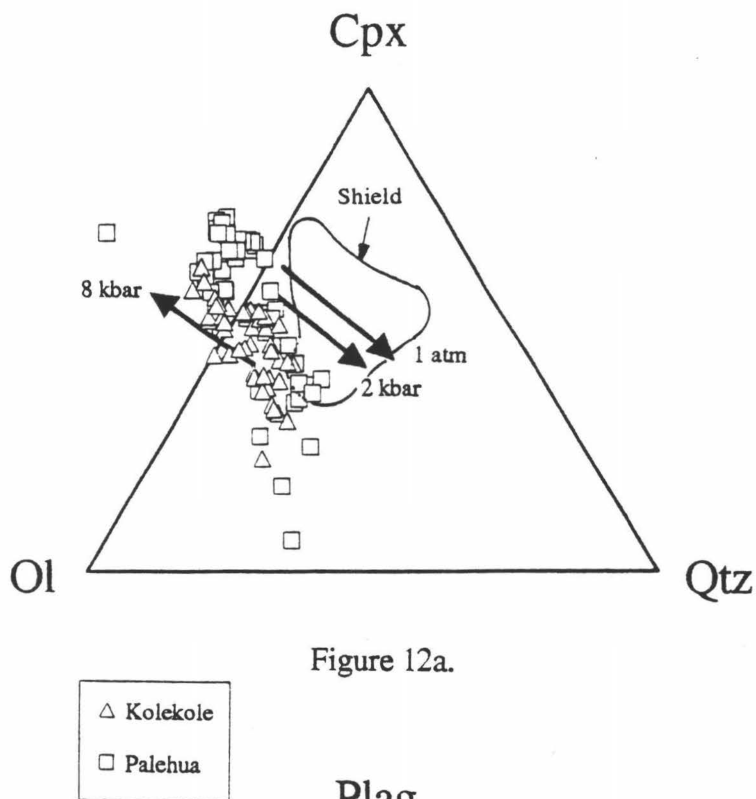


Figure 12a.

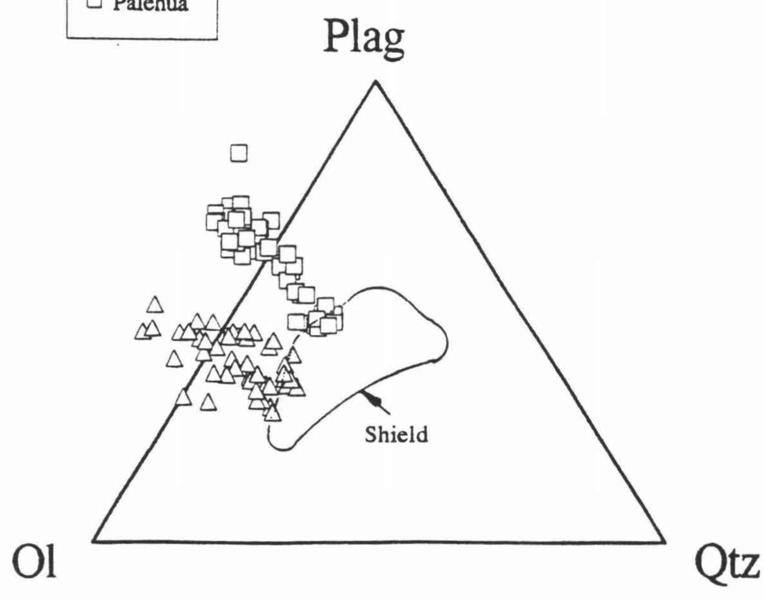


Figure 12b.

Figure 13a and 13b. Ternary projections following the conventions of Sack et al. (1987), which are better suited for alkalic rocks. (a) The general progression from Shield-Palehua-Kolekole plotting closer to the olivine apex suggests progressively deeper fractionation for these three series. The scatter of the Kolekole samples suggests that some of the Kolekole samples may not have reached clinopyroxene saturation. Fields for Haleakala and Mauna Kea postshield lavas also are plotted within the diagram. Haleakala lavas plot as a relatively low pressure cotectic, whereas Mauna Kea lavas indicate a cotectic intermediate in pressure between that of Palehua and Kolekole lavas (see text). (b) Summary of magma evolution of postshield lavas in Waianae Volcano. Liquid lines of descent (heavy arrows) emanate from a field of inferred parental magma compostitions (position on this diagram is schematic, only). Olivine fractionation of the range of primary magmas (arrows) leads to multiple saturation along cotectics approximating the data clusters.

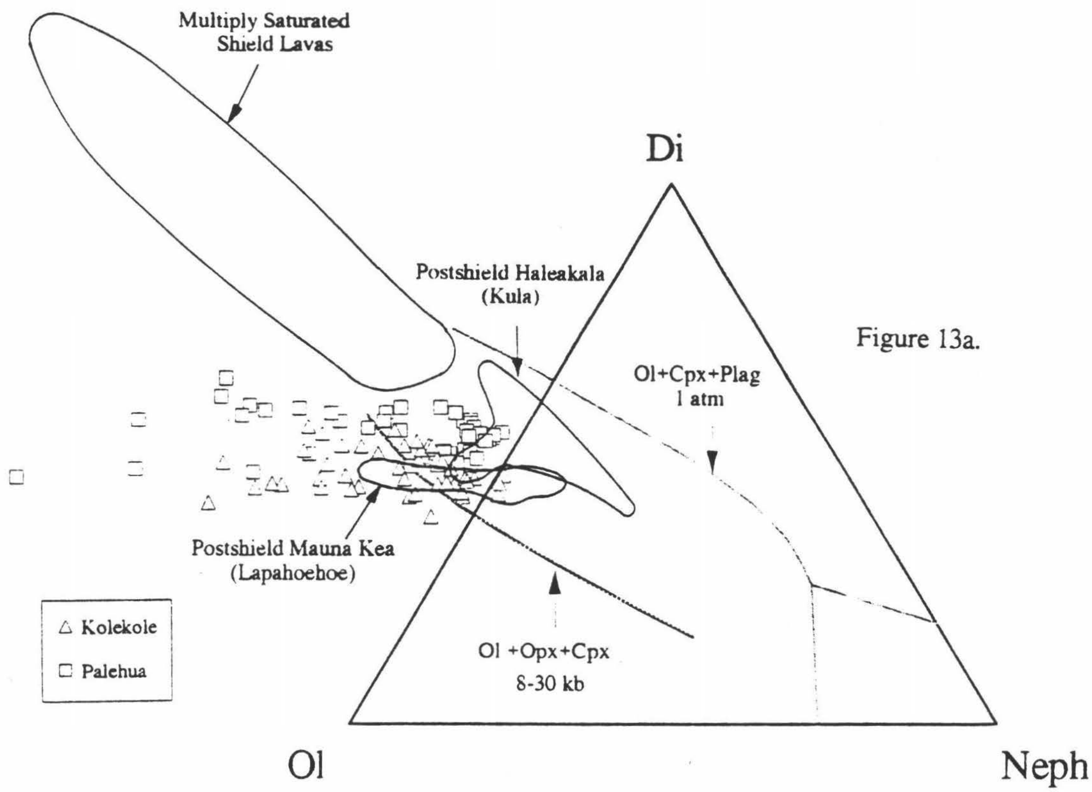


Figure 13a.

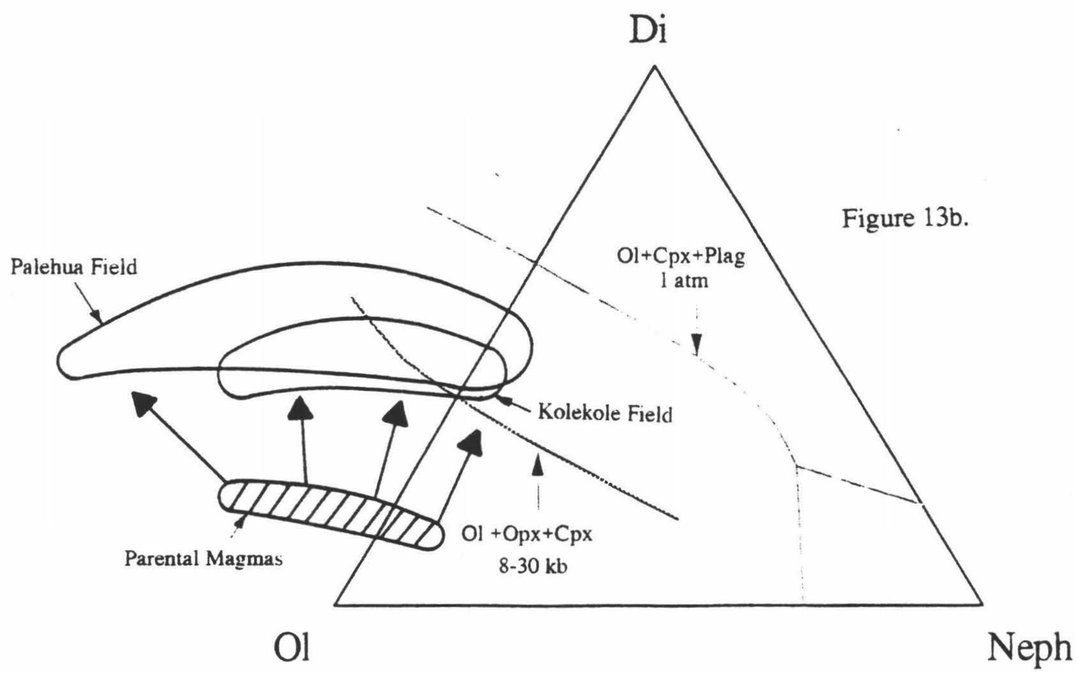
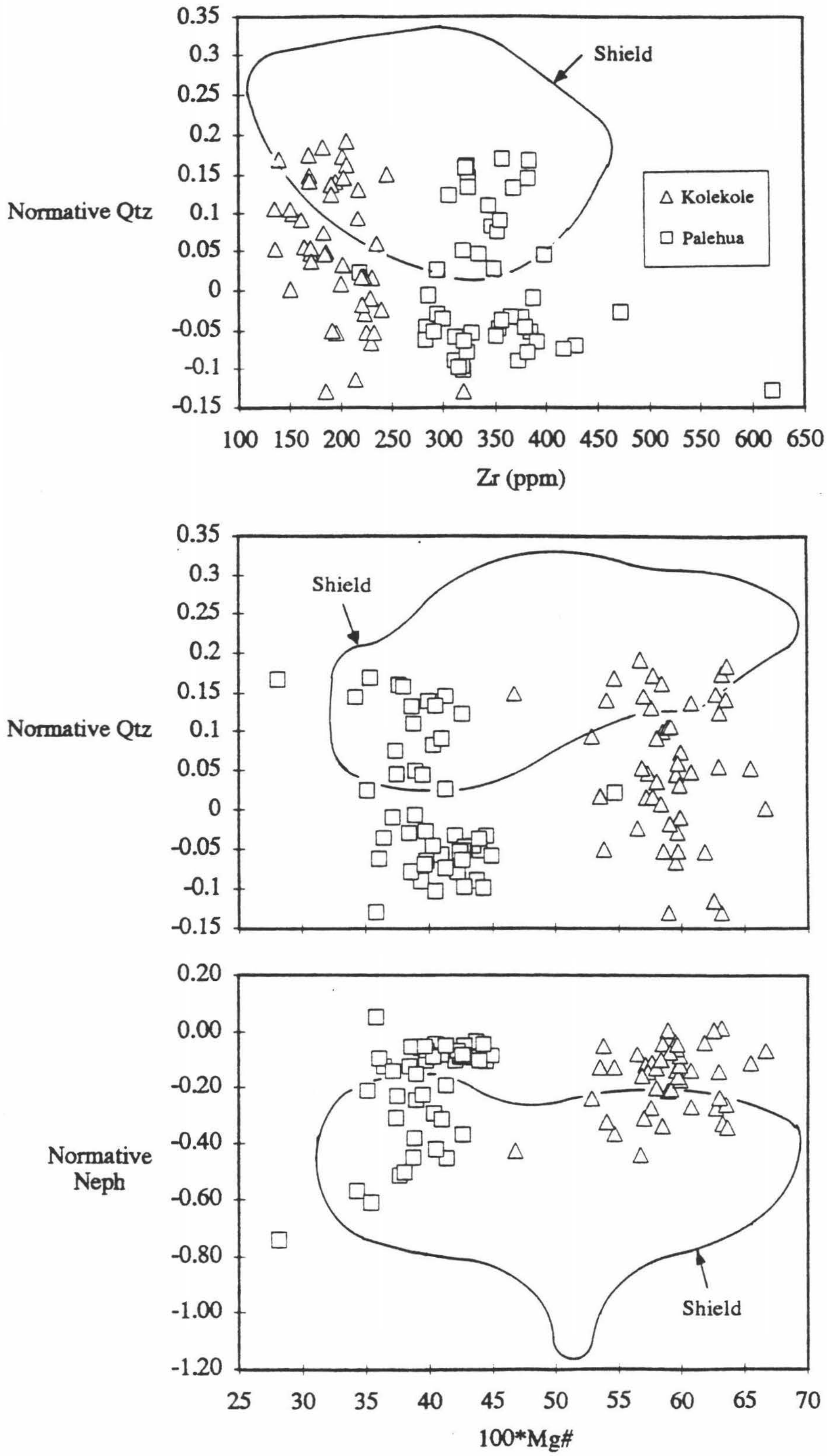


Figure 13b.

Figure 14. Normative Qtz (based on Grove et al. 1992) versus Zr (ppm) and 100*Mg#, and Normative Nepheline (based on Sack et al., 1987) versus 100*Mg#. The lack of systematic variation in normative components with Mg# indicates that the data clusters in the projections of Figures 12a & b and 13a are not liquid lines of descent from unique primary magmas. These clusters, however, probably approximate the projections of the multiple saturation surface (cotectics); olivine fractionation from a range of primary magmas leads to multiple saturation at different positions along the cotectics (Figure 13b). Normative Nepheline versus 100*Mg# behaves as the inverse of Normative Qtz, despite the different algorithms used for alkalic and MORB type rocks.



Shield
Δ Kolekole
□ Palehua
Normative Qtz
Zr (ppm)
Shield
Normative Qtz
Normative Neph
Shield
100*Mg#

appear in such a plot. Instead, the data appear to require a range of primary magma compositions, as diagrammed on Figure 13b, to produce the trends in Figure 14. Each of these primary magma compositions then fractionate olivine until they arrive at the multiply saturated cotectic for the pressure conditions where they reside.

Laupahoehoe lavas from Mauna Kea show a trends subparallel to the Waianae data, but extend to more nepheline-normative compositions. Chen et al. (1990) showed that postshield Kula hawaiites, mugearites and alkali basalts from Haleakala mainly evolved at lower pressures, with only a small proportion of hawaiites forming at moderate depths similar to those of Mauna Kea (Figure 13a).

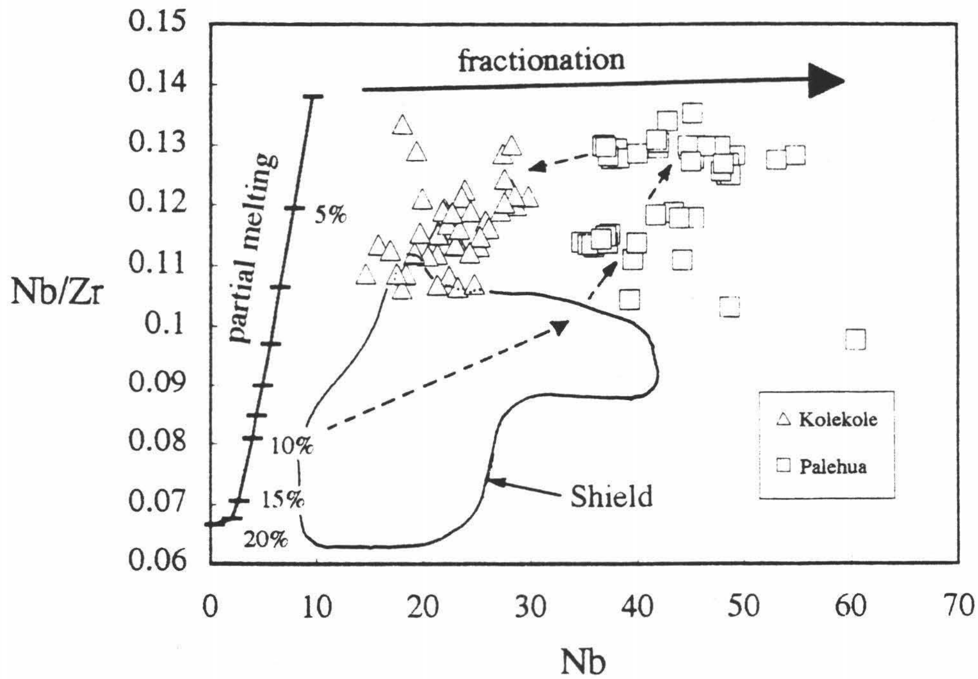
Source Compositions and Extent of Partial Melting

Sr and Nd isotopic data of Stille et al. (1983) and Feigenson and Sinton (unpublished) indicate that Waianae shield and postshield magmas and Kolekole magmas were derived from sources that are isotopically similar. Although some source variations cannot be precluded, the incompatible element enrichments of the postshield lavas relative to the shield lavas of Waianae (and other Hawaiian volcanoes) is at least qualitatively consistent with an evolution to lower degrees of melting in the later stages of volcano development. A detailed, quantitative analysis of the melting processes involved in the production of Waianae magmas is inhibited by the difficulty in adequately correcting for the effects of fractionation, especially for the highly evolved Palehua hawaiites. However, the various roles of fractionation and melting of a constant source can be evaluated in plots like that shown in Figure 15, where a ratio of a highly incompatible element to a moderately incompatible element is plotted against the highly incompatible element abundance. On such plots, melting trends are steep, whereas fractionation trends are nearly horizontal (Figure 15).

It is apparent from Figure 15 that, if source composition is not a factor in Waianae magmagenesis, then post-shield magmas formed from lower degrees of melting than did the shield magmas. Furthermore, there is a tendency for decreasing amounts of melting from shield lavas, through older Palehua lavas to younger Palehua lavas. However, the Nb/Zr ratios of Kolekole lavas are more like the older Palehua than the younger Palehua, suggesting a change to greater extents of partial melting in the latest postshield magmatism. A melting model based on accumulated fractional melting (Shaw, 1977) and using typical modal melting proportions and mantle starting compositions in Figure 15 suggests that

Figure 15. Nb/Zr vs Nb (ppm) for Waianae lavas. Postshield lavas generally have higher Nb/Zr ratios than do shield lavas, a feature that is consistent with lower extents of partial melting of upwelling mantle as illustrated by the melting trend shown. Fractionation generally increases Nb contents with little effect on Nb/Zr. The melting trend was calculated with the accumulated fractional melting equation of Shaw (1977) using the following: mineral/melt partition coeffecients for Nb and Zr are, respectively, 0.001 and 0.01 (olivine), 0.002 and 0.05 (opx), 0.07 and 0.25 (cpx), and 0.005 and 0.14 (garnet). Source modes and melt proportions are, respectively, 0.55 and 0.03 (olivine), 0.20 and 0.03 (opx), 0.15 and 0.44 (cpx) and 0.10 and 0.50 (garnet). The modeled mantle source concentrations of Nb and Zr are, respectively, 0.4 ppm and 6.0 ppm.

Although many other choices of melting parameters, source compositions, etc., are possible, the model can be used to illustrate some general melting and differentiation effects in Waianae magmas. The dashed arrows show the general evolution of Waianae magmas from shield lavas through early Palehua magmas with relatively low Nb/Zr to later Palehua with higher Nb/Zr, followed by relatively unfractionated Kolekole lavas with lower Nb/Zr ratios.


fractionation
partial melting
5%
10%
15%
20%
Shield
△ Kolekole
□ Palehua
Nb/Zr
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0
10
20
30
40
50
60
70
Nb

postshield lavas in general can be derived by melting extents approximately 5-10% less than that for the shield lavas, the Nb/Zr ratios of younger Palehua lavas are consistent with melting extents approximately 1-2% less than that for older Palehua lavas and most Kolekole lavas. The relative extents of fractionation, with Palehua being substantially greater than that of Kolekole lavas, is apparent in Figure 15 as well.

SUMMARY

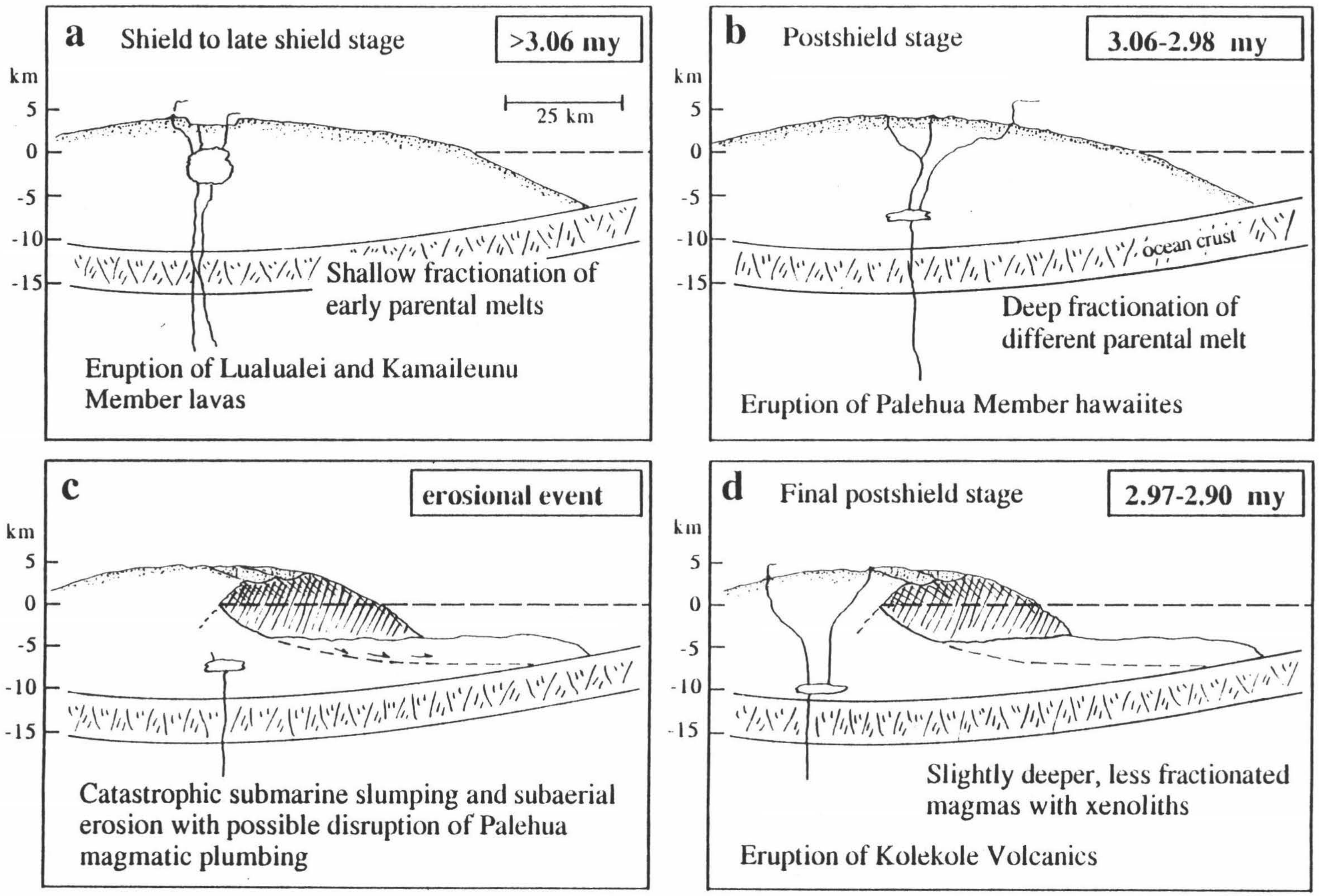
Postshield evolution of Waianae Volcano

The shield building stage of Waianae Volcano was dominated by a shallow magma chamber which fed summit and rift eruptions (Figure 16a). Toward the end of the shield stage magma began to become more alkalic and increasingly porphyritic, and eruptions were less frequent (Sinton, 1987). The end of the shield stage marks the end of the shallow magma plumbing system of Waianae Volcano.

The late postshield alkalic cap began with reversed magnetic polarity lavas of the Kaena Subchron, about 3.06 Ma (Figure 16b). These lavas mainly are aphyric hawaiites that formed by moderately high pressure fractionation of parental magmas derived by lower extents of partial melting than for shield lavas. Although a range of primary melt compositions probably were produced during this stage, they likely fractionated at a common depth, presumably in a magma chamber lying deep in the volcanic edifice. Fractionation proceeded until magmas of hawaiite composition were erupted. Younger Palehua magmas were derived by slightly lower extents of melting and tended to fractionate more prior to eruption than did older Palehua magmas. Thus, Palehua magmatism represents a period of decreasing magma supply as the volcano moved off the Hawaiian hotspot.

However, about 2.98 Ma a major erosional episode occurred within a short time frame suggested by the K-Ar dating (Figure 16c). Following this episode, Kolekole magmatism is characterized by slightly increased extents of partial melting of upwelling mantle, and eruption of less differentiated magmas (Figure 16d). This apparent reversal in extents of melting and degree of of differentiation may be tied to the erosional event that separates Palehua and Kolekole eruptions.

Figure 16a, 16b, 16c and 16d. Diagram depicting Waianae volcanic evolution. Each frame is a generalized cross-section of Waianae Volcano looking east to west. (a) During the shield and late shield stage of Waianae Volcano, magma supply rates were high. Tholeiitic magmas erupted from shallow magma chambers underneath a summit caldera. Magma supply rates were decreasing during the late shield stage, producing caldera filling transitional and alkalic lavas of the Kamaileunu Member. (b) Postshield volcanism produced an alkalic cap of mostly aphyric hawaiites (Palehua Member). Parental melts with different trace element signatures fed deeper magma chambers where efficient fractionation of olivine, plagioclase, clinopyroxene and oxides occurred. Magma supply rates were diminished. (c) An erosional event, where the beginnings of the extremely large Lualualei Valley formed, occurred at the end of eruptive activity of the Palehua Member. The event may have been the movement of the Waianae Slump. The event may have caused a disruption of Palehua magmatic plumbing, causing the cease of eruption of aphric hawaiite. (d) Kolekole volcanism begins shortly after the erosional event. Kolekole volcanism eruptions were small and localized. Eruptive activity ceased with the last eruptions of Kolekole Volcanics.


a
Shield to late shield stage
>3.06 my
km
5
0
-5
-10
-15
25 km
Shallow fractionation of early parental melts
Eruption of Lualualei and Kamaileunu Member lavas
b
Postshield stage
3.06-2.98 my
ocean crust
Deep fractionation of different parental melt
Eruption of Palehua Member hawaiites
c
erosional event
Catastrophic submarine slumping and subaerial erosion with possible disruption of Palehua magmatic plumbing
d
Final postshield stage
2.97-2.90 my
Slightly deeper, less fractionated magmas with xenoliths
Eruption of Kolekole Volcanics

Mass Wasting on Waianae Volcano

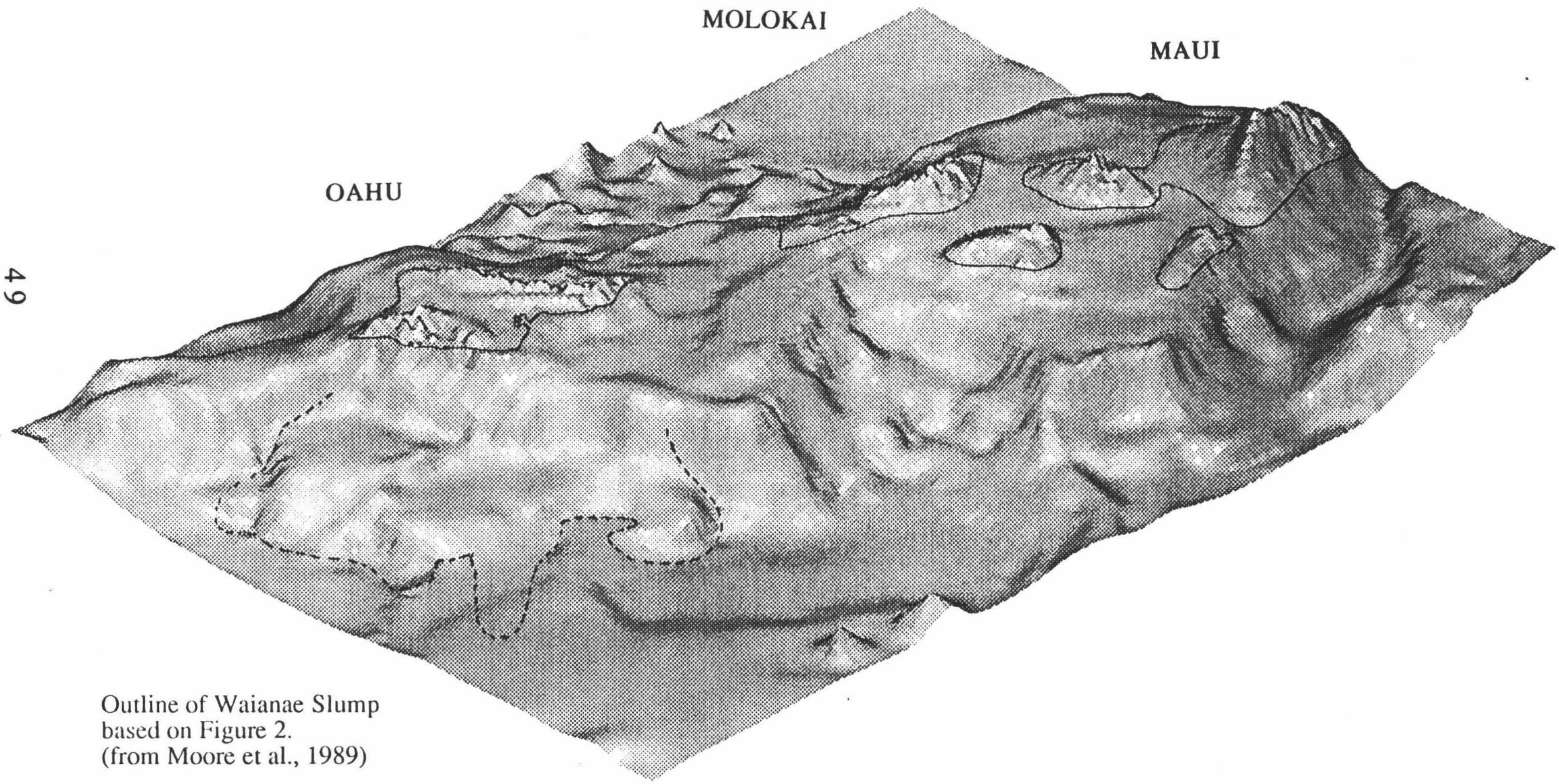
Whether or not the formation of the giant Waianae slump is in fact the erosional event that separates Palehua and Kolekole volcanism cannot be confirmed without dating the slump itself. However it is clear from the field relations of the Waianae volcano that some major event took place and circumstantial evidence suggests this as the probable, indeed the only known suspect. Such arguments will be strengthened, however if it can be shown that such a mass wasting event can account for the petrological characteristics of the Kolekole Volcanics.

At the type locality for the Kolekole Volcanics near Kolekole Pass, a lava flow mantles present day topography at the head of Lualualei Valley. This huge valley represents an enigma in Hawaiian geomorphology because it lies on the lee side of the island of Oahu where marine erosion is less severe than on the exposed windward coastlines. Several other geomorphological enigmas, such as the great sea cliffs on the north side of the East Molokai and Kohala volcanoes, and the spectacular "pali" cliffs on the Koolau Volcano have all been correlated with great submarine landslide deposits in the associated off-shore regions (Moore et al. 1989). Hence, the origin of these unusual erosional features may be related to large scale mass wasting events.

The Waianae Slump (Figures 2, 17) covers an area of approximately 6100 km^2 (Moore et al. 1989). The thickness of this deposit is generally unknown, but an estimate based on profiles of the deposit (Figure 18) is about 1 to 2 km, thus resulting in a conservative volume estimate of about 6100 km^3. The Waianae Slump may not be formed from material entirely from Waianae Volcano. Contributions from a presumed younger volcanic center that formed Penguin Bank and a possible volcanic center forming the Kaena ridge (Moore et al., 1989) are most likely involved aswell. However, it is notable that the Waianae deposit is classified as a slump, rather than a debris flow, and it appears to be primarily from the Waianae volcanic edifice.

Assuming that the total volume of the Waianae Slump is approximately 6100 km^3, and that this entire volume was derived from the Waianae volcano, allows for an estimate of the amount of decompression that the Waianae edifice and underlying mantle would undergo following the mass wasting event. The current outcrop exposure of the Waianae Volcano is approximately 740 km^2. Much of the western part of the volcano is missing however, and assuming that the volcano was more or less symmetrical prior to slumping increases the outcrop area to about 1060 km^2. Thus if the volume of the Waianae Slump

Figure 17. Three-dimensional representation of Oahu offshore bathymetry showing extent and size of Waianae Slump based on Figure 2 (Moore et al., 1989). The slump removed a great portion of the Waianae Volcano. The change of loading on the lithosphere from the slump may have triggered subsequent magma production and eruptive activity.



Outline of Waianae Slump
based on Figure 2.
(from Moore et al., 1989)

Figure 18a and 18b. Cross-sections of Waianae Slump. (a) This section is redrawn from Moore et al., (1989). Thickness for this section is approximately 1 km based on the fault plane drawn. (b) Two cross sections from Hussong et al., (1987), section A-A' trends due west from Kepuhi Point and section B-B' trends slightly south of due west from Maili Point. Inferred thicknesses for these cross-sections is approximately 2 km.

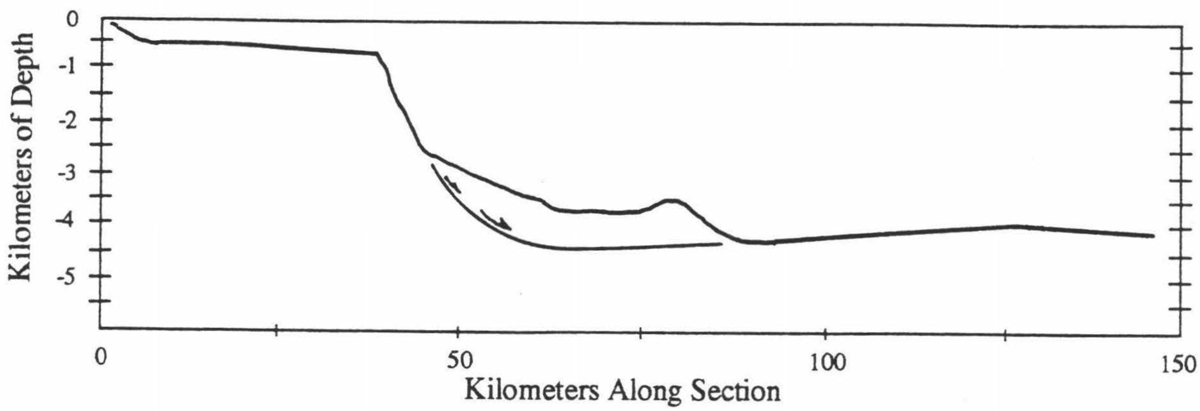


Figure 18a.

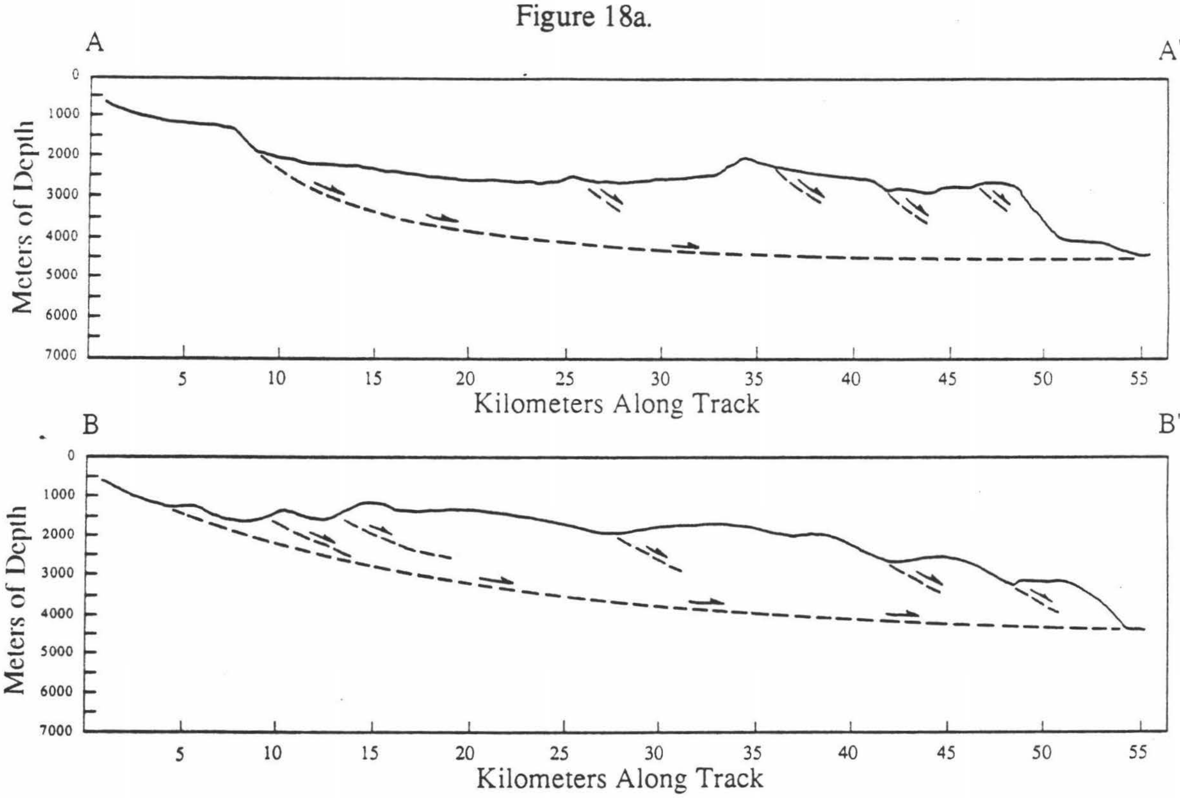


Figure 18b.

were to be superposed evenly over the Waianae Volcano, it would comprise a blanket approximately 6 km thick. There are many uncertainties in this exercise, including the volume and ultimate origin of the deposit, and the appropriate locations for restoring this volume on the edifice. Nevertheless, the critical point is that the Waianae slump, like most of the other near-shore Hawaiian landslide deposits, is truly huge. Furthermore, removal of volumes similar to the Waianae Slump, likely could cause decompression in the deep interior of the Waianae Volcano of 1-2 kbar.

The amount of magma production by decompression melting of adiabatically upwelling mantle above the solidus (dF/dP) has been estimated by a number of workers to be on the order of 1-2% per kbar (Klein and Langmuir, 1987; Mckenzie and Bickle, 1988; Langmuir et al., 1992). Thus, for the case of upwelling mantle in the melting region that produced Palehua magmas, decompression by an additional 1-2 kbar would produce average extents of melting increased by 1-4%. Note that our rather crude trace element melting (Figure 15) requires an increase of melting of only about 1% to account for the changes in Nb/Zr ratio between the youngest Palehua primary magmas and Kolekole primary magmas. Although we do not have great confidence in the absolute values emerging from this exercise, we conclude that if the huge volume of the Waianae slump were indeed removed from the Waianae Volcano, significant decompression of the upwelling mantle should occur. The petrological manifestations of this decompression would produce a change in extent of mantle melting in the direction (greater extent) and of approximately the same magnitude (about 1%) determined independently from geochemical considerations.

The explanation why Kolekole magmas should be less fractionated than the earlier, pre-slump Palehua hawaiites presumably lies in a consideration of the plumbing system of the volcano. Different Hawaiian volcanoes seem to have distinct extents of differentiation in their postshield alkalic caps, e.g. benmoreites and trachytes at West Maui (Sinton et al., 1987), mugearites at East Molokai (Beeson 1976, Sinton, unpublished data), hawaiites at Kohala (Spengler and Garcia, 1988), hawaiites at Mauna Kea (e.g. Frey et al., 1990; 1991), and Haleakala (e.g. Chen and Frey, 1985; Chen et al., 1991). This suggests that there are critical extents of differentiation and associated buoyancy that must be attained in each volcano in order to overcome the resistive forces that inhibit magma ascent and eruption. As well as simply removing a substantial amount of overburden, catastrophic failure of a large part of the volcanic edifice might significantly alter the conduit systems. For example, large fractures and / or other modifications to the conduit system might eventuate. In any case, the evidence from the Waianae Volcano is that less differentiated magma erupted after the erosional event terminating in Palehua volcanism. In view of the hypothesis that this event may have involved massive removal of huge volumes of overburden and untold alteration to the structural integrity of the volcanic edifice, this result is perhaps not surprising.

Mechanisms that Control Differences in Eruptive Behavior

Many theories have been proposed to explain the transitions between different suite of lavas in Hawaiian volcanoes. Many factors are pertinent to the eruptibility of a given magma, such as viscosity and crystallinity (Marsh (1981, 1989); volatile components (Spera, 1984); neutral buoyancy (Ryan, 1987), to name a few. In addition, the composition of the lavas are dependent on the eruptibility (Thompson, 1972a, 1974), and the change in composition of parental magmas due to waning melt production as the volcano moves off of the hotspot (Chen and Frey, 1985). Xenoliths give important clues to eruptive conditions and the depth of magmatic evolution (Irving 1980, Clague 1987). Finally, lithospheric flexure and rheology as the volcano grows and moves off the hotspot may also influence the ascent of magma (ten Brink and Brocher, 1987). Hawaiian volcanoes do evolve differently as they move off the hotspot. Therefore, it is important to be aware of how these mechanisms influenced each volcanic center differently.

Comparisons to Other Hawaiian Volcanoes

The distinction between shield and postshield stages of Waianae Volcano is very similar to that of several other Hawaiian volcanoes in that the alkalic cap is composed mainly of differentiated alkalic lavas bearing the signatures of early fractionation of clinopyroxene. The duration of the late differentiated postshield activity of Waianae (148 ±77 ky) also is generally similar to that of other Hawaiian volcanoes, i.e. ~62 ky for the dormant Mauna Kea, (see Frey et al., 1990), ~170 ky for Kohala (see Spengler and Garcia, 1988) but different than Haleakala, where postshield volcanism may have lasted ~400 ky (see Chen et al., 1990). Field and geochronological evidence suggest that there was no profound hiatus between shield and postshield eruptions on Waianae, Mauna Kea, Kohala or Haleakala volcanoes, although a quiescent period up to about 130 ky may have separated the Wailuku (shield) and Honolua (postshield) volcanics of West Maui volcano (e.g. Sinton et al., 1987).

The eruption of more mafic Kolekole lavas in the late postshield of Waianae Volcano is a feature not commonly observed in the postshield caps of other Hawaiian volcanoes. Only at Hualalai, where early trachyte eruptions ~100 ka were followed by more voluminous eruptions of alkalic basalt extending to historic times (Clague, 1987), has there been an apparently sustained, systematic reversal in the degree of differentiation. Although there have been relatively short-lived reversals of extent of differentiation within the postshield Kula volcanics of Haleakala, these reversals can be tied to periodic magma chamber replenishment events (West and Leeman, 1987, submitted).

Some volcanoes have experienced rejuvenation volcanism, i.e. following a significant period of quiescence of up to 2 million years, but in such cases the later lavas can normally be shown to have been derived from a mantle source that is isotopically and chemically different from that giving rise to earlier magmas. For example, the rejuvenated Hana volcanics of Haleakala are, on average, less differentiated than earlier postshield Kula lavas (Chen and Frey, 1985; West and Leeman, 1987). Similarly, rejuvenated basanites and alkali basalts of Kalaupapa Peninsula (Clague et al., 1982), post-date mugearites of East Molokai (Beeson, 1976). Other examples of rejuvenated mafic volcanism include the Honolulu Volcanics of Oahu, the Koloa Volcanics of Kauai and the Kiekie Volcanics of Niihau, but none of these volcanoes had significant postshield cap eruptions.

In view of our argument that a large mass wasting event may have produced increased melting in the Waianae Volcano, it is appropriate to assess whether similar events might be responsible for the so-called rejuvenation of other Hawaiian volcanoes. It is clear from field relations that the Koloa Volcanics post-date massive erosional events on that island, that Honolulu Volcanics are younger than the Nuuanu Slide of Oahu, an event that removed much of the Koolau shield, and that the eruption of Kalaupapa Pennisula is younger than the Wailau Slide that removed the northern half of East Molokai Volcano. However, any association between rejuvenation volcanism on Haleakala and the Hana slide (Moore et al., 1989) is far more tenuous. It is notable that four small rejuvenation eruptions also occurred on West Maui, which apparently has not been affected by any known massive landslides. Furthermore, there are other volcanoes that have experienced substantial mass wasting without becoming rejuvenated. Lanai has no post-slide volcanism and Hawi lavas were possibly erupting before and after the Pololu Debris Avalanche on Kohala (Moore et al., 1989).

Other than the relative ages discussed above, the exact age of landslide deposits in and around the Hawaiian chain are unknown. However, landslides can occur at almost any stage of volcano evolution. Landslides occurred during the active shield stage of Kilauea and Mauna Loa, and may have post-dated shield and / or postshield activity on East Molokai, Koolau and Kauai (Moore et al., 1989). In this paper we have presented evidence to suggest that the Waianae slump occurred within the postshield stage of Waianae Volcano.

Until more is known about the exact timing of other slides relative to the thermal and magmatic stage of evolution of the affected volcanoes it is impossible to draw conclusions about the likelihood that these events could have been responsible for volcano rejuvenation. However, as emphasized by Moore et al. (1989), the volumes incorporated into these slides are truly tremendous. We conclude that if the mantle beneath an affected volcano was near or above its solidus at the time of a mass wasting event, decompression associated with the prodigious mass removal could have caused renewed or increased melt formation and, under favorable structural circumstances, a new period of volcanism.

CONCLUSIONS

The results of this study show that postshield volcanism on Waianae Volcano was unique with respect to other Hawaiian Volcanoes. The findings of this study are:

1. Postshield volcanism of the Waianae Volcano consists of two mappable units, the 3.06-2.98 Ma Palehua Member of the Waianae Volcanics, and the 2.97-2.90 Ma posterosional Kolekole Volcanics.

2. These two units are separated by an erosional "event" of duration no greater than 65 ky and probably much less.

3. Kolekole lavas formed from extents of mantle melting slightly greater than that for Palehua lavas, and are less differentiated.

4. Removal of a volume of material approximately equal to that of the offshore Waianae slump deposit (~6100 km^3) about 2.98 Ma, can account for the field, geochronological and geochemical characteristics of the later postshield volcanics of Waianae Volcano.

5. Whether or not massive slumping events can be invoked as a (partial) general explanation for rejuvenation volcanism on some other Hawaiian volcanoes must await better definition of the respective ages of the individual slides, and a full definition of the thermal and magmatic character of the individual volcanoes prior to, and subsequent to, the mass wasting events.

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APPENDIX

Sample locations:

PALEHUA MEMBER, WAIANAE VOLCANICS

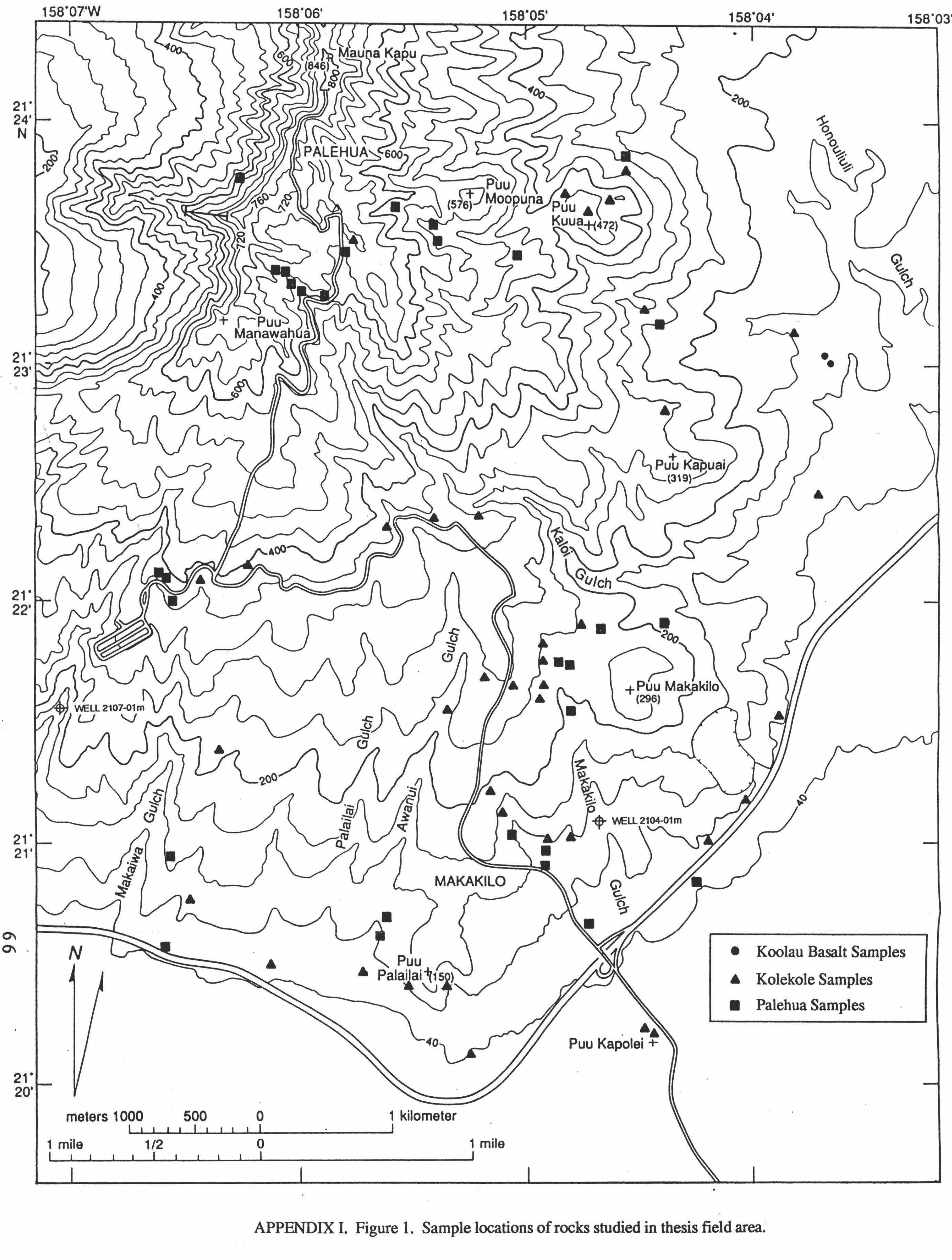
OW-128	Palehua hawaiite. West ridge between Waianae and Makaha Valleys leading up to Mt. Kaala. Sample taken from outcrop of first aphyric flow near ridge line trail, 1025 m elevation, .75 km S 26° W of radio towers near the summit of Mt. Kaala (using USGS Kaena Quadrangle).
PW-6	Palehua hawaiite. Bottom of cement drainage at the end of Nohona Road, Makakilo town, north western side of Puu Palailai. 96 m elevation, .55 km N 31° W from summit of Puu Palailai. Normal Polarity
PW-20	Palehua hawaiite. Road Cut along Farrington Hwy (93). 45 m elevation, 2.00 km N 83° W from summit of Puu Palailai. Normal Polarity
PW-32	Palehua hawaiite. .5 km down abandoned Air Force station road, from intersection with upper Palehua Road. Outcrop in north facing roadcut, 3 to 4 Palehua flows exposed here. 367 m elevation, 2.0 km S 14° W from summit of Puu Manawahua. Normal Polarity
PW-35A	Palehua hawaiite. Upper approximately 6 m thick aa flow in cliff band, next to waterfall, Avocado Valley, Palehua. 580 m elevation, .55 km form summit of Puu Moopuna. Normal Polarity
PW-35B	Palehua hawaiite. Lower 6 m thick aa flow in same cliff band as PW-35A. Normal Polarity
PW-37	Palehua hawaiite. Outcrop near road, north of entrance to Avocado Valley, Palehua. 515 m elevation, .35 km S 55° W from summit of Puu Moopuna. Normal Polarity
PW-38	Palehua hawaiite. Outcrop near road, south of entrance to Avocado Valley, Palehua. .38 km S 37° W from summit of Puu Moopuna. Loren Kroenke, sampler. Normal Polarity
PW-43	Palehua hawaiite. Top of aa flow cliff band, approx. 60 m above bottom of gulch. 300 m elevation, .55 km N 31° E from summit of Puu Kuua.
PW-52	Palehua hawaiite. In base of first cliff band up from Palehua Road, Banana Patch, upper Kaloi Gulch. 600 m elevation, .65 km N 68° E from summit of Puu Manawahua.
PW-53A	Palehua hawaiite. Vesicular aa core, in base of second cliff band up from Palehua Road, Banana Patch, upper Kaloi Gulch. 635 m elevation, .65 km N 68° E from summit of Puu Manawahua.
PW-53B	Palehua hawaiite. Massive aa flow directly above flow containing PW-53A. 1.5 m of clinker separate the flows. Normal Polarity

PW-54	Palehua hawaiite. Small cliff band 30 m NW of bottom of gulch, in Banana Patch, upper Kaloi Gulch. 645 m elevation, .60 km N 52° E from summit of Puu Manawahua. Normal Polarity
PW-55	Palehua basalt. Third cliff band up from Palehua Road, Banana Patch, upper Kaloi Gulch. 660 m elevation, .58 km N 45° E from Puu Manawahua. Plag phyric with large phenocrysts of 2 cm or more. Not analysed. Refer to sample C-31 in Macdonald and Katsura, 1964 for analysis. Normal Polarity
PW-78	Palehua hawaiite. Slabby, large, 8 m high outcrop, east side of small gulch west of Makakilo Gulch, across gulch from construction yard and buildings. 101 m elevation, 1.35 km S 28° W from summit of Puu Makakilo. Normal Polarity
PW-85	Palehua hawaiite. 30 m above base of small tributary gulch to Kaloi Gulch, on side of Puu Makakilo. 175 m elevation, .65 km N 26° E from summit of Puu Makakilo. Normal Polarity
C-section:	Palehua Member section collected by GA Macdonald, originally part of paper, Macdonald 1968. Section located from 613 to 736 m elevation along ridge projecting WNW into Nanakuli Valley from the unnamed 782 m elevation peak.
C-170	Palehua hawaiite. Platy, 613 m elevation.
C-171	Palehua hawaiite. Slightly platy, 627 m elevation.
C-172	Palehua hawaiite. Massive, 630 m elevation.
C-173	Palehua hawaiite. Moderately platy, 640 m elevation.
C-174	Palehua hawaiite. Somewhat oxidized, 645 m elevation.
C-175	Palehua hawaiite. Massive, somewhat oxidized, 647 m elevation.
C-176	Palehua hawaiite. Slightly platy, somewhat oxidized, 651 m elevation.
C-177	Palehua hawaiite. Somewhat oxidized, 656 m elevation.
C-178	Palehua hawaiite. Oxidized, 663 m elevation.
C-179	Palehua hawaiite. Oxidized, 693 m elevation.
C-180	Palehua hawaiite. Oxidized, 711 m elevation.
C-181	Palehua hawaiite. Massive and vesicular, with pahoehoe-type vesicles, somewhat oxidized, 731 m elevation.
C-182	Palehua hawaiite. Massive to slightly platy, somewhat oxidized, 736 m elevation.

KOLEKOLE VOLCANICS

OW-76	Sample of Puu Makakilo flow tongue, taken from freeway roadcut. 75 m elevation, 1.35 km S 24° E from summit of Puu Makakilo. Normal Polarity
OW-80X	Outcrop of Kolekole lava at Kolekole Pass. 520 m elevation, approximately .2 km W from parking lot for sacrificial stone. Normal Polarity
OW-118A	Uppermost veneer flow overlying Puu Makakilo cinder. Samples taken from the same flow near water tank north of Maukalani School, in embankment behind new condominiums. 265 m elevation, 0.9 km N 86° W from summit of Puu Makakilo. Normal Polarity
OW-123a	Veneer flow. Sample taken from embankment for water tank nearest blocked off intersection of Freeway H-1 and Kalaeloa road. Contact of Kolekole and Palehua lavas located in same embankment. Kolekole basalt. 48 m elevation. 1.2 km N 84° W from summit of Puu Palailai. Normal Polarity
PW-17	Puu Palailai flow. Sample taken 30 m down from summit inside crater. 80 m elevation. .15 km S 77° E from summit of Puu Palailai. Normal polarity
PW-19	Puu Palailai flow. Sample taken on western outer flank of Puu Palailai, 82 m elevation. .15 km S 82° W from summit of Puu Palailai. Normal polarity
PW-29	Veneer flow in road cut, 300 m west past lower gate to the private upper Palehua Road. 360 m elevation. 2.3 km N 55° W from summit of Puu Makakilo. Normal Polarity
PW-39	Puu Kuua lava , sample taken from road cut in overgrown access road north of summit of Puu Kuua 420 m elevation. 0.25 km N 45° W from summit of Puu Kuua. Normal polarity
PW-42	Puu Kuua lava. Sample taken 25 m down from dirt road on northern side of cinder cone, towards gulch. 327 m elevation, 0.5 km N 50° E from summit of Puu Palailai.
PW-47	Large outcrop of coarse grained Kolekole basalt. Across dirt road from radio antenna Building 203, off of upper Palehua Road. 680 m elevation, 1.25 km N 45° E from summit of Puu Manawahua. Sample taken very close to locked steel gate.
PW-61	Puu Kapolei basalt. Sample taken near gate to park inside Puu Kapolei. 30 m elevation, 1.70 km S 78° E from summit of Puu Palailai. Normal polarity
PW-69	Veneer lava, 30 m above bottom of upper Makakilo Gulch, 500 m NE of Maukalani school.. 233 m elevation, 0.70 km N 69° W from summit of Puu Makakilo.
PW-81	Veneer lava. Sample taken on next flow stratigraphically up from Palehua hawaiite flow PW-78. 120 m elevation, 1.3 km S 28° W from summit of Puu Makakilo. Normal Polarity

PW-89 Puu Kapuai, Outcrop on road near uppermost part of Puu Kapuai. 281 m elevation, 0.42 km N 6° W from summit of Puu Kapuai.
Normal Polarity



APPENDIX I. Figure 1. Sample locations of rocks studied in thesis field area.

APPENDIX I. Sample locations for all samples of study.

KOOLAU SAMPLES NEAR PUU KAPUAI

PW-86	Koolau oceanite, bottom flank of Puu Kapuai, Waianae side of small gulch west of Honouliuli gulch. 134 m elevation, 2.25 km S 62° E of summit of Puu Kuua.
PW-87	Koolau basalt, taken near PW-86. 137 m elevation, 2.20 km S 62° E of summit of Puu Kuua.

LUALUALEI MEMBER, WAIANAE VOLCANICS

OW-15	Sample taken .30 km due east of summit of Puu o Hulu Kai, at the 170 m elevation. Puu o Hulu kai is a small ridge south and makai of Lualualei valley. Sampled form outcrop along ridge.
OW-16	Sample taken 30 m due west of summit of Puu o Hulu Kai, 250 m elevation. Sampled form outcrop along ridge.
OW-66A	From northwestern spur of Puu Heleakala, Lualualei Valley. 60 m elevation, 1.15 km N 58° W of summit of Puu Heleakala.
OW-69B	Same spur as OW-66a, 220 m elevation, .90 km N 55° W of summit of Puu Heleakala
OW-70	Same spur as OW-66a, sample taken along ridge crest, 330 m elevation, .65 km N 51° W of summit of Puu Heleakala
OW-91	Sample taken from southern most southwestern projecting spur from Puu Kaua, along ridge crest. 465 m elevation, 1.15 km S 50° W of summit of Puu Kaua.
C-46	Macdonald sample, from Macdonald and Katsura (1964). 8 m above bottom of gully at base of ridge 1.2 km E of Puu Heleakala on north side of Nanakuli Valley. The locality is 60 m below the outcrop of the breccia at the boundary of what was called the Middle Member for the Waianae Volcano.
WD-88	Dike, Lualualei member. See Zbindon and Sinton (1988) for sample location.
PW-99	Dike, stream channel in Waimanalo Gulch, directly beneath first set of power poles. Dike trends N 20° W, dips 85° W. Sample location at 73 m elevation, 3.45 km N 63° W of summit of Puu Palailai.

KAMAILEUNU MEMBER, WAIANAE VOLCANICS

OW-4	Sampled from summit of small hill southwest of Puu Kailio, 160 m elevation, 1.00 km S 64° W of summit of Puu Kailio.
OW-12	Southwestern flank of Puu Kailio, 232 m elevation.70 km S 22° W of Puu Kailio.
OW-92	Same spur as OW-91, along ridge crest. 550 m elevation. .95 km S 46° W of Puu Kaua.
OW-93A	Same spur as OW-91, along ridge crest. 597 m elevation. .85 km S 47° W of Puu Kaua.
OW-95A	Same spur as OW-91, along ridge crest. 634 m elevation. .75 km S 47° W of Puu Kaua.

OW-97	Southeastern pointing spur off of Kamaileunu Ridge, accessed from Waianae Valley. Ridge continues to Puu Kepauala. 268 m elevation, 1.1 km S 29° E of Puu Kepauala.
OW-99	Same ridge as OW-97, 330 m elevation, .95 km S 29° E of Puu Kepauala.
OW-101	Same ridge as OW-97, 549 m elevation, .60 km S 29° E of Puu Kepauala.
OW-127	West ridge between Waianae and Makaha Valleys leading up to Mt. Kaala. Sample taken from outcrop near ridge line trail, 951 m elevation, .87 km S 38° W of radio towers near the summit of Mt. Kaala (using USGS Kaena Quadrangle).
WD-21	Dike, Kamaileunu member. See Zbindon and Sinton, 1988 for sample location.
WD-25	"
WD-50	"
WD-60	"
WD-62	"
WD-65	"
WD-103	"
WD-132	"
WD-144	"
WD-192	"
WD-193	"
WD-204	"
WD-235	"
WD-240	"
WD-265	"
WD-304	"
WD-335	"
WD-342	"
WD-354	"
WD-501	Dike, located in roadcut off of Kolekole Pass Road. Across from scenic overlook parking lot for sights of the Great Lualualei Valley Naval Magazine. No pictures please.

PALEHUA MEMBER, WAIANAE VOLCANICS

OW-55	Sample taken from Lualualei side of Pohakea Pass. 671 m elevation, .10 km due N from Pohakea Pass.
OW-102	Summit of Puu Kepauala, along Kamaileunu Ridge.
OW-122	Palehua hawaiite. Flow in roadcut of access road to Air Force station, beneath small cinder cone and vent structure. 365 m elevation, 2.2 km S 10° W from summit of Puu Manawahua.
OW-128	Palehua hawaiite. West ridge between Waianae and Makaha Valleys leading up to Mt. Kaala. Sample taken from outcrop of first aphyric flow near ridge line trail, 1025 m elevation, .75 km S 26° W of radio towers near the summit of Mt. Kaala (using USGS Kaena Quadrangle).
OW-133	Palehua hawaiite. In road cut along dirt road heading west above Puu Kuua. 463 m elevation, .6 km S 62° W from summit of Puu Kuua. Normal Polarity

PW-6	Palehua hawaiite. Bottom of cement drainage at the end of Nohona Road, Makakilo town, north western side of Puu Palailai. 96 m elevation, .55 km N 31° W from summit of Puu Palailai. Normal Polarity
PW-8	Palehua hawaiite. Six meters above base of Awunui gulch, north side of Puu Palailai. 80 m elevation, .50 km N 47° W from summit of Puu Palailai. Normal Polarity
PW-20	Palehua hawaiite. Road Cut along Farrington Hwy (93). 45 m elevation, 2.00 km N 83° W from summit of Puu Palailai. Normal Polarity
PW-22	Palehua basalt. Noriega formation. Very plagioclase phyric basalt exposed in bottom of unamed gulch just east of Makaiwa Gulch. Great samples located in drill cores for foundations of large power poles. 160 m elevation, 2.15 km N 49° W of summit of Puu Palailai. Pock-marked appearance.
PW-28	Palehua Hawaiite, near end of dirt road along ridge east of Makaiwa Gulch. 125 m elevation, 2.20 km N 64° W from summit of Puu Palailai.
PW-32	Palehua hawaiite. .5 km down abandoned Air Force station road, from intersection with upper Palehua Road. Outcrop in north facing roadcut, 3 to 4 Palehua flows exposed here. 367 m elevation, 2.0 km S 14° W from summit of Puu Manawahua. Normal Polarity
PW-32A	Palehua hawaiite. One flow down stratigraphically from PW-32, 20 m further down the road, 362 m elevation. Normal Polarity
PW-35A	Palehua hawaiite. Upper approximately 6 m thick aa flow in cliff band, next to waterfall, Avocado Valley, Palehua. 580 m elevation, .55 km form summit of Puu Moopuna. Normal Polarity
PW-35B	Palehua hawaiite. Lower 6 m thick aa flow in same cliff band as PW-35A. Normal Polarity
PW-37	Palehua hawaiite. Outcrop near road, north of entrance to Avocado Valley, Palehua. 515 m elevation, .35 km S 55° W from summit of Puu Moopuna. Normal Polarity
PW-38	Palehua hawaiite. Ouctcrop near road, south of entrance to Avocado Valley, Palehua. .38 km S 37° W from summit of Puu Moopuna. Loren Kroenke, sampler. Normal Polarity
PW-43	Palehua hawaiite. Top of aa flow cliff band, approx. 60 m above bottom of gulch. 300 m elevation, .55 km N 31° E from summit of Puu Kuua.
PW-52	Palehua hawaiite. In base of first cliff band up from Palehua Road, Banana Patch, upper Kaloi Gulch. 600 m elevation, .65 km N 68° E from summit of Puu Manawahua.
PW-53A	Palehua hawaiite. Vesicular aa core, in base of second cliff band up from Palehua Road, Banana Patch, upper Kaloi Gulch. 635 m elevation, .65 km N 68° E from summit of Puu Manawahua.

PW-53B	Palehua hawaiite. Massive aa flow directly above flow containing PW-53A. 1.5 m of clinker separate the flows. Normal Polarity
PW-54	Palehua hawaiite. Small cliff band 30 m NW of bottom of gulch, in Banana Patch, upper Kaloi Gulch. 645 m elevation, .60 km N 52° E from summit of Puu Manawahua. Normal Polarity
PW-55	Palehua basalt. Third cliff band up from Palehua Road, Banana Patch, upper Kaloi Gulch. 660 m elevation, .58 km N 45° E from Puu Manawahua. Plag phyric with large phenocrysts of 2 cm or more. Not analysed. Refer to sample C-31 in Macdonald and Katsura, 1964 for analysis. Normal Polarity
PW-57	Palehua hawaiite. NW side of Palehua road, up from Banana Patch, across from big cliffs of upper Kaloi Gulch. 615 m elevation, .80 km N 76° E from summit of Puu Manawahua.
PW-58	Palehua hawaiite. Along Palehua Road up from Banana Patch, near Antenna Building 203. Possibly only one flow above PW-57. 640 m elevation, 1.1 km N 60° E from summit of Puu Manawahua.
PW-62	Palehua hawaiite. Platy, aphyric outcrop in bottom of Makakilo Gulch, down from Maukalani School. 181 m elevation, .45 km S 73° W from summit of Puu Makakilo. Normal Polarity
PW-67	Palehua hawaiite. Outcrop 10 m from stream channel on east side of Makakilo Gulch. 207 m elevation, .5 km N 64° W from summit of Puu Makakilo.
PW-68	Palehua hawaiite. Outcrop on west side of stream channel, higher elevation than PW-67, one flow stratigraphically up. 217 m elevation, .6 km N 69° W from summit of Puu Makakilo.
PW-72	Palehua hawaiite. Located in small tributary gulch to Kaloi Gulch, north side of Puu Makakilo. 217 m elevation, .55 km N 23° W from summit of Puu Makakilo.
PW-74	Palehua hawaiite. Small outcrop near bottom of gulch west of Makakilo Gulch, down from fire station and water tank. 135 m elevation, 1.35 km S 42° W from summit of Puu Makakilo.
PW-78	Palehua hawaiite. Slabby, large, 8 m high outcrop, east side of small gulch west of Makakilo Gulch, across gulch from construction yard and buildings. 101 m elevation, 1.35 km S 28° W from summit of Puu Makakilo. Normal Polarity
PW-79	Palehua hawaiite. Small outcrop alongside road that accesses Assembly of God Church and construction yard of PW-78, near flume. 60 m elevation, 1.75 km S 9° W from summit of Puu Makakilo.
PW-80	Palehua hawaiite. Flow exposed in excavation behind construction yard and buildings near PW-78. 110 m elevation, 1.40 km S 26° W from summit of Puu Makakilo.
PW-85	Palehua hawaiite. 30 m above base of small tributary gulch to Kaloi Gulch, on side of Puu Makakilo. 175 m elevation, .65 km N 26° E from summit of Puu Makakilo. Normal Polarity

PW-94 Palehua hawaiite. Outcrop of thin spatter flows down from 282 m small hill on south side of Puu Kuua. 240 m elevation, .95 km S 34° W from summit of Puu Kuua.

PW-98 Palehua hawaiite. Base of small gulch east of Makakilo Gulch, under freeway covert and embankment, southeast side. 45 m elevation, 1.55 km S 19° E from summit of Puu Makakilo.

C-section: Palehua Member section collected by GA Macdonald, originally part of paper, Macdonald 1968. Section located from 613 to 736 m elevation along ridge projecting WNW into Nanakuli Valley from the unamed 782 m elevation peak.

C-170 Palehua hawaiite. Platy, 613 m elevation.

C-171 Palehua hawaiite. Slightly platy, 627 m elevation.

C-172 Palehua hawaiite. Massive, 630 m elevation.

C-173 Palehua hawaiite. Moderately platy, 640 m elevation.

C-174 Palehua hawaiite. Somewhat oxidized, 645 m elevation.

C-175 Palehua hawaiite. Massive, somewhat oxidized, 647 m elevation.

C-176 Palehua hawaiite. Slightly platy, somewhat oxidized, 651 m elevation.

C-177 Palehua hawaiite. Somewhat oxidized, 656 m elevation.

C-178 Palehua hawaiite. Oxidized, 663 m elevation.

C-179 Palehua hawaiite. Oxidized, 693 m elevation.

C-180 Palehua hawaiite. Oxidized, 711 m elevation.

C-181 Palehua hawaiite. Massive and vesicular, with pahoehoe-type vesicles, somewhat oxidized, 731 m elevation.

C-182 Palehua hawaiite. Massive to slightly platy, somewhat oxidized, 736 m elevation.

WD-222 Palehua hawaiite in dike. See Zbindon and Sinton, 1988 for sample location.

PALEHUA MEMBER SECTION LOCALITIES

Mt. Kaala
Banana Patch, off Palehua Road
Avocado Valley, down from Palehua Road on 4 wheel drive track near radio tower Building 203
Macdonald "C" Section, above Nanakuli Valley
Puu Makakilo and Puu Palailai area
Puu Kapuai and Puu Kuua area

KOLEKOLE VOLCANICS

OW-76 Sample of Puu Makakilo flow tongue, taken from freeway roadcut. 75 m elevation, 1.35 km S 24° E from summit of Puu Makakilo.
Normal Polarity

OW-77	Sample of Puu Palailai flow tongue, taken from abandoned quarry. 50 m elevation, .67 km S 34° E from summit of Puu Palailai. Normal Polarity
OW-78	Puu Kapolei basalt. 30 m elevation, 1.7 km S 78° E of summit of Puu Palailai.
OW-80	Outrop of Kolekole lava at Kolekole Pass. 520 m elevation, approximately .2 km W from parking lot for sacrificial stone. Normal Polarity
OW-80X	Same as above.
OW-118a,b	Uppermost veneer flow overlying Puu Makakilo cinder. Samples taken from the same flow near water tank north of Maukalani School, in embankment behind new condominiums. 265 m elevation, 0.9 km N 86° W from summit of Puu Makakilo. Normal Polarity
OW-119	Veneer flow, 40 m above bottom of Awanui Gulch, below houses and apartment complex. 240 m elevation, 1.4 km S 85° W from summit of Puu Makakilo.
OW-120	Uppermost veneer flow, sample taken during excavation for sidewalk and cement wall, along Palahia Road, 150 meters west from intersection with Makakilo Blvd in Makakilo town. 271 m elevation, 1.05 km N 86° W from summit of Puu Makakilo. Normal Polarity
OW-121	Uppermost veneer flow, sample taken during excavation for new housing, upper Palehua Road. 320 m elevation, 1.75 km N 41° W from summit of Puu Makakilo.
OW-123a	Veneer flow. Sample taken from embankment for water tank nearest blocked off intersersection of Freeway H-1 and Kalaeloa road. Contact of Kolekole and Palehua lavas located in same embankment. Kolekole basalt. 48 m elevation. 1.2 km N 84° W from summit of Puu Palailai. Normal Polarity
PW-4	Kolekole basalt. Sample taken from excavation and barren spot off of upper Palehua Road, 200 m from intersection with Kikaha Road, above Makakilo town. 356 m elevation. 2.0 km N 48° W from summit of Puu Makakilo. Normal polarity
PW-10	Veneer flow under Puu Palailai flows. Near fence surrounding water tanks on west side of Puu Palailai. 50 m elevation. .50 km N 85° W from summit of Puu Palailai. Normal polarity
PW-17	Puu Palailai flow. Sample taken 30 m down from summit inside crater. 80 m elevation. .15 km S 77° E from summit of Puu Palailai. Normal polarity
PW-19	Puu Palailai flow. Sample taken on western outer flank of Puu Palailai, 82 m elevation. .15 km S 82° W from summit of Puu Palailai. Normal polarity
PW-21	Along small ridge just parallel and just east to ridge east of Makaiwa Gulch, .5 km from freeway. 98 m elevation. 1.90 km N 72° W from summit of Puu Palailai. Normal polarity
PW-24	Veneer flow. Sample taken near dirt road on ridge east of Makaiwa Gulch, 1.5 km from freeway. 205 m elevation. 2.35 km N 43° W from summit of Puu Palailai.

PW-29	Veneer flow in road cut, 300 m west past lower gate to the private upper Palehua Road. 360 m elevation. 2.3 km N 55° W from summit of Puu Makakilo. Normal Polarity
PW-31	Veneer flow in road cut in upper Palehua Road, .5 km road distance east from intersection of Palehua Road and access road to abandoned Air Force station. 395 m elevation, 1.9 km S 7° E from summit of Puu Manawahua.
PW-34	Veneer flow. Sample location 100 m west of intersection along upper Palehua Road, 370 m elevation. 2.0 km S 5° W from summit of Puu Manawahua.
PW-39	Puu Kuua lava , sample taken from road cut in overgrown access road north of summit of Puu Kuua 420 m elevation. 0.25 km N 45° W from summit of Puu Kuua. Normal polarity
PW-40	Puu Kuua lava. Sample taken from summit of Puu Kuua. 472 m elevation.
PW-41	Puu Kuua lava. Sample taken from outcrop on ridge near false summit of Puu Kuua. 445 m elevation, 0.2 km N 50° E from summit of Puu Palailai.
PW-42	Puu Kuua lava. Sample taken 25 m down from dirt road on northern side of cinder cone, towards gulch. 327 m elevation, 0.5 km N 50° E from summit of Puu Palailai.
PW-47	Large outcrop of coarse grained Kolekole basalt. Across dirt road from radio antenna Building 203, off of upper Palehua Road. 680 m elevation, 1.25 km N 45° E from summit of Puu Manawahua. Sample taken very close to locked steel gate.
PW-47B	Same location as above, sample taken from top of outcrop, north of PW-47 by 30 m. Coarse grained.
PW-47C	Same location as above, sample taken 3 m from chained gate along coral paved road. Coarse grained.
PW-48	Same location as above, sample taken 30 m N of chain gate along coral paved road.
PW-60	Outcrop along small ridge extending SE from radio antenna Building 203. 722 m elevation, 1.2 km N 56° E from summit of Puu Manawahua.
PW-61	Puu Kapolei basalt. Sample taken near gate to park inside Puu Kapolei. 30 m elevation, 1.70 km S 78° E from summit of Puu Palailai. Normal polarity
PW-65	Veneer lava, 25 m above bottom of upper Makakilo Gulch, 300 m NE of Maukalani school.. Outcrop is below cinder and ash layer. 220 m elevation, 0.65 km N 85° W from summit of Puu Makakilo.
PW-66	Veneer lava, 35 m above bottom of upper Makakilo Gulch, 150 m NE of Maukalani school.. Outcrop is below cinder and ash layer. 231 m elevation, 0.65 km S 85° W from summit of Puu Makakilo.
PW-69	Veneer lava, 30 m above bottom of upper Makakilo Gulch, 500 m NE of Maukalani school.. 233 m elevation, 0.70 km N 69° W from summit of Puu Makakilo.
PW-70	Veneer lava, 10 m from base of upper Makakilo Gulch, 150 m N of sample PW-70. 233 m elevation, 0.75 km N 60° W from summit of Puu Makakilo.

PW-71 Veneer lava. Sample taken under new excavation for houses, east side of Makakilo Gulch. 231 m elevation, 0.65 km N 34° W from summit of Puu Makakilo.

PW-75 Veneer lava, Near base of small gulch west of Makakilo Gulch. 155 m elevation, 1.35 km S 48° W from summit of Puu Makakilo.

PW-77 Veneer lava, Sample taken from upper extent of small gulch west of Makakilo Gulch, 150 m from Makakilo Blvd. 184 m elevation, 1.30 km S 54° W from summit of Puu Makakilo.

PW-81 Veneer lava. Sample taken on next flow stratigraphically up from Palehua hawaiite flow PW-78. 120 m elevation, 1.3 km S 28° W from summit of Puu Makakilo.
Normal Polartiy

PW-83 Veneer lava, Sample taken in small gulch, 300 m west of Makakilo gulch, very close to Kolekole-Palehua contact. 120 m elevation, 1.1 km S 21° W from summit of Puu Makakilo.

PW-88 Puu Kuua flow tongue, near Koolau contact. 155 m elevation, 1.80 km S 62° E from summit of Puu Kuua.

PW-89 Puu Kapuai, Outcrop on road near uppermost part of Puu Kapuai. 281 m elevation, 0.42 km N 6° W from summit of Puu Kapuai.
Normal Polarity

PW-93 Residual Boulder on 302 m topographical high between Puu Kuua and Puu Kapuai, 295 m elevation, 0.8 km S 32° E from summit of Puu Kuua.

PW-95 Puu Kapuai, Sample taken from road cut of lower sugar cane road. 95 m elevation, 1.20 km S 79° E from summit of Puu Kapuai.

PW-96 Puu Makakilo. Sample taken from road cut of H-1 freeway, approx. 2.5 km along freeway from intersection with Makakilo Blvd, Puu Makakilo side. 80 m elevation, 1.2 km S 80° W from summit of Puu Makakilo.
Normal Polarity

PW-97 Puu Makakilo. Sample taken from road cut of H-1 freeway, approx. 0.9 km along freeway from intersection with Makakilo Blvd, Puu Makakilo side. 80 m elevation, 1.25 km S 48° E from summit of Puu Makakilo.

C-169 Puu Kuua. Sample collected by Macdonald (1968), from summit of Puu Kuua.

KOLEKOLE VOLCANICS SECTION AREAS

Radio station Building 203
Kolekole Pass
Mt. Kaala
Puu Kuua
Puu Palailai
Puu Makakilo
Puu Kapolei
Puu Kapuai
Upper and lower veneers, covering most of the Makakilo town areas

Appendix II, Table 1. XRF Analyses of Koolau Vocanics, Waianae Volcanics and Kolekole Volcanics.

	Standard Runs ¥		Koolau Volcanics		Waianae Volcanics, Lualualei Member								
	BHVO-1	BCR-1	PW-86	PW-87	OW-15	OW-16	OW-66a	OW-69b	OW-70	OW-91	C-46	WD-88	PW-99
SiO2	49.79	53.91	51.79	47.43	49.62	49.52	50.65	50.70	49.76	51.89	48.43	51.64	51.49
TiO2	2.71	2.21	2.21	1.22	2.50	2.20	2.87	2.74	2.53	1.99	2.66	2.37	2.19
Al2O3	13.51	13.41	14.12	8.42	13.19	11.34	14.09	13.73	14.96	13.54	12.50	13.98	12.86
Fe2O3*	12.31	13.37	11.47	13.12	12.27	13.04	12.21	12.84	12.11	10.71	14.58	12.12	11.94
MnO	0.16	0.18	0.14	0.16	0.17	0.19	0.17	0.18	0.17	0.15	0.18	0.18	0.15
MgO	8.00	3.51	7.01	22.45	8.14	12.37	5.97	6.60	5.74	8.01	6.82	6.71	9.12
CaO	11.22	6.99	9.07	5.05	10.45	9.83	11.03	10.51	10.27	10.09	10.77	10.02	8.89
Na2O	2.28	3.30	2.84	1.58	2.11	1.73	2.49	2.52	2.43	2.53	2.15	2.44	2.35
K2O	0.51	1.69	0.73	0.23	0.35	0.27	0.34	0.42	0.39	0.18	0.32	0.39	0.52
P2O5	0.27	0.36	0.19	0.15	0.25	0.26	0.34	0.47	0.30	0.22	0.42	0.29	0.29
LOI §	0.25	1.59	0.60	0.50	0.73	0.62	0.61	1.06	0.76	0.96	1.35	0.94	0.73
TOTAL	101.01	100.53	100.18	100.31	99.78	101.37	100.77	101.77	99.42	100.27	100.18	101.08	100.54
Sc	33	32	20	13	29	27	28	28	28	24		30	25
V	313	404	255	159	293	261	290	310	288	238		264	272
Cr	299	15	285	1061	595	870	173	120	97	434		303	631
Ni	124	10	161	1524	228	436	87	82	72	222		114	321
Co	47	38	48	118	67	80	52	60	63	67		44	50
Cu	139	19	111	52	285	118	95	68	98	172		123	118
Zn	104	127	106	127	107	108	101	107	101	89		95	108
Rb	9	48	11	3	5	4	6	6	5	3		6	7
Sr	390	327	483	260	322	309	407	431	393	392		348	378
Y	28	38	27	46	30	26	30	28	29	165		32	30
Zr	176	192	165	89	145	129	162	162	160	121		140	149
Nb	19	12	11	6	13	11	13	15	13	9		10	10
Ba	120	714	185	174	67	70	87	117	80	77		80	108
Pb	3	14	<2	<2	<2	<2	<2	<2	<2	<2		<2	<2
Th	2	6	<2	<2	<2	<2	<2	<2	<2	<2		<2	<2

*Total iron is listed as Fe2O3

§ LOI listed as total loss on ignition. Condition for ignition was 900° C for eight hours.

¥ The two international standards were run along with unknowns.

Waianae Volcanics, Kamaileunu Member

	OW-4	OW-12	OW-92	OW-93a	OW-95a	OW-97	OW-99	OW-101	OW-127	WD-21	WD-25	WD-50	WD-60	WD-62	WD-65
SiO2	53.50	50.74	47.49	45.82	49.73	49.07	48.67	47.92	48.72	51.43	48.74	51.65	49.23	49.35	51.22
TiO2	2.87	2.64	4.19	5.03	3.21	2.34	2.97	3.41	3.68	3.61	3.89	3.21	3.35	3.38	3.69
Al2O3	14.71	15.18	13.27	12.66	12.83	14.33	14.38	13.76	14.45	13.83	13.60	13.69	13.13	13.04	13.42
Fe2O3*	12.02	11.00	14.51	17.67	13.95	11.51	12.68	14.39	13.60	10.30	13.61	11.36	13.74	13.94	12.96
MnO	0.16	0.15	0.21	0.22	0.18	0.15	0.16	0.19	0.16	0.14	0.17	0.17	0.17	0.18	0.20
MgO	2.61	5.55	4.34	3.87	5.57	7.66	6.18	5.32	5.10	4.75	5.19	5.23	5.84	5.75	3.50
CaO	6.49	10.44	8.20	7.20	9.87	10.52	10.30	9.59	9.12	9.75	9.32	9.36	9.75	9.85	8.04
Na2O	4.47	2.87	3.81	3.53	3.00	2.61	2.92	2.95	2.74	2.85	2.78	2.70	2.63	2.64	3.64
K2O	1.55	0.62	1.06	1.23	0.53	0.53	0.58	0.54	1.08	0.85	0.55	0.83	0.66	0.60	1.33
P2O5	1.05	0.49	0.77	0.95	0.41	0.32	0.38	0.46	0.49	0.56	0.77	0.48	0.51	0.52	0.79
LOI §	1.27	0.84	0.56	1.43	0.48	0.72	0.44	0.88	0.76	2.11	1.61	1.37	1.69	2.62	1.68
TOTAL	100.70	100.52	98.41	99.61	99.76	99.76	99.66	99.41	99.91	100.18	100.23	100.05	100.70	101.87	100.47
Sc	19	24	11	21	27	25	27	26	27	29	27	29	26	25	23
V	194	248	211	267	336	241	288	363	333	359	331	341	299	305	302
Cr	4	139	5	6	92	364	143	83	56	59	46	34	76	81	5
Ni	5	89	7	91	71	198	98	61	69	79	62	55	88	84	21
Co	22	42	41	41	55	61	55	49	39	52	59	52	53	52	55
Cu	11	100	14	98	96	117	88	69	99	115	61	73	92	86	13
Zn	178	99	139	126	121	94	108	124	124	144	134	145	129	132	162
Rb	23	12	21	19	14	8	9	6	17	19	9	13	12	11	26
Sr	574	538	628	540	520	503	553	544	653	553	571	516	499	492	530
Y	78	27	45	48	35	27	31	36	35	41	39	42	33	33	51
Zr	449	171	315	409	207	160	204	230	282	244	336	218	225	222	353
Nb	41	17	28	40	21	15	19	21	29	19	22	20	16	16	32
Ba	452	161	430	211	176	127	165	218	289	211	159	229	137	113	346
Pb	3	<2	<2	3	<2	<2	<2	<2	2	2	2	<2	<2	<2	2
Th	2	<2	<2	2	<2	<2	2	<2	2	2	<2	<2	<2	<2	<2

Waianae Volcanics, Kamaileunu Member cont.

	WD-103	WD-132	WD-144	WD-192	WD-193	WD-204	WD-235	WD-240	WD-265	WD-304	WD-335	WD-342	WD-354	WD-501
SiO2	48.63	50.13	50.13	50.06	49.96	49.16	48.29	49.67	50.00	51.22	51.61	51.70	52.25	49.30
TiO2	3.03	3.19	3.51	3.41	3.80	3.29	3.45	3.49	4.40	2.57	2.50	2.53	3.83	2.73
Al2O3	14.32	14.05	13.10	13.46	12.65	13.71	12.94	14.67	12.28	13.79	13.54	13.63	13.16	13.82
Fe2O3*	11.72	12.50	13.71	10.68	13.84	14.24	14.26	12.25	15.94	12.10	11.74	12.53	10.68	12.56
MnO	0.16	0.16	0.17	0.15	0.22	0.19	0.18	0.16	0.21	0.18	0.17	0.18	0.17	0.16
MgO	6.18	5.01	5.26	5.05	5.03	4.72	5.18	4.97	4.86	6.93	6.73	6.04	4.81	6.06
CaO	10.95	10.15	9.54	9.92	9.11	9.87	9.76	9.72	8.86	10.73	10.24	9.96	8.90	10.59
Na2O	2.72	2.76	2.73	2.71	2.74	2.80	2.72	2.74	2.79	2.34	2.46	2.77	3.00	2.09
K2O	0.60	0.65	0.63	0.69	0.83	0.61	0.65	0.67	0.71	0.36	0.49	0.38	0.98	0.72
P2O5	0.51	0.50	0.56	0.51	0.61	0.46	0.54	0.71	0.70	0.32	0.35	0.32	0.77	0.36
LOI §	2.12	1.46	1.88	2.99	1.48	1.76	2.01	1.59	1.19	1.03	1.33	1.39	1.63	1.32
TOTAL	100.94	100.56	101.22	99.63	100.27	100.81	99.98	100.64	101.94	101.57	101.16	101.43	100.18	99.71
Sc	25	26	27	28	29	29	26	22	28	31	28	28	29	23
V	299	334	373	328	344	379	324	301	371	305	288	285	356	291
Cr	176	125	55	64	51	39	55	75	43	271	260	95	36	77
Ni	105	88	90	132	84	56	67	50	52	107	111	73	49	14
Co	52	487	47	51	67	58	52	37	48	49	49	44	50	55
Cu	89	110	86	122	124	121	96	75	122	123	93	122	81	121
Zn	104	119	133	133	153	136	135	124	158	103	100	97	158	142
Rb	9	14	16	12	15	10	12	9	14	6	8	6	17	13
Sr	612	533	591	475	477	510	518	590	497	364	429	388	568	507
Y	29	34	39	60	39	35	38	34	46	30	38	38	56	27
Zr	210	217	249	222	312	208	226	295	343	156	161	159	315	168
Nb	21	22	24	16	20	19	18	20	24	12	13	11	26	18
Ba	188	184	188	198	158	161	233	146	233	68	120	92	453	226
Pb	2	<2	<2	<2	<2	<2	2	<2	<2	<2	<2	<2	2	<2
Th	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2

Waianae Volcanics, Palehua Member

	OW-55	OW-102	OW-122	OW-128	OW-133	PW-6	PW-8	PW-20	PW-28	PW-32	PW-32a	PW-35a	PW-35b	PW-37	PW-38
SiO2	50.99	47.95	48.48	48.47	48.92	49.16	50.35	49.75	48.38	49.33	48.34	49.96	49.80	49.39	49.93
TiO2	2.63	3.61	3.68	3.23	3.79	3.37	3.42	3.47	3.90	3.32	3.78	3.78	3.68	3.45	3.51
Al2O3	16.57	15.79	15.41	15.48	15.33	15.30	15.45	15.45	15.84	15.38	15.92	17.03	16.66	15.68	15.84
Fe2O3*	10.74	13.10	13.85	12.44	14.11	13.30	13.09	12.74	14.21	12.54	13.99	14.23	13.78	13.14	13.10
MnO	0.17	0.18	0.17	0.15	0.18	0.17	0.13	0.13	0.13	0.14	0.17	0.18	0.18	0.18	0.18
MgO	3.04	4.50	3.56	4.19	3.66	3.86	3.95	3.97	3.89	4.18	3.58	2.39	3.08	3.92	3.55
CaO	5.67	7.20	7.00	6.84	6.83	6.60	6.43	7.04	7.05	7.27	6.05	4.82	5.25	6.92	6.33
Na2O	4.85	4.01	3.81	4.19	3.43	3.81	4.33	4.37	3.74	4.40	3.93	4.00	3.93	3.67	3.76
K2O	2.09	1.57	1.74	1.80	1.58	1.78	1.81	1.76	1.66	1.79	1.69	2.00	1.95	1.83	1.87
P2O5	1.12	0.82	0.87	0.92	0.69	0.91	0.72	0.71	0.85	0.94	0.88	0.70	0.64	0.89	0.64
LOI §	1.35	0.72	1.25	2.27	1.31	1.26	0.45	0.75	0.53	0.77	1.55	2.22	1.27	0.36	0.57
TOTAL	99.22	99.45	99.82	99.97	99.84	99.51	100.14	100.14	100.18	100.06	99.88	101.31	100.22	99.43	99.28
Sc	21	20	17	15	18	16	13	14	16	13	16	18	17	17	15
V	132	175	257	180	304	227	236	214	257	186	241	192	191	193	207
Cr	5	6	7	6	10	8	7	6	7	5	6	6	7	5	7
Ni	11	6	24	11	22	38	4	<3	14	<3	7	<3	<3	<3	<3
Co	24	36	40	33	73	44	45	36	48	29	37	25	26	26	26
Cu	7	20	12	11	23	16	1	9	18	8	12	7	9	8	8
Zn	169	117	151	135	181	135	145	147	131	145	163	158	157	142	154
Rb	40	23	36	35	31	35	37	31	33	33	31	38	39	36	36
Sr	906	844	870	919	741	815	814	873	795	914	907	950	940	913	913
Y	163	41	64	55	245	98	35	36	40	45	61	32	35	72	38
Zr	472	376	334	385	324	347	349	366	319	373	353	384	383	355	369
Nb	49	39	45	45	42	45	45	43	43	44	42	49	49	45	48
Ba	307	296	555	741	520	1111	511	457	502	480	506	621	597	539	548
Pb	5	3	4	<2	<2	3	3	4	4	4	4	4	4	4	3
Th	3	4	3	3	3	3	3	2	3	3	3	4	4	5	3

Waianae Volcanics, Palehua Member cont.

	PW-43	PW-52	PW-53a	PW-53b	PW-54	PW-57	PW-58	PW-62	PW-67	PW-68	PW-72	PW-74	PW-78	PW-79	PW-80
SiO2	48.65	49.64	46.74	47.43	47.55	48.28	46.75	47.82	47.83	47.50	47.24	49.07	47.81	47.36	49.60
TiO2	3.75	3.29	4.27	4.13	4.15	3.90	3.97	3.97	4.17	4.08	4.17	3.49	4.04	4.01	3.32
Al2O3	16.16	15.97	15.23	15.48	15.55	15.41	15.92	14.97	15.45	15.12	15.29	15.31	15.18	15.91	15.68
Fe2O3*	13.94	12.67	14.78	14.52	14.46	14.50	14.88	14.31	14.68	14.58	14.80	13.62	14.60	14.60	13.29
MnO	0.16	0.17	0.17	0.17	0.18	0.17	0.21	0.18	0.14	0.15	0.16	0.18	0.17	0.15	0.19
MgO	3.28	3.55	4.71	4.39	4.23	3.82	4.05	4.72	3.41	3.91	3.64	4.37	4.07	3.53	3.37
CaO	6.11	6.82	7.64	6.99	7.09	6.83	6.30	8.11	7.15	7.70	7.67	7.38	7.23	6.85	5.68
Na2O	3.46	4.00	2.97	3.13	3.23	3.28	3.28	3.88	3.95	3.92	3.93	4.14	4.28	4.30	4.60
K2O	1.75	1.87	1.42	1.51	1.50	1.58	1.67	1.37	1.46	1.45	1.44	1.69	1.53	1.41	1.85
P2O5	0.77	0.99	0.72	0.63	0.63	0.82	0.85	0.70	0.75	0.73	0.73	0.89	0.79	0.72	0.95
LOI §	1.79	0.50	0.69	0.81	0.80	0.94	1.66	0.18	1.41	1.01	1.20	0.18	0.99	1.82	1.77
TOTAL	99.82	99.47	99.34	99.20	99.37	99.53	99.54	100.24	100.41	100.16	100.26	100.32	100.68	100.67	100.30
Sc	19	15	19	19	18	20	21	19	20	21	20	15	19	20	16
V	263	205	281	250	251	303	317	364	331	313	344	253	327	286	228
Cr	<2	5	4	5	6	9	9	50	20	17	20	8	11	40	7
Ni	6	<3	12	4	6	16	16	57	104	77	85	17	25	40	9
Co	27	24	40	33	34	33	38	42	42	44	43	29	36	32	31
Cu	15	9	17	15	15	27	27	29	30	32	33	16	23	30	16
Zn	135	160	143	140	137	142	145	160	284	138	167	134	140	144	160
Rb	35	34	23	26	26	32	34	25	29	28	27	24	30	27	34
Sr	810	927	912	922	944	777	726	773	801	858	803	778	857	825	777
Y	96	54	46	37	36	63	178	45	61	258	71	44	52	64	56
Zr	358	399	306	325	324	322	344	284	294	295	300	354	311	283	388
Nb	46	44	35	37	37	42	45	37	38	38	38	45	40	37	48
Ba	576	516	467	459	484	483	518	445	441	1662	512	534	664	690	574
Pb	3	4	2	4	3	2	3	2	3	<2	<2	4	3	3	3
Th	3	4	2	3	3	3	4	3	4	3	3	4	2	3	4

Waianae Volcanics, Palehua Member cont.

	PW-85	PW-94	PW-98	C-170	C-171	C-172	C-173	C-174	C-175	C-176	C-177	C-178	C-179	C-180	C-181
SiO2	47.64	47.27	47.55	46.96	47.82	47.35	47.45	47.89	47.36	47.38	47.16	49.59	49.60	49.30	50.25
TiO2	4.06	3.90	4.01	4.17	3.73	4.03	4.04	3.79	4.00	4.06	4.09	3.24	3.29	3.35	3.06
Al2O3	14.90	15.03	15.06	15.00	15.64	15.22	15.10	15.19	15.01	15.06	15.01	15.93	15.86	15.84	16.36
Fe2O3*	14.49	14.30	14.47	14.60	13.71	14.35	14.30	13.94	14.44	14.49	14.65	12.72	12.83	13.01	12.23
MnO	0.16	0.19	0.15	0.17	0.18	0.17	0.18	0.18	0.18	0.18	0.18	0.17	0.17	0.19	0.18
MgO	4.63	4.18	3.96	5.11	4.61	4.60	4.87	4.15	4.57	4.55	4.67	3.61	3.46	3.77	3.45
CaO	7.89	7.46	7.74	8.13	7.30	7.75	8.01	7.56	7.73	7.74	7.71	6.57	6.79	6.31	6.26
Na2O	3.91	4.06	3.85	3.71	3.92	4.06	3.99	4.04	3.87	3.99	3.89	4.49	4.52	4.43	4.61
K2O	1.44	1.66	1.38	1.38	1.59	1.45	1.44	1.57	1.49	1.47	1.45	1.92	1.89	1.90	2.12
P2O5	0.73	1.00	0.88	0.73	0.84	0.75	0.76	0.82	0.77	0.75	0.75	0.95	0.93	0.94	1.08
LOI §	0.37	1.15	1.28	0.18	0.96	0.71	0.22	1.10	0.91	0.72	0.66	1.49	0.81	0.92	0.95
TOTAL	100.21	100.19	100.33	100.14	100.29	100.45	100.37	100.23	100.36	100.39	100.24	100.67	100.14	99.95	100.54
Sc	19	18	19	15	15	17	15	16	17	17	17	15	13	15	12
V	309	309	330	270	223	269	249	234	269	273	271	173	187	193	178
Cr	17	13	45	6	5	6	4	6	7	6	8	6	6	6	6
Ni	36	25	67	7	7	<3	5	5	4	4	3	<3	<3	<3	<3
Co	36	37	36	37	31	35	34	31	36	34	36	22	25	26	19
Cu	32	30	35	15	14	14	14	11	13	12	11	7	8	9	7
Zn	127	141	138	138	142	144	138	154	150	144	144	141	144	153	149
Rb	30	34	27	23	27	24	24	28	27	26	24	37	36	35	39
Sr	842	830	772	915	885	923	932	877	861	872	874	882	875	886	869
Y	52	45	75	41	47	47	49	107	62	48	45	78	50	84	62
Zr	291	319	286	312	357	318	315	351	327	323	320	391	382	380	429
Nb	37	42	37	35	40	36	36	40	37	37	37	49	48	48	55
Ba	672	929	526	427	487	416	415	461	426	413	420	575	545	582	650
Pb	3	3	2	3	3	3	2	4	3	3	3	4	5	3	3
Th	3	4	2	3	3	3	3	3	3	3	3	3	4	3	4

	Palehua Member cont.		Kolekole Volcanics											
	C-182	WD-222	OW-76	OW-77	OW-78	OW-80	OW-80x	OW-118a	OW-119	OW-120	OW-121	OW-123a	PW-4	PW-10
SiO2	49.78	51.59	46.09	46.38	45.93	45.86	46.80	48.55	46.66	47.99	47.43	47.37	46.23	46.47
TiO2	3.17	2.20	3.24	3.15	2.89	2.92	2.89	2.03	3.15	3.25	2.33	2.97	3.04	3.15
Al2O3	16.12	17.26	13.50	14.37	12.79	13.24	13.34	14.63	13.88	15.86	14.06	12.70	13.83	13.85
Fe2O3*	12.48	9.47	13.96	13.56	14.28	13.51	13.50	13.79	13.64	14.55	13.99	13.87	14.16	14.27
MnO	0.19	0.17	0.16	0.19	0.18	0.18	0.16	0.14	0.12	0.10	0.15	0.17	0.16	0.15
MgO	3.77	2.27	8.61	7.56	9.95	9.96	9.70	7.14	7.82	5.49	8.62	9.23	8.26	7.06
CaO	6.63	4.97	9.08	8.81	8.79	9.16	9.39	8.15	9.06	6.73	8.89	9.59	8.78	8.88
Na2O	4.42	5.39	3.34	2.98	2.88	3.06	3.08	2.80	2.83	3.12	2.51	2.65	2.13	2.91
K2O	2.08	2.49	0.98	1.22	0.97	1.04	1.12	0.66	1.11	1.29	0.76	0.82	1.08	1.09
P2O5	1.06	1.51	0.57	0.72	0.56	0.51	0.52	0.35	0.50	0.48	0.36	0.46	0.91	0.58
LOI §	0.65	2.11	0.60	1.42	1.51	1.06	-0.01	2.51	1.82	2.27	1.04	0.74	0.99	1.63
TOTAL	100.35	99.43	100.13	100.36	100.73	100.50	100.50	100.75	100.58	101.13	100.12	100.56	99.56	100.05
Sc	14	11	23	16	22	11	22	27	21	21	21	25	18	21
V	186	89	290	258	262	291	305	274	266	291	275	276	284	305
Cr	5	5	328	258	491	457	453	517	311	352	339	401	280	339
Ni	4	4	305	221	1070	411	348	468	258	295	316	341	326	293
Co	24	21	65	59	79	84	61	70	71	49	52	74	86	65
Cu	10	7	62	63	431	62	77	103	62	70	75	75	66	64
Zn	141	134	126	116	116	185	226	340	113	131	115	117	155	133
Rb	39	40	17	24	18	14	21	10	21	24	14	14	20	20
Sr	847	772	695	828	648	643	656	436	787	776	552	643	780	775
Y	58	57	27	28	30	1814	293	31	27	22	36	27	87	32
Zr	417	619	207	239	195	185	213	139	230	245	150	186	217	222
Nb	53	61	22	29	24	21	27	16	28	30	17	21	28	28
Ba	690	590	268	368	289	662	336	185	412	408	226	244	724	648
Pb	4	4	<2	<2	3	<2	2	<2	2	3	<2	<2	3	<2
Th	4	5	<2	<2	2	2	<2	<2	<2	<2	<2	<2	3	<2

Kolekole Volcanics, cont.

	PW-17	PW-19	PW-21	PW-24	PW-29	PW-31	PW-34	PW-39	PW-40	PW-41	PW-42	PW-47	PW-47b	PW-47c	PW-48
SiO2	48.28	47.82	47.27	48.11	47.04	47.24	48.19	47.22	47.52	47.74	47.23	48.11	48.16	48.21	48.30
TiO2	2.32	2.81	2.85	2.90	3.14	2.82	3.08	3.02	2.82	2.85	2.98	2.41	2.44	2.43	2.56
Al2O3	13.33	13.76	13.23	13.26	13.66	13.10	14.12	14.73	13.54	13.88	14.12	13.45	13.43	13.33	13.51
Fe2O3*	13.77	13.27	13.70	13.57	13.98	13.46	14.00	13.58	13.31	13.09	13.47	13.33	13.43	13.38	13.13
MnO	0.15	0.19	0.15	0.15	0.17	0.13	0.12	0.14	0.15	0.15	0.15	0.16	0.16	0.18	0.16
MgO	8.57	7.77	8.67	8.72	8.90	9.84	7.07	7.65	8.86	7.91	7.67	9.85	9.72	10.01	9.61
CaO	9.34	8.67	8.98	9.20	8.97	8.86	7.92	8.31	9.26	9.08	9.10	8.65	8.86	8.67	8.79
Na2O	2.72	3.12	2.82	2.76	2.53	2.71	2.96	2.19	2.21	2.27	2.29	2.16	2.28	2.35	2.45
K2O	0.57	1.16	0.91	0.92	1.13	0.82	0.94	1.03	0.97	1.01	1.01	0.81	0.84	0.82	0.95
P2O5	0.34	0.61	0.48	0.37	0.49	0.38	0.37	0.41	0.39	0.44	0.50	0.29	0.27	0.29	0.32
LOI §	1.25	0.73	1.10	0.24	0.19	0.85	1.39	1.30	0.54	1.09	0.94	0.77	0.49	0.65	0.35
TOTAL	100.64	99.90	100.16	100.19	100.21	100.21	100.17	99.59	99.56	99.51	99.45	99.99	100.08	100.31	100.14
Sc	25	21	24	24	20	23	27	20	21	19	21	20	21	21	23
V	260	255	274	286	270	272	322	279	278	285	276	244	241	257	268
Cr	393	328	404	422	319	433	479	305	417	382	286	409	420	429	416
Ni	304	490	329	622	260	354	406	225	324	349	244	313	330	322	334
Co	63	69	70	69	55	85	87	61	75	77	52	56	55	63	62
Cu	82	75	84	76	69	75	66	79	82	76	65	62	71	87	56
Zn	118	315	126	177	113	115	194	179	117	110	107	113	188	265	179
Rb	9	24	18	17	22	17	15	19	20	20	20	16	15	15	18
Sr	484	816	657	659	743	629	671	641	655	644	719	523	551	532	602
Y	25	44	31	42	29	100	41	256	50	84	31	41	59	229	204
Zr	135	220	184	183	235	164	195	206	191	205	203	169	169	170	190
Nb	15	26	22	22	29	20	24	23	22	24	23	18	18	18	21
Ba	174	2604	275	411	343	371	314	297	296	293	310	241	271	285	285
Pb	<2	<2	<2	<2	<2	<2	<2	3	<2	3	<2	<2	3	<2	2
Th	<2	<2	<2	<2	3	<2	<2	2	<2	2	2	<2	<2	<2	<2

Kolekole Volcanics, cont.

	PW-60	PW-61	PW-65	PW-66	PW-69	PW-70	PW-71	PW-75	PW-77	PW-81	PW-83	PW-88	PW-89	PW-93	PW-95
SiO_2	47.90	46.61	46.56	46.76	46.33	47.34	47.51	48.23	49.18	48.68	48.46	47.43	46.43	46.59	47.20
TiO_2	2.50	2.81	3.09	2.84	3.14	2.84	2.87	2.70	2.56	2.67	2.65	2.96	2.38	2.98	2.14
Al_2O_3	13.30	13.10	13.68	14.03	13.62	13.91	13.96	14.14	14.05	14.33	14.27	14.66	12.22	13.98	11.85
Fe_2O_3*	13.31	14.55	14.16	13.81	14.13	13.65	13.83	13.27	12.86	13.02	12.89	13.38	13.98	14.87	13.90
MnO	0.16	0.15	0.16	0.17	0.17	0.16	0.15	0.20	0.16	0.16	0.14	0.17	0.15	0.16	0.15
MgO	10.01	9.32	9.08	8.37	8.93	8.67	8.57	7.66	7.63	7.37	7.65	6.45	12.02	7.44	11.33
CaO	8.58	8.41	8.90	8.58	9.20	8.85	8.77	9.15	9.28	9.15	9.26	8.37	8.96	8.77	9.18
Na_2O	2.03	2.76	2.80	3.18	2.95	3.08	3.08	3.13	3.10	3.24	3.23	2.96	2.50	3.25	2.41
K_2O	0.90	0.95	1.05	1.10	1.08	1.10	1.10	0.78	0.70	0.74	0.75	1.07	0.74	0.95	0.73
P_2O_5	0.35	0.51	0.56	0.55	0.58	0.56	0.56	0.44	0.40	0.42	0.42	0.45	0.28	0.60	0.33
LOI §	0.50	1.35	0.55	1.04	0.28	0.16	0.28	0.78	0.58	0.83	0.66	2.02	0.39	0.95	1.24
TOTAL	99.55	100.51	100.60	100.43	100.40	100.32	100.67	100.47	100.49	100.61	100.40	99.92	100.04	100.54	100.47
Sc	21	22	20	17	19	19	20	19	21	21	19	20	25	18	23
V	271	268	268	259	270	246	258	251	266	256	260	291	300	285	278
Cr	426	498	326	297	314	302	332	326	324	293	297	343	630	262	697
Ni	313	962	333	311	269	286	308	295	290	246	235	320	574	321	680
Co	58	64	60	82	58	55	53	67	53	51	50	100	68	79	66
Cu	74	378	64	60	67	79	79	71	78	66	73	72	59	59	80
Zn	110	119	117	128	115	115	115	126	122	114	113	147	136	129	114
Rb	18	19	18	20	19	21	21	12	11	12	12	19	14	19	15
Sr	563	637	727	770	761	767	760	634	556	577	564	630	521	635	459
Y	54	32	64	55	32	33	39	42	30	30	38	488	28	162	32
Zr	183	229	225	229	223	202	221	171	161	171	171	217	150	191	136
Nb	20	27	26	28	25	23	25	20	18	19	19	24	19	23	18
Ba	248	366	687	356	397	338	351	1013	302	285	254	381	244	380	257
Pb	<2	<2	3	3	<2	<2	4	<2	<2	<2	<2	<2	<2	<2	<2
Th	<2	<2	2	3	<2	2	3	<2	2	<2	<2	<2	<2	<2	<2

Kolekole Volcanics, cont.

	PW-96	PW-97	C-169
SiO2	46.75	46.48	47.13
TiO2	3.01	3.20	3.00
Al2O3	13.31	13.91	13.66
Fe2O3*	14.12	14.34	13.79
MnO	0.16	0.14	0.15
MgO	8.50	7.43	8.77
CaO	9.15	8.86	8.79
Na2O	2.86	2.93	3.20
K2O	0.93	0.98	1.06
P2O5	0.65	0.56	0.57
LOI §	0.84	1.49	0.24
TOTAL	100.27	100.32	100.35
Sc	22	20	19
V	313	290	267
Cr	392	323	353
Ni	403	373	564
Co	63	53	61
Cu	55	66	182
Zn	211	160	136
Rb	18	18	19
Sr	648	685	712
Y	33	31	44
Zr	200	218	232
Nb	21	23	25
Ba	274	306	297
Pb	7	3	2
Th	3	<2	2

APPENDIX II. Table 2. Petrographic Data for Palehua and Kolekole samples.

Palehua Member, Waianae Volcanics

	% OL PHENO	% OL GRMS	% CPX GRMS	% PLG GRMS	% PLG PHENO	% OX GRMS	% OX PHENO	% MCRO XTALN	BIO?	XENO?	XENO SIZE (mm)	OL SIZE (mm)	GRMSS SIZE (mm)	OL PH EQM*	PLG PH EQM	OX PH EQM
OW-55	not available															
OW-102	1	2	15	72	0	9	1	0	N	N	-	0.25	0.04	Y	-	Y
OW-122	5	5	1	55	0	15	10	0	Y	N	-	0.2	0.05	N	-	Y
OW-128	0	10	0	70	0	19	1	0	N	N	-	0.02	0.02	-	-	Y
OW-133	1	9	0	20	1	0	2	70	Y	N	-	0.02	0.001	Y	N	Y
PW-6	0	25	3	17	0	15	0	40	N	N	-	0.02	0.02	-	-	-
PW-8	0	25	3	17	0	15	0	40	N	N	-	0.02	0.02	-	-	-
PW-20	0	15	2	58	2	20	3	0	Y	N	-	0.1	0.02	-	Y	N
PW-28	3	20	2	30	1	25	3	20	Y	N	-	0.5	0.03	Y	Y	N
PW-32	5	10	1	44	5	18	2	15	Y	N	-	0.5	0.02	Y	Y	N
PW-32A	1	14	10	45	0	10	5	15	Y	N	-	0.25	0.02	Y	-	Y
PW-35A	2	15	0	55	0	15	3	10	Y	N	-	0.3	0.03	Y	-	Y
PW-35B	1	19	0	64	1	13	2	0	N	N	-	0.3	0.02	Y	N	Y
PW-37	0	10	10	70	0	8	2	0	Y	N	-	0.1	0.02	Y	-	Y
PW-38	0	5	10	60	0	13	2	10	Y	Y	2	0.2	0.01	Y	-	Y
PW-43	0	5	3	50	0	20	2	20	Y	N	-	0.2	0.1	Y	-	N
PW-52	1	14	0	30	0	19	1	30	Y	N	-	0.2	0.02	Y	-	N
PW-53A	1	14	0	35	0	19	1	30	N	N	-	0.5	0.04	Y	-	Y
PW-53B	0	20	2	38	0	19	1	20	N	N	-	0.2	0.04	Y	-	Y
PW-54	0	15	0	70	0	14	1	0	N	N	-	0.4	0.05	Y	-	Y
PW-57	15	10	10	30	0	14	1	20	Y	N	-	0.4	0.02	Y	-	Y
PW-58	0	2	0	20	0	19	1	58	Y	N	-	0.1	0.01	-	-	Y
PW-62	1	9	0	19	1	29	1	40	N	N	-	0.5	0.01	N	N	N
PW-67	1	9	5	70	0	14	1	0	Y	N	-	1	0.02	N	-	Y
PW-68	5	5	15	53	0	18	2	2	N	N	-	0.4	0.02	Y	-	N
PW-72	5	5	2	20	2	14	1	46	Y	Y	1	0.3	0.02	Y	N	Y
PW-74	2	3	30	40	1	14	1	9	N	N	-	0.5	0.04	N	N	N
PW-78	1	14	3	55	0	19	1	10	Y	N	-	0.5	0.03	N	-	N
PW-79	3	7	20	55	5	15	0	5	Y	N	-	1	0.05	Y	Y	-
PW-80	0	20	0	40	0	19	1	20	N	N	-	0.2	0.04	-	-	Y
PW-85	1	19	5	55	1	18	2	0	Y	N	-	0.2	0.04	Y	N	Y
PW-94	2	8	5	45	0	3	2	35	Y	N	-	0.5	0.001	N	-	N
PW-98	1	19	5	30	2	18	2	23	Y	N	-	0.2	0.02	N	Y	Y
C-170	0	10	10	50	0	18	2	10	Y	N	-	0.2	0.05	-	-	Y
C-171	0	10	10	45	5	18	2	10	N	N	-	0.5	0.05	-	Y	Y
C-172	0	15	5	50	0	15	5	10	N	N	-	0.05	0.02	-	-	Y
C-173	2	8	5	70	0	13	2	0	N	N	-	0.5	0.04	Y	-	Y
C-174	0	10	10	50	0	18	2	10	N	N	-	0.1	0.01	-	-	Y
C-175	0	15	10	45	0	18	2	10	N	N	-	0.05	0.02	-	-	Y
C-176	0	15	10	45	0	18	2	10	N	N	-	0.05	0.02	-	-	Y
C-177	1	14	5	40	0	24	1	15	N	N	-	0.5	0.03	Y	-	Y
C-178	2	8	5	64	1	18	2	0	Y	N	-	0.5	0.03	N	-	Y
C-179	2	8	10	65	0	13	2	0	Y	N	-	0.5	0.02	N	-	Y
C-180	2	13	5	60	0	18	2	0	Y	N	-	0.5	0.04	N	-	Y
C-181	3	2	15	50	10	17	3	0	Y	Y	1	0.5	0.02	N	-	Y
C-182	2	3	10	60	10	7	3	0	Y	N	-	0.5	0.05	N	-	Y
WD-222	20	0	0	70	0	8	2	0	N	N	-	1	0.01	N	-	N

APPENDIX II. Table 2. Petrographic Data for Palehua and Kolekole samples continued.

Kolekole Volcanics

	% OL PHENO	% OL GRMS	% CPX	% PLAG	% PLG PHENO	% OX GRMS	% OX PHENO	% MCRO XTALN	BIO?	XENO?	XENO SIZE (mm)	OL PH SIZE (mm)	GRMSS SIZE (mm)	OL PH EQM	PLG PH EQM	OX PH EQM
OW-76	10	20	0	50	0	20	0	0	N	N	–	0.5	0.05	Y	–	–
OW-77	5	20	15	40	0	20	0	0	Y	N	–	1	0.05	Y	–	–
OW-78	10	20	10	50	0	9	1	0	N	Y	20	1	0.02	Y	–	Y
OW-80	10	10	10	50	0	15	5	0	N	N	–	1	0.02	Y	–	Y
OW-80X	10	10	10	50	0	15	5	0	N	Y	10	1	0.02	Y	–	Y
OW-118a	5	5	15	65	0	10	0	0	N	N	–	0.5	0.05	Y	–	–
OW-119	5	15	15	50	0	15	0	0	N	N	–	2	0.05	Y	–	–
OW-120	3	27	15	40	0	15	0	0	Y	Y	15	0.5	0.01	N	–	–
OW-121	2	23	20	40	0	13	2	0	N	Y	5	1	0.01	N	N	N
OW-123a	10	10	20	35	0	20	5	0	Y	N	–	1	0.01	Y	–	–
PW-4	3	7	25	40	0	20	5	0	N	Y	10	1	0.02	N	–	–
PW-10	10	10	15	20	0	18	2	20	N	N	–	2	0.05	Y	–	–
PW-17	10	10	20	40	0	18	2	0	N	N	–	2	0.05	Y	–	–
PW-19	5	10	20	55	0	8	2	0	N	N	–	2	0.05	N	–	–
PW-21	5	15	15	30	0	15	0	20	N	Y	2	2	0.04	N		
PW-24	5	10	20	20	0	18	2	25	N	N	–	1	0.02	N		
PW-29	5	15	30	35	0	15	0	0	Y	N	–	1	0.03	N		
PW-31	5	15	25	15	0	18	2	20	Y	Y	6	4	0.02	N	–	N
PW-34	5	10	10	30	0	15	0	30	N	N	–	0.5	0.03	N	–	–
PW-39	20	0	20	20	0	17	3	20	N	Y	4	1	0.02	N	–	
PW-40	5	10	20	45	0	9	1	10	N	Y	–	2	0.04	N	N	N
PW-41	5	20	5	30	0	12	3	25	Y	Y	10	1	0.02	N	–	N
PW-42	10	10	25	40	0	10	5	0	N	N	–	2	0.03	Y	–	Y
PW-47	20	20	2	48	0	10	5	0	N	N	–	2	0.03	Y	–	Y
PW-47B	20	20	2	48	0	10	0	0	N	Y	5	2	0.1	N	–	–
PW-47C	20	5	2	48	0	5	0	20	N	N	–	2	0.1	N	–	–
PW-48	20	10	15	20	0	8	2	25	Y	Y	10	2	0.04	N	–	N
PW-60	20	5	10	50	0	10	0	0	Y	Y	10	0.02	0.02	N	–	–
PW-61	10	20	10	45	0	15	0	0	N	Y	10	2	0.04	N	–	–
PW-65	10	20	20	45	0	5	0	0	N	N	–	0.5	0.04	N	–	–
PW-66	5	10	20	55	0	8	2	0	N	N	–	0.5	0.04	N	–	N
PW-69	10	5	25	50	0	8	2	0	N	N	–	1	0.05	N	–	Y
PW-70	10	15	20	45	0	5	5	0	N	Y	5	1	0.05	N	–	N
PW-71	5	20	15	50	0	3	7	0	N	Y	10	1	0.05	N	–	Y
PW-75	10	15	15	50	0	10	0	0	N	N	–	1	0.05	N	–	–
PW-77	10	10	20	20	0	10	0	30	N	N	–	1	0.01	N	–	–
PW-81	10	20	10	40	0	5	5	10	N	N	–	1	0.07	Y	–	Y
PW-83	3	22	5	60	0	10	0	0	N	Y	10	0	0.04	N	–	Y
PW-88	10	10	10	35	0	15	0	20	N	N	–	1	0.05	Y	–	–
PW-89	10	15	0	0	0	7	1	67	Y	Y	20	4	0.005	N	–	Y
PW-93	2	18	5	15	0	10	0	50	N	Y	4	0.5	0.02	Y	–	–
PW-95	15	20	0	10	0	9	1	45	Y	N	–	3	0.02	Y	–	Y
PW-96	10	20	0	20	0	9	1	40	Y	N	–	0.5	0.01	N	–	N
PW-97	15	10	3	35	0	10	0	30	N	N	–	0.5	0.02	N	–	–
C-169	20	5	10	45	0	18	2	0	Y	N	–	1	0.01	N	–	N

* EQM = Equilibrium

APPENDIX II. Distinguishing features and notes of thin sections for samples of the Palehua Member and the Kolekole Volcanics.

OW-55	Slide not available
OW-102	Microphenocrysts of olivine and oxides with euhedral outlines. Trachytic flow texture.
OW-122	Very small olivine microphenocrysts altered to iddingsite. Abundant biotite in groundmass and vesicles.
OW-128	Fine grained hawaiite with large oxide microphenocryst, .2 mm size.
OW-133	Abundant dark microcrystalline material with oxides, yet groundmass is nonhomogeneous in texture. Large plagioclase phenocryst with embayed outline.
PW-6	Microcrystalline material in groundmass.
PW-8	Almost identical to PW-6, probably the same flow.
PW-20	Large oxide microphenocrysts with irregular outlines. Biotite in vesicles. Plagioclase microphenocrysts with euhedral outlines.
PW-28	Abundant oxide microphenocrysts and smaller amounts of plagioclase and olivine microphenocrysts.
PW-32	No trachytic texture. Olivine grains are altered to iddingsite, often with skeletal outlines.
PW-32A	Rare microphenocrysts of olivine. Small cpx in groundmass, <.01 size.
PW-35A	Small microphenocrysts of olivine. Biotite in groundmass and vesicles.
PW-35B	Glomerocrysts (xenolith?) of olivine and oxides.
PW-37	Extremely microscopic cpx grains in groundmass. Biotite in vesicles.
PW-38	Biotite in vesicles. Xenolith of olivine and plagioclase, with small amounts of oxide.
PW-43	Coarser than most Palehua hawaiites. Biotite in vesicles. Groundmass cpx very small.
PW-52	Biotite in groundmass and vesicles.
PW-53A	Skeletal olivine microphenocrysts, oxide microphenocrysts, .2 mm, coarser than PW-52, but no biotite.
PW-53B	No trachytic texture, plagioclase less lath-like.
PW-54	Coarser groundmass than most Palehua samples, trachytic groundmass texture.
PW-57	Biotite in groundmass, most olivines larger than groundmass. Abundant olivine with skeletal outlines.
PW-58	Glassy and microcrystalline material composes most of the groundmass. Abundant biotite in groundmass and vesicles.

PW-62	Abundant microcrystalline material in groundmass. Microphenocrysts of olivine, oxide and plagioclase.
PW-67	Olivine phenocryst, perhaps a xenocryst. Biotite in vesicles and groundmass.
PW-68	Some glass in groundmass.
PW-72	Abundant olivine, oxide and plagioclase microphenocrysts. Larger grained glomerocryst of olivine and plagioclase. Trachytic texture, very vesicular. Biotite in vesicles.
PW-74	Needles of oxide and abundant cpx in groundmass. Olivine is also very abundant in groundmass. No trachytic texture. Cpx very conspicuous. A few large plagioclase and olivine microphenocrysts with embayed outlines. A few slightly larger oxide grains.
PW-78	Abundant biotite in vesicles and groundmass. Plagioclase appears as both laths and in microcrystalline material. Fresh olivine in groundmass. Olivine phenocryst, 3 mm, euhedral. Oxide microphenocrysts are embayed or euhedral. Slight trachytic texture.
PW-79	Very similar to PW-74 with more olivine. Rare biotite.
PW-80	Microcrystalline material of oxide and clear plagioclase. Needles of oxide and groundmass plus a few slightly larger oxide grains. Trachytic texture.
PW-85	Large plagioclase phenocryst with rounded outline. Most all of the olivine has been altered to iddingsite. Olivine, cpx and plagioclase groundmass with two sizes of oxides. Trachytic texture.
PW-94	Some groundmass coarser material of plagioclase and olivine with abundant microcrystalline cpx, olivine and plagioclase.
PW-98	Olivine, oxide and plagioclase microphenocryst. Olivine altered to iddingsite. More vesicular than most Palchua samples.
C-170	Slightly coarser than typical Palchua hawaiites and very plagioclase rich.
C-171	Similar to C-170 and 172.
C-172	Plagioclase has 10° extinction angle between twins, approximate composition is oligoclase. Extremely fine grained material around oxides composed of plag, cpx and olivine mixture. Olivine is altered to iddingsite. Large oxides microphenocrysts, euhedral.
C-173	Oxide microphenocrysts, some needle like, .25 mm size, with sharp outlines. Olivine microphenocrysts, .5 mm long, some with skeletal outlines and others with euhedral outlines.
C-174	Euhedral oxide microphenocrysts. Groundmass is fine grained with abundant smaller oxide grains.
C-175	Similar to C-174 except with greater amounts of olivine.
C-176	Very similar to C-175.
C-177	Rare slightly larger oxide grains and olivine grains. Abundant oxide and olivine in groundmass.

C-178	Abundant biotite in groundmass and vesicles. Plagioclase crystals are small needles.
C-179	Very similar to C-178
C-180	Rare biotite.
C-181	Some larger laths of plagioclase. Large microphenocryst of Cpx with oxide inclusions.
C-182	Similar to C-181 without the Cpx phenocryst. Oxide grains are angular and euhedral.
WD-222	Very small olivine microphenocrysts, .2 mm size. Oxide microphenocrysts. Abundant olivine and oxide in groundmass. Vesicular.

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OW-76	Euhedral olivine phenocrysts with altered rims. Olivine in groundmass almost completely altered to iddingsite.
OW-77	Trachytic groundmass texture and slightly coarser grained. A few grains of slightly larger oxide grains in the groundmass.
OW-78	Great amounts of olivine and clinopyroxene phenocrysts, and xenoliths composed of glomerocrysts of opx, cpx, olivine and/or plagioclase. Groundmass of olivine, cpx, plagioclase and oxides.
OW-80	Fresh rock with little iddingsite alteration. Olivines are euhedral.
OW-80X	Identical to OW-80, with a small glomerocryst, possibly a xenolith, of olivine grains.
OW-118a	Olivine phyric, mostly altered to iddingsite. Olivine grains are euhedral or skeletal, and fractured. Plagioclase are laths but do not exhibit trachytic fabric. Very few vesicles. Cpx is present as small elongate prisms.
OW-119	Typical 1 to 2 mm olivine phenocrysts with iddingsite rims. Fractured but euhedral outlines. Olivine in groundmass mostly altered to iddingsite. Oxides are cubic.
OW-120	Xenolith of cpx, plagioclase and olivine. Cpx is fractured and has veining of different mineralogy. No fabric. Phenocryst olivines are euhedral, but some are skeletal or embayed. Vesicles often have zeolites in them, yet very little biotite.
OW-121	Large glomerocryst of of plagioclase, approximate composition is calcic oligoclase. Olivines are almost completely altered to iddingsite, with fractured and embayed outlines.
OW-123A	Plentiful olivine phenocrysts, .5 to 1 mm size, mostly altered to iddingsite. Somewhat trachytic groundmass texture. Rare flecks of biotite.
PW-4	Big glomerocryst of olivine, minute grains almost all completely altered to iddingsite. Olivine phenocryst with altered rims, euhedral and skeletal outlines, and fractured. No trachytic texture but groundmass is very uniform.
PW-10	Olivine phenocrysts have euhedral and skeletal outlines. Olivine grains have considerable alteration to iddingsite. Small plag and cpx in groundmass. Vesicles have needles of possibly calcite in them.
PW-17	Identical to PW-10 except much less alteration to iddingsite of the olivine grains.

PW-19	Olivine grains are almost all fractured with skeletal, euhedral, or embayed outlines. Cpx grains are part of a fine grained groundmass with some trachytic groundmass texture.
PW-21	Slightly embayed olivines, glomerocryst of olivines and oxides.
PW-24A	Slightly vesicular. A few larger oxide grains. Olivines are rounded and altered to iddingsite.
PW-29	Plagioclase glomerocrysts. Olivine grains are resorbed, but very fresh.
PW-31	Olivine xenolith with embayed edges. Also has olivine phenocrysts and oxide microphenocrysts all with rounded outlines.
PW-34	Olivine grains are sharply euhedral or skeletal with iddingsite rims. Oxides are small euhedral grains. Groundmass is somewhat microcrystalline and glassy.
PW-39	Abundant olivine phenocrysts in an olivine poor fine-grained groundmass. Olivine plus oxide glomerocryst.
PW-40	Olivine phenocrysts are often skeletal. Large plagioclase glomerocrysts with embayed and rounded outline.
PW-41	Extremely fine grained groundmass. Glomerocryst of olivine.
PW-42	Unaltered olivine glomerocryst. Abundant oxide microphenocrysts, .1mm size.
PW-47	Coarser grained olivine phyric rock. Odd shaped cpx grains with some microcrystalline material.
PW-47B	Very similar to PW-47 except with less microcrystalline material and a glomerocryst of olivine.
PW-47C	Similar to PW-47 and PW-47C.
PW-48	Pretty rock. Olivine glomerocryst and abundant plagioclase plus olivine glomerocrysts Two sizes of oxides in a fine grained groundmass. Biotite in groundmass and vesicles. Plagioclase in glomerocryst has approximately andesine composition.
PW-60	Large plagioclase glomerocryst. Olivines are rounded and embayed. Glomerocryst of olivine also.
PW-61	Abundant olivine phenocryst. Groundmass plagioclase has approximate composition of oligoclase.
PW-65	Clinopyroxene rich groundmass. Large embayed olivine phenocryst. Groundmass grain size variable.
PW-66	Similar to PW-65 with cpx rich groundmass and embayed olivine phenocrysts. Rims of olivine grains altered to iddingsite. Trachytic groundmass texture.
PW-69	Similar to PW-65 and PW-66.
PW-70	Xenolith of olivine and orthopyroxene. Two sizes of oxide grains. Opx grains surrounded by very fine grained altered olivine grains.

PW-71	Xenolith of olivine, really fine grained glomerocryst of olivine and oxide, almost all altered to iddingsite. Plagioclase and cpx grains conglomerated within the very fine iddingsite glomerocryst.
PW-75	Many needle oxide grains, trachytic groundmass texture.
PW-77	Needle oxide grains, very fine grained groundmass. Lots of microcrystalline groundmass. Olivine phenocrysts are euhedral or embayed with altered rims. Abundant groundmass cpx.
PW-81	Trachytic groundmass texture. Olivine phenocrysts are euhedral with altered rims. Abundant olivine in groundmass.
PW-83	Trachytic groundmass texture. Olivine phenocrysts are euhedral and almost completely altered to iddingsite. Abundant microcrystalline groundmass material.
PW-88	Glomerocrysts of olivine and oxide showing embayed outlines. Oxides in groundmass have needle or euhedral outlines. Extensive alteration to iddingsite.
PW-89	Olivine glomerocryst xenolith. Rare larger oxide grains, some associated with xenolith and others as microphenocrysts. Olivine outlines are embayed or euhedral.
PW-93	A few glomerocrysts of olivine. Olivine phenocrysts are euhedral but altered to iddingsite.
PW-95A	Olivine phenocrysts are euhedral but altered to iddingsite. Microcrystalline groundmass with a few plagioclase needles, olivines and oxides. Rare larger grains of cubic oxides.
PW-97	Abundant groundmass olivine. Olivine phenocryst up to 1 cm, mostly altered to iddingsite. Outlines are euhedral, skeletal or embayed. Some slightly larger oxide grains. No trachytic texture.
PW-98	Olivine microphenocrysts with embayed outlines. Very fine grained groundmass. A few biotite flecks with nice birds-eye extinction.
C-169	Abundant olivine phenocrysts of different sizes, with embayed outlines and alteration to iddingsite.

APPENDIX II. Table 3. Summary of previous age determinations for Waianae Volcano.

SMPL. NO.	UNIT	NEW CONSTANTS	OLD CONSTANTS	POLARITY	AUTHOR	STRAT NO.	LOCATION
HK144	LUALUALEI?		3.8 ± 0.8	UNKNOWN	3	1	I
GA557	UNDIV. LUALUALEI OR KAMAILEUNU		2.95	REVERSED	2	1	U
GA810	KAMAILEUNU	3.36 ± 0.02	3.28	NORMAL	2	1	L
13	KAMAILEUNU		4.05 ± 0.17		1	1	N
			3.15 ± 0.18		1	1	N
7	KAMAILEUNU		3.76 ± 0.28		1	2	N
			3.53 ± 0.26		1	2	N
	best previous date location N		3.6 ± 0.1	NORMAL			
55	UNDIV. LUALUALEI OR KAMAILEUNU		3.12 ± 0.23		1	1	V
54	UNDIV. LUALUALEI OR KAMAILEUNU		3.00 ± 0.16		1	2	V
			2.55 ± 0.14		1	2	V
HK142			4.6 ± 0.6		3	?	V
	best previous date location V		3.1 ± 0.1	REVERSED			
41	KAMAILEUNU		2.61 ± 0.16		1	1	O
			2.61 ± 0.17		1	1	O
31	KAMAILEUNU		3.12 ± 0.15		1	2	O
HK146	KAMAILEUNU		3.0 ± 0.1		3	3	O
HK145	KAMAILEUNU		3.6 ± 0.3		3	4	O
20	KAMAILEUNU	2.84 ± 0.08	2.77 ± 0.08		1	5	O
19	KAMAILEUNU	2.70 ± 0.06	2.63 ± 0.06		1	6	O
15	KAMAILEUNU		1.70 ± 0.15		1	7	O
	best previous date location O		3.0 ± 0.4	REVERSED			
GA560	KAMAILEUNU		3.46	REVERSED	2	1	P
HK119	KAMAILEUNU		3.2 ± 0.2		3	1	Q
HK143	KAMAILEUNU		4.3 ± 1.1		3	2	Q
HK121	KAMAILEUNU		2.3 ± 0.4		3	3	Q
HK122	KAMAILEUNU		2.6 ± 0.5		3	4	Q
	best previous date location Q		2.7 ± 0.2	NORMAL			
GA554	UNDIV. LUALUALEI OR KAMAILEUNU		3.02	UNKNOWN	2	1	R
46	UNDIV. LUALUALEI OR KAMAILEUNU		3.34 ± 0.17		1	1	X
43	UNDIV. LUALUALEI OR KAMAILEUNU		2.95 ± 0.17		1	2	X
	best previous date location X		3.1 ± 0.1	NORMAL			
61	PALEHUA	3.14 ± 0.08	3.06 ± 0.08		1	1	K
59	PALEHUA	3.18 ± 0.10	3.10 ± 0.10		1	2	K
GA809	PALEHUA	2.90 ± 0.02	2.83		2	?	K
	best previous date location K		3.0 ± 0.1	NORMAL			
GA556	PALEHUA		2.74 ± 0.04	NORMAL	2	1	M
HK132	PALEHUA		2.4 ± 0.1	UNKNOWN	3	1	T
HK126	PALEHUA		2.4 ± 0.1	UNKNOWN	3	1	W

APPENDIX II. Table 3. Summary of previous age determinations for Waianae Volcano, cont.

SMPL. NO.	UNIT	NEW CONSTANTS			OLD CONSTANTS				AUTHOR	STRAT NO.	LOCATION
52	PALEHUA	2.87	±	0.07	2.68	±	0.06		1	1	Y
					2.90	±	0.12		1	1	Y
48	PALEHUA				3.29	±	0.22		1	2	Y
					3.38	±	0.30		1	2	Y
GA553	PALEHUA				2.76				2	?	Y
	best previous date location Y				3.0	±	0.3	NORMAL			
62	PALEHUA	2.94	±	0.05	2.93	±	0.06		1	1	Z
					2.90	±	0.08		1	1	Z
					2.70	±	0.24		1	1	Z
GA1128	PALEHUA				2.87	±	0.03		2	?	Z
	best previous date location Z				2.8	±	0.1	REVERSED			
56	KOLEKOLE	3.38	±	0.10	3.30	±	0.10		1	1	J
HK124	KOLEKOLE				2.90	±	0.10		3	?	J
	best previous date location J				3.1	±	0.1	NORMAL			

All data from Doell and Dalrymple (1973), and Mankinen and Dalrymple (1979).

Waianae stratigraphy has been changed to that of Sinton (1987).

New age determinations are recalculated using constants recommended by the IUGS Subcommission on Geochronology listed in table 1 of Mankinen and Dalrymple (1979). These new dates are used in the revised polarity time scale.

"best previous date location _" correspond to averages for multiply sampled locations in Doell and Dalrymple (1973).

Author no.s correspond to: 1) Doell and Dalrymple (1973); 2) McDougall (1964), McDougall and Chamalaun (1966), and McDougall and Ur Rahman (1972); and 3) Funkhouser and others (1968).

Stratigraphical number corresponds to stratigraphical relationships where known in the field.

See figure _ for locations, or see Doell and Dalrymple (1973) for further descriptions of locations.

APPENDIX III.

Figure 1. Geologic log of drill core from Well No. 2104-01m, located at approximately 109 m elevation in Makakilo Gulch (see map in Appendix I, Figure 1).

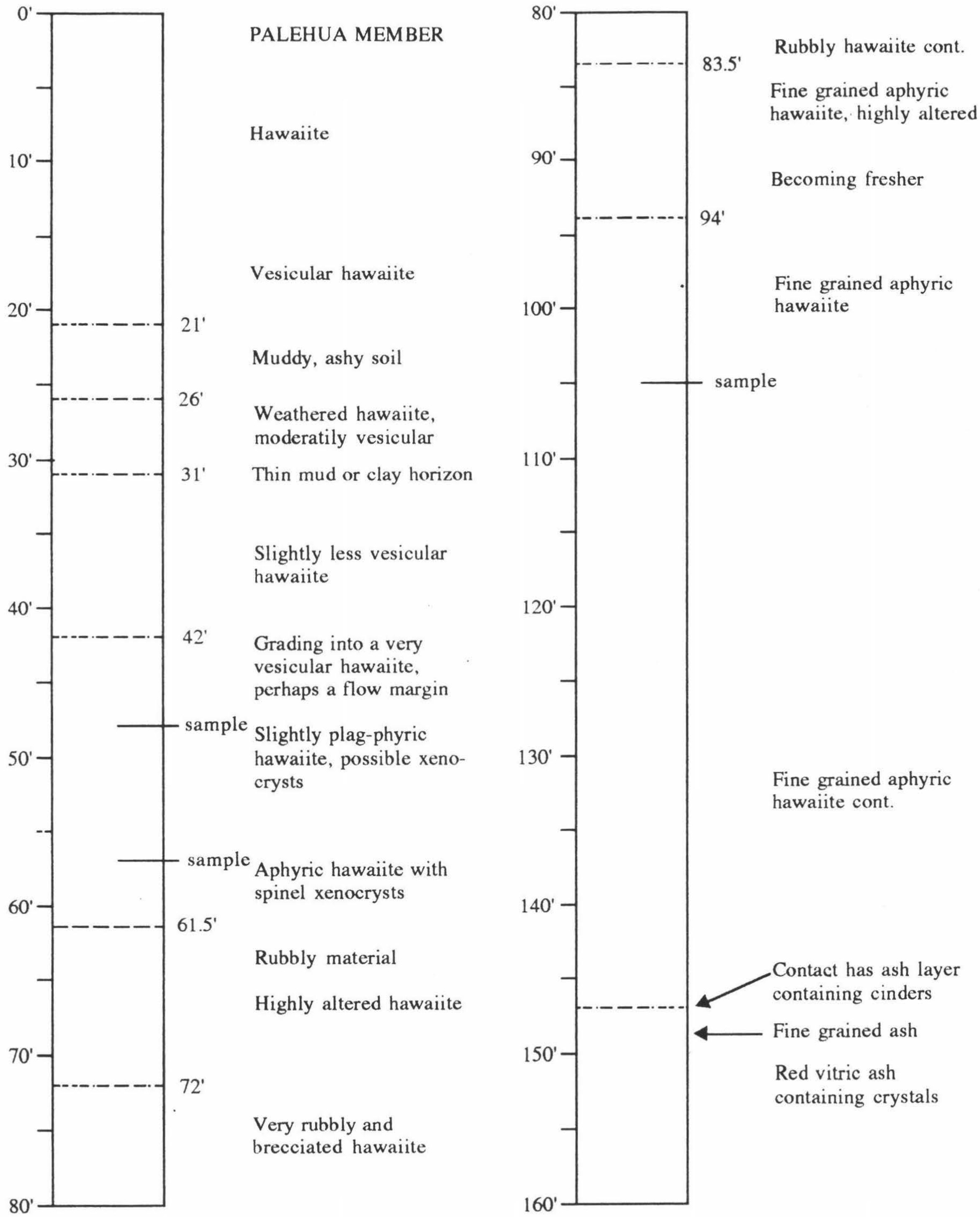


Figure 1. Makakilo Gulch geologic log continued.

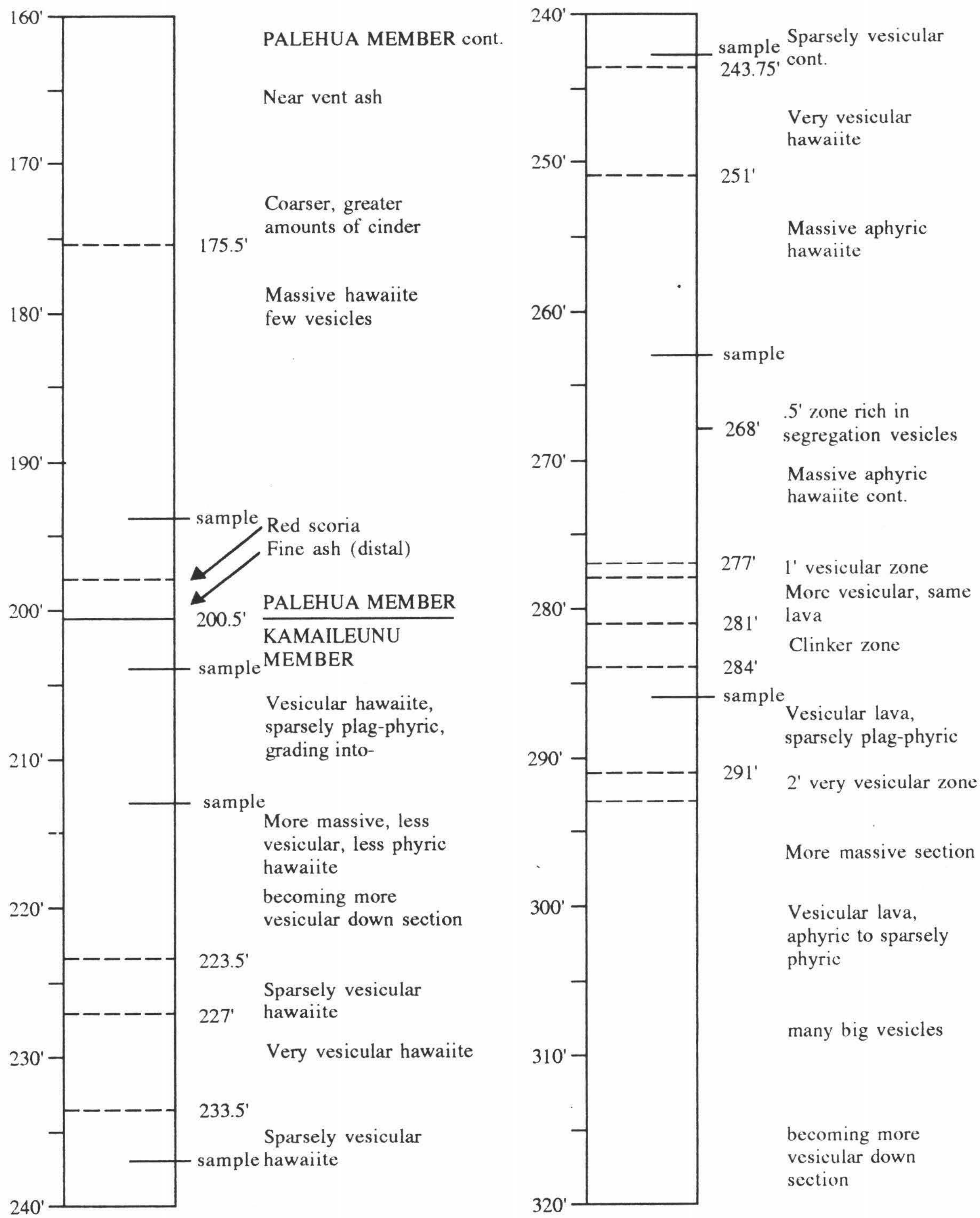
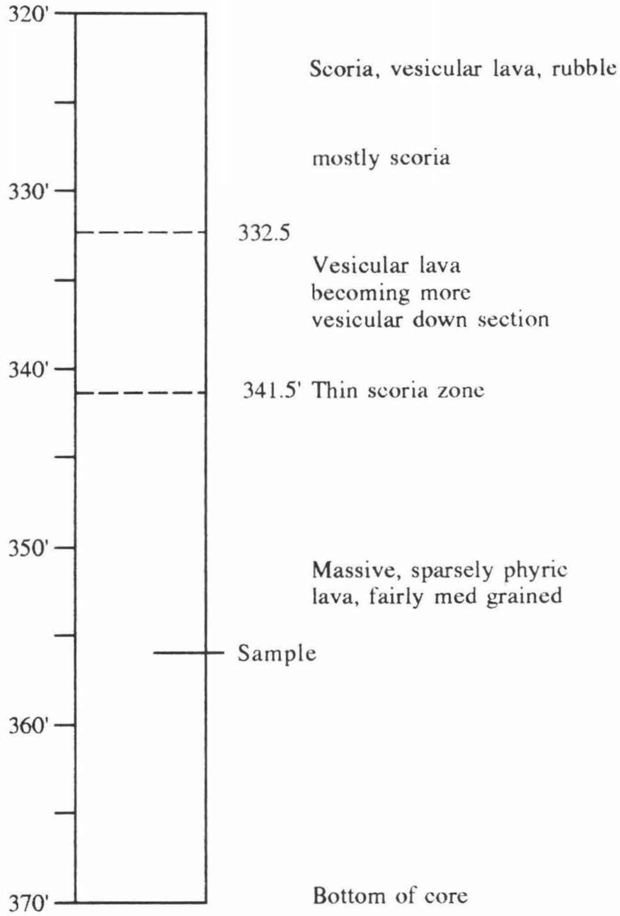


Figure 1. Makakilo Gulch geologic log continued.



APPENDIX III.

Figure 2. Geologic log of drill core from Well No. 2107-01m, located at approximately 134 m elevation in Waimanalo Gulch (see map in Appendix I, Figure 1).

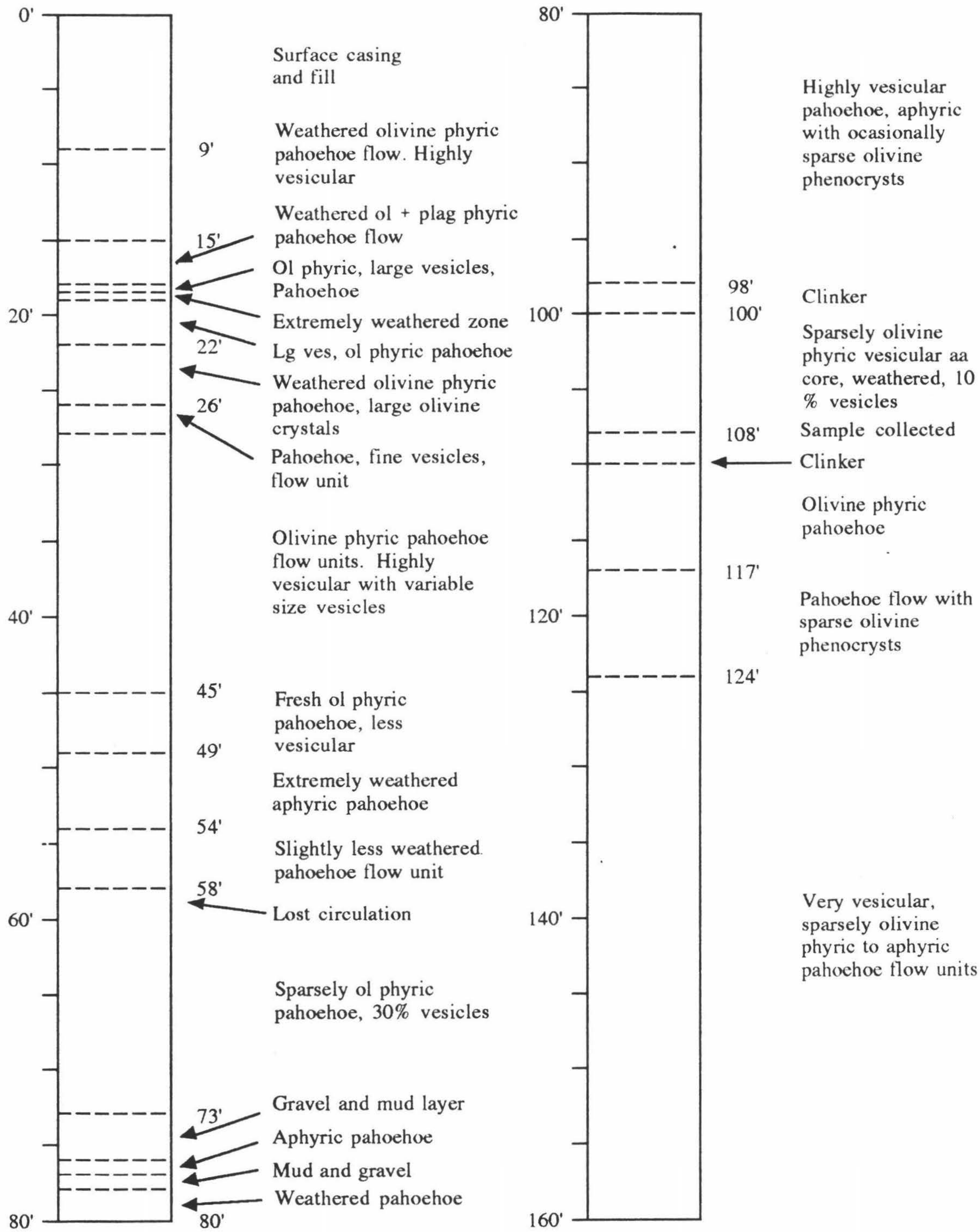


Figure 2. Waimanalo Gulch geologic log continued.

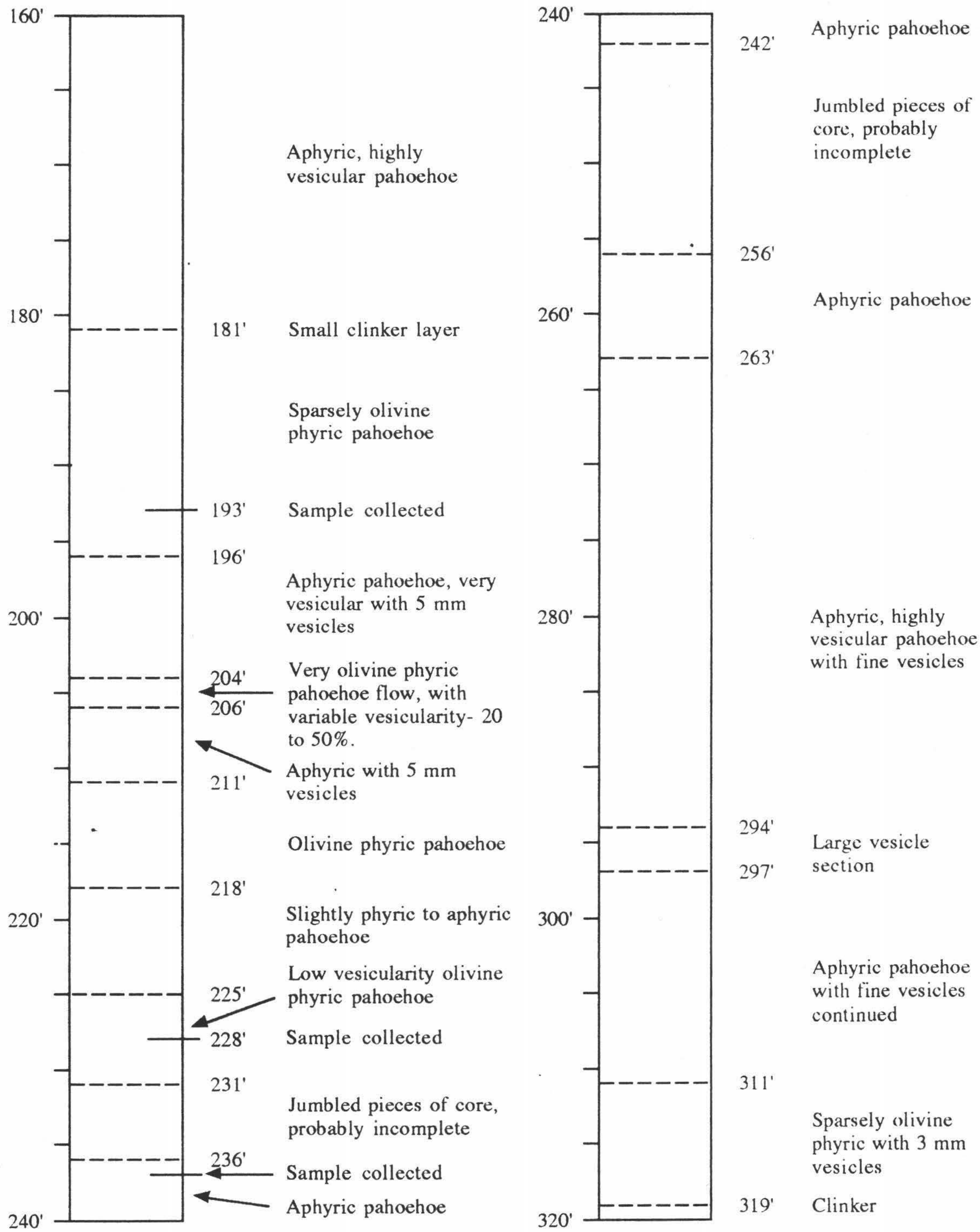
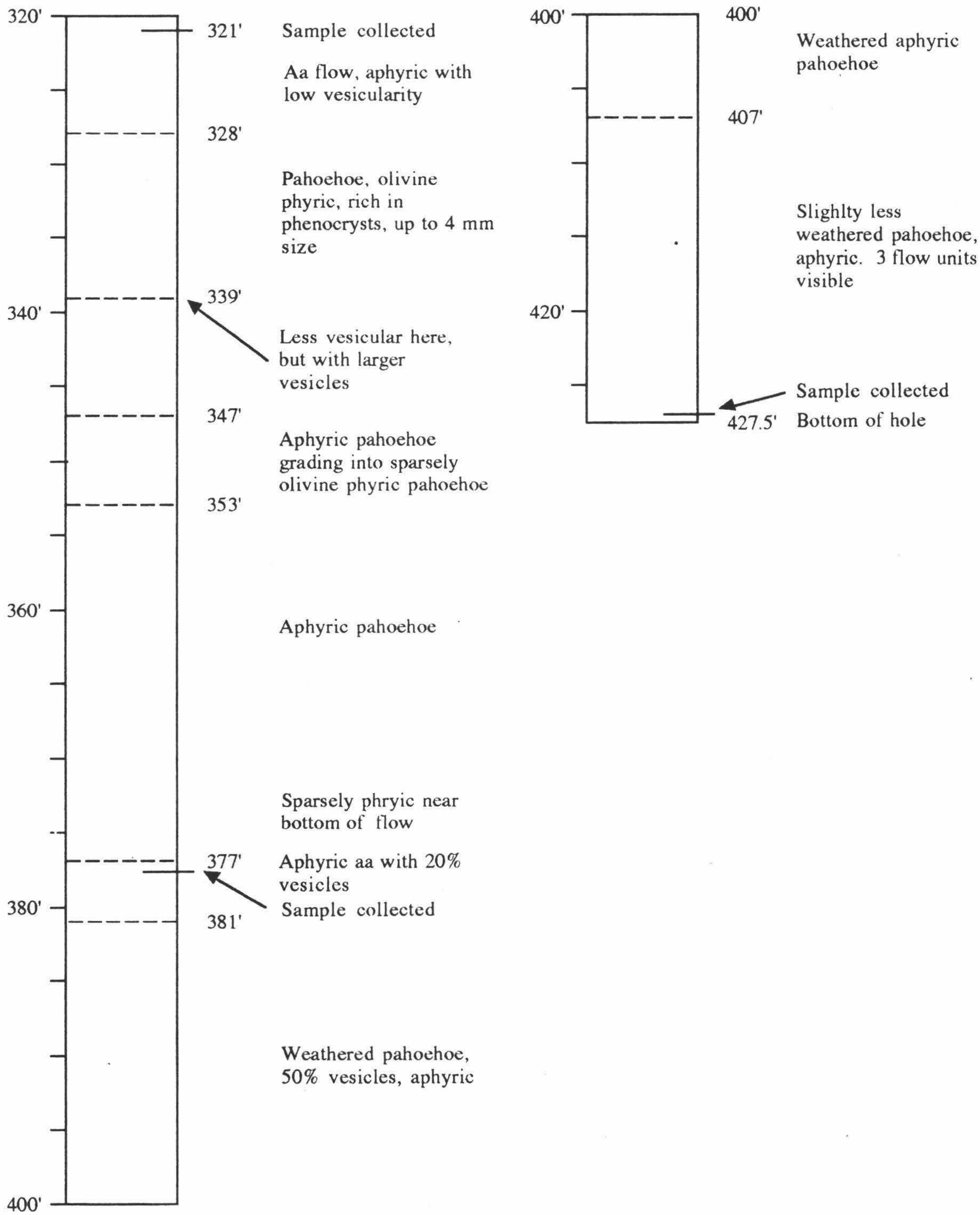


Figure 2. Waimanalo Gulch geologic log continued.



APPENDIX IV. Brief geographical history of the Honouliuli Area.

The Laeloa cones, first named and described geologically by Hitchcock (1849), was the primary locality of this study. These cones lay in the Hawaiian subdivision, or ahupuaa, called Honouliuli. This subdivision underwent different stages of development due to the change of ownership from the early 1800's to around the turn of the century. The different stages of development were documented by Frierson (1973) from a botanical perspective. Before the early 1800's, vegetation included indigenous forest cover down to about the 1000 foot elevation, from ohia, banana, ginger, koa, sandalwood and kukui on the wetter windward side and wiliwili, ohe, and maile on the leeward side. There were also pockets of sandalwood trees down to about 300 feet elevation on the windward side. Below these elevations there were grasslands. In the early 1800's almost all of the sandalwood forest was harvested for fuel. After the Great Mahele (arond 1850), where land ownership was divided amongst the children of the chiefs, parcels of land were rented to various ranchers until Campell purchased the land in 1877. The area was heavily grazed during this time with cattle and goats which led to the destruction of what was left of the forest and understory. This overgrazing led to erosion and later introduction of foreign species which overtook weaker indigenous grasses and shrubs. The gulches once used for raising taro were now left fallow or used to grow rice by immigrant workers.

By the end of the 1800's, most of the forest was destroyed up to the ridge at Palehua. The land owner at the time, von Holt, started a replanting project which reforested the area above 1500 foot elevation. Unfortunately, mostly introduced species were planted. At lower elevations, sugar and pineapple agriculture was beginning to take shape. Plowing techniques were incorporated to increase erosion to bring better topsoil down to the Ewa plain for increased sugar and pineapple production.

There were no large scale changes to land use for much of the period between the beginning of this century to 1975. Sugar cane and pineapple were grown on the lower elevations, cattle grazing on the steeper middle elevations and the upper forest was set aside as a forest preserve in 1925.

During the industrialization and growth of Oahu, much gravel and quarry rock was needed for building materials and pavement. Puu Palailai, Puu Makakilo, Puu Kuua and Puu Kapolei were extensively quarried because of the fresh 'blue' rock available from the thick flow tongues emanating from the cones. The quarrying has radically altered the appearance of Puu Kapolei, where there once was considerable cinder now rest an archery park, and Puu Palailai, where there is now a large landfill being reclaimed.

At present, the area is once again undergoing a rapid transformation. Local government and developing firms have decided to create a "second city" to Honolulu, developing the cane fields surrounding Puu Kapolei as the business district, and surrounding the town with suburban residences. Golf courses, malls, and hotels are also being constructed at a great rate in the surrounding areas. The sugar cane industry and pineapple industry has not been greatly profitable compared to foreign sources in recent years, and slowly the industries are being phased out.

The town of Makakilo, a community fed by one boulevard winding its way up the hill, has doubled in size during the 3 years of this study. It has grown mostly out of expectations of the second city. The initial bulldozing allowed the authors to have brief exposure to some fresh rock, only to be buried forever by the developments.

Further housing and golfcourse devopment is planned for this area. To see how the use of the land will change will be interesting, for the already established Barbers Point Air Force station, Cambell industrial park, and the Waimanalo Dump will have to be encorportated into a master plan. Of all the regions in Oahu, this hot and dry region has the best quarry rock resource. It also has the beauty of the Palehua forest reserve and surrounding peaceful grass lands, with spectacular views of the Koolau Range and of Honolulu. My hopes are for the best utilization of this land, yet it may be already too late.