STRUCTURE AND PETROLOGY OF THE
DIKE SWARM OF WAIANAE VOLCANO

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ABSTRACT

Dikes of Waianae volcano show common orientation in the northeast rift zone and the south rift zone and are randomly oriented in the caldera region. The caldera region is roughly 14 x 7 km in dimension, but at any given time there was propably a smaller caldera.

Of 85 Chemical analyses, there are 79 tholeiitic and 6 alkalic samples. The tholeiitic samples fall into a strongly tholeiitic and a mildly tholeiitic group.

Four of the dikes have a high silica, low magnesia composition of a type not yet found in flows. The can be classified as tholeiitic andesites and are not related to the icelandite and rhyodacite flows of Waianae volcano. Rather, they probably formed by crystal fractiuonation of basaltic magma.

All the differentiated samples and the majority of the mildly tholeiitic basalts come from dikes in the caldera region. The strongly tholeiitic dikes are concentrarted in the rift zones.

I. INTRODUCTION

A. The problem

The purpose of this work is to study the dike swarm of Waianae volcano in order to understand the relationship between its structure and petrological evolution.

B. An overview of the field area

Waianae is the western of two volcanoes that form the island of Oahu. It is in the lee of Koolau, the other Oahu volcano, so is fairly dry; the amount of vegetation and chemical weathering are less than on the Koolau Range. Radiometric dating (Doell and Dalrymple, 1973) indicates that Waianae's subaerial activity, about 3.8 to 2.4 m.y. ago, was nearly complete before Koolau broke the surface of the ocean; the oldest date from Koolau is 2.6 m.y. Significant erosion occurred before Koolau grew tall enough to shelter Waianae from the tradewinds.

Much of the land of Waianae Range is military or watershed reservation; there is good access by road and foot trail and few buildings or other artificial covers to outcrops. It is not nearly so well-studied as Kilauea or Mauna Loa, but early volcanic history is more easily observed in the deep valleys of leeward Waianae than at either of those active volcanoes, and two classic papers on Hawaiian petrology (Macdonald and Katsura 1964 and Macdonald 1968) included much work on Waianae. The two above-mentioned works have provided an understanding of the volcano through its flows; I aimed to discover what other information could be gained from studying its dikes.

C. Previous investigations

1. Geology

One of the earliest geological investigators of the Hawaiian Islands was James D. Dana, who was a member of the United States Exploring Expedition of 1838-1842 under Charles Wilkes. He recognized that the two mountain ranges on Oahu are remnants of two volcanoes. In describing the morphology of the Waianaes, he said, "These mountains are very abrupt towards the southwest...But to the eastward and northward of east, the slopes are gradual and they pass into the gentle declivities of the dividing plain." (p. 250). He spent some time observing Kolekole Pass, the lowest pass over the range, discovering the coarse breccia which fills the pass and tops some hills and ridges, and also noting the dike swarm outcropping there. He decided that a large part of the "abrupt" southwest side of the volcano had been lost and credited the loss to subsidence.

Annexation in the last decade of the nineteenth century brought increased interest from American geologists, and in 1900 C.H. Hitchcock published the first detailed look at the geology of Oahu. As the population of Oahu grew, the search for water prompted more geological investigations. In the early 1930s H.T. Stearns mapped Oahu, and published the Territory of Hawaii Division of Hydrography Bulletin 1, Geology and Groundwater Resources of the Island of Oahu (hereafter identified as Bulletin 1) (Stearns and Vaksvik, 1935). The map was engraved and published in 1939 as part of Bulletin 2; the Waianae portion of it was updated by G.A. Macdonald for the 1940 Bulletin 5 by separating the uppermost formation of the volcano from the lower ones. J.M. Sinton (1979) re-examined Lualualei Valley (the caldera area) but for the rest of Waianae, Stearns' and Macdonald's work remains unsuperseded.

2. Petrology

Dana (1849) noted that Waianae is a basaltic volcano, with flows being generally vesicular and feldspar-phyric. A.B. Lyons studied weathering processes and analysed nine fresh Hawaiian rocks, two of them from Waianae, as well as six "rotten lavas and tufas" (p.427) and ten soils. In 1915 Cross produced the first comprehensive work on the petrography of these islands. He explained (p.7)

> Although many geologists have visited these islands, interest has attached largely to the volcanic phenomena, and there is a singular dearth of petrographic literature concerning the lavas themselves. The reason for this dearth I did not appreciate until I had visited the islands. The lavas of Hawaii are generally referred to as basaltic. Many of them are plainly so, containing olivine and augite in prominent crystals. By far the larger number of rocks are, however, chiefly black and aphanitic and of seemingly few varieties. The collector, be he layman or petrographer, is unfortunately likely to assume that they are basaltic and to limit his collection to a few marked varieties. The truth is that there is a very considerable range in composition in the lavas of Hawaii, and systematic study will add many types to those now known.

Cross examined both flows and dikes from Waianae, and divided them into two categories: olivine-plagioclase basalt (consisting of some twenty samples) and bronzite-bearing basalt (of which he had two examples definitely from Waianae and one from the saddle between Waianae and Koolau).

G.A. Macdonald included an extensive petrographic description of Waianae rocks in Bulletin 5. He decided that the lower and middle members of the volcano primarily consist of olivine basalt, with some olivine-free basalt. The upper member, he wrote, is chiefly "basaltic andesite" frequently containing biotite (he later renamed the rocks hawaiite and mugearite instead of andesite: Macdonald, 1960).

D. Methods of investigation

1. Field work

The field work for this project took approximately three months, covering military, state-owned, and privately-owned land. It concentrated on the back and sides of Lualualei Valley because that was the volcano's eruptive center; many dikes are exposed there. Field work also included the ridges north and south of the valley--chiefly the leeward side of the central ridge because that is drier and thus better exposed than the windward side. The owners of Makaha and Keaau Valleys did not permit access to their land. I occupied 388 stations; measuring orientations of 369 dikes and taking samples of 329 dikes. For some dikes I sampled both chilled margins and more coarsely-crystalline interiors. At some stations, I measured an orientation but took no sample because of the extremely weathered condition of the dike; at others I took a sample but did not measure the orientation because the dike orientation was so irregular that a measurement would be meaningless.

2. Laboratory methods

a. Thin Sections

I examined thin sections of 322 dikes. Results are in the section titled Petrography.

b. Whole-rock composition

These are the criteria for selecting the twenty seven rocks for complete whole-rock analysis: (1) Distribution--the samples represent all portions of the field area. (2) Petrography--a) thin sections of the rocks have a minimum of post magmatic alteration. b) with two exceptions the rocks have less than 5% (by volume, based on point counting of thin sections) phenocrysts. The two exceptions are WD-305 with 13% olivine, and WD-315 with 6% plagioclase and 0.5% olivine; these two rocks separated into whole-rock and matrix-only splits. For the rest of the rocks, those phenocrysts that do occur are in petrographic equilibrium with the matrix. The purpose of the concern about phenocrysts is to try to get compositions which are, as nearly as possible, liquid compositions. (3) Sample size--The sample collected is large enough (considering grainsize, phenocryst content, and general macroscopic homogeneity) that it is representative of the flow.

For these 27 rocks, the oxides SiO_2, TiO_2, Al_2O_3, Fe_2O_3 (total iron), MnO, MgO, CaO, K_2O, P_2O_5, and SO_2 were analyzed by X-ray fluorescence (XRF). Analyses were done on glass discs made from the crushed sample fused with a flux of lithium metaborate, lithium carbonate, lanthanum oxide, and sodium nitrate, following the method of Norrish and Hutton (1969). Abundances of the trace elements Sc, Ni, Cu, Zn, Sr, Y, Rb, Zr, and Nb were also determined by XRF, using a pressed powder pellet after the methods of Norrish and Chappell (1977). Volatiles were extracted by heating: H_2O^- at 110°C, and percentage calculated by weight difference of the sample; H_2O^+ and CO_2 at 1070°C, collected in glass tubes filled with absorbing reagents, the percentages determined by weight difference of the tubes. V. Greenberg analyzed the samples for Na_2O, Ba, V, and Cr using atomic absorption . FeO was determined by titrating with ferrous ammonium sulfate; FeO/Fe_2O_3 was computed using this number and the total iron as determined by XRF (Table I).

c. Glass Composition

Sixty of the dikes sampled have glassy margins; the glasses were analysed by microprobe for SiO_2, Al_2O_3, TiO_2, FeO (total iron), MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5. The machine used was an automated 3-spectrometer Cameca microprobe, with accelerating voltage of 15kV, count time of 10 seconds, and defocussed beam of 50 microns diameter. One of the glasses (1.1.42) is from a dike collected by G.A. Macdonald. For each of dikes 354 and 193 the crystalline portion was analysed by XRF and the glassy margin was analysed by microprobe (Table II). Two glass samples were analysed from each of dikes 10 and 162 as a check on instrumental precision (Table III).

In total, there are 91 analyses representing 85 different dikes. The analyses, CIPW norms, and selected geochemical parameters are presented in Appendix 1.

The microprobe analysis of glass is repeatable within about 5% relative (Table III). The most poorly-analyzed oxide is MnO. Na_2O and P_2O_5 are each repeatable to better than 1% relative.

Table I. Analysed iron, and calculated FeO/Fe_2O_3

SAMPLE	Total Fe as Fe_2O_3	analyzed FeO	calculated Fe_2O_3	Fe_2O_3 / FeO
WD21	10.30	4.83	4.93	1.02
WD25	13.62	6.43	6.47	1.01
WD50	11.36	5.16	5.63	1.09
WD60	13.73	8.80	3.95	0.45
WD62	13.94	8.19	4.84	0.59
WD65	12.96	7.48	4.65	0.62
WD88	12.13	7.77	3.49	0.29
WD103	11.72	6.91	4.04	0.58
WD132	12.50	6.44	5.34	0.83
WD134	11.85	6.53	4.59	0.70
WD144	13.71	6.84	6.11	0.89
WD192	11.24	5.10	5.57	1.09
WD193	14.22	9.26	3.93	0.42
WD202	14.26	7.46	5.97	0.80
WD204	14.23	7.30	6.12	0.84
WD222	9.43	3.45	5.62	1.63
WD235	14.25	7.28	6.16	0.85
WD240	12.25	5.60	6.03	1.08
WD241	14.17	9.17	3.98	0.43
WD265	15.93	10.63	4.12	0.39
WD304	12.10	7.40	3.88	0.52
WD305WR	13.07	7.90	4.29	0.54
WD305MX	13.29	7.92	4.49	0.57
WD315WR	11.55	8.25	2.38	0.29
WD315MX	15.14	10.26	3.74	0.36
WD335	11.73	7.75	3.12	0.40
WD342	12.52	6.38	5.43	0.85
WD354	10.69	6.43	3.54	0.55
WD375	12.79	5.42	6.77	1.25

Table II. Comparison between glass and whole-rock analyses

	WD193 ROCK	WD193 GLASS	WD354 ROCK	WD354 GLASS
SiO_2	49.96	51.23	52.23	51.97
TiO_2	3.80	3.96	3.83	3.62
Al_2O_3	12.65	12.75	13.16	13.10
FeO	12.80	13.82	9.62	12.41
MnO	0.22	0.16	0.17	0.13
MgO	5.03	4.66	4.81	4.50
CaO	9.11	9.12	8.90	8.64
Na_2O	2.74	2.92	3.00	2.98
K_2O	0.83	0.87	0.98	1.90
P_2O_5	0.61	0.45	0.77	0.44
Sum	98.14	99.94	97.87	99.69

Table III. Comparison between duplicate glass analyses

	WD10B	WD10C	WD162A	WD162
SiO_2	51.80	52.64	52.64	51.28
TiO_2	2.84	2.77	3.22	3.06
Al_2O_3	13.79	14.01	13.59	13.24
FeO	11.77	10.76	12.54	12.05
MnO	0.22	0.16	0.15	0.16
MgO	5.55	5.74	5.03	5.23
CaO	9.71	10.69	9.01	8.84
Na_2O	2.62	2.61	2.84	2.82
K_2O	0.66	0.66	0.90	0.85
P_2O_5	0.32	0.33	0.36	0.35
Sum	99.28	100.37	100.28	97.88

The comparison between whole-rock and glass analyses is nearly as good as repeatablility between two glass samples (Table II). Na_2O is higher in the probed glass of WD-193 than in the rock analyzed by AA; for WD-354 the two analyses are within 0.02 absolute. There is no apparent problem with Na_2O volatilizing in the defocussed microprobe beam.

P_2O_5 is consistently lower in glass analyses than in whole-rock analyses. This bias is apparent not only in the two rocks analyzed in duplicate, but also when all whole-rock analyses are compared to all glass analyses. Whole-rock P_2O_5 (basalts only) ranges generally from 0.4 to 0.7%; glass P_2O_5 (basalts only) ranges generally from 0.3 to 0.5%. If the glasses were slightly more differentiated than the whole rock (because the glass has none of the crystals that are in the whole rock), P_2O_5 would be higher in the glass than in the whole rock. It seems that the bias is not a result of a true difference between glass and whole rock, but is an analytical discrepancy.

Sample WD-354 is peculiar. There is 1.90% K_2O in the glass, nearly twice the amount of K_2O in the whole rock (0.98%). K_2O in the whole rock is also somewhat higher than the K_2O in most of the other basalts. Each of the three chips of glass showed similarly high K_2O content, and the anomaly persisted when the sample was re-analyzed several hours and several samples after the initial analysis. None of the other samples in the same plastic microprobe mount had anomalously high K_2O. So the anomaly was not the result of a short term variation in the microprobe beam, nor of a fingerprint on the polished surface. The thin section does not show any peculiarities to cause such an anomaly. Weathering normally leaches K_2O from basalts. Maybe this sample was contaminated by a fluid that previously had been enriched in K_2O by passing through other strata. The fluid contacted the glass, on the outside of the dike, more than it did the interior.

With the exceptions noted above, the glass and the whole-rock analyses are sufficiently close that one may examine them as a single group. For the four samples WD-10B, WD-162, WD-193, and WD-354, averages appear in chemical plots (in later chapters). For WD-354, the potassium value is not an average but the lower whole-rock value.

d. Fe_2O_3/FeO Ratio

The analyzed rocks are, in general, petrographically fresh. Still the least-oxidized rock has a ferric-ferrous ratio of 0.29 (WD-315); the most oxidized, 1.63 (WD-222); the average for all 29 analyses is 0.72. Since the CIPW norm calculation is sensitive to Fe_2O_3/FeO, and since this ratio is affected by post-magmatic weathering and alteration, it is desirable to make some assumptions about the oxidation state of fresh samples before doing any manipulations involving normative components. With respect to oxidation state, freshly erupted lava or glass from Kilauea should be a good analog to Waianae magmas. Analyses of fresh eruption products (e.g. Murata and Richter, 1966; Wright, Swanson, and Duffield, 1975) show that the oxidation state varies somewhat with degree of differentiation, but 0.15 is a good average ratio. Normative calculations in this work assume this value.

e. Comparing data sets

The most logical data set with which to compare these analyses of Waianae intrusive rocks would be the analyses of Waianae extrusive rocks by Macdonald and Katsura (1964) and Macdonald (1968). Unfortunately, there seems to be more than the usual amount of interlaboratory discrepancy between their numbers and the results from this study. Tholeiites analysed by Macdonald and Katsura occupy a different field from tholeiites of this study in every oxide or normative component plot examined. Comparison plots were made of rocks analyzed by Macdonald and Katsura and then re-analysed by other workers. Discrepancies were consistent enough that comparisons between numbers from that study and the present study would yield no useful information.

A few Waianae lavas were analysed in the same laboratory as dikes of this study. They are three caldera-filling member flows, four late-stage alkalic flows, and nine samples of rhyodacite and underlying icelandite. Those analyses are included in some plots.

Diller (1982) analyzed West Maui rocks in the same laboratory as the rocks of this study. They are included in some plots.

Helz and Luth have analysed (but not published) a large suite of glasses from Kilauea Iki lava lake drill cores and pumice from fire fountains of the same eruption. Although their analyses were done in a different laboratory and there are no cross-checked samples, there is sufficient overlap of data that where different trends do appear they are probably not the result of analytical bias.

II. BACKGROUND

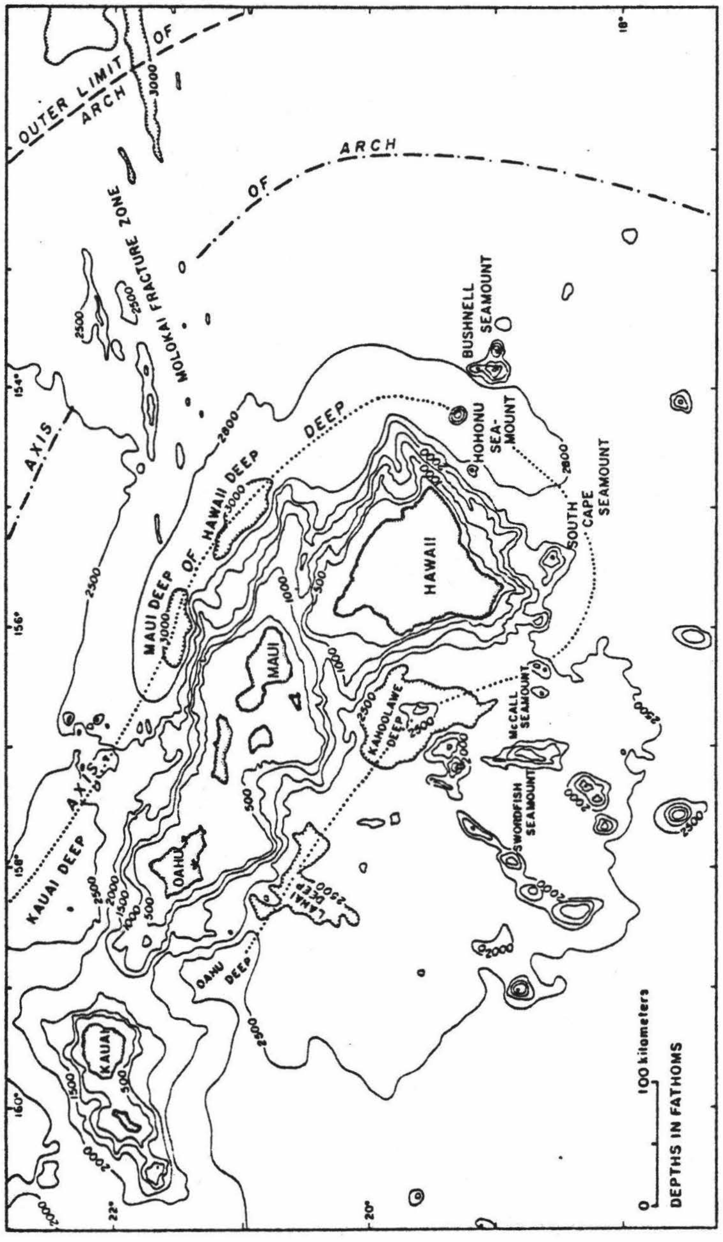
A. Regional structure

The Hawaiian Islands are part of a linear chain of volcanic islands, shoals, and seamounts that crosses the north Pacific from Hawaii Island at $20^{o}N$ latitude to Kanmu Seamount at about $32^{o}N$; the chain bends and continues under the name Emperor Seamounts as far as Meiji Seamount at about $52^{o}N$. Two volcanoes, Kilauea and Mauna Loa, are vigorously active; two others, Hualalai and Haleakala, have had historic eruptions; Loihi Seamount, south of Hawaii Island, is also probably active (Moore et al., 1979).

There is a regular increase in the age of the volcanoes from Loihi towards the northwest. The original Hawaiian residents of the islands noticed that progression, recording it in their stories about the travels of Pele. Dana (1849) was able to confirm to his satisfaction that there was a regular progression in the time of cessation of activity, based on observations on the state of erosion of the islands; he was not so sure about the time of initiation of activity. Later studies using radiometric techniques have reconfirmed and quantified what earlier investigators had concluded, and extended that conclusion to the submarine portion of the chain (e.g. McDougall, 1964; MacDougall and Swanson, 1972; Doell and Dalrymple, 1973; Dalrymple, Clague, and Lanphere, 1980). The most generally accepted explanation for the origin of the Emperor-Hawaii chain is that there is a melting anomaly fixed in the mantle which generates magma more or less constantly; the Pacific plate moves over that anomaly, known as a hotspot, and islands are formed and carried northwestward (Wilson, 1963; Morgan, 1972).

The island chain includes several large structural features (fig. 1). The Hawaiian Ridge is an extensive constructional volcanic mountain range built up from the seafloor, the highest peaks of which extend above the sea surface to make the islands. Seismic studies (e.g. Zucca and Hill, 1980; Zucca, Hill, and Kovach, 1982, Furumoto and Woollard, 1965; Furumoto et al. 1968) indicate that the ridge has an isostatic "root"; oceanic crust, elsewhere about 5 km thick, is 15 to 20 km thick in the neighborhood of the islands. The Hawaiian Deep, partly surrounding the ridge, is well-defined to the northeast of the chain and as it bends around the island of Hawaii; it is less obvious topographically on the southwest side of the ridge. The Deep does not descend below the general abyssal level; rather, it is defined by the Ridge on one side and a gentle upwelling known as the Hawaiian Arch on the other side. The Arch rises about 900 m above the Deep and the abyssal floor (Macdonald, Abbott, and Peterson, 1983). The assemblage of Ridge, Deep and Arch is known as the Hawaiian Swell; it extends 2500 km along the chain from south of the Big Island at least as far as Kure Island, the most northwestern member of the Hawaiian archipelago, and across the chain for about 800-1000 km. An interpretation of the structure is that the volcanic pile produces a load on the lithosphere, which in response flexes downwards over an area somewhat larger than the pile itself. The mantle below the downflexed lithosphere flows and raises the crust slightly, just outside of the downwarped area. The raised area is the arch, and the downwarped portion is the deep. The deep is less clearly expressed on

Figure 1. Map showing the major islands of the Hawaiian chain, with the Hawaiian Ridge, Deep, and Arch. From Macdonald, Abbott, and Peterson, 1983.



OUTER LIMIT OF ARCH
AXIS OF ARCH
MOLOKAI FRACTURE ZONE
KAUAI DEEP
AXIS
MAUI DEEP OF HAWAII DEEP
DEEP
OAHU DEEP
LANAI DEEP
KAHOOLAWE DEEP
KAUAI
OAHU
MAUI
HAWAII
BUSHNELL SEAMOUNT
HOHONU SEA-MOUNT
SOUTH CAPE SEAMOUNT
McCALL SEAMOUNT
SWORDFISH SEAMOUNT
160°
158°
156°
154°
22°
20°
18°
0
100 kilometers
DEPTHS IN FATHOMS

the south side of the ridge due to "infilling of the Deep on the south by Hawaiian volcanic debris delivered from prevailing winds." (Wallin, 1982, p 1.) The axis of the deep lies 80 to 110 km from the shorelines of the islands (Macdonald, Abbott, and Peterson 1983).

The Hawaiian Swell is a single linear feature, but within it the eruptive centers can be divided into parallel or en echelon curved segments. Dana (1849) identified a Kea and a Loa trend in the seven southern islands. His Kea trend consists of Mauna Kea, both Maui peaks, East Molokai, and Koolau; the Loa trend includes Lua Pele (Kilauea), Mauna Loa, Hualalai, Kahoolawe, Lanai, Waianae, and Kauai. He did not identify either Kohala or West Molokai as separate volcanic edifices.

Jackson, Silver, and Dalrymple (1972) rearranged these two series and identified "loci of volcanism" consisting of segments of three to nine edifices along the entire Emperor-Hawaii chain. Their Locus 1 consists of Kilauea, Mauna Loa, Kohala, Haleakala, West Maui, East Molokai; to Locus 2 they assigned Mauna Kea, Hualalai, Kahoolawe, Lanai, West Molokai, Koolau, Waianae, and Kauai. Loihi, now recognized as a volcano of the Hawaiian chain (Moore et al., 1979; Malahoff et al., 1982), lies on Locus 2. Niihau is on Locus 3, which also contains Nihoa and an unnamed seamount between these two islands.

Jackson, Shaw, and Bargar (1972) argued that the orientations of their loci reflect stress fields in the Pacific plate at the time the volcanoes were active. Clockwise stresses produced right-lateral offset of the segments; counterclockwise net stress on the plate caused left-lateral offset.

B Local structure

A Hawaiian volcano is not a radially symmetrical cone with all its eruptions spewing forth from the summit. Rather, it is irregular, often elongate. Its location is defined by an eruptive center, often with a caldera, and the rift zones radiating from it. A rift zone is a curvilinear fissure zone along which eruptions tend to be concentrated. Hawaiian volcanoes commonly have two major rift zones which meet at an obtuse angle and a third minor rift in the external angle. On some edifices they are quite obvious; on others they are sufficiently diffuse or obscure that each worker may identify different numbers and locations of rifts.

Several signs may identify the presence of a rift zone: elongation of the edifice, a topographic ridge, locations of observed eruptions, locations of cinder cones, locations of pit craters, outcrop of a dike swarm, or a geophysical anomaly such as gravity, seismic velocity, magnetic force, or electrical resistivity. The interpretation of geophysical anomalies is based on the assumption that they are caused by intrusive bodies and that these bodies are solidified magma chambers or dike swarms (e.g. Zucca and Hill, 1980; Malahoff and Woollard, 1965, 1968; Strange, Woollard, and Rose, 1965). Hydrological studies can also give clues to the locations of buried dike swarms: dikes impede the flow and mixing of groundwater. Interpretations as to the number of rift zones and their locations may vary depending on which of the above signs one considers to be more reliable. For example, Macdonald and Abbott (1970) identified east-west rifts on Kauai, based on outcrops of dikes; Fiske and Jackson (1972) using Bouguer gravity anomalies regarded the rifts as extending northwest and southeast from the summit caldera. Koolau volcano is another example. There are dikes in a zone that trends SSW between Maunawili and Diamond Head. They are all tholeiitic basalts (Bigelow, 1968) and so do not belong to the Honolulu Series. Stearns (1939), Macdonald (1972) and Takasaki (1981) identify a minor rift zone coinciding with those dikes. There is a high in the Bouguer gravity anomaly which trends NE along the Mokapu Peninsula (Strange, Machesky, and Woollard, 1966; see fig. 3). Fiske and Jackson (1972) identify a minor NE Koolau rift zone parallel to the gravity high and show no SW rift.

Rift zones are apparently present from the earliest stages of construction (Moore, Clague, and Normark, 1982) and largely determine the shape of the volcano. Stresses on the edifice produce and determine the orientation of the rifts. Fiske and Jackson (1972) made a series of qualitative models showing that, once the shape of the edifice is determined, gravitational stresses will concentrate eruptions along linear paths. When a volcano grows near one or more pre-existing eruptive centers, the presence of these neighbors will buttress and control the shape of the growing volcano, also then affecting the orientations of its rifts. When a volcano begins well away from any other, it is the larger stresses of the plate which influence positions of the fissures. The rift zones may, like the loci of volcanic activity of Jackson et al. (1972), reflect rotational stresses of the entire plate; they may reflect the formation of the Hawaiian Ridge as the plate elevates in response to heating by the hotspot. Rift zones of edifices that grew in isolation cluster about 40°clockwise from the azimuth of the Hawaiian Ridge. Loihi is elongated north-south (Emery, 1956; Moore et al., 1982); presumably this shape reflects north-south rift zones. It is on the south submarine flank of Hawaii Island (Malahoff et al., 1982) and thus should fall under the category of buttressed volcanoes, yet its rift zones are roughly perpendicular rather than tangential or parallel to those of Mauna Loa.

Orientations of rifts may change with time, as neighboring volcanoes interact with each other. Mauna Loa grew nestled in the re-entrant outlined by Mauna Kea and Hualalai. Kilauea then began on the flanks of Mauna Loa, and now the presence of Kilauea's southwest rift zone seems to be causing Mauna Loa's southwest rift zone to migrate laterally westward (Lipman, 1980). There is evidence that the rift zones on Kilauea and West Maui also have shifted (Swanson, Duffield, and Fiske, 1970; Diller, 1982).

C. Geology of Hawaiian volcanoes

Hawaiian volcanoes develop through a distinctly recognizable sequence of stages in their eruptive history. One might say that a volcano is born, matures, and dies, and as it does so the frequency of eruption, style of eruption, and nature of erupted product vary. Stearns (1940b) developed a scenario of life-stages of Hawaiian volcanoes which has been modified as further study (Macdonald and Katsura, 1964; Moore, Clague, and Normark, 1982) revealed more details in the "biography" of the volcanoes. Presented below is an idealized version; not every volcano goes through every stage.

Moore et al. (1982) dredged tholeiites, alkalic basalts, and basanites from Loihi. Based on the thickness of palagonite rinds, they consider the alkalic basalts to be older than the tholeiitic samples. Thus, when the volcano first breaks through the ocean floor it apparently erupts alkalic basalt.

After the initial alkalic phase, lavas of both the submarine and subaerial shield-building phase are tholeiites. The shield builds up quickly, in about 10^6 years, according to Jackson, Silver, and Dalrymple (1972) and makes up about 97%-99% of the volcano. When the growing pile gets to within a few hundred meters of the surface, the steam produced by the contact of the hot lava with the ocean water can explode, causing phreatomagmatic eruptions. These produce a layer of hyaloclastite at the subaerial/submarine transition (Macdonald, Abbott, and Peterson, 1983).

The subaerial portion consists of many thin, fluid flows with relatively little ash and minor explosive activity. The main structural elements of the volcano--the lava shield, caldera, and rift zones--are present from early in the submarine phase of volcanism. In other types of volcanoes, such as those at continental margins, caldera formation tends to be a later-stage development, and until a caldera, with included pit craters, was discovered on Loihi (Malahoff et al., 1982) it was thought that calderas form only late in the life of Hawaiian volcanoes too.

Towards the end of shield-building, transitional and alkalic basalts interstratify between tholeiitic flows. Being somewhat more gas-rich and viscous than the underlying lavas these eruptions are somewhat more explosive; they are also less frequent. Eventually no more tholeiitic basalt is erupted, and alkalic differentiates are erupted with the alkalic basalts. This is the old age stage of the volcano's activity. The alkalic flows generally are thicker and extend for shorter distances from their vents than do tholeiites, and form a cap-like veneer for the edifice; thus this is commonly called the 'alkalic cap' stage. These flows also fill in and cover the caldera so that on Hualalai and Mauna Kea, for example, the cap makes it hard to tell whether there ever was a caldera. Another name for this stage is post-caldera (Macdonald, Abbott, and Peterson, 1983).

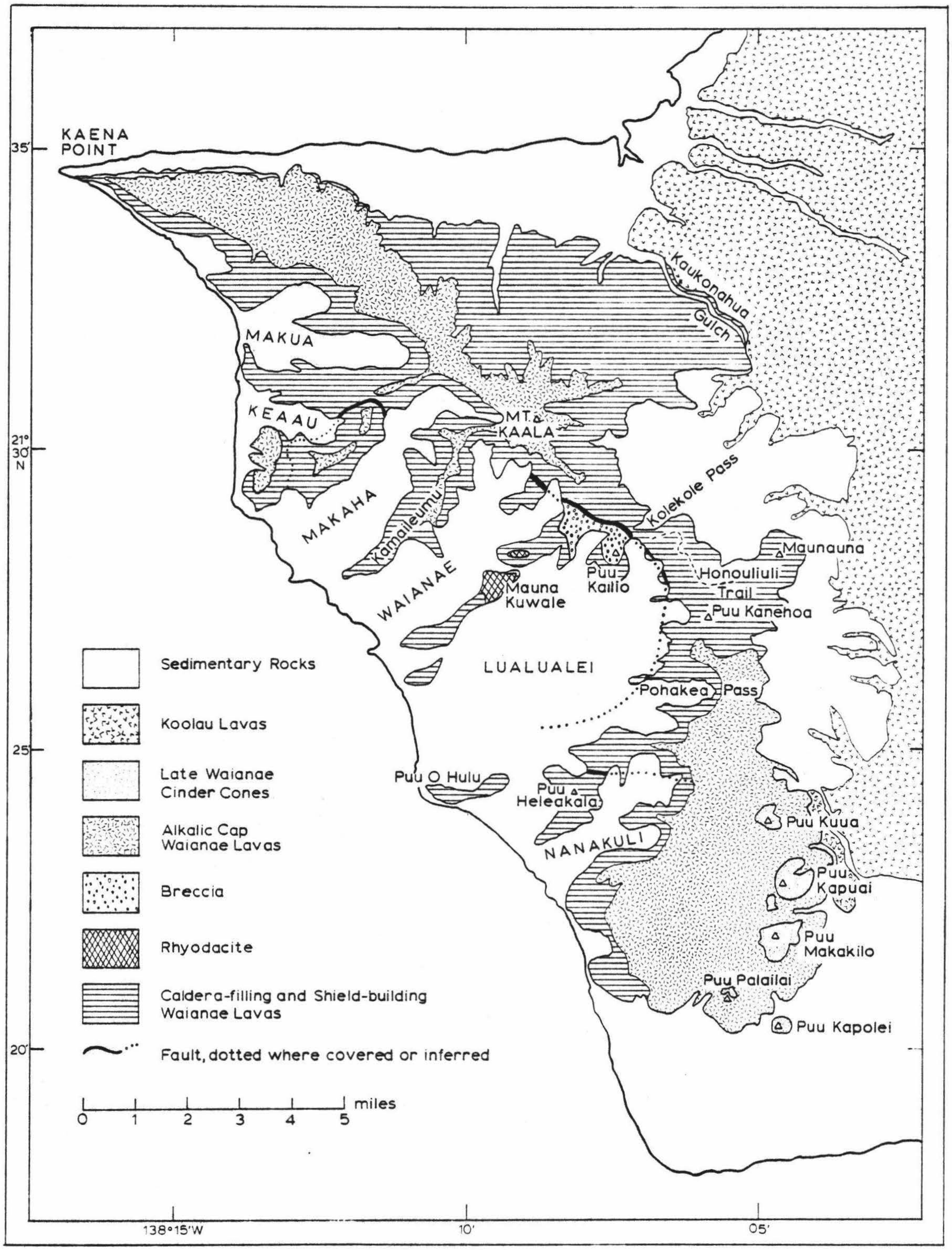
The transition from shield to cap may take place in one of two ways. Kohala-type volcanoes (Macdonald and Katsura, 1964) undergo an eruptive hiatus of perhaps 10^5 years (McDougall and Swanson, 1972) between the two stages; alkalic basalts appear before the hiatus. When eruptions resume they consist of rare alkalic basalts plus mugearites, benmoreites, and trachytes. Haleakala-type volcanoes have no extended hiatus, although eruptions come so infrequently that there may be local erosional unconformities especially on the flanks of the volcano. Alkalic basalts interbed with hawaiites and mugearites; these volcanoes seldom produce rocks more differentiated than mugearite. Waianae is a Haleakala-type volcano.

Gradually postcaldera eruptions happen even less frequently, and then stop altogether. Erosion, which has of course been active all along, takes over; deep valleys, thick soil cover, alluvial plains, and coral reefs begin to reshape the island. For some volcanoes this is the last stage: erosion and reef-building become the operative forces. Other volcanoes undergo one more volcanic phase known as post-erosional or rejuvenation. Posterosional is a poor name, since a flow may rest on a well-developed paleosol horizon and not belong to this last phase. Rejuvenation rocks are commonly but not always more silica-undersaturated than alkalic cap rocks. They include alkali olivine basalts, basanites, nephelinites, and melilitites. Some eruptions encounter groundwater or come up offshore, making phreatomagmatic explosions and leaving tuff cones for their record. They usually do not follow the same vent systems as the shield and cap eruptions; Haleakala is the one exception. Some of them carry xenoliths, such as lherzolite or garnet pyroxenite (Jackson, 1968), which must have originated at great depth.

D. Waianae geology

Stearns (Stearns and Vaksvik, 1935) divided lavas of Waianae volcano into three members: lower, middle, and upper. Macdonald (1940) interpreted the lower member to be the tholeiitic shield; the middle member to be caldera-filling flows; and the upper member to be the alkalic cap. Lower and middle members are essentially contemporaneous; radiometric ages for the upper member overlap somewhat with ages for the other two members but in general are younger (Doell and Dalrymple, 1973). The lower and middle members are generally adjacent rather than superposed (Stearns and Vaksvik, 1935; Stearns, 1939; Macdonald, 1940). It seems appropriate to refer to the members as shield-building, caldera-filling, and cap rather than by names which imply a relative stratigraphy that does not always exist (fig.2). At the same time it must be noted that these terms primarily describe physical relationships, and not necessarily petrological

Figure 2. Geologic map of Waianae volcano. Assembled from published sources: Stearns, 1939; Macdonald, 1940; Macdonald and Katsura, 1964; Pukui, 1974; Bauer, 1979; Sinton, 1979. Erratum: The name of the ridge between Makaha and Waianae valleys is Kamaileunu.


KAENA POINT
MAKUA
KEAAU
MAKAHA
WAIANAE
LUALUALEI
NANAKULI
MT. KAALA
Kaukonahua Gulch
Kolekole Pass
Kamaileunu
Mauna Kuwale
Puu Kailio
Maunauna
Honouliuli Trail
Puu Kanehoa
Pohakea Pass
Puu O Hulu
Puu Heleakala
Puu Kuua
Puu Kapuai
Puu Makakilo
Puu Palailai
Puu Kapolei
Sedimentary Rocks
Koolau Lavas
Late Waianae Cinder Cones
Alkalic Cap Waianae Lavas
Breccia
Rhyodacite
Caldera-filling and Shield-building Waianae Lavas
Fault, dotted where covered or inferred
0 1 2 3 4 5 miles
35'
21° 30' N
25'
20'
138°15'W
10'
05'

ones, though there are corresponding petrological variations (see chapter III, sections E, F, and G).

The shield-building basalt consists of thin-bedded pahoehoe and aa flows. Puu o Hulu, Puu Heleakala, the lower portions of the walls of Nanakuli and Lualualei Valleys, and the ridges from Keaau to Kaena Point are formed of shield-building lavas (Stearns and Vaksvik, 1935; Stearns, 1939; Macdonald, 1940; Macdonald and Katsura, 1964; Sinton, 1979). There is a wide range of vesicularity and phenocryst content. Most are olivine-phyric; feldspar is common but not abundant as a phenocryst phase. There are few tuffs or ashes and no paleosols among the shield-building basalts; they must have accumulated quietly and rapidly. The shield-building basalts are found up to about 600m elevation. The eruptive center was approximately where Puu Kailio is now; flows dip at angles of up to about 15^{o} away from Puu Kailio (Stearns and Vaksvik, 1935; Sinton, 1979).

In those places where the contact between shield-building and caldera-filling members has been identified, it is an angular unconformity, sometimes also accompanied by talus or soil. Some flows of the caldera-filling member have gentler dips than the shield-building flows; other flows are horizontal. Those that are not flat dip outward from the same Kolekole Pass area that the shield-building flows do. Lavas of the caldera-filling member are thicker and have a higher proportion of aa than do the shield-building basalts. Relative to shield-building lavas, feldspar is more abundant and olivine less abundant as a phenocryst phase; pyroxene is also common. The member is at least 600m thick, as that is the height of the continuous section exposed before the cap appears on Kamaileunu.

Two sets of flows in the caldera-filling member deserve special mention. The upper of the two was identified by Stearns as a hornblende-biotite trachyte, but has since been reclassified as a rhyodacite because of its low alkali-silica ratio (Macdonald and Katsura, 1964). Two outcrops on opposite sides of a small valley probably represent one flow divided by erosion. It is quite thick (over 100m), but of relatively small areal extent. Its phenocrysts are biotite, hornblende, feldspar, pyroxene and opaques; it is the most siliceous flow yet found in Hawaii (Bauer, 1979; Macdonald and Katsura, 1964). The rhyodacite rests on an 80 m thick section of icelandite lavas and tuffs (J.M. Sinton, pers. comm.). There are several flows of the icelandite around the north part of the base of Lualualei Valley. Sinton (1979) mapped it as a pyroxene basalt; it also locally carries feldspar and olivine. The rhyodacite and icelandite are confined to the caldera so in that sense are certainly part of the caldera-filling member; but their petrological affinities are uncertain.

In places there is a soil layer between flows of the caldera-fill and the cap; for example, there is a horizon of up to about a meter in thickness at Pohakea Pass (Sinton, 1979). Elsewhere there is no evidence for a significant time break. The cap reaches a maximum thickness of 700m. Flows are typically more massive, thicker, (often 15 to 30m), lighter grey, and more felsic than those of previous stages. The last known eruption products of the volcano are a series of short flows, some of which accompany cinder cones. They fall within the compositional field of hawaiite but are somewhat richer in

MgO and poorer in alumina and alkalies and so can be called `mafic hawaiites` (Sinton, 1981).

Outcrops of breccia occur several places around the Waianae range. Stearns (1939, 1940a; Stearns and Vaksvik, 1935) considered them all to be talus breccias, accumulated at the bases of cliffs. The area northeast of Kauaopuu he mapped originally as talus breccia but Sinton (1979) remapped it as icelandite flow. At the boundary of the northeastern breccia on Keaau ridge, Stearns found fault gouge. Though he found no other fault gouge, he believed the other cliffs to be fault scarps also and so he mapped faults on one side of each breccia outcrop. There are faults in Keaau-Makaha ridge, on the east side of Lualualei valley, and between Puu Heleakala and Nanakuli Ridge. Sinton (1979) identified additional faults on the eastern side of Lualualei valley.

Dikes cut several of the breccias; dikes of wide range in composition (Sinton, 1979; and this study) are particularly abundant in Puu Kailio. "This region probably marks the site of pronounced post-caldera activity and is interpreted as a vent. Flows that must have once covered breccia in this region have been removed by erosion" (Sinton, 1979, p. 48). The beds of Puu Kailio are caldera-filling but dip toward the middle of the caldera. Stearns (1940a, p.47) wrote that they are "flows that accumulated in a crater and then sagged because of the removal of the underlying support." He calls the resulting structure the Kailio Syncline.

Near Puu Kailio, in Kolekole Pass, is a conglomerate. "Compared to the Puu Kailio breccia, this unit is poorly bedded, probably quite thin...has generally more rounded clasts and is more deeply weathered"

(Sinton, 1979, p. 45). On this conglomerate is a flow which has clearly been erupted through it (Stearns and Vaksvik, 1935; Stearns, 1939; Sinton, 1979). Stearns (Stearns and Vaksvik, 1935) identified it as the sole example of posterosional volcanism on the Waianae range. Its composition is mafic hawaiite, similar to other very late alkalic cap member flows and unlike rejuvenation-stage eruption products of other volcanoes.

A gravity survey of Oahu (Strange, Machesky, and Woollard, 1965) (fig. 3) shows a Bouguer anomaly peaking not far from Puu Kailio. The complete Bouguer anomaly attempts to remove the effect of rocks above a datum plane (sea level), and look at gravity as though from a plane slicing through the island at that level. For Oahu, this is a useful point of view since the distribution of mass above sea level is caused as much by erosion patterns as by primary structure, and the purpose of examining the gravity anomaly is to learn about primary volcanic structure. The shape of Waianae's Bouguer anomaly is slightly triangular (i.e. has three legs, as opposed to just two), supporting the contention that there is a third minor rift zone. Legs extend from the peak (1) south-southeast, parallel to the coast between Nanakuli and Barbers Point; (2) northwest, pointing towards the coastline between Makua and Keaau valleys; (3) northeast, towards Kaukonahua Gulch. None of these legs is as well-defined as the northeast and northwest legs of the Koolau gravity anomaly.

The free air anomaly reflects topography more than the Bouguer anomaly does. Below sea level, both the free air gravity anomaly and the topography (bathymetry) have more structural significance than above sea level, so a free air anomaly map of the area around Oahu can

Figure 3 Bouguer gravity map of Oahu. From Strange, Machesky, and Woollard, 1965.

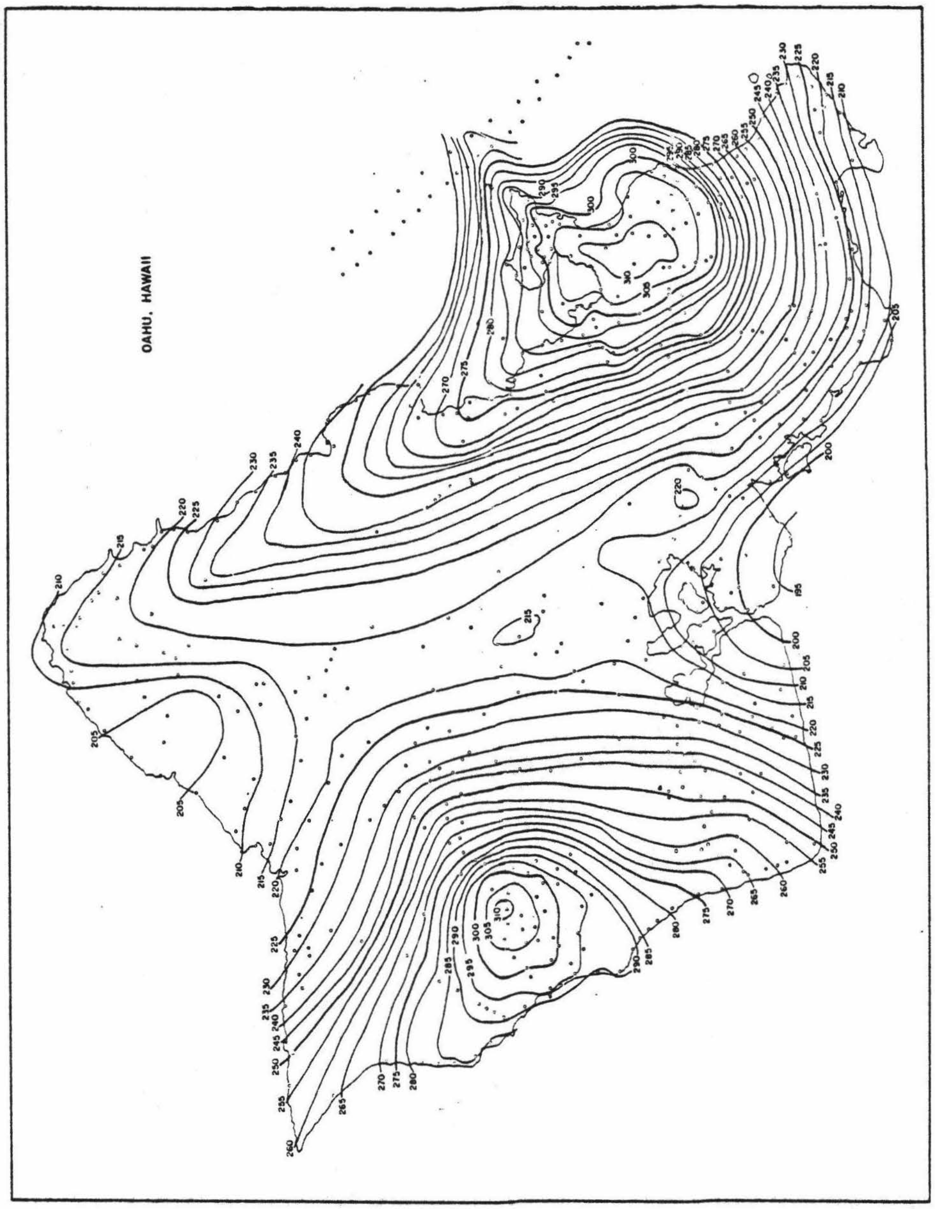
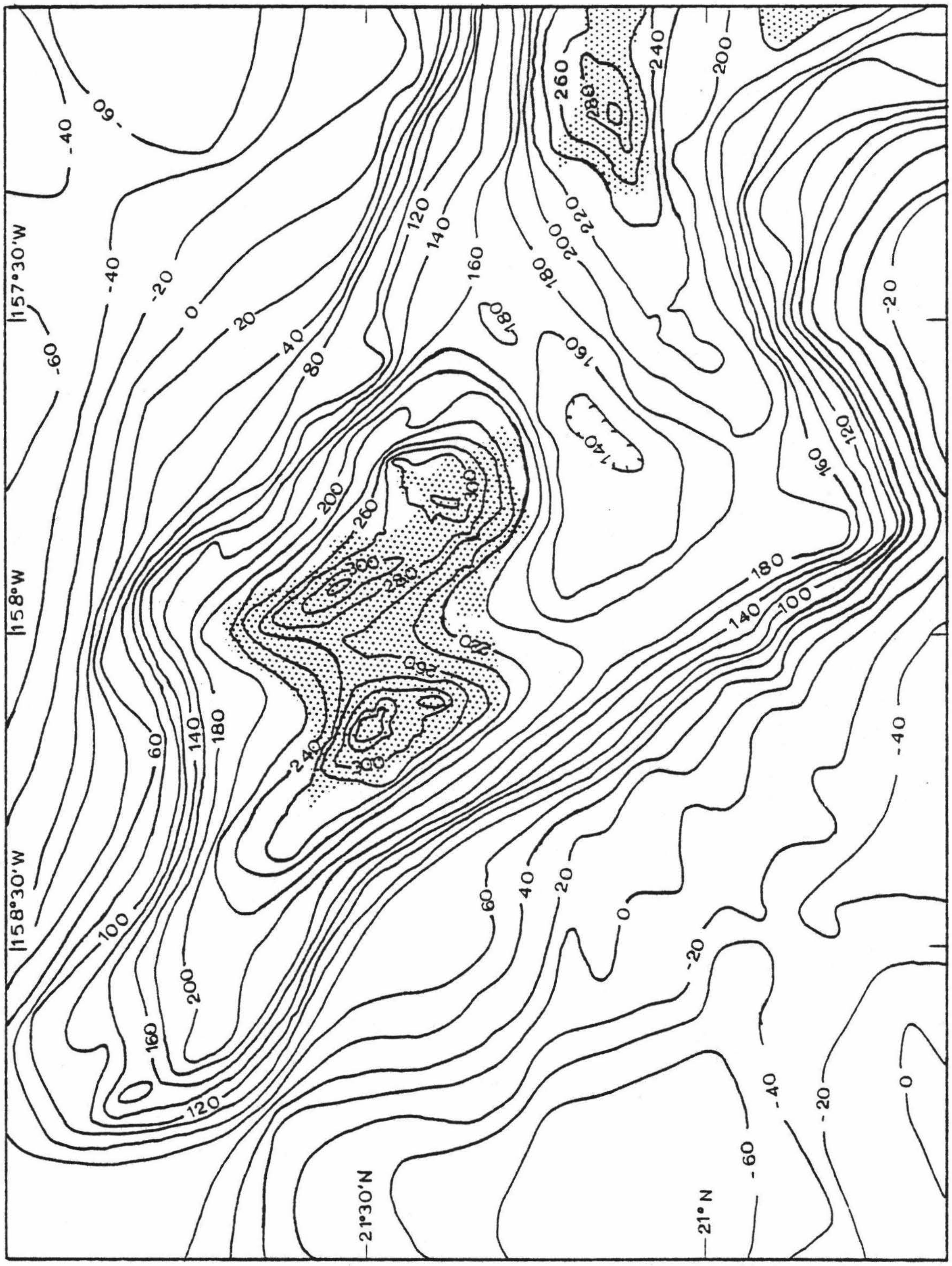

OAHU, HAWAII

Figure 4. Free-air gravity map of Oahu and vicinity. Redrafted from Lindwall, PhD dissertation, in prep.


157°30'W
158°W
158°30'W
21°30'N
21° N

provide some information about the structure of Waianae volcano. Figure 4 is such a map, provided by D. Lindwall (unpub. data), showing gravity highs extending both northwest and south of Waianae volcano.

Malahoff and Woollard (1965) conducted an aeromagnetic survey of the Hawaiian Islands. They identified magnetic "primary rift zones" and "volcanic pipe zones." For the most part these magnetically-defined zones do not correspond to rift zones and calderas as identified by field geology and other geophysical methods. Those areas where magnetic and geological interpretations overlap, are too few to be more than coincidence. A new interpretation of the magnetic anomaly data is needed before it will be of much use in understanding the structure of Waianae volcano.

III. RESULTS: DIKE CHARACTERISTICS

A. Distribution

Dikes are most abundant in Puu Kailio, Kolekole Pass, and Kauaopuu, that is, in the region around the eruptive center of the volcano. Elsewhere in the caldera, farther from the eruptive center, dikes are rarer. In the rift zones, dikes vary in abundance normal to the strike of the rift zone (see figs. 7 and 8; also maps by Stearns (1939) and Takasaki (1971)). I discovered no dikes in the following areas: the Lualualei side of Pohakea Pass, the crest of the range between Palikea and Pohakea Pass, in the alkalic cap member south of Pohakea Pass, and the west approach to Mt. Kaala. West of Kunia town between Maunauna and Puu Kanehoa I found only two dikes, both extremely weathered.

B. Thickness and dip

Intrusions vary in width from about 5 cm to about 5 m. Eighty-six percent are one meter or less in width, and the greatest number are 21-40 cm wide (fig. 5).

Waianae dikes vary in dip from horizontal to vertical; most are within 20° of vertical (fig. 6). Four of the six horizontal or nearly so intrusions are concordant within the flat-lying flows of Paheehee Ridge and thus are sills, not dikes; of the other two, one cuts at a shallow angle across dipping flows of Puu Heleakala and the other intrudes dipping breccia of Puu Kailio so they are true dikes.

<u>Figure 5.</u> Widths of dikes measured in Waianae volcano.

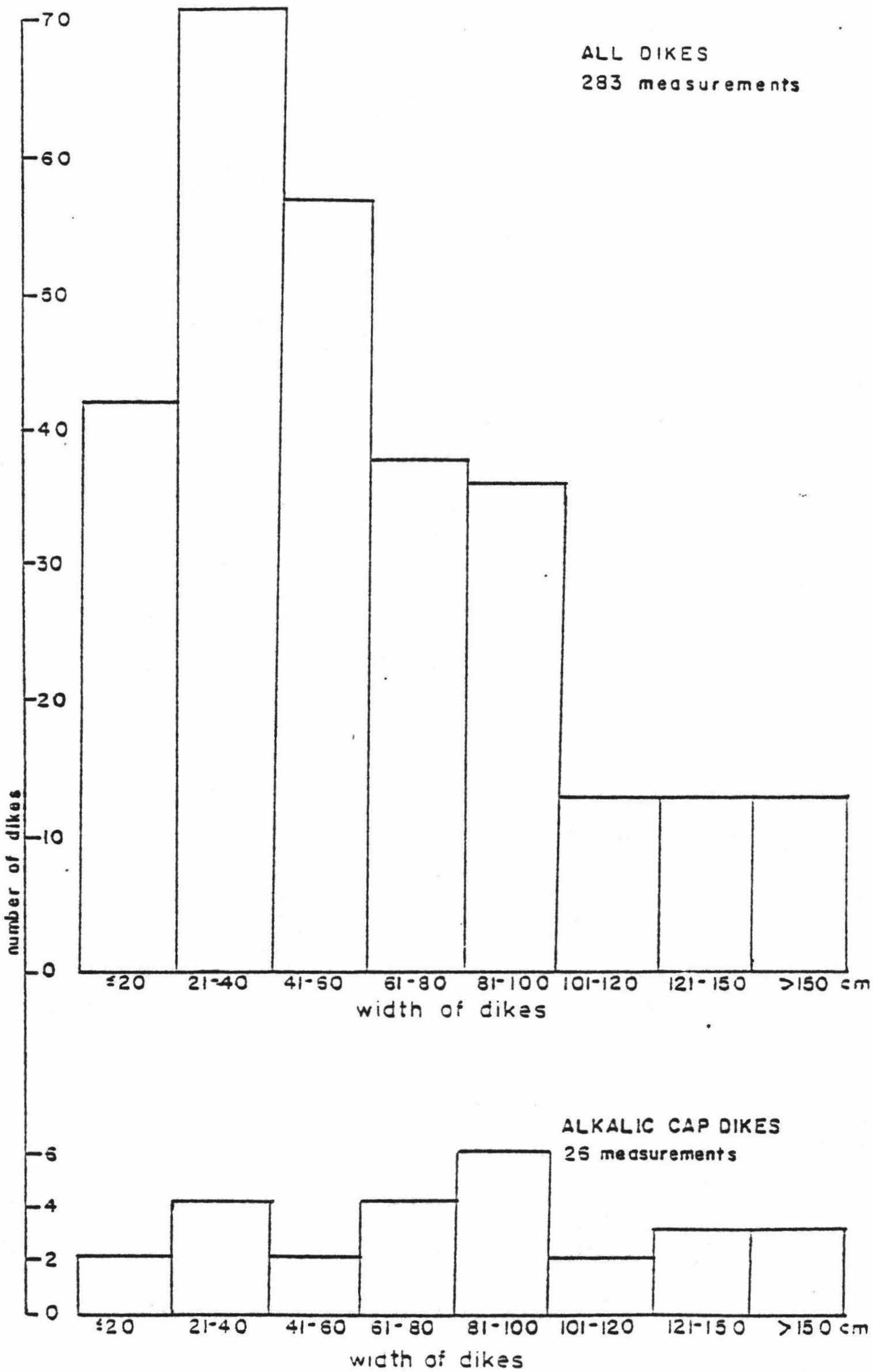
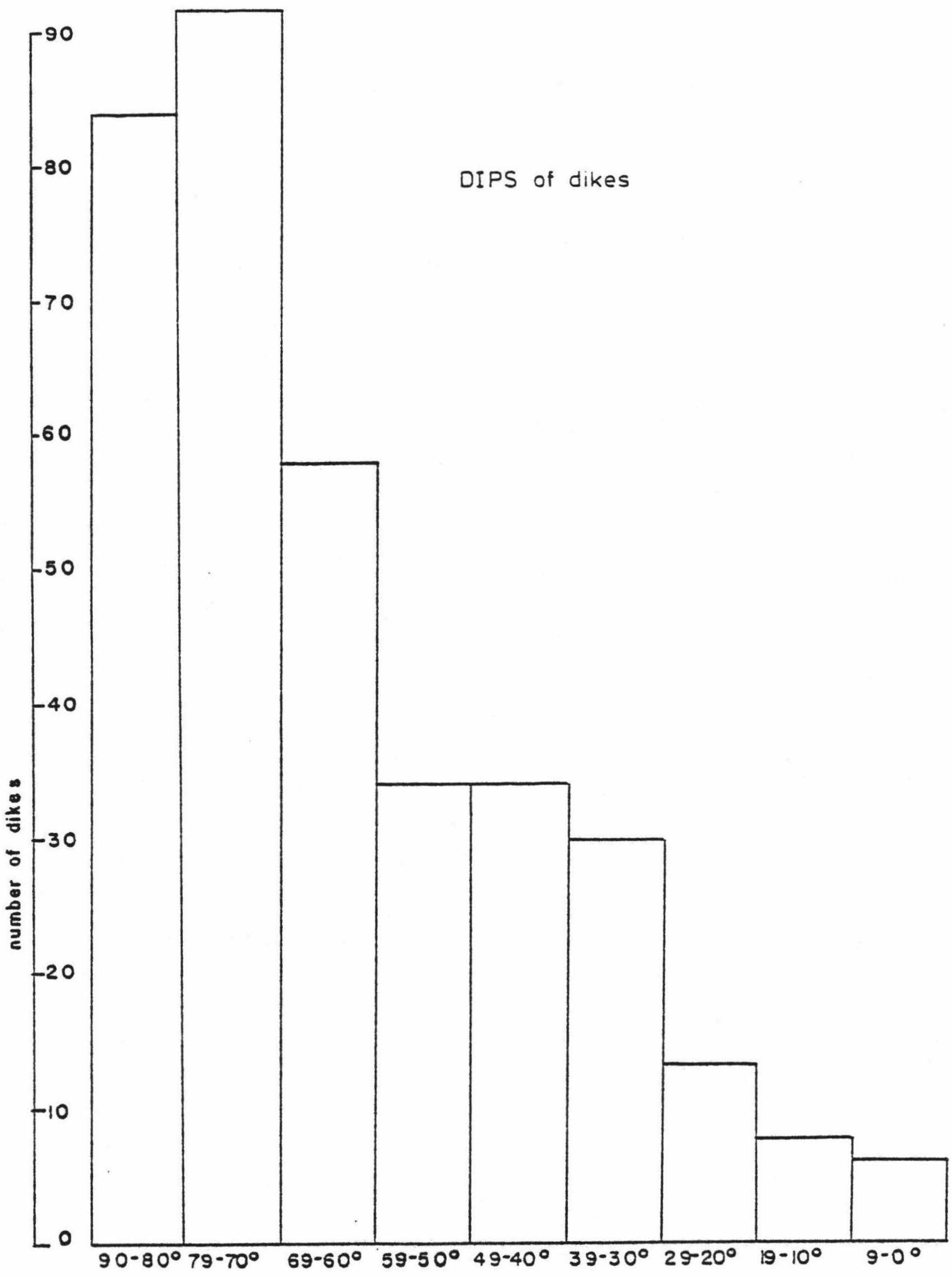

ALL DIKES
283 measurements
number of dikes
70
60
50
40
30
20
10
0
≤20
21-40
41-60
61-80
81-100
101-120
121-150
>150 cm
width of dikes
ALKALIC CAP DIKES
26 measurements
6
4
2
0
≤20
21-40
41-60
61-80
81-100
101-120
121-150
>150 cm
width of dikes

Figure 6. Dips of dikes measured in Waianae volcano.


DIPS of dikes
number of dikes
90
80
70
60
50
40
30
20
10
0
90-80° 79-70° 69-60° 59-50° 49-40° 39-30° 29-20° 19-10° 9-0°

Several of the gently-dipping intrusions that penetrate the rhyodacite of Mauna Kuwale follow flow planes and so are also sills. Except for these instances, sills are rare in Waianae volcano.

C. Orientations

In some areas dikes have a common alignment; in other areas, alignment is less well defined; elsewhere the dikes are randomly oriented (fig. 8).

The areas where dikes have strongly preferred orientations are: Kaena Point, Kuaokala, Makua center, Makua edge, Kolealiilii, Puu O Hulu Uka, and Puu O Hulu Kai.

Those areas where the dikes show slightly less well-defined alignment, are Puu Heleakala, Nanakuli Ridge, and Honouliuli 1.

Areas which show an indistinct alignment of dikes are: Kamaileunu, Kauaopuu, Mauna Kuwale, and Paheehee Ridge. The last three are part of the same discontinuous ridge, but the dikes show different azimuths of alignment.

Those areas where dikes have apparently random orientation are: Puu Kailio, Navy Ridge, Kolekole Pass, Kolekole roadcut, and Honouliuli 2.

Dikes of Kaena Point, Kuaokala, Makua center, Makua edge, and Kolealiilii all have a clear northwest-southeast preferred orientation. The center and edge of Makua Valley, Kaena Point, and Kuaokala are part of the northwest rift zone as defined by Stearns (Stearns and Vaksvik, 1935; Stearns, 1939), Macdonald (1940, 1972), and Takasaki (1971). Kolealiilii is within the caldera outlined by

Figure 7. Names of subdivisions in the study area. Erratum: The name of the ridge between Makaha and Waianae valleys is Kamaileunu.

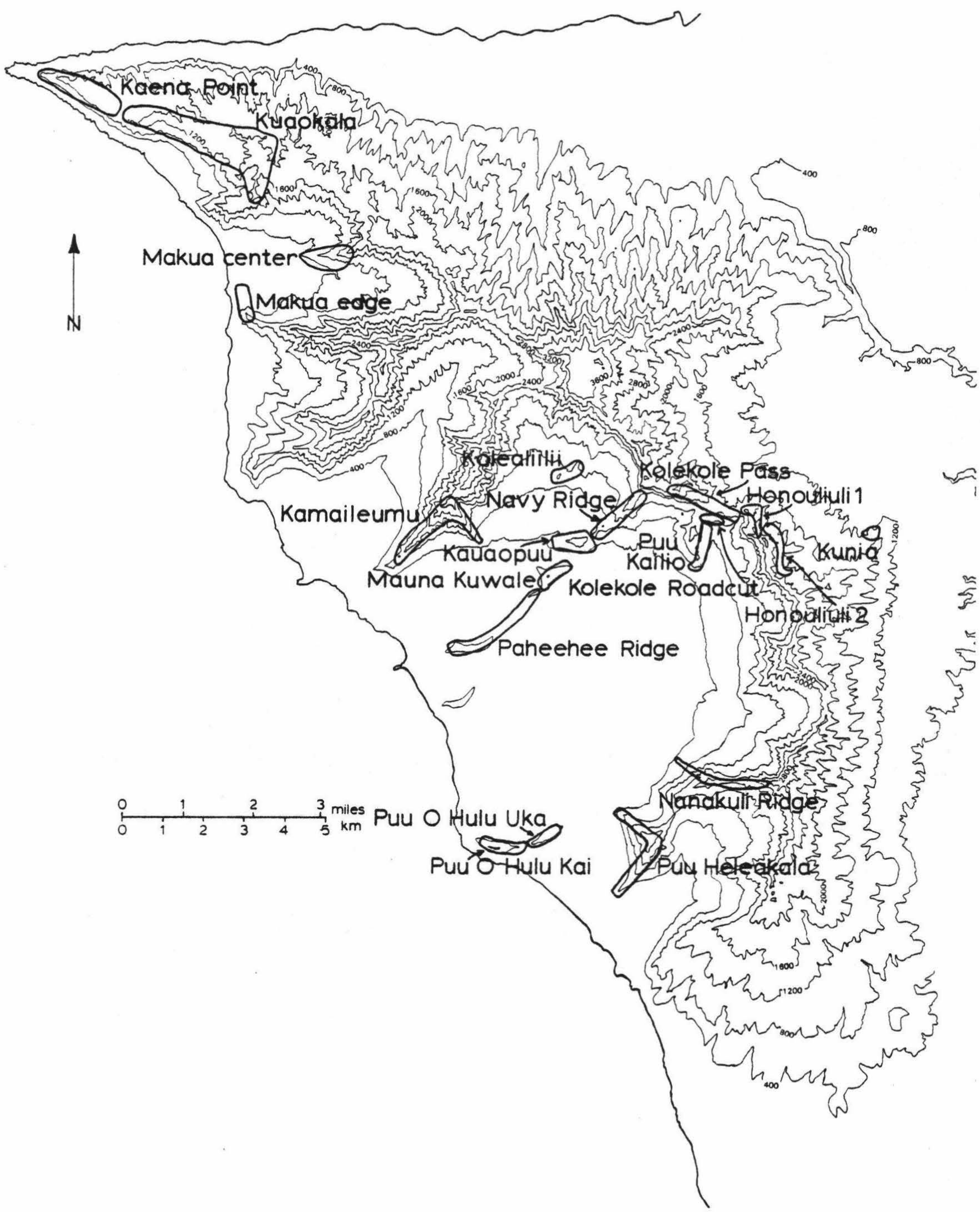
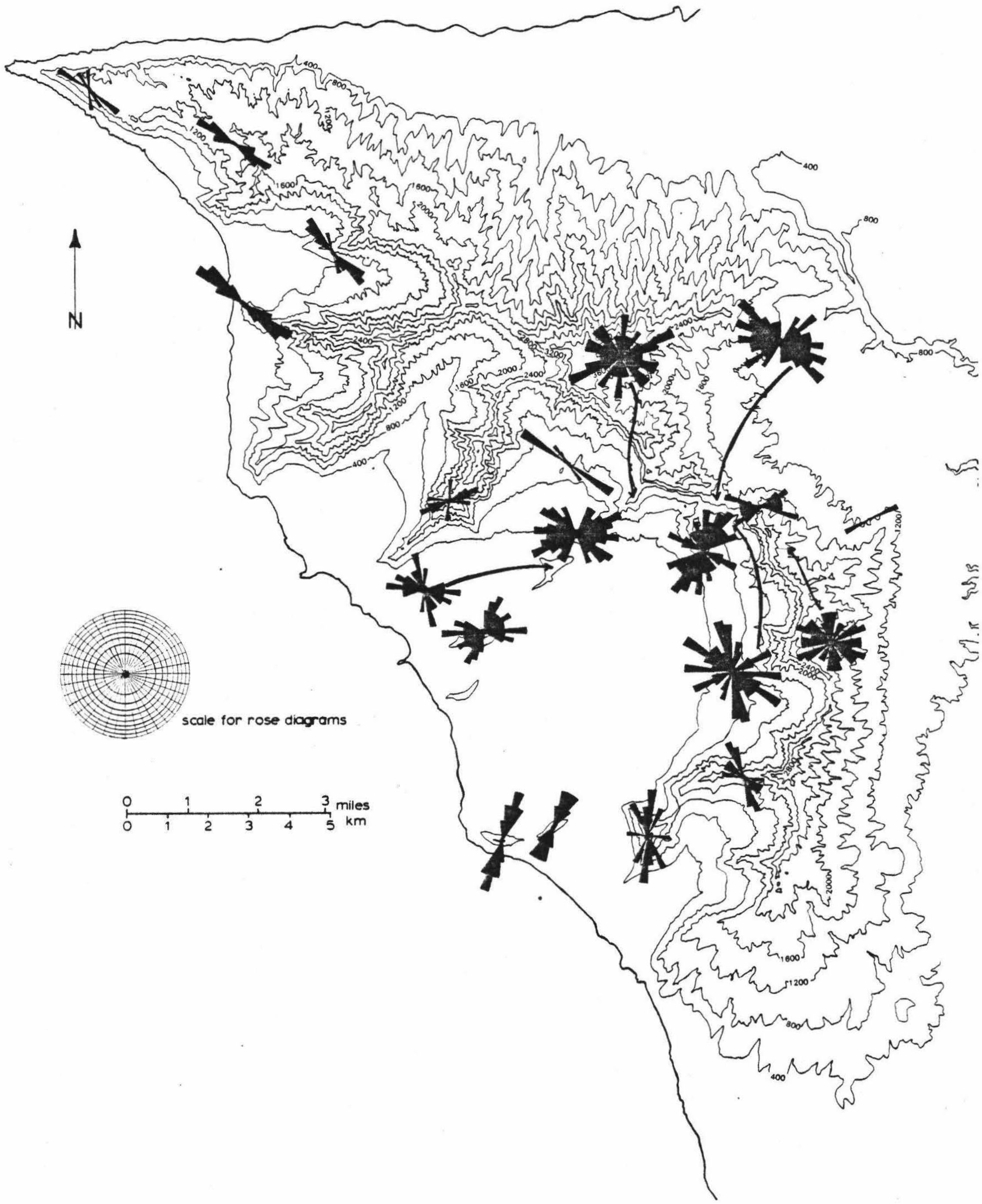

Kaena Point
Kuaokala
Makua center
Makua edge
N
Kaleaiiiii
Kolekole Pass
Honouliuli 1
Navy Ridge
Kamaileumu
Kauaopuu
Puu
Kaiiio
Kunia
Mauna Kuwale
Kolekole Roadcut
Honouliuli 2
Paheehee Ridge
Nanakuli Ridge
0 1 2 3 miles
0 1 2 3 4 5 km
Puu O Hulu Uka
Puu O Hulu Kai
Puu Heleakala

Figure 8. Orientations of dikes measured in Waianae volcano, divided by area. Rose diagrams represent absolute numbers of dikes. Each polygon is half a dike; its mirror image is the other half dike.


N
scale for rose diagrams
0 1 2 3 miles
0 1 2 3 4 5 km
400
800
1200
1600
2000
2400

Macdonald and Abbott (1970). Its flows are part of Stearns' (1939) lower member. Takasaki (Takasaki, 1981) included this region in the dike complex of the northwest rift zone. For the purposes of this study, Kolealiilii is part of the northwest rift zone.

Dikes of Puu O Hulu Uka, Puu O Hulu Kai, and Puu Heleakala intrude flows of the shield-building member. They are included in the south rift zone as defined by Stearns, by Macdonald, and by Takasaki (ibid.). Dikes in Puu O Hulu Kai and Uka are not parallel to the south rift zone, but they are radial to the eruptive center. Dikes of Nanakuli Ridge intrude flows of the caldera-filling and alkalic cap members. They are within the caldera outlined by Macdonald and Abbott (1970), and outside the caldera outlined by Sinton (1970). Dikes of Puu Heleakala and Nanakuli Ridge are roughly parallel to Waianae's south rift zone as well as radial to its eruptive center. For the purpose of this work, Puu O Hulu Uka, Puu O Hulu Kai, Puu Heleakala, and Nanakuli Ridge are all part of the south rift zone. The flows of Nanakuli Ridge may have erupted at a time when that area was within a caldera. However at the time the dikes were emplaced, it was a rift zone. This is explained more carefully in Chapter 4, section B1.

The two dikes of Kunia area both strike in the same direction: both roughly parallel to the northeast rift zone and radial to the eruptive center. The northeast rift zone is the most poorly defined of Waianae's rift zones. According to Macdonald (1972) and to Takasaki (1971) this area is on the southern edge of the northeast rift zone.

Dikes of Kamaileunu intrude flat-lying caldera-filling member flows. They are within Macdonald's caldera; the area mapped by Sinton does not include Kamaileunu. These dikes have a slight ENE-WSW preferred orientation, but it is not clear why. They are not parallel to the eruptive center. They strike parallel to the northeast rift zone, but are on the far side of the eruptive center from that rift zone. It is possible that these dikes point to an as-yet-undiscovered second eruptive center; it is possible that their strike is influenced by the northeast rift zone; it is possible that the apparent common orientation is fortuitous.

The areas Paheehee Ridge, Mauna Kuwale, Kauaopuu, Navy Ridge, Nanakuli Ridge, Puu Kailio, and Kolekole Pass are all within the caldera as defined by Macdonald (Macdonald and Abbott, 1970) by Takasaki (1971), and by Sinton (1979). Dikes emplaced in Puu Kailio may show two intersecting preferred orientations: one to the northwest-southeast, parallel to the morthwest rift zone, the other to the northeast-southwest, parallel to the northeast rift zone. But according to Stearns (1939, Stearns and Vaksvik, 1935), the beds of Puu Kailio sagged after they were laid down. If this is true, the present azimuths of the dikes may be different from strikes at the time of emplacement, so one should use care in drawing any conclusion from the strikes of the dikes in Puu Kailio. In other areas of the caldera region, dikes strike in seemingly random directions. Takasaki (1981) suggested that the dikes are always parallel to rift zones, and crossing dikes in the caldera area are parallel to intersecting rift zones. Although this is oversimplified, some of the scatter in dike orientation could be explained this way.

Honouliuli Trail crosses flows of Macdonald's (Macdonald and Katsura, 1964) lower and upper members (here, the shield-building and alkalic cap members). Dikes of Honouliuli 1 show some alignment. They are not parallel to the northeast rift zone, but they are radial to the eruptive center. Honouliuli 2 dikes show no preferred orientation. It is not clear whether Honouliuli 1 should be considered to be within the caldera region or a rift zone. Because the apparently random strikes of the Honouliuli 2 dikes are similar to the apparently random strikes of dikes in the areas of the caldera region, Honouliuli 2 is part of the caldera region. Honouliuli 1 is also within the caldera region for the purpose of this study because of its location and because it is not obviously part of any rift zone.

The dikes of Paheehee Ridge, Mauna Kuwale, Kauaopuu have poorly defined common alignments. Because the azimuth of alignment is different in each of these adjoining areas, and because the alignment is poorly defined, the alignment must be fortuitous.

In contrast to dikes in the caldera region of Waianae volcano, many cracks and eruptive fissures in Kilauea caldera are parallel to the rift zones (Holcomb, 1980). Some dikes within the caldera of West Maui volcano are parallel to its south rift zone (Diller, 1982). The reason for the difference among the caldera areas of Waianae, Kilauea, and West Maui volcanos is not apparent.

D. Petrography

1. texture

a. general observations

Shallow intrusions such as those sampled in this study are similar in hand sample and thin section to extrusive rocks. They can be highly vesicular, though not so frothy as cinder from a firefountain. The most vesicular samples have about 20% vesicles. Some cooled slowly enough to show intergranular or other virtually holocrystalline textures; but for the most part the grainsize and degree of crystallinity are comparable to those of extrusive rocks--that is, glass is an essential constituent. Typically the margins are finer-grained than the interiors and in about 20% of the sampled dikes the margins are chilled to glass free of quenched crystals. Plagioclase is the most common phenocryst phase. Olivine and, less commonly, pyroxene also form phenocrysts easily visible in hand sample. On both thin section and hand sample scale many samples show flow segregation: vesicles, phenocrysts, and matrix crystals are concentrated into layers which are parallel to dike margins and presumably also to flow direction.

One dike, WD-166, could represent a mixed magma. The dike intrudes icelandite on Kauaopuu Ridge. The hand sample looks like a breccia. The thin section matrix consists of a brown and a dark grey matrix glass with plagioclase microlites. In some places there is a sharp contact between the two glasses, elsewhere a gradational contact. Olivine phenocrysts are completely altered to pseudomorphs; euhedral augite and hypersthene phenocrysts are fresh. There are also microphenocrysts of hypersthene and augite.

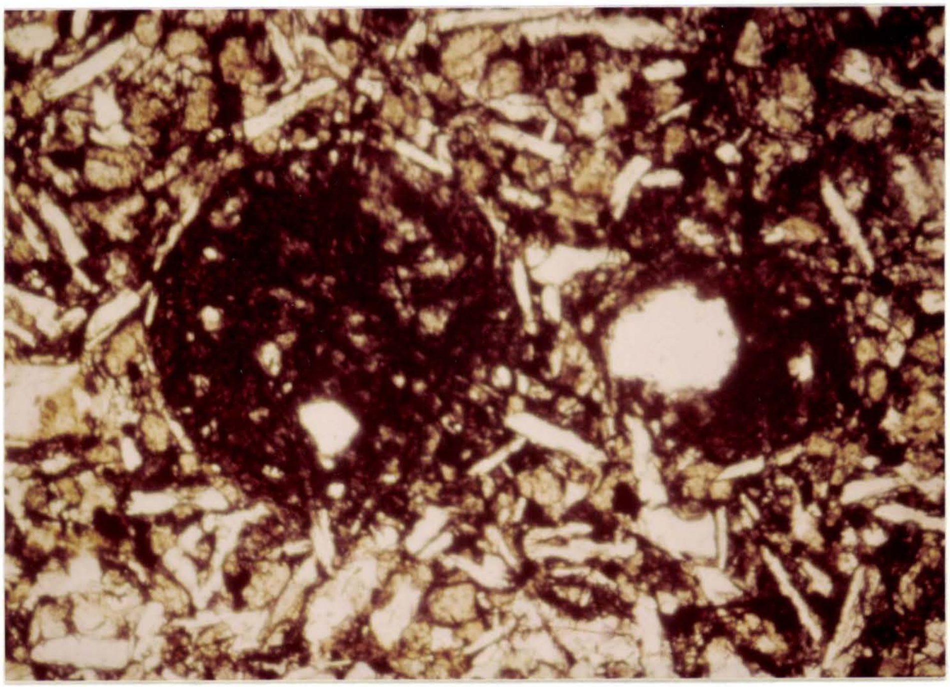
b. Segregation vesicles

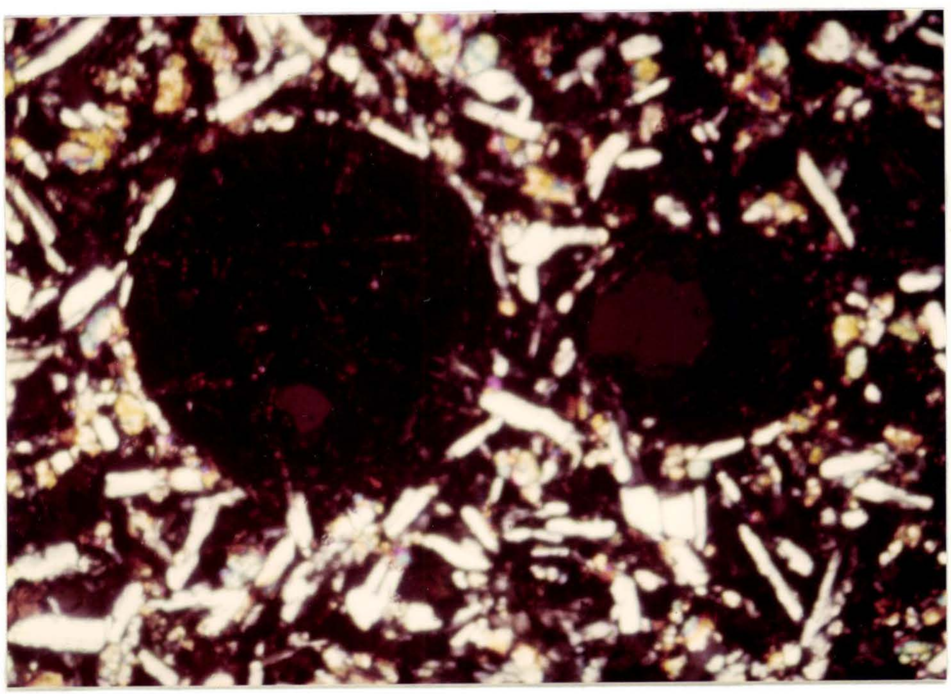
About a quarter of the thin sections have segregation vesicles: vesicle-shaped patches of matter less well crystallized than the rest of the rock (fig. 9). Segregation vesicles have been recognized in igneous rocks at least since the description of Skye in 1904 (Harker et al., quoted in Van Wagoner, 1983); they were first named and examined in detail by R.E. Smith (1967). He worked with lavas of Ordovician or older age from New South Wales, Australia. Similar textures have been described from a historic flow of Reunion Island (Upton and Wadsworth, 1971), from Medicine Lake and Mount Shasta in the Cascades (Anderson et. al., 1984), and from numerous ocean-floor samples (e.g. Bideau et al. 1977, Sato, 1978, Van Wagoner, 1983). Beeson (1976) said of rocks from East Molokai, (p.11) "Hypocrystalline patches occur near vesicles in some of these otherwise holocrystalline samples." Apparently he saw segregation vesicles but did not identify them as such. All described occurrences have been in basalts.

Segregation vesicles may be round, elliptical, or irregular in shape; they are similar in size and shape to normal gas-filled vesicles in the rock. They may be completely or partially filled with segregated material. If only partly filled, there are often one large and one or more smaller gas vesicles within the segregated material.

Smith (1967) warned that a filled segregation vesicle may be mistakenly identified as a droplet of immiscible liquid. Sato (1978) found both features in one DSDP drill core and described the differences. The diameters of immiscible liquid droplets are measured in microns; they are surrounded by glass of different color and refractive index. Segregation vesicles, in contrast, are millimeters

Figure 9. Photomicrograph of a segregation vesicle in sample WD-52. Above, plane light; below, crossed polars.





in size and are surrounded by crystalline groundmass; they are similar in texture and chemistry to the interstitial matter of the rest of the rock. Segregations and interstitial material may be charged with droplets of immiscible liquid.

In order to form segregations, the lava must be partly crystalline. Ordinary gas vesicles form in the liquid, then interstitial liquid flows out from between the crystals and into the vesicle. Smith (1967) described four ways that this might happen: (1) The gas shrinks on cooling. (2) gas escapes during cooling. (3) solubility of vesicle gas in melt increases during cooling. (4) exterior pressure increases. If the gas behaves according to the Ideal Gas Law, possibility (1) provides insufficient shrinkage to explain the observed volume of residual melt intruding the vesicles. The other three mechanisms have been invoked to explain segregation vesicles in different environments.

Bideau et al. (1977) invoked escape of gas to explain segregation vesicles in ocean floor basalts. They point at protuberances from the vesicles as escape conduits for the gas. Some segregation vesicles in Waianae rocks have irregularities similar to those that Bideau et al. interpreted as escape conduits. Another possible method of formation is similar to the idea of escaping gas but does not require true reduction in volume. The gas vesicle begins to rise. As it does so it squeezes together the crystals above it, squeezing out the liquid from between those crystals and into the vesicle below.

Since by all models offered so far, segregation vesicles form by residual liquid squeezing out from between matrix crystals, there is a lower limit to the degree of crystallinity of magma below which segregation vesicles do not develop. Bideau et al. (1977) examined slices of pillow lavas from the chilled rim to the well-crystallized core and observed that segregation vesicles do not develop close to the chilled rim. Based on volume of filling observed in the vesicle, they estimated that segregation vesicles develop after about 70% crystallization of the lava. Sato (1978) analyzed the composition of the filling and the bulk rock and calculated that the segregation vesicle developed after 40% to 60% crystallization.

2. Mineralogy

Minerals that form phenocrysts are, in order of frequency of occurrence: plagioclase, augite, olivine, magnetite, orthopyroxene, and rarely apatite. The most abundant as well as the most commonly occurring phase is plagioclase. (Abundance in this context means areal proportion in thin section, which is equivalent to volume % but not to weight % or to molecular %.) Plagioclase, olivine, and magnetite can occur alone; pyroxenes occur only in combination with, and generally subordinate in abundance to, another phase. Although augite is the second-most-common phenocryst phase, rarely (in only two samples) is it the most abundant phase. That is, augite phenocrysts are found in many rocks, but there is nearly always more plagioclase than augite in any given thin section. Olivine locally contains isometric inclusions which are probably early-forming phenocrysts of chromite (Cr-spinel). By contrast with augite, olivine occurs in fewer samples, but where present, it tends to be more abundant.

Olivine and especially augite are commonly intergrown with plagioclase as glomerocrysts. Plagioclase-augite and plagioclase-augite-olivine are by far the most common assemblages (fig. 10). Wright (1971) attributed glomeroporphyritic texture in flows to cooling of magma at shallow depth in a rift zone or a summit magma chamber before eruption. Since dikes are necessarily cooled at shallow depth, it is consistent that they characteristically have this texture.

Orthopyroxene is mainly found in dikes of the shield-building member, and is particularly concentrated in the ridge on the southwest edge of Makua valley. Six of the fifteen samples from that ridge contain orthopyroxene (as phenocryst or matrix mineral); none of the dikes from the center spur in Makua contain orthopyroxene. Perhaps those six dikes belong to a single eruption series. Throughout Waianae, olivine commonly occurs in the same sample as orthopyroxene. Locally (as in WD-43) there is a reaction relationship: orthopyroxene forms a `necklace` around olivine phenocrysts. Elsewhere (as in WD-86) the two minerals coexist in petrographic equilibrium. Groundmass orthopyroxene has been positively identified in only three rocks.

Olivine is commonly altered. The most common alteration product is orange or red-brown iddingsite. Iddingsitized olivine may be surrounded by a rim of fresh olivine, which in turn may be partly altered. Both groundmass and phenocryst grains may have altered cores rimmed with fresh olivine. Formation of iddingsite is an oxidation process involving volatile constituents (Macdonald, 1949; Sun, 1957; and others). The process may occur intratellurically (Macdonald, 1949), deuterically (Sun, 1957; Haggerty and Baker, 1967), or during low-temperature weathering (Sun, 1957; Baker and Haggerty, 1967). In some samples from Heleakala, Mauna Kuwale, Puu Kailio, and Paheehee Ridge, olivine alters to a pleochroic blue-green phyllosilicate, probably celadonite. Iddingsite and the phyllosilicate may both exist in the same thin section (for example, WD-341). Another alteration product is an opaque mossy green or brown, possibly microcrystalline chlorite. This is never found in the same sample as iddingsite. Where it does occur, the entire grain of olivine is generally replaced, rather than a rim or fracture replacement. In a few samples, calcium carbonate replaces olivine. Carbonate also never coexists with iddingsite. In many samples, olivine is the only altered mineral of the rock; in some, even interstitial glass is still fresh while olivine is altered.

Magnetite occurs as a phenocryst in about 10% of the thin sections. Of those, about 1/3 appear to be alkalic. Two rocks have magnetite as the sole phenocryst phase; both of those are differentiated alkalic rocks. Magnetite phenocrysts are proportionately more common in alkalic rocks than in tholeiitic rocks (alkalic rocks are about 8% of those analysed), but it is a phase which ought not be overlooked when discussing tholeiites. Its presence is related to degree of differentiation of a magma since it generally appears rather late in the crystallization sequence of most basaltic magmas (Osborn, 1979), and alkalic differentiates are proportionately more abundant than tholeiitic differentiates.

Figure 10 shows relative frequency of various phenocryst assemblages in Waianae dikes. Note that these are not the same as petrographic types of section E.

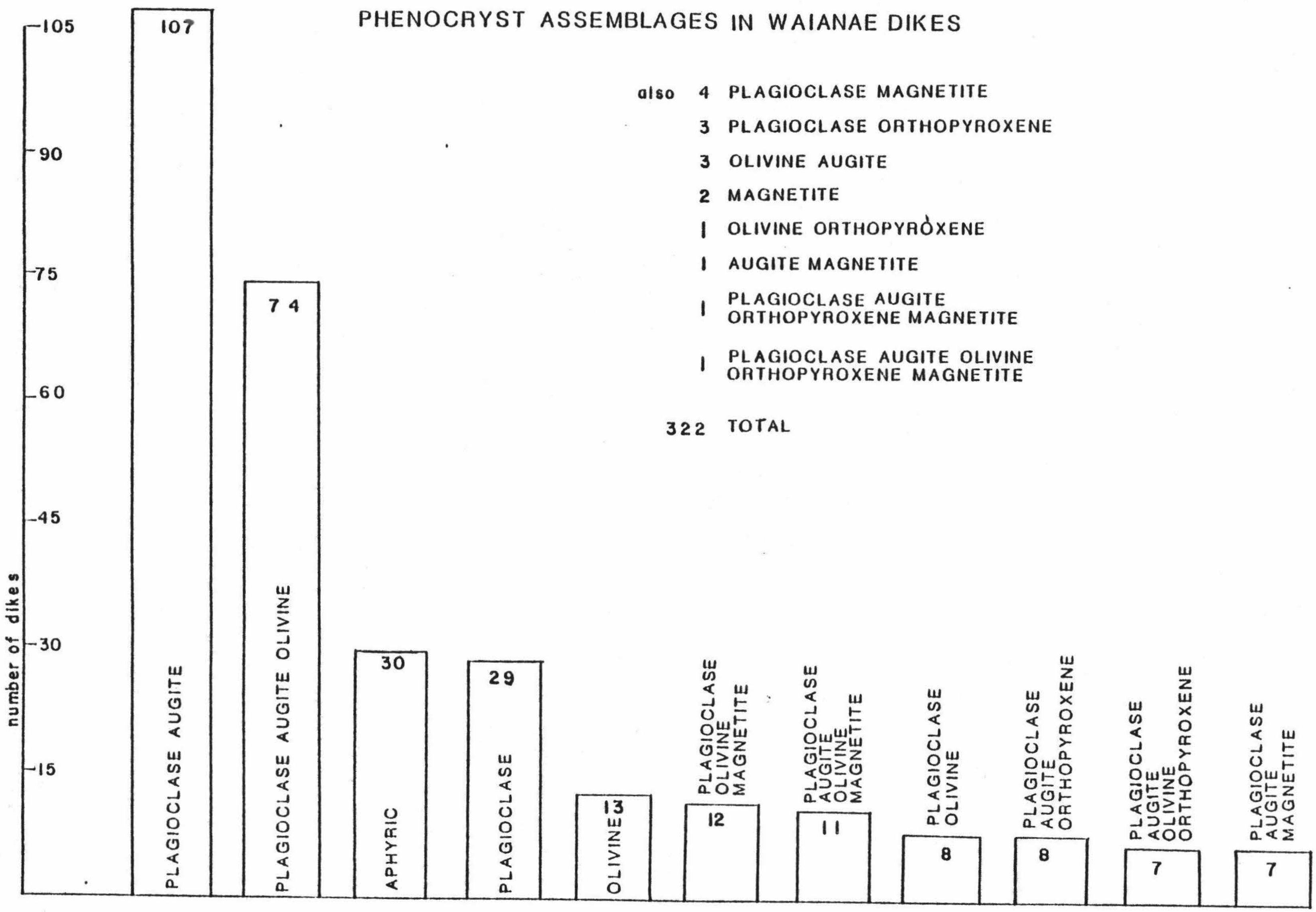
Macdonald (1940) listed pigeonite as an ubiquitous phase in Waianae lavas. There are no pigeonite phenocrysts and probably no matrix pigeonite crystals in Waianae dikes. The discrepancy does not lie in a quick phase change between feeder conduit and flow, but in the definition of pigeonite. Macdonald's pigeonite had +2V of up to about 50^{o}; but according to Deer, Howie, and Zussman (1978), crystals of that 2V are augite.

E. Petrographic categories

The rocks can be placed into eight broad petrographic categories. Two categories (trachytic, aphyric) are based on texture; the others are based on mineralogy, primarily phenocryst assemblage.

1. <u>Trachytic</u> This is a textural category. These rocks have a high proportion of feldspar and correspondingly low pyroxene. They all have olivine growing in elongate rather than equant grains that are typically completely altered to iddingsite. Crystals are flow-aligned, hence the label trachytic. Often they are relatively coarse-grained and have no phenocrysts. Vesicles and segregation vesicles are elongate and aligned in the same direction as the crystals. Some rocks with the characteristic mineralogy and mineral morphology but without the flow texture have also been placed into this category. Rocks in this category are identified as differentiated alkalic rocks, hawaiites and mugearites, though it is

Figure 10. Phenocryst assemblages in Waianae dikes.


PHENOCRYST ASSEMBLAGES IN WAIANAE DIKES
also 4 PLAGIOCLASE MAGNETITE
3 PLAGIOCLASE ORTHOPYROXENE
3 OLIVINE AUGITE
2 MAGNETITE
1 OLIVINE ORTHOPYROXENE
1 AUGITE MAGNETITE
1 PLAGIOCLASE AUGITE ORTHOPYROXENE MAGNETITE
1 PLAGIOCLASE AUGITE OLIVINE ORTHOPYROXENE MAGNETITE
322 TOTAL
number of dikes
105
90
75
60
45
30
15
107 PLAGIOCLASE AUGITE
74 PLAGIOCLASE AUGITE OLIVINE
30 APHYRIC
29 PLAGIOCLASE
13 OLIVINE
12 PLAGIOCLASE OLIVINE MAGNETITE
11 PLAGIOCLASE AUGITE OLIVINE MAGNETITE
8 PLAGIOCLASE OLIVINE
8 PLAGIOCLASE AUGITE ORTHOPYROXENE
7 PLAGIOCLASE AUGITE OLIVINE ORTHOPYROXENE
7 PLAGIOCLASE AUGITE MAGNETITE

possible that some might be alkalic basalts. The only analysed rock from this category, WD-222, is a mugearite. There are 26 trachytic rocks in the study collection.

2. Orthopyroxene All rocks which have orthopyroxene are in this category. One, WD-331, is aphyric; orthopyroxene is a groundmass phase only. All others have orthopyroxene in combination with some other phase or phases as phenocrysts. Presence of low-calcium pyroxene is the simplest diagnostic criterion of tholeiitic basalts (for references, see discussion on classification below, section F1); so all rocks in this category are tholeiitic. Samples WD-25, WD-96, WD-147, and WD-342 from this category have been analyzed. There are 22 orthopyroxene rocks in the study collection.

3. Olivine These rocks have phenocrysts only of olivine, or large olivines with significantly smaller other phenocryst phases. Olivine is the first silicate mineral to crystallize from many basaltic liquids, so rocks in this category may have undergone less fractional crystallization than rocks with several phenocrystic minerals. They may be either tholeiitic or alkalic. Analyzed rocks from this category are WD-88, WD-142, WD-304, WD-305, WD-335, and WD-341. There are 19 olivine samplesin the study collection.

4. Magnetite Some rocks with magnetite phenocrysts were assigned in the preceding paragraphs to trachytic or orthopyroxene groups. All other samples with magnetite phenocrysts are assigned to the present group. Since magnetite is relatively late in the

crystallization sequence of many basaltic liquids (e.g. Osborn, 1979), samples with magnetite phenocrysts represent liquids which are relatively fractionated. WD-65, WD-101, WD-133, WD-328 and 1.1.42 from this group have been analyzed. There are 22 magnetite samples in the study collection.

5. Plagioclase These rocks have only plagioclase as a phenocryst phase. The petrogenetic significance of this category is not immediately obvious. From this group, WD-6, WD-21, WD-37, WD-55, WD-160, WD-164, WD258, and WD320 have been analyzed. There are 31 plagioclase samples in the study collection.

6. Plagioclase-augite This is the most commonly occurring phenocryst assemblage. From this group, WD-3, WD-10a, WD-28, WD-29, WD-41, WD-49, WD-50, WD-52, WD-60, WD-95, WD-99, WD-129, WD-132, WD-136, WD-162, WD-163, WD-168, WD-179, WD-185, WD-187, WD-192, WD-210, WD-228, WD-235, WD-240, WD-241, WD-250, WD-256, WD-257, WD-259, WD-260, WD-267, WD-273, WD-319, WD-323, and WD-354 have been analyzed. There are 103 plagioclase-augite samples in the study collection.

7. Plagioclase-augite-olivine This is the second most common phenocryst assemblage. Rocks of this group and the preceding one probably represent a cotectic fractionation trend for Waianae. It is not obvious why some apparently cotectic magmas have olivine and some do not. WD-53a, WD-103, WD-134, WD-173, WD-190, WD-193, WD-202, WD-204, WD-230, WD-265, WD-294, WD-315, WD-369, WD-370, WD-372, and

WD-375 have been analyzed. There are 71 plagioclase-augite-olivine samples in the study collection.

8. Aphyric/other Aphyric rocks represent the other textural category. These are the rocks which have no phenocrysts and also are not trachytic (Except WD-331, as noted above). There are 22 aphyric samples in the study collection. Of those, WD-62, WD-131, WD-141, WD-144, WD-177, and WD-282 were analyzed. Under "other" are two phenocryst assemblages with few representative members. There are four rocks with plagioclase plus olivine, and two rocks with olivine plus augite; none were analyzed. This category has 28 samples in all.

F. Lithologic relationship between country rock and dikes

In most of the caldera region and the rift zones, dikes tend to have the same lithology as the flows in which they are emplaced. This generalization is not true in Puu Kailio, where the country rock is mostly breccia, or in the icelandite-rhyodacite ridges adjacent to Puu Kailio (table IV).

G. Distribution of dikes of various petrographic types

There is a correlation between a dike's location within the volcano and its petrographic type (fig. 11). Caldera-area dikes tend to be different from rift-zone dikes, though no petrographic type is confined exclusively to one area or the other. Olivine,

Table IV Lithology of dikes and country rock

REGION	COUNTRY ROCK	INTRUSIONS	DIKES OBSERVED
Puu Kailio	breccia and icelandite	pl-au mt pl-au-ol	33
Kolekole Roadcut	pl-phyric basalt	pl-au pl-au-ol	40
Kolekole Pass	pl-phyric basalt	pl-au pl-au-ol	38
Honouliuli 1	pl-phyric basalt	pl-au-ol	10
Honouliuli 2	pl-phyric basalt	pl pl-au	26
Navy Ridge	icelandite	pl-au pl-au-ol pl	39
Kauaopuu	icelandite and rhyodacite	pl-au pl	43
Mauna Kuwale	icelandite, rhyodacite, pl-phyric basalt	pl-au-ol pl-au ol	17
Paheehee Ridge	pl-phyric basalt	aphyric pl-au-ol	25
Kamaileunu	caldera-filling member	pl-au pl-au-ol	8
Nanakuli Ridge	pl-phyric basalt and hawaiite	trach	9

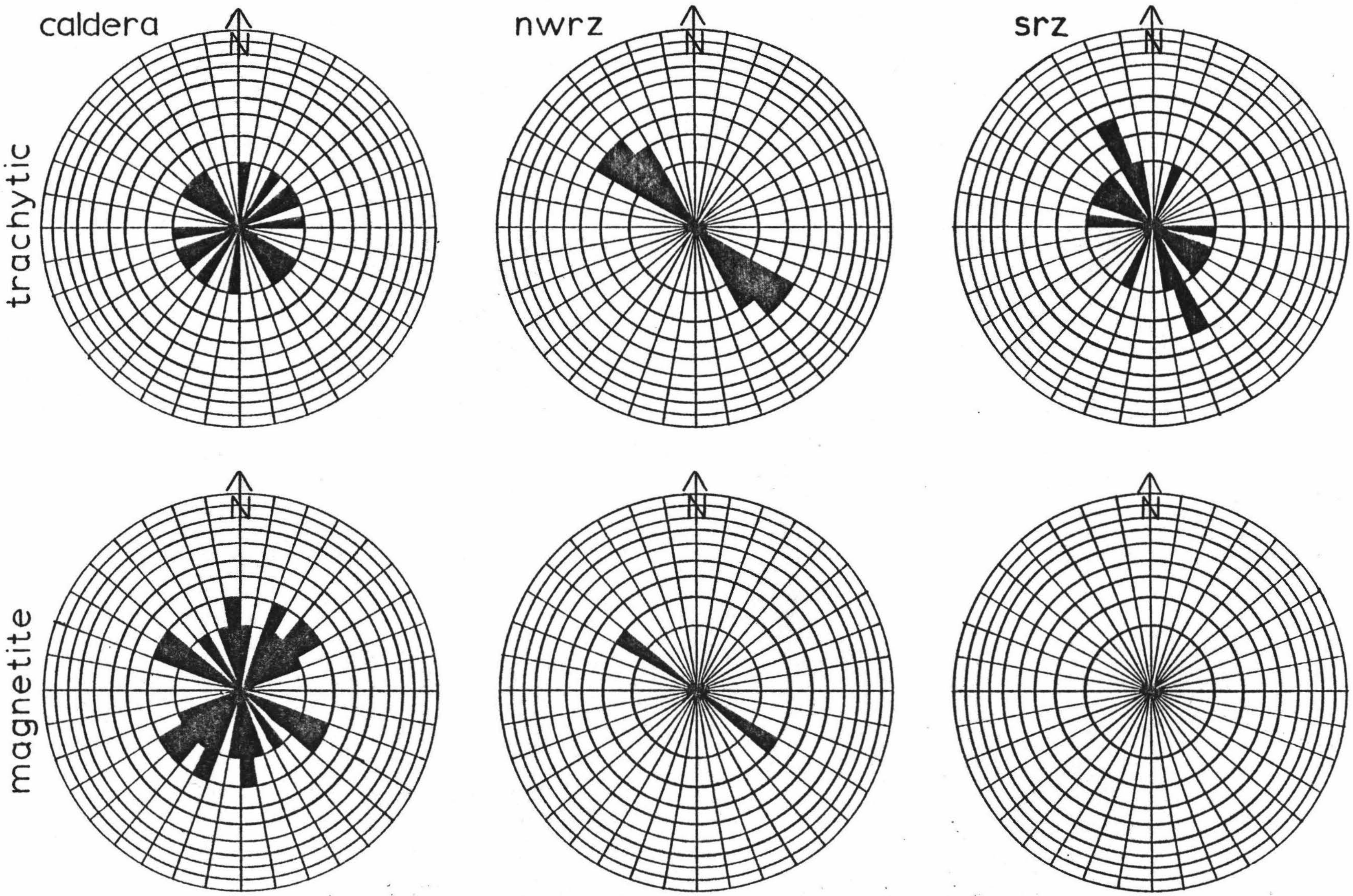
Table IV, continued

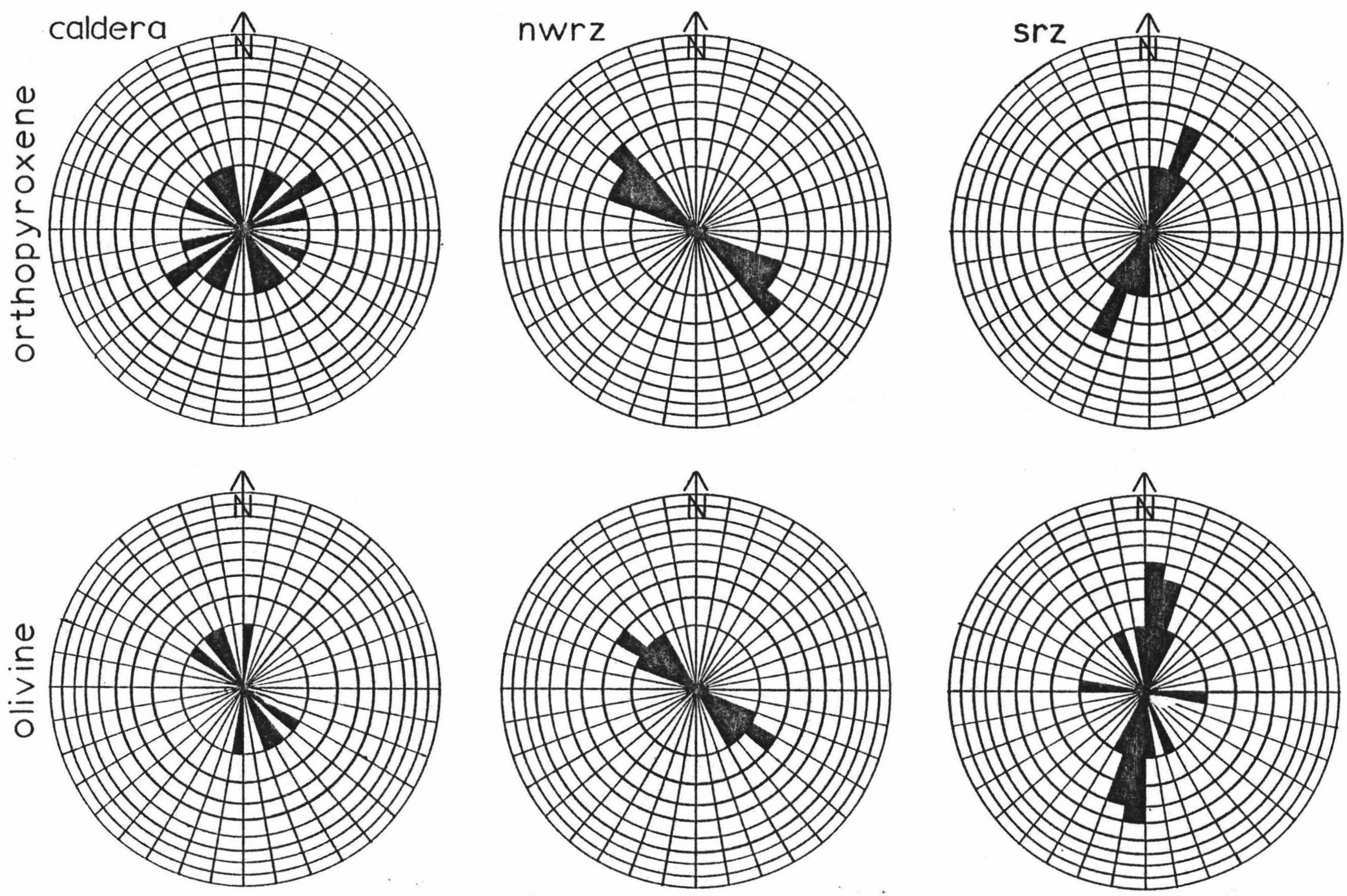
REGION	COUNTRY ROCK	INTRUSIONS	OBSERVED
Puu Heleakala	pl-phyric basalt with one layer of pl-phyric basalt	ol pl-au-ol opx	16
Puu O Hulu Kai	ol-phyric basalt	opx pl-au-ol pl-au	14
Puu O Hulu Uka	ol-phyric basalt	ol opx pl-au	13
Kolealiilii	shield-building member	pl-au	8
Makua edge	shield-building member	opx	16
Makua center	shield-building member alkalic cap member	trach	9
Kuaokala	alkalic cap member	trach mt	8
Kaena Point	shield-building member alkalic cap member	pl-au-ol	6

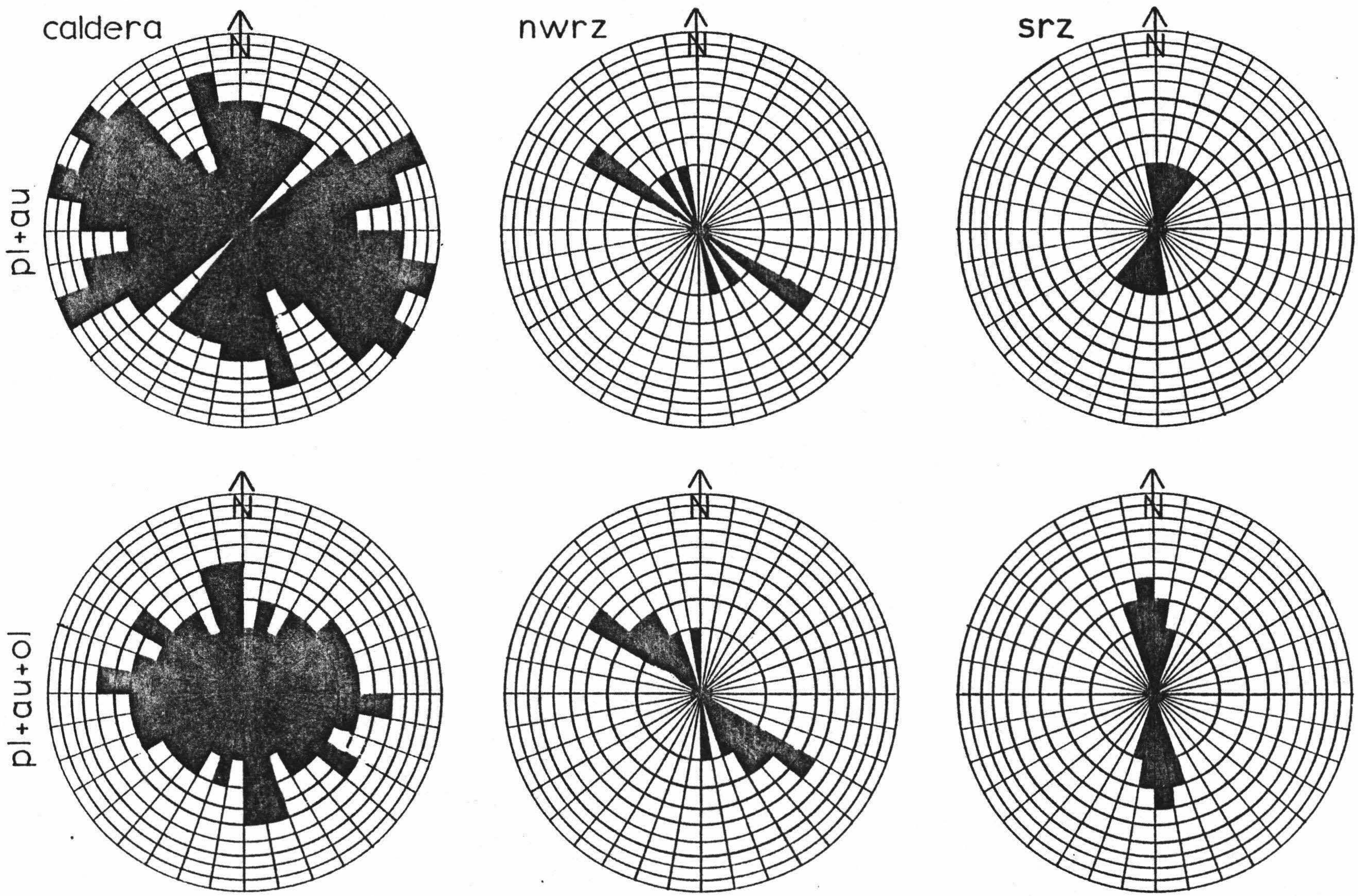
Abbreviations: au = augite; mt = magnetite; ol = olivine; opx = orthopyroxene; pl = plagioclase; trach = trachytic

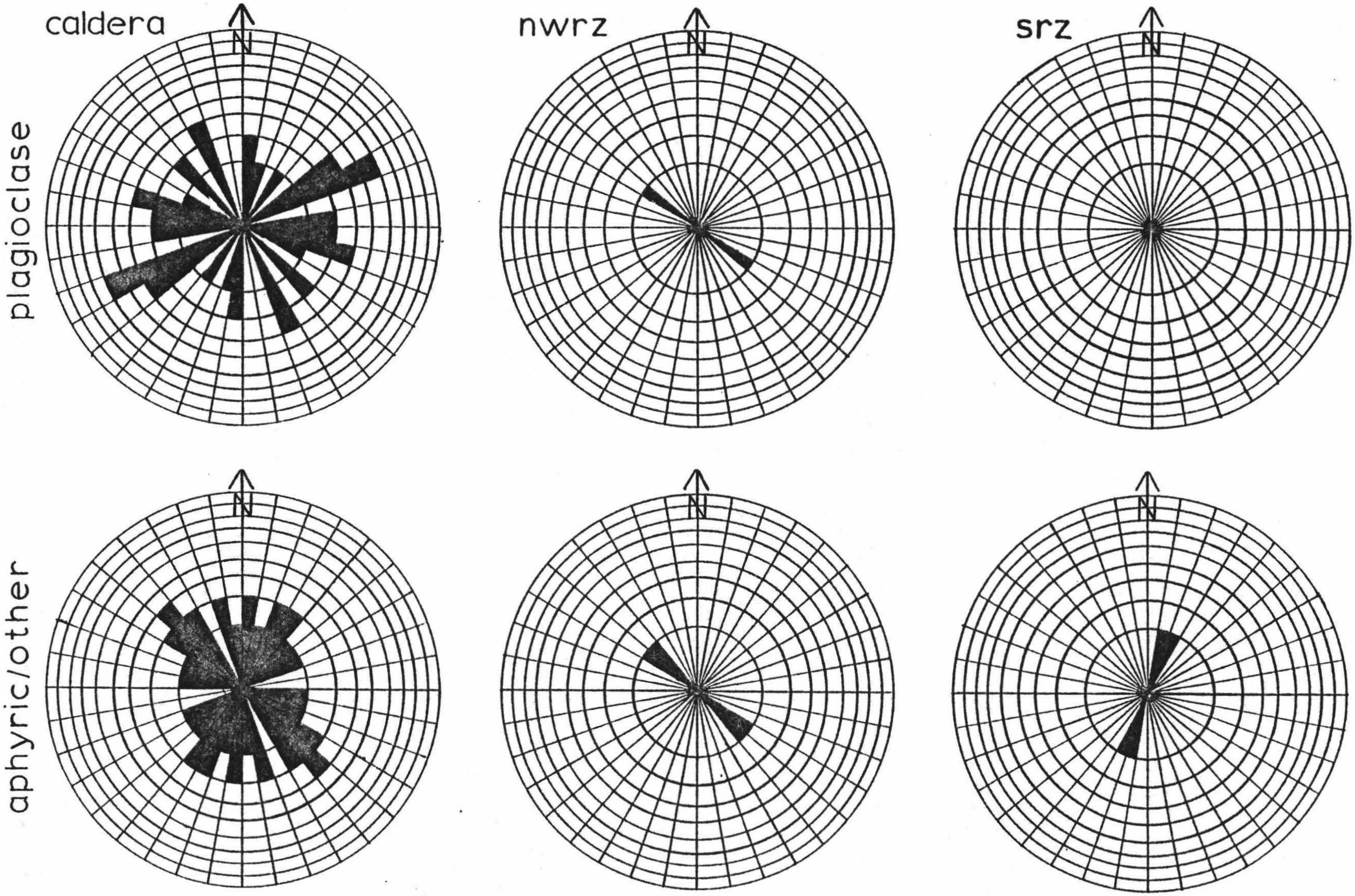
References for country rock type: Stearns and Vaskvik, 1935; Macdonald, 1940; Macdonald and Katsura, 1964; and Sinton, 1979.

Figure 11. Rose diagrams of Waianae dikes, comparing azimuth with petrographic type and with location in the volcano. As in figure 8, rose diagrams represent absolute numbers of dikes.


caldera
nwrz
srz
trachytic
magnetite
N
N
N
N
N
N


caldera
nwrz
srz
orthopyroxene
olivine
N
N
N
N
N
N


caldera
nwrz
srz
pl+au
pl+au+ol
N


caldera
nwrz
srz
plagioclase
aphyric/other
N
N
N
N
N
N

orthopyroxene, and trachytic dikes are concentrated in the rift zones. Plagioclase, magnetite, and aphyric dikes are concentrated in the caldera region. Olivine, as a phenocryst phase in general, even when it is accompanied by other phases, is relatively more common in the rift zones than in the caldera. For instance, there are more plagioclase-augite-olivine than plagioclase-augite samples in the rift zones, even though the latter is overall more common assemblage.

The assemblage plagioclase-augite is most common in the immediate vicinity of the eruptive center. Kauaopuu, Navy Ridge, Puu Kailio, Kolekole Roadcut, Kolekole Pass, and Honouliuli 1 and 2 have many samples with this assemblage. So does KoleaIiiilii, which is near the eruptive center yet is part of the Northwest Rift Zone. Mauna Kuwale, Kamaileunu, Puu O Hulu Kai, Puu O Hulu Uka, and Nanakuli Ridge have fewer samples of this petrographic type; in Heleakala, Paheehee Ridge, and the distal portions of the Northwest Rift Zone (Kaena Point, Kuaokala, Makua center, and Makua edge) plagioclase-augite samples are completely absent.

The trachytic dikes of Lualualei-Nanakuli Ridge strike slightly west of other dikes of the South Rift Zone; in fact, they seem to be more closely aligned with dikes of the Northwest Rift Zone than with other South Rift Zone dikes. In each of the three structural divisions of Waianae volcano studied here (Northwest Rift Zone, caldera region, and South Rift Zone), there is about the same number of trachytic samples. There are many more total samples from the caldera region than from the rift zones, so the trachytic dikes seem to be proportionately concentrated in the rift zones, but they are distributed relatively evenly along the length of the volcano.

Trachytic dikes are associated with the alkalic cap. During the alkalic phase of activity the caldera may fill in and disappear; yet it evidently still exerts a structural influence, since trachytic dikes from the caldera region have the same random orientation as other caldera region dikes.

Nearly all of the magnetite group dikes are within the caldera. Examining the compositions of these dikes (appendix C) indicates that rocks in this group are indeed relatively differentiated, as postulated previously (section E4). Four of the five dikes analyzed are in the low-magnesium silicic chemical group. All five are tholeiitic.

H. Composition

Appendix I lists the compositions of the dikes analyzed in this study. These compositions are discussed in the following chapter.

IV. INTERPRETATIONS

A. Petrological evolution

1. Classification schemes for basalts

The volcanic rocks of Waianae Range have been assigned to two principal series, tholeiitic and alkalic. Differentiated alkalic rocks (hawaiite through trachyte) are fairly easy to distinguish from differentiated tholeiitic rocks (icelandite through rhyolite). In the basalt range there is a chemical and mineralogical continuum between the clearly alkalic and the clearly tholeiitic samples. Because the two suites differentiate along obviously diverging trends and because petrologists strive to make neat boxes to contain their data, petrologists have tried to draw a line across that continuum, based on petrography or chemical composition.

Macdonald and Katsura (1964) designed a discrimination diagram based on the weight ratio of total alkalis ($Na_2O + K_2O$) to silica. It does indeed separate many tholeiitic from many alkalic basalts but it is not quite the "remarkably clean separation of rocks" (Macdonald and Katsura, 1964, p. 86) that it seemed to be when first used. For example, three Waianae dike analyses, WD-65, WD-210, WD-320 fall between basalt and rhyodacite, rather than between basalt and trachyte, so they are certainly tholeiitic, yet they plot in the alkalic field (fig. 12). The authors are vague as to what criteria are used to separate tholeiitic from alkalic rocks. They say "mineral composition" (p. 87) but fail to indicate whether normative or modal.

Figure 12. Alkali-silica diagram for Waianae dikes, cast in witght percent. Diagonal line is Macdonald-Katsura line, from Macdonald and Katsura (1964). Squares, mildly tholeiitic basalt; triangles, strongly tholeiitic basalt (see section A2); circles, differentiated tholeiites; crosses, alkalic rocks.

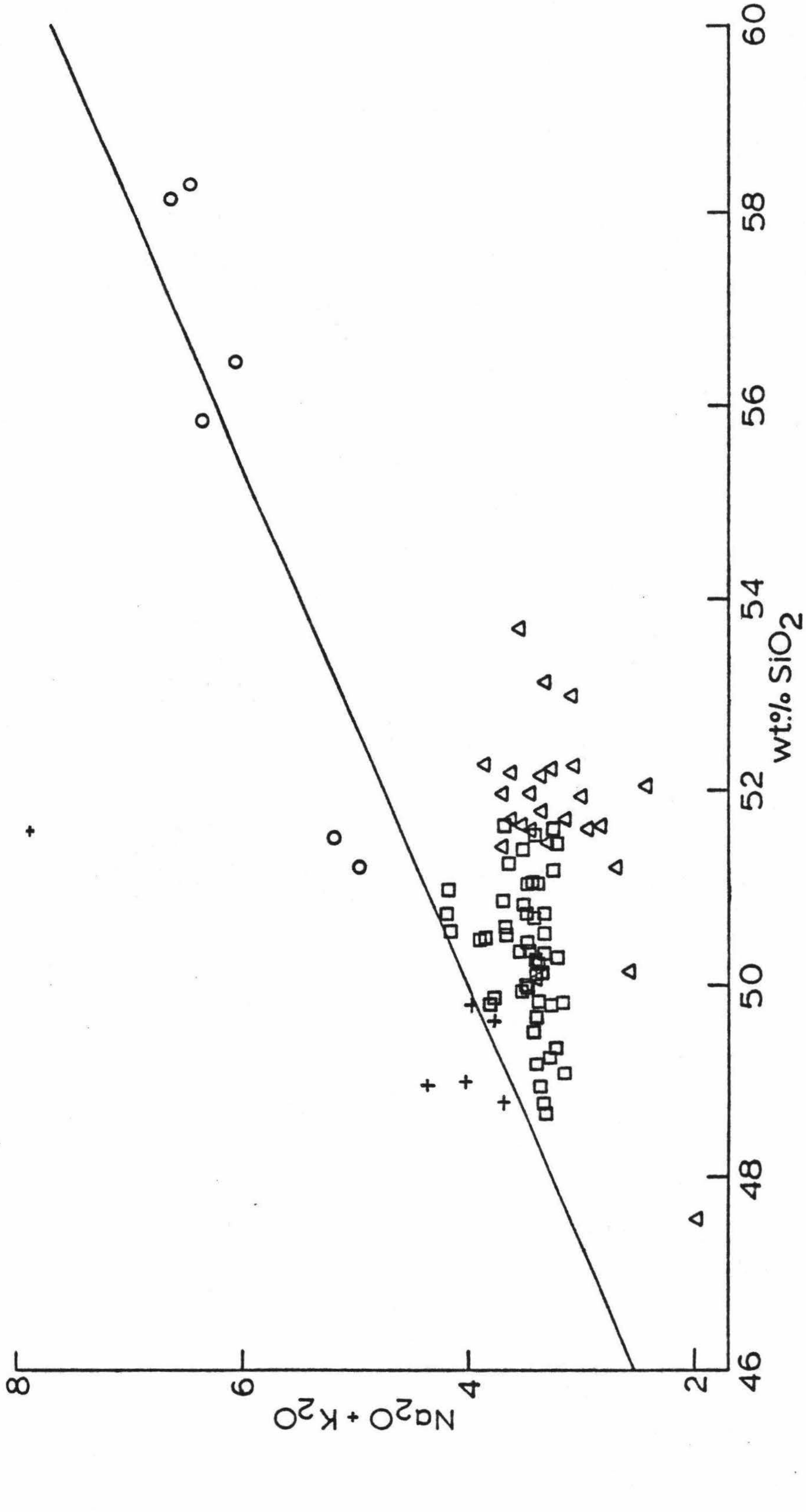
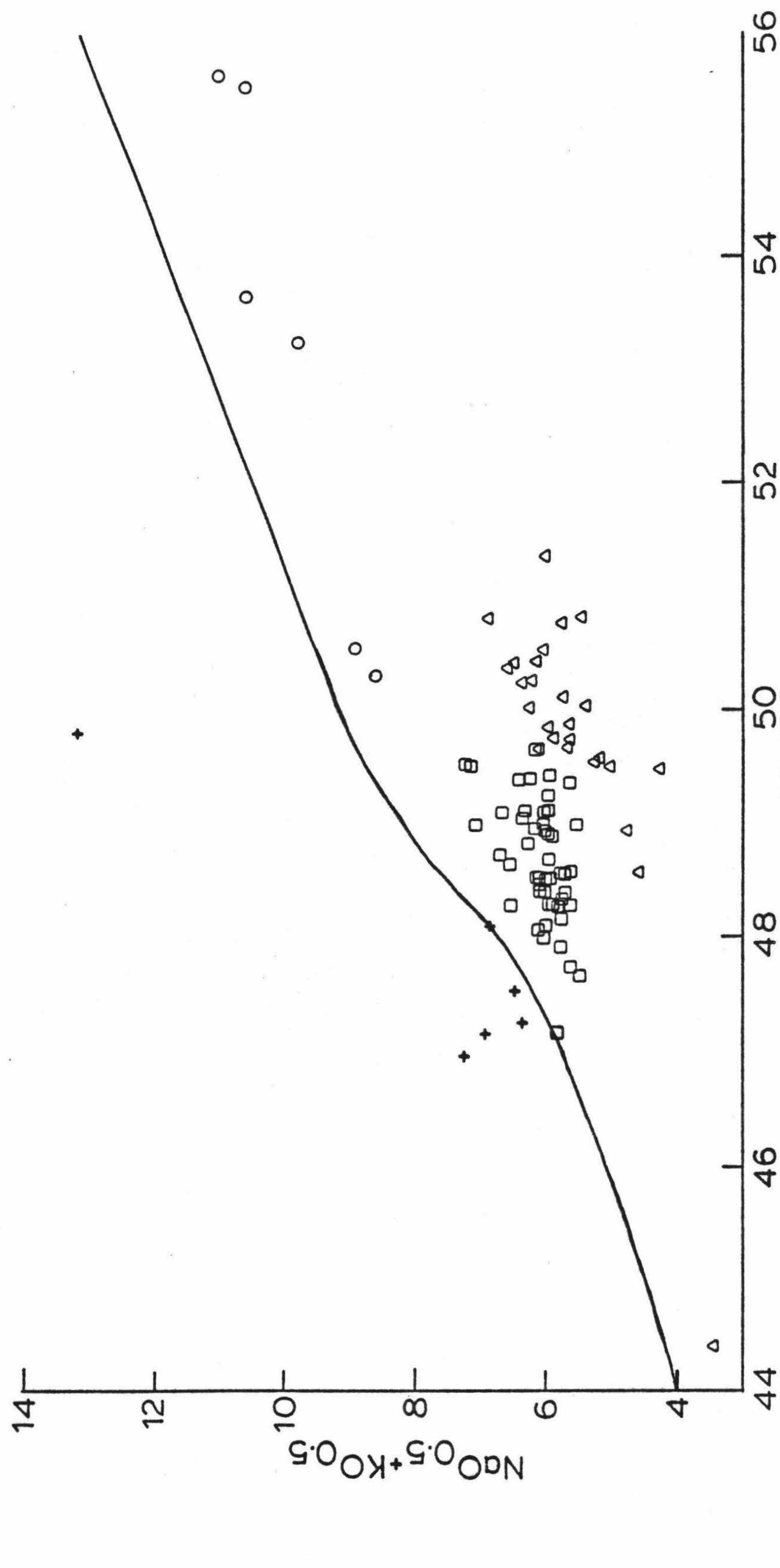

Na2O + K2O
wt.% SiO2
2
4
6
8
46
48
50
52
54
56
58
60

Figure 13. Alkali-silica diagram for Waianae dikes, cast in cation mol percent. Symbols as for fig. 12. Note changes in relative positions of points between figures 12 and 13. Diagonal curve is discriminant between tholeiitic and alkalic series, from Diller (1982).



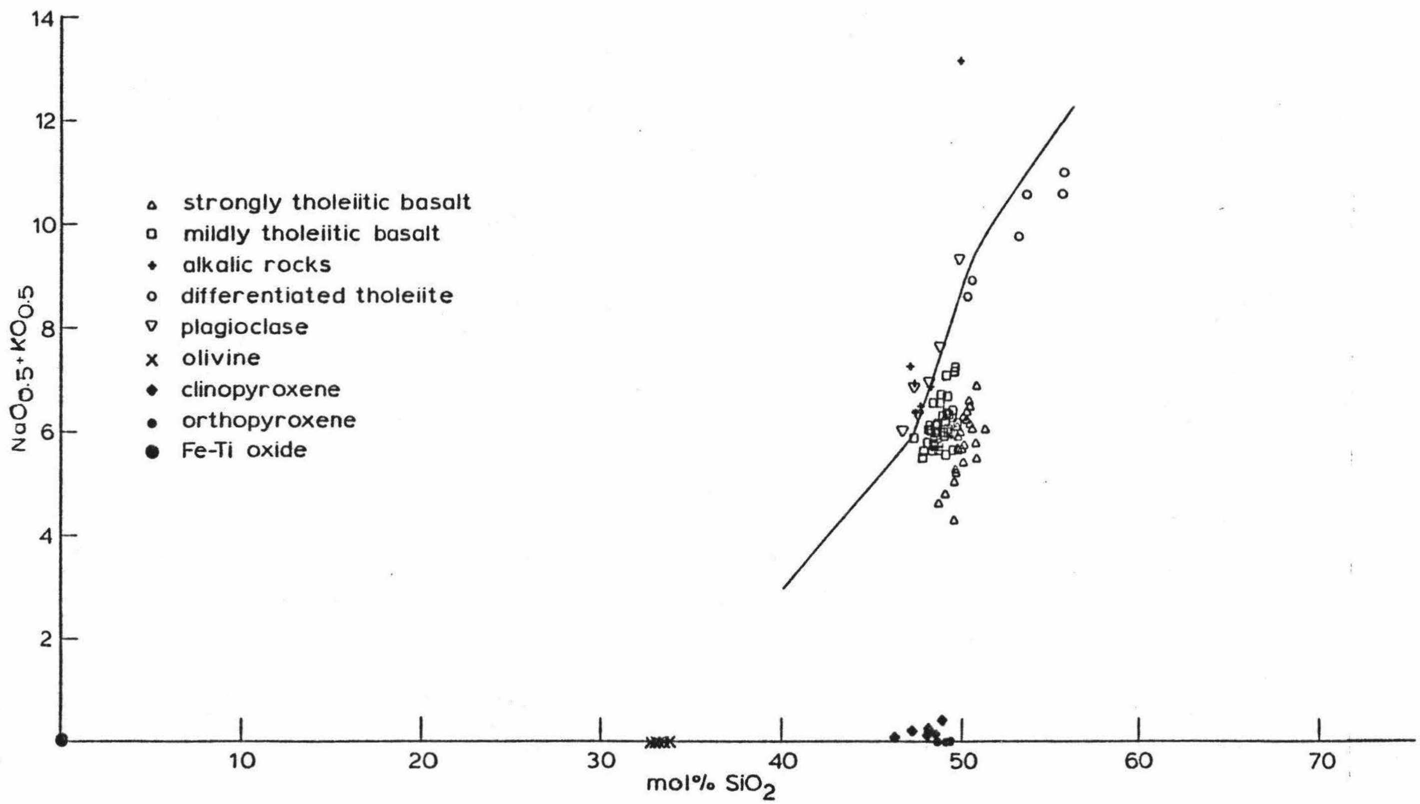
14
12
10
8
6
4
NaO0.5+KO0.5
44
46
48
50
52
54
56
mol% SiO2

Two refinements to the Macdonald-Katsura diagram, pointed out by Diller (1982), make it a more reliable discriminant.

First, analyses must be cast in mol %. Figures 12 and 13 are alkali-silica diagrams of Waianae and West Maui rocks in weight % and mol %, respectively. A moment's examination will make it apparent that the points shift with respect to each other, particularly in the horizontal (silica) direction. This indicates that the two methods of plotting are not interchangeable. A plot that is used to interpret crystallization paths or differentiation differences among liquids should be cast into mol % because a liquid crystallizes one molecule at a time, not one gram at a time. For instance, as olivine grows in an evolving liquid, the weight proportion of silica goes down as heavy iron enters the lattice in greater proportion, rather than lighter magnesium, even though the proportion of silica does not change. A molecular percent plot correctly shows the constant silica proportion. Plagioclase and clinopyroxene show similar, though more complex, phenomena.

Second, a curve, rather than a straight line, divides the two groups. Diller describes the curve thus (p.109), "The discriminant used in this study is a line of olivine control to the albite-anorthite join, where it nearly parallels the join until fractionation of low-silica phases (chiefly Fe-Ti oxides) requires a deviation from the join." An alkali-silica plot that includes analysed Hawaiian minerals illustrates this (fig. 14).

Figure 14. Cation mol percent alkali-silica diagram for Waianae dikes, including some phases observed as phenocrysts in these rocks. Mineral analyses are from samples taken on the island of Hawaii (Basaltic Volcanism Study Project, 1981).



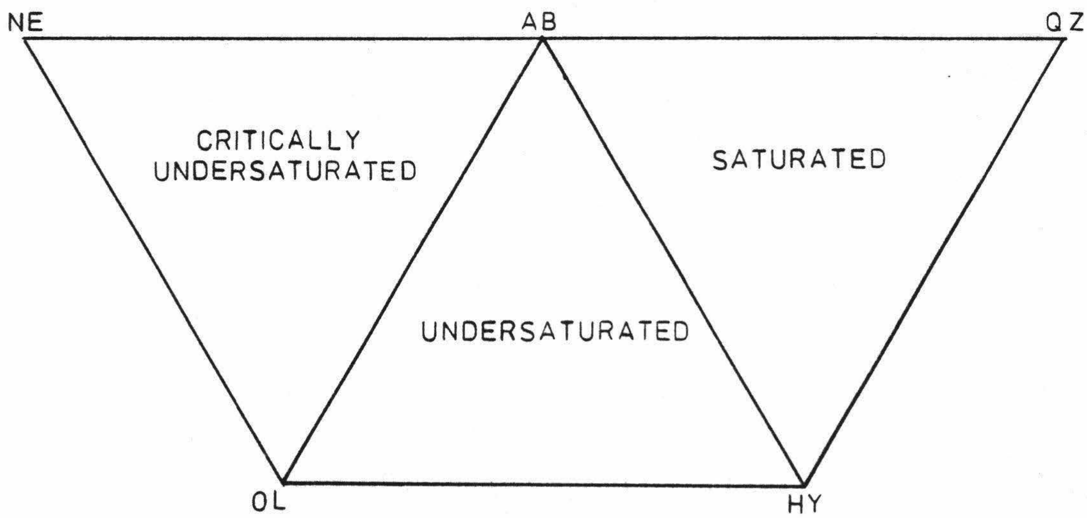
14
12
10
8
6
4
2
$NaO_{0.5}+KO_{0.5}$
strongly tholeiitic basalt
mildly tholeiitic basalt
alkalic rocks
differentiated tholeiite
plagioclase
olivine
clinopyroxene
orthopyroxene
Fe-Ti oxide
10
20
30
40
50
60
70
mol% SiO_2

2. Subdivisions among tholeiites in Waianae

It is possible to derive tholeiitic and alkalic basalts from sources that have the same major-element composition. The difference between them originates in circumstances surrounding initial melting and separation from the mantle source (Yoder & Tilley, 1962; Yoder, 1976; Frey, Green, & Roy, 1978). Small degrees of melting, high pressure (great depth), and high CO_2/H_2O tend to produce alkalic basalts; greater degrees of melting, low pressure (shallow depth), and high H_2O/CO_2 tend to produce tholeiitic basalts (ibid.). With at least three variables, each of which can vary continuously and independently, one would expect not only a continuum between alkalic and tholeiitic basalts, but also the large observed variation within each field. Examining variations among tholeiites might allow one to learn something about changes in magma generation during the prolific shield-building phase, and perhaps identify precursors to the transition to alkalic magmas.

It is commonly assumed that liquid at equilibrium with mantle has a magnesium number (mg#; defined as $100Mg/(Mg + Fe^{+2})$) of 72-74 (Basaltic Volcanism Study Project, 1982). As depth of separation increases, silica saturation decreases but initial mg# remains roughly constant. So comparing silica saturation at constant mg# should reveal something about depth of separation and degree of "tholeiicity". The concepts of saturation, undersaturation, and critical undersaturation with respect to silica are defined by normative minerals, (fig. 15), so one may use normative quartz and olivine as plotting parameters to illustrate silica saturation (fig. 16).

Figure 15. Igneous rocks that are saturated, undersaturated, or critically undersaturated with respect to silica are defined on the basis of normative quartz, hypersthene, olivine, and nepheline, as illustrated on this opened-out basalt tetrahedron (after Yoder and Tilley, 1962).

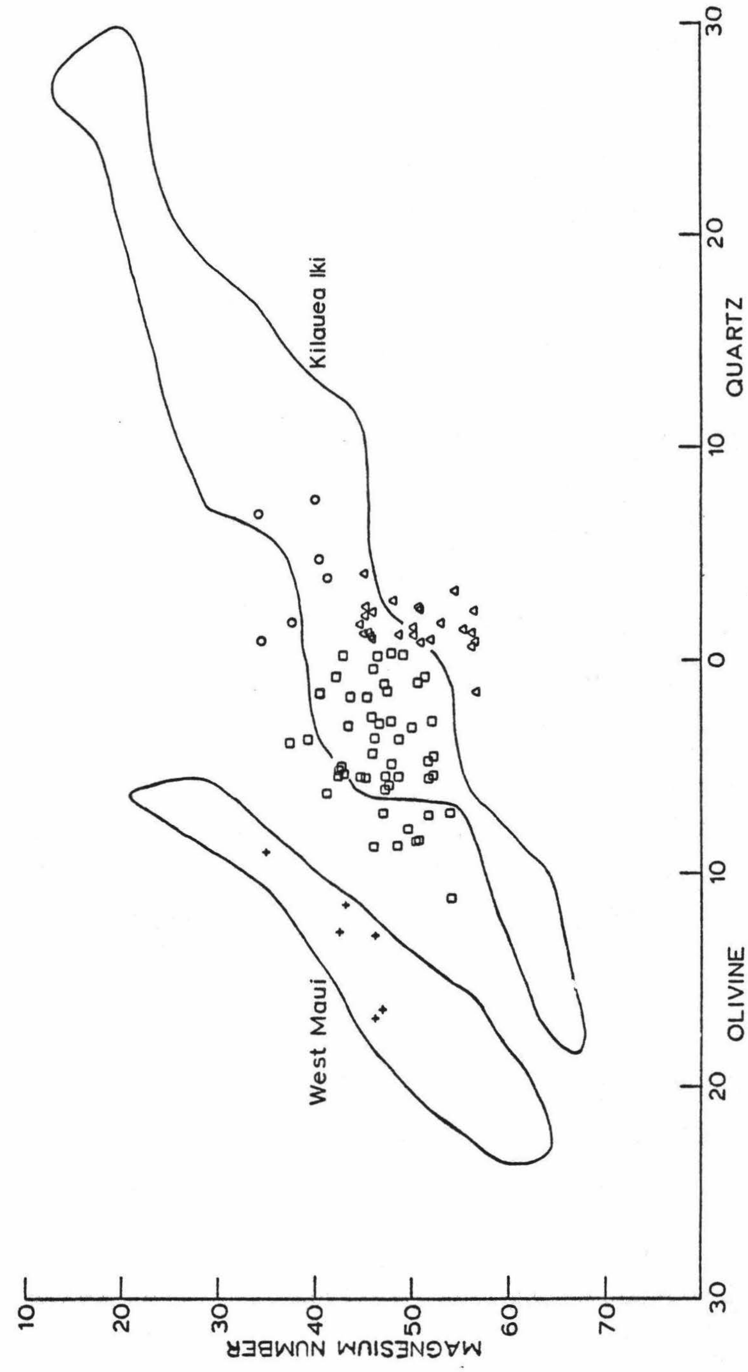

NE
AB
QZ
CRITICALLY UNDERSATURATED
SATURATED
UNDERSATURATED
OL
HY

Glasses from Kilauea Iki lava lake (Helz and Luth, unpublished data) appear in fig. 16 to show the trend and degree of scatter to be expected from a cogenetic suite. West Maui alkalic rocks (Diller, 1982) show a similar trend, offset in the direction of greater normative olivine (less saturation, or greater undersaturation). Waianae basalts have a different trend entirely. This may be because the basalts have been sampled at similar degrees of differentiation, but from several different levels of "tholeiicity"; whereas the Kilauea and West Maui rocks are from a single level of "tholeiicity" (or "alkalicity") but with varying differentiation.

Note that there is a clearer separation between alkalic and tholeiitic rocks in this plot than in the alkali-silica diagram. Among the tholeiites there are no such obvious gaps, but one may identify subgroups. Those that are most silica-saturated will be called "strongly tholeiitic"; those that are less saturated will be called "mildly tholeiitic".

Those samples which are designated "strongly tholeiitic" form a coherent group; they fall close to each other in every plot examined. When Fe^{+3}/Fe^{+2} is set at .15, the strongly tholeiitic basalts that have mg# between 56 and 44 have cation mol% quartz > 0.5%. WD-305MX is olivine-normative, and it appears to be strongly tholeiitic because it lies on a trend from other strongly tholeiitic samples. Like all mantle derived liquids, these initially have olivine (plus Cr-spinel) on the liquidus. It seems that the difference between strongly and mildly tholeiitic liquids is that strongly tholeiitic liquids precipitate only olivine (plus Cr-spinel) until they become quartz-normative. Only after they become quartz-normative does plagioclase

Figure 16. Magnesium number vs. normative quartz and olivine, using norms calculated by the method of Irvine (1979). Symbols as for figure 12. See text for explanation.


MAGNESIUM NUMBER
10
20
30
40
50
60
70
OLIVINE
QUARTZ
30
20
10
0
10
20
30
Kilauea Iki
West Maui

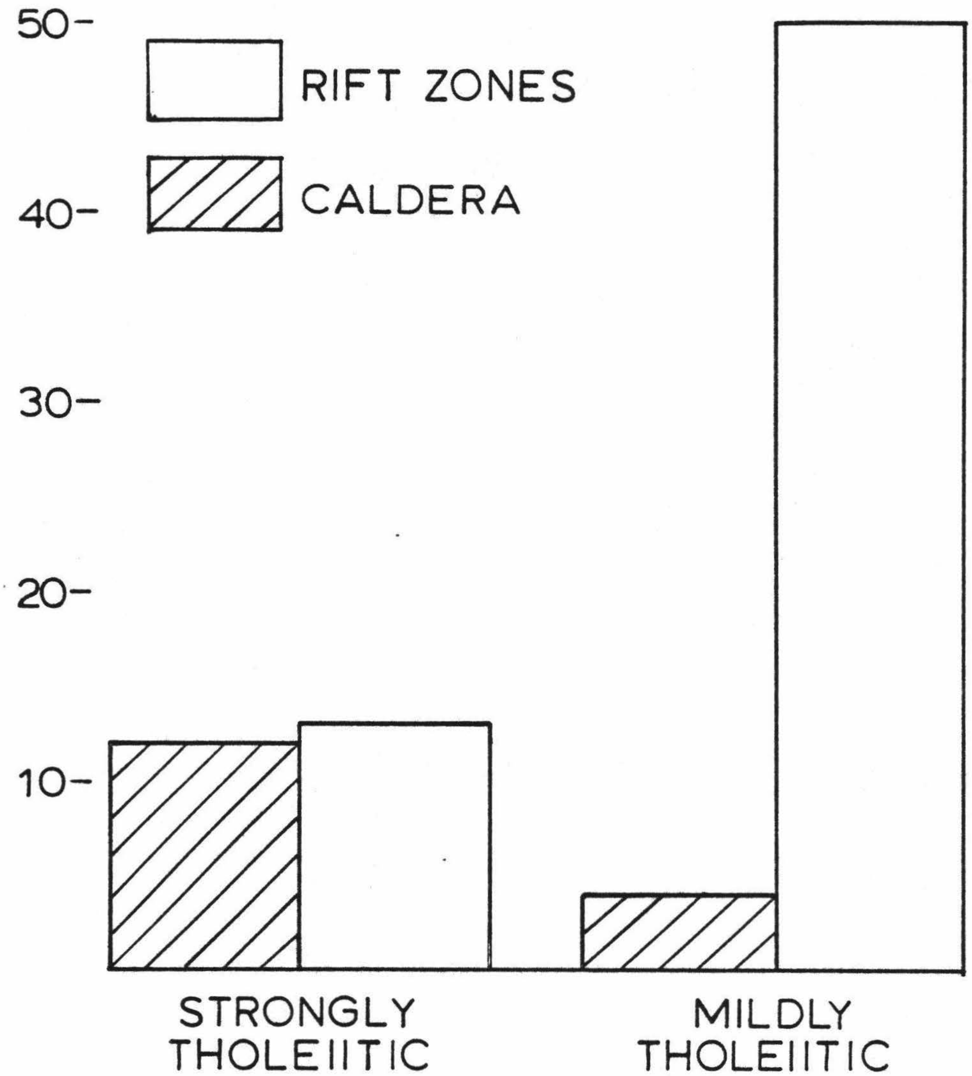
crystallize and fractionate. Other tholeiites begin to crystallize plagioclase while they are still olivine-normative, and with further crystal fractionation may become quartz-normative.

3. Correlations among chemistry, petrography, and structural location of dikes

There is some correlation between chemical groups and petrographic groups. The olivine and orthopyroxene rocks are typically strongly tholeiitic, and also are typically found in the rift zones. Plagioclase-augite and plagioclase-augite-olivine samples are typically mildly tholeiitic. Their distribution between rift zones and caldera is roughly in proportion to total number of samples collected. Magnetite and aphyric samples are typically mildly tholeiitic; they are strongly concentrated in the caldera. Plagioclase samples are evenly divided between strongly and mildly tholeiitic, but they are almost exclusively found in the caldera.

Of the 79 analyzed tholeiites, 14 come from the rift zones and 65 from the caldera region. In the rift zones, most of the dikes are strongly tholeiitic (fig.17). In the caldera the reverse is true and most of the dikes are mildly tholeiitic. The strongly tholeiitic magmas may represent the shield-building phase, and the mildly tholeiitic magmas would be transitional to alkalic. Although the two groups of rocks are significant to the petrological evolution of the volcano, they cannot be correlated with time-stratigraphic units. Dikes WD-95, WD-96, and WD-99 all intrude the breccia of Puu Kailio a few steps away from each other, at 1400 ft elevation. That means they all erupted after the breccia had formed. WD-95 is alkalic, WD-96 is

<u>Figure 17.</u> Numbers of mildly and strongly tholeiitic samples from caldera region and rift zones.


50-
40-
30-
20-
10-
RIFT ZONES
CALDERA
STRONGLY
THOLEIITIC
MILDLY
THOLEIITIC

strongly tholeiitic, and WD-99 is mildly tholeiitic. Just as caldera-filling and shield-building lavas were erupted contemporaneously, so mildly and strongly tholeiitic magmas were erupted over the same time interval.

4. Some tholeiites of unusual composition

Tholeiitic lavas are far more abundant (as volume percent of subaerially-exposed volcano) than alkalic lavas in Hawaiian volcanoes. Yet for the most part the only tholeiites that are found are basalts: differentiated tholeiites are rare. Occasional examples of in situ differentiation of magma pockets are found (such as Palolo Valley, Oahu and Kilauea Iki lava lake). The icelandite and rhyodacite of Waianae are tholeiitic, but formed by some process other than simple crystal fractionation of tholeiitic basaltic magma (Sinton, 1981). Many differentiated alkalic magmas erupt which can be related to primitive alkalic magmas by crystal fractionation (Diller, 1982; West, 1982). Kuno (1957) also noted that alkalic magmas seem to differentiate far more readily than tholeiitic magmas but offered no explanation.

Waianae, on the other hand, has produced a few evolved lavas which seem to have formed by normal crystal fractionation, in addition to the enigmatic rhyodacite and icelandite. Four analysed dike glasses prove to be silica-rich, low-magnesium tholeiites of a type not previously found in flows. They are WD-101, WD-320, WD-328, and 1.1.42, all from Puu Kailio, within or above the breccia. They can be divided into two pairs: WD-101 and WD-320 with about 56 wt% silica and 3 wt % magnesia, and WD-328 and 1.1.42 with about 58 wt% silica and

2.5 wt% magnesia. Two other dikes, WD-65 and WD-210, also have unusually low magnesium, about 3.5 wt %, though not outside normal limits for basalts. Together, the six samples form a series between tholeiitic basalt and more evolved compositions. All six samples come from the eruptive center of the volcano. WD-210 is emplaced in Waianae-Lualualei Ridge; the other six are emplaced in the breccia of Puu Kailio. WD-65 is a whole-rock analysis; WD-210, WD-101, WD-320, WD-328, and 1.1.42 are glass analyses and thus represent liquid compositions.

What might be the origin of these liquids? (A) They could be related to the rhyodacite and icelandite. (B) They could be mixed between two magmas, or one magma with assimilated solid material. (C) They could be partial melts of crustal material. (D) They could show influence of Soret separation. (E) They could be residual liquids from in situ differentiation. (F) They could form by fractional crystallization of basaltic magma.

a. Relation to rhyodacite and icelandite: WD-328 and 1.1.42 are similar in silica content to the rocks mapped as pyroxene-phyric basalt by Sinton (1979) and since identified as icelandite (Sinton, 1981) (Table IV). Both the flows and the dikes can be classified as tholeiitic andesites or icelandites.

Five samples of icelandite flows were studied to compare them to the Puu Kailio high-silica dikes. They are OW-85 from Mauna Kuwale, OW-46 from the southeast side of Lualualei valley, and OW-18G, OW-32B, and OW-26 from Kauaopuu. The first four flows are similar to each other in thin section: there are olivine or pyroxene megacrysts (probably xenocrysts) with reaction rims and other forms of

Table IV Silicic flows and silicic dikes of Waianae

Silicic flows of Waianae

	OW18G	OW26	OW32B	OW46	OW85
SiO2	60.78	59.69	60.43	58.60	58.53
TiO2	1.22	1.72	1.23	1.52	1.29
Al2O3	14.17	15.58	14.38	14.80	14.06
Fe2O3	0.72	0.79	0.77	0.87	0.81
FeO	4.79	5.23	5.13	5.77	5.42
MnO	0.12	0.06	0.11	0.12	0.12
MgO	4.86	2.24	5.10	4.89	5.81
CaO	5.55	3.96	5.62	5.75	5.72
Na2O	3.57	4.74	3.70	3.61	3.40
K2O	2.89	2.74	3.01	2.34	2.58
P2O5	0.25	0.53	0.26	0.33	0.19
H2O+	1.13	0.90	0.87	1.13	1.18
H2O-	0.42	1.60	0.28	0.66	0.84
CO2	0.11	0.04	0.07	0.04	0.13
SumOx	100.58	99.82	100.96	100.43	100.09

Silicic dikes of Waianae

	WD101	WD320	WD328	1.1.42
SiO2	56.45	55.85	58.12	58.28
TiO2	2.60	2.44	1.93	2.11
Al2O3	14.52	14.18	15.08	15.17
Fe2O3	1.29	1.19	1.14	1.05
FeO	8.56	7.89	7.58	6.96
MnO	0.21	0.13	0.17	0.12
MgO	3.28	3.13	2.22	2.62
CaO	6.58	6.25	5.07	5.47
Na2O	3.97	4.37	4.56	4.31
K2O	2.09	1.98	2.07	2.15
P2O5	1.08	0.76	0.51	0.50
SumOx	100.62	98.17	98.45	98.74

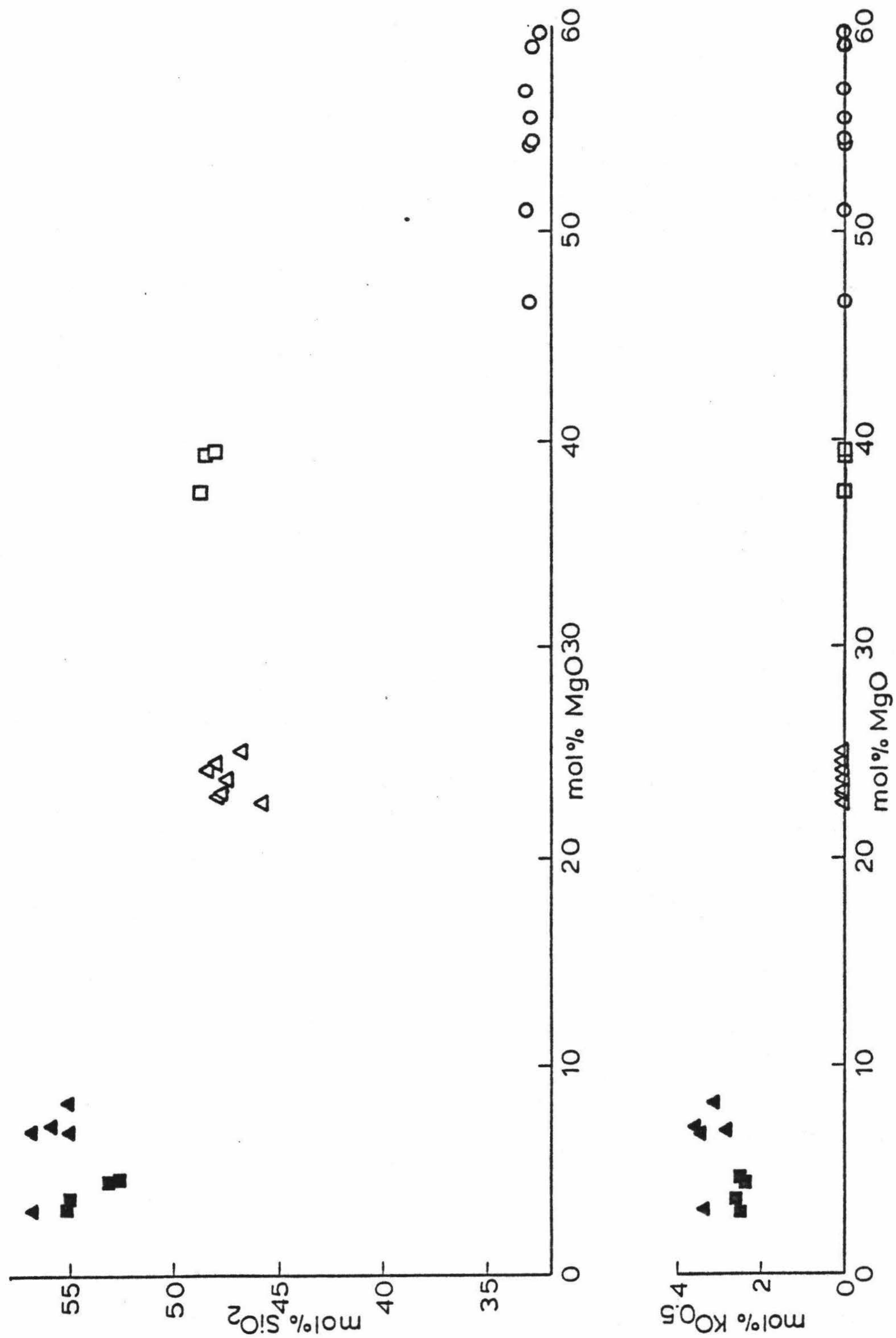
alteration. The rest of the rock has seriate crystals set in interstitial brown glass containing droplets of a gray liquid. There are two pyroxenes: orthopyroxene greater than or equal to augite in abundance. Neither plagioclase nor magnetite forms phenocrysts in the flows. OW-26 is difficult to interpret. The thin section is aphyric with a pilotaxitic texture. Clay or other alteration minerals fill the vesicles.

By contrast, the dikes have no megacrysts, and the phenocrysts do not include olivine or orthopyroxene. They have phenocrysts of plagioclase, augite, and magnetite in subequal amounts, and a smaller amount of apatite. The glass is homogeneous in appearance; if there are immiscible droplets they are submicroscopic in size.

The analyses of the two groups of rocks show distinct differences too. At a given silica content, the flows (except OW-26) are higher in MgO, and lower in TiO_2, Al_2O_3, Na_2O, and P_2O_5 than the dikes. OW-26 is closer in composition to the dikes than the flows; however in the field it seems to be part of the same flow or set of flows as OW-18G and OW-32B (J.M. Sinton, pers comm.). If the megacrysts were removed from the other icelandite samples, would the dikes and flows have the same composition? The icelandite flows are about 56 mol% (60 wt%) silica. The xenocrysts of bronzite, augite, and olivine are all less than 50 mol% silica. Their presence thus has the effect of reducing the silica content of the bulk rock and the matrix silica content of the flows must be higher than 56 mol%. The dikes have silica contents of 53-55 mol% (56-58 wt %), which is lower than the bulk silica content of the flows. In other words, if the dikes and flows were related as suggested, the composition of the

Figure 18. MgO vs. $KO_{0.5}$ and MgO vs. SiO_2 for 4 Waianae differentiated tholeiitic dikes (filled squares), 5 Waianae icelandite flows (filled triangles), 7 Hawaiian augites (open triangles), 3 Hawaiian orthopyroxenes), and 9 Hawaiian olivines (open circles). Mineral analyses from Basaltic Volcanism Study Project, 1981.

Are differentiated tholeiitic dikes related to icelandite flows by addition of xenocrysts to the flows or by subtraction of xenocrysts from the dikes? The composition of any xenocryst assemblage would fall within the field bounded by the mineral compositions. If the flows and dikes were related as suggested in the question, a mixing line should connect flows, dikes, and the field bounded by the mineral compositions. This is not the case.


mol% SiO_2
mol% MgO
mol% $KO_{0.5}$
mol% MgO
55
50
45
40
35
4
2
0
0
10
20
30
40
50
60

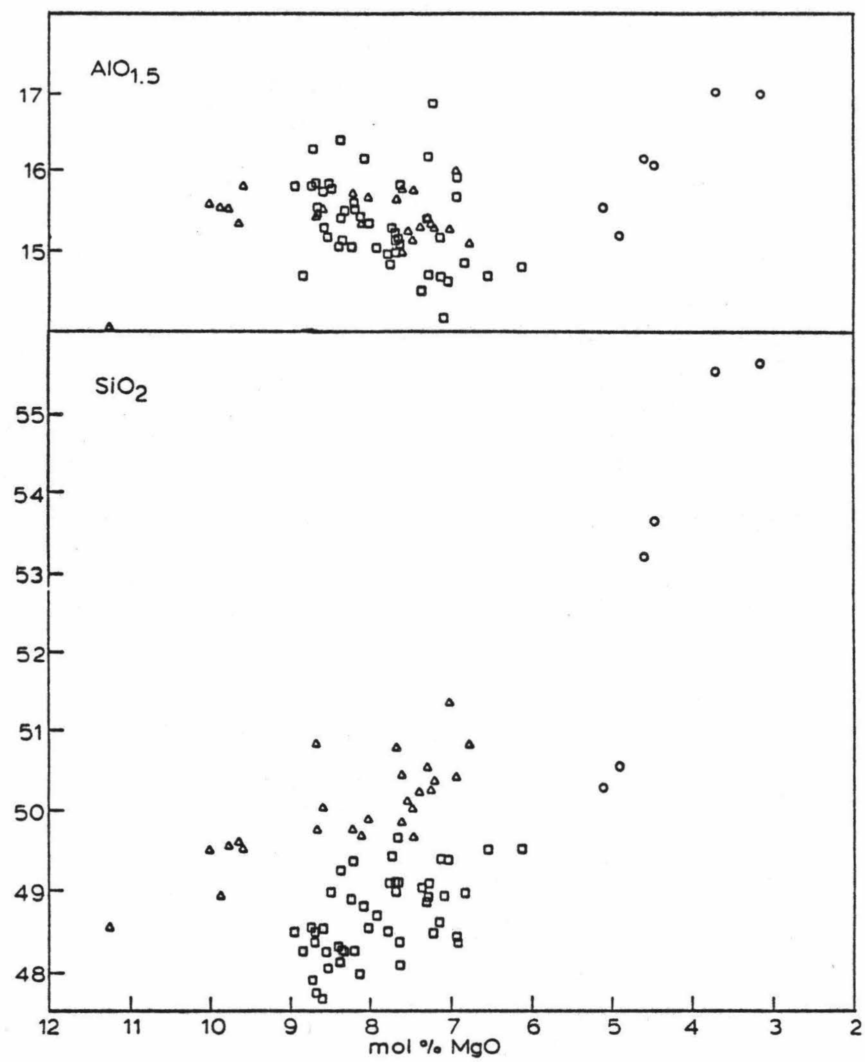
flows would be a mixture between that of aphyric (dike) liquid and that of the xenocrysts. This is not the case (fig. 18). Thus the silicic dikes and silicic flows are not related by addition of xenocrysts to the flows or subtraction of xenocrysts from the dikes.

b. Mixing or assimilation: The effect of mixing between two liquids, or assimilation of solid material by a liquid, are often visible in thin section. WD-166 is an example of a rock from this study that may have undergone mixing (see petrography section). There is no petrographic evidence for mixing or assimilation in the silicic dikes: phenocrysts are euhedral and the matrix is homogeneous. However, these processes do not always leave a petrographic signature if equilibrium is established after mixing or assimilation occurs, if the two endmembers of mixing are close in composition, or if assimilated crystals are stable in the the liquid. More evidence than petrography is needed.

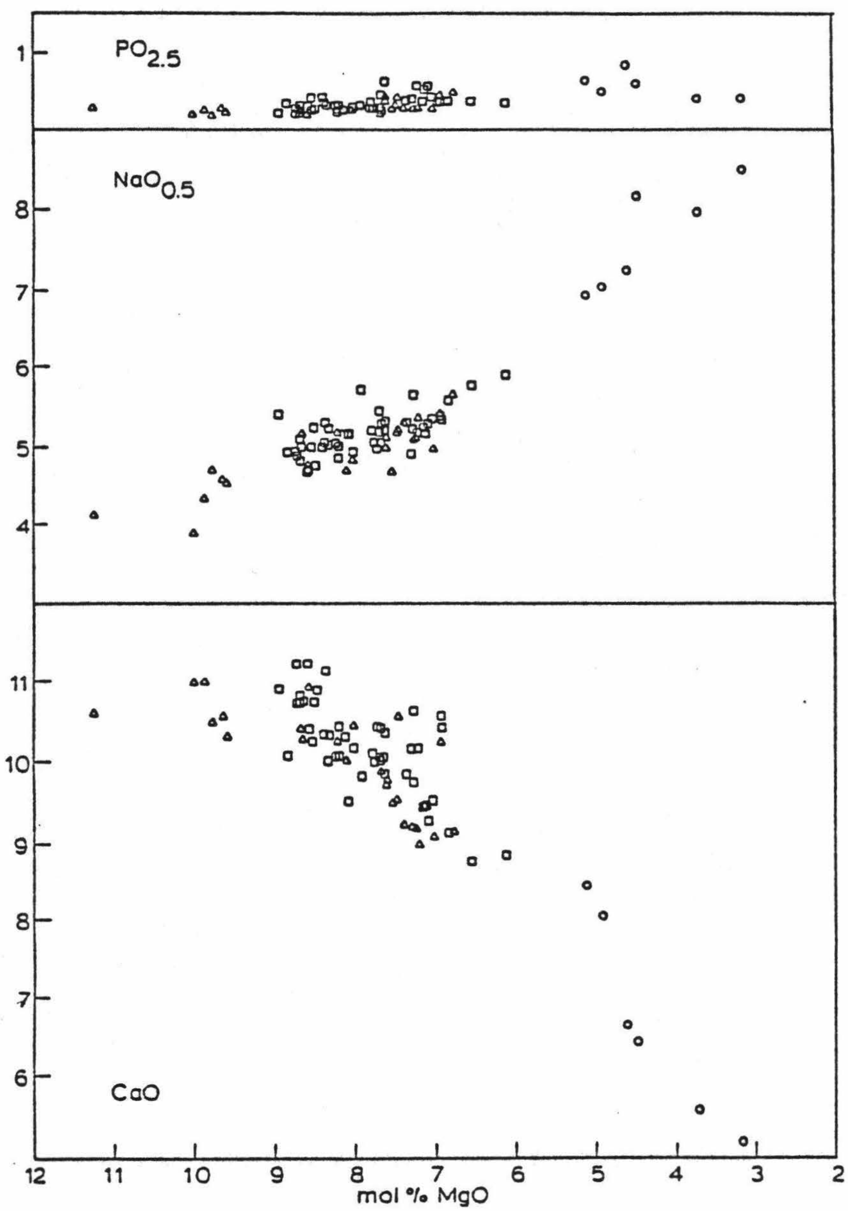
The compositions of rocks formed by mixing should lie on a straight line between the compositions of the endmembers. Mixing has been known to produce a series of rocks of varying composition, all lying along straight mixing lines (Wilcox, 1979). But, the compositions of the dikes in question do not lie on straight lines; rather, they lie on paths more reminiscent of fractionation curves than of mixing lines (fig. 19). The silicic dikes did not originate by mixing.

c. Partial melts: The crustal material beneath Waianae should include, in ascending stratigraphic order, mid-ocean ridge basaltic assemblage, a small amount of sediment, alkalic basalt, and tholeiitic basalt. Any of these might be partially melted. The

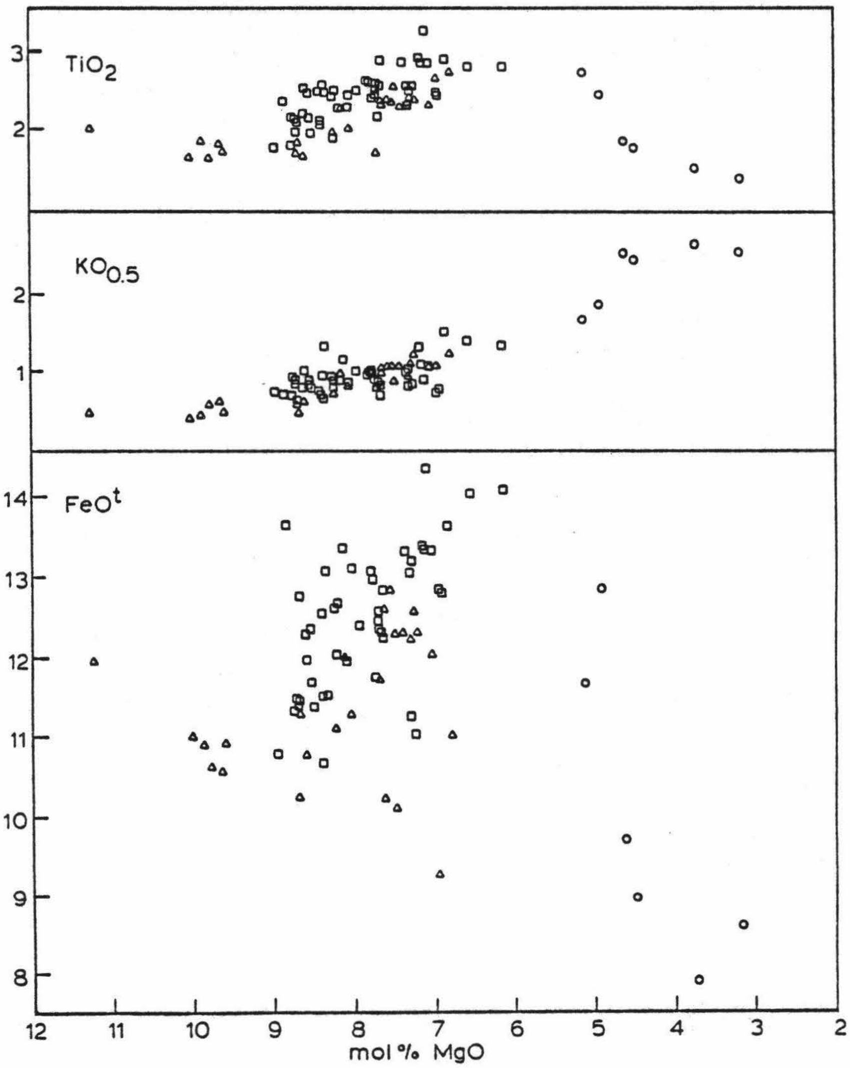
Figure 19. Variation diagram for Waianae dikes, with MgO as x-axis.



AlO1.5
17
16
15
SiO2
55
54
53
52
51
50
49
48
12
11
10
9
8
7
6
5
4
3
2
mol % MgO



$PO_{2.5}$
$NaO_{0.5}$
CaO
1
8
7
6
5
4
11
10
9
8
7
6
12
11
10
9
8
7
6
5
4
3
2
mol % MgO



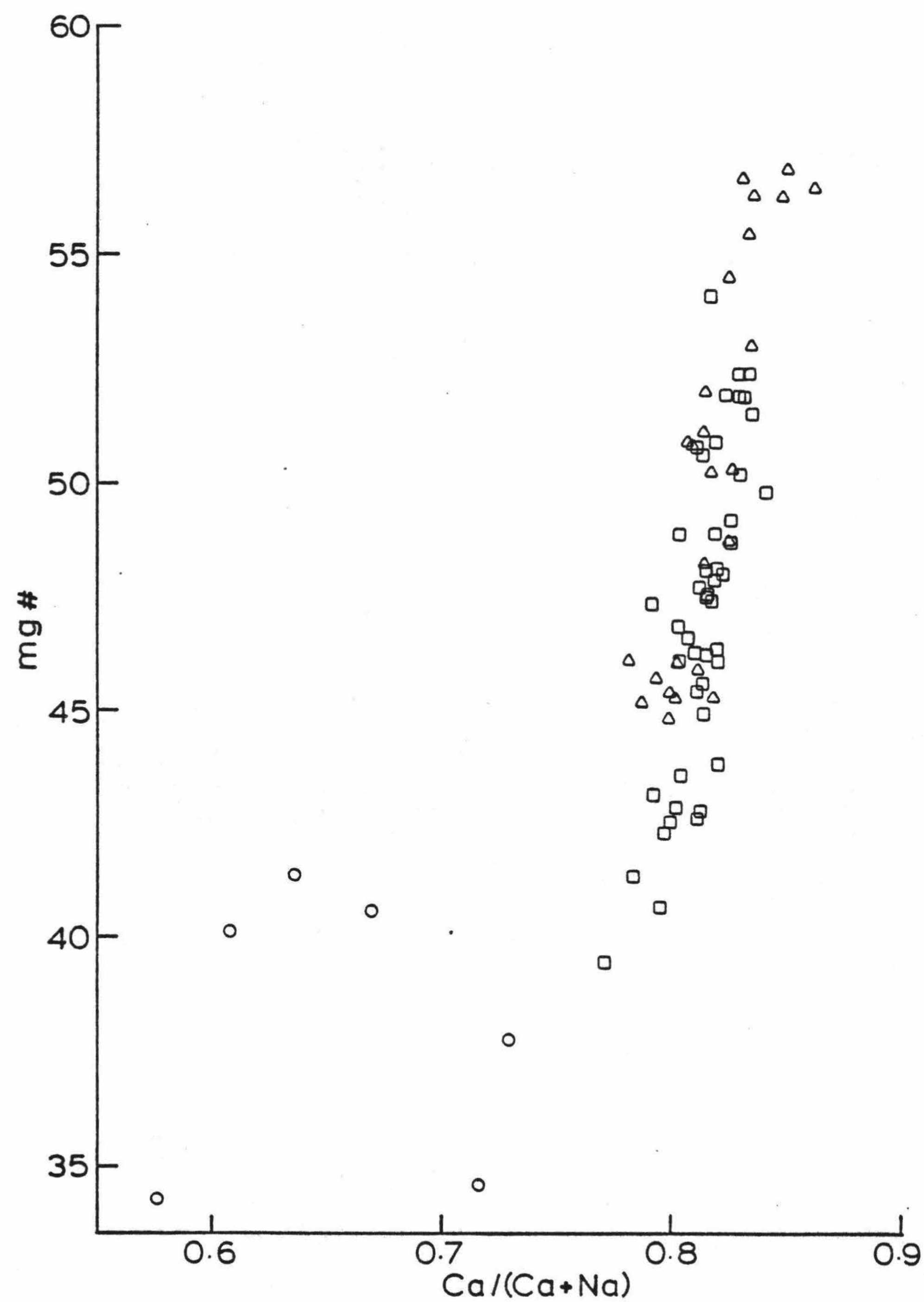
TiO2
KO0.5
FeOt
3
2
1
14
13
12
11
10
9
8
12
11
10
9
8
7
6
5
4
3
2
mol % MgO

materials might be fresh or they might be hydrothermally altered; the melting would almost certainly be hydrous. Helz (1976) performed hydrous melting experiments on three basalts, Kilauea tholeiite, Hualalai alkalic basalt, and Picture Gorge tholeiite at two different oxygen fugacities. She concluded that, for tholeiites, melt composition depends more on degree of melting than on initial composition or water activity. Thus her results for Hawaiian and Picture Gorge tholeiite could be applied to ocean floor tholeiite as well. Almost all of the experimental liquids (including those from alkalic starting material) were corundum-normative, making then much too high in alumina to have produced liquids like those of the dikes in Waianae. Iron, sodium, and potassium in the experimental liquids were lower than in Waianae dikes at a comparable silica content, while calcium was higher. The silicic dikes did not form by melting basalt under conditions approximated by these experiments.

d. Soret separation: Normal crystal fractionation should produce large change in mg# with small changes in Ca /(Ca + Na), while Soret separation would produce large variation in Ca /(Ca + Na) at relatively constant, high, mg#. Ca /(Ca + Na) varies, but at a low mg#, for the dikes (fig. 20). Soret separation was not a significant factor in the origin of these dikes.

e. Residual liquids: *In situ* differentiation has produced some evolved liquids in lava lakes and large intrusions (Kilauea Iki lava lake, Helz, 1980; Palolo granophyre, Kuno, 1957; Alae lava lake, Wright and Fiske, 1971). The common occurrence of segregation vesicles in Waianae dikes is evidence that residual liquids do form small aggregates. Wright (1971) described flows which

Figure 20. Ca /(Ca + Na) vs mg# for Waianae dikes.



60
55
50
45
40
35
mg #
0·6
0·7
0·8
0·9
Ca/(Ca+Na)

oozed to the surface through cracks in the crust of Halemaumau lava lake. A crack feeding such an "eruption" would be a dike of sorts. If the source of the "ooze" were a shallow intrusion, then the crack feeding it might be recognized as a dike. Perhaps aggregates considerably larger than segregation vesicle size developed and squeezed out from an intrusion, in the form of a dike. The volume of residual liquid that could form by such a mechanism would be small, and might not reach the surface in the form of a flow. Silicic dike WD-101 is quite thick, about 3 m. It seems unlikely that a flow of small volume would be fed by such a wide dike, although I know of no evidence against such a possibility. The other silicic dikes are narrower--half a meter or less.

Residual liquids form by fractional crystallization. The difference between this category and the following is one of scale. Residual liquids develop in a lava lake or shallow intrusion. Fractional crystallization liquids are produced in a magma chamber. The magma chamber may be (but is not necessarily) open to additions of fresh, less fractionated, magma. It is deeper and larger than a shallow intrusion. Liquid in a lava lake loses volatiles at the time of eruption and later during cooling. Liquid in a shallow intrusion could also lose volatiles through cracks and pore spaces in overlying beds. Thus residual liquids are likely to be depleted in volatiles relative to fractional crystallization liquids. However there is not enough information at this time on the volatile content of the silicic dikes to distinguish between the two mechanisms.

There is evidence that there are several magma chambers or magma "staging areas" between magma source and eruptive vents (Wright, 1971); the uppermost of these is likely to be shallow enough (2-4 km deep) that it is effectively at the surface with respect to mineral phase stability. One cannot distinguish between the two mechanisms on the basis of mineralogy. The compositions of the silicic dikes are not similar to the compositions of the glasses analyzed from Kilauea Iki (Helz and Luth, unpublished data) or of the granophyre of the Palolo intrusion (Kuno, 1957), but the differences could be ascribed to intervolcano variation.

f. Fractional crystallization: Crystal fractionation could form a series of magmas, as observed, with trends of the shape observed (fig 19). The phases involved would be those found as phenocrysts in the rocks: augite, plagioclase, and magnetite. The modelling program MIXING (Diller, 1982, modified by Christie, 1984) was successful in reproducing the trends observed, but not in reproducing realistic liquid compositions. This could be because crystal fractionation is not the correct origin for the liquids. It is more likely that it is due to the presence of magnetite as a fractionating phase. Partition coefficients for magnetite are not as well understood as those for other basaltic minerals, and the authors of the program consider it to be less reliable in calculations involving magnetite than when calculating other phases.

Why have evolved tholeiites been found here and not at other Hawaiian volcanoes? One possible explanation may be in the change in magma production rate as the volcano ages. Another possibility is that Waianae had a higher oxygen fugacity, allowing FeTi oxides to start fractionating sooner. Finally, maybe Waianae is not extraordinary but merely representative of a complete Hawaiian volcano, and a careful search of late pre-alkalic rocks in other volcanoes would reveal similar rocks.

5. Distribution of less and more differentiated rocks.

Among alkalic rocks, the differentiated dikes are distributed fairly evenly over the whole field area. All of the alkalic basalts identified are from the caldera area, but there are too few to draw a generalization from this observation.

Among tholeiites, the less differentiated rocks are (1) those of the "strongly tholeiitic" chemical type, (2) the olivine petrographic group, (3) the orthopyroxene petrographic group. These less differentiated rocks are concentrated in rift zones. The more differentiated tholeiites are (1) the "mildly tholeiitic" chemical group, (2) the "low magnesium silicic" chemical type, (3) the magnetite petrographic group. These more differentiated rocks are concentrated in the caldera region.

B. Structural evolution

1. Caldera

A caldera is "a large, basinlike volcanic depression, more or less circular or cirquelike in form, the diameter of which is many times greater than that of the included vent or vents," (Bates and Jackson, 1980). Implicit in this definition is that there are included vents, and it is this aspect that differentiates a caldera from a pit crater.

Various workers hold different perceptions of the size of Waianae caldera and the location of its boundaries. Here follows a history of the understanding of Waianae caldera.

Stearns (Stearns and Vaksvik, 1935, p. 175-176) summarized the subaerial eruptive history of Waianae this way:

> The lower lavas of the Waianae volcanic series were extruded during this first phase, and a flat oval dome at least 3000 feet high was built over two rifts intersecting near Kolekole Pass. One of these rifts trends south-southeast, and the other northwest...A period of faulting (?) (sic) followed this first phase, and most of the northeast part of the dome collapsed, leaving cliffs, some of which were 2000 feet high, extending across what is now the head of Nanakuli and Lualualei Valleys, and along the north side of Makaha Valley. This period of collapse appears to have been nearly concurrent in all three places. It is not known whether it led to the formation of great calderas or great cliffs exposed to wave attack or both. In any event, the land to the south and west was free from inundation by flows for a period long enough for a soil a foot or so thick to form and for erosion to expose dikes. During this cycle of erosion the ancestral streams of the large westward-draining valleys of Waianae Range were started. After and perhaps concurrent with the period of collapse an additional 2000 to 3000 feet of lavas were poured from the two rifts. These were ponded by the cliffs on the southwest, so that they spread mostly northeastward. They were similar to the earlier basalts except that aa flows ceased to be scarce. Thus were the middle basalts of the Waianae series laid down. Finally they overtopped the earlier basalts near the present site of Makaha Valley and cascaded westward over an erosional slope, which exposed dikes that fed the lower basalt. The time interval between flows that cascaded in this manner was long enough to allow some of the first cascading flows to be truncated by erosion also.

Elsewhere, (ibid, p. 83) he wrote,

> When the beds in the Waianae Range are viewed from an airplane it is at once apparent that all of them dip away from the Puu Kailio-Kauaopuu area. Before erosion it was probably the highest part of the range, and the breccia at this place appears to have accumulated within a former caldera on the summit of Waianae volcano. The small crater mentioned above [at the upper end of Kauaopuu Ridge] probably lay within the caldera like Halemaumau crater lies in the Kilauea caldera.

The middle member, he wrote, (ibid., p.72)

> is exposed continuously from the breccia at the head of Nanakuli Valley around the head of Lualualei and Waianae Valleys. It forms all but the uppermost part of Kamaileunu and most of the Keaau-Makaha Ridge southwest of the breccia outcrop crossing the ridge. Lava flows apparently belonging to this member are exposed in the re-entrant behind Schofield Barracks, but in the north side of the range between this place and Kaena Point they were not distinguishable with certainty from the lower basalt.

As of 1935, then, Stearns thought that Waianae must have had a caldera, but did not have enough evidence to state that with certainty. As defined in 1935, the middle member flows were not necessarily only caldera-filling, but they were erupted after collapse had formed cliffs against which they could pond. Four years later, Stearns′ ideas had changed slightly (1939, p. 8-9).

> Both volcanoes [Waianae and Koolau] were built over three sets of fissures intersecting at a summit crater and both at frequent intervals erupted highly fluid basaltic flows that built up shield-shaped cones. The Waianae volcano gradually developed a large summit caldera near the present site of Kolekole Pass and also a high, steep fault cliff that formed a wall bounding the southwest margin of the two main rift zones.

In the interval between writing Bulletin 1 and Bulletin 2, Stearns discovered a minor third rift on Waianae, and satisfied himself that Waianae indeed had possessed a caldera. Apparently he was not certain of the dimensions of the caldera.

In Bulletin 5 (1940), Stearns made no change to his earlier statements about the locations of the caldera, rift zones, and various members. Macdonald, in his chapter of that work, re-defined the location of the middle member. He said that it is "exposed in Keaau Ridge, in Kamaileunu Ridge southwest of Puu Kawiwi, and in the ridge northeast of Puu Heleakala."(p. 74) The middle member as Macdonald (1940) defined it does not appear in the re-entrant behind Schofield or in the north side of the range between Schofield and Kaena Point. A map included in Macdonald's portion of the bulletin shows the upper member as a separate unit from the lower two members (Stearns' 1939 map shows the three members undifferentiated), but does not explicitly delimit the middle member. Macdonald's map also shows faults bordering several of the breccia outcrops; the text does not state that the faults are caldera-bounding.

Macdonald and Katsura (1964), in describing sections sampled for a comprehensive study of Hawaiian petrologic evolution, stated,

> The western side of the Waianae volcano has been deeply dissected by a series of stream valleys that have cut across and exposed the boundaries between the massive horizontal flows accumulated within the caldera and the thin outward-dipping flows that built the shield enclosing the caldera. The two groups of flows are termed, respectively, the lower (extra-caldera) and middle (caldera-filling) members of the Waianae volcanic series...At many places the two are separated by talus breccia accumulated at the floor of the cliffs bounding the caldera...The rocks of the middle member grade upward into those of the upper member, which formed a cap of basalt and hawaiite...that completely buried the caldera and extended outward over the upper slopes of the shield. Outside the caldera the rocks of the lower member are separated from those of the upper member by a layer of red ashy soil, 2 or 3 feet thick.

The preceding paragraph expresses a different view of the Waianae caldera and of the middle member than that expressed by Stearns (Stearns and Vaksvik,1935; Stearns, 1939). One may infer from it either that there were no extracaldera eruptions during the time of caldera filling, or that products of extracaldera eruptions that did occur during the time of caldera filling are assigned to the lower or the upper member. In either case one may conclude that where middle member flows are, there was a caldera. This is the understanding of

Waianae geological structure that this work uses in defining shield-building, caldera-filling, and alkalic cap members. The distribution of middle member flows stated implicitly in Macdonald and Katsura (1964) is the same as that stated explicitly in Macdonald (1940).

Macdonald and Abbott (1970) published a map of the caldera boundaries. Their figure 174 (here, fig. 21) is a map of Oahu with Koolau and Waianae calderas superimposed on Bouguer gravity anomaly isogals. A slightly generalized map of calderas and rift zones of the two volcanoes appeared in Macdonald (1972, fig. 15-6) (here, fig. 22). The Waianae caldera drawn in those two works is about 14 x 7 km in size; considerably larger than Kilauea caldera (5 x 3 km) or Mokuaweoweo (6 x 2 km).

In re-mapping Lualualei Valley and environs, Sinton (1979) noted some previously unrecorded fault exposures on the east side of Lualualei Valley and considered them to be segments of a caldera-bounding fault. The west and southwest walls of the caldera, he wrote, "appear to be eroded away, or buried by younger flows," (p. 46), and the north rim is outside the mapped area. He estimated a caldera of about 7 km maximum dimension. The fault northeast of Puu Heleakala, he suggested, could bound a pit crater.

A caldera may grow by coalescence with adjacent pit craters (Macdonald, Abbott, and Peterson, 1983; Lipman, 1980). In a related process, or perhaps another way of viewing the same process, caldera collapse may proceed in "successive steps above discrete centers " (Holcomb, 1980, p.194; de Saint Ours, 1979; Ryan et al., 1983). A caldera may expand when the rim collapses in an earthquake (e.g. Kilauea in November 1983: Decker and Decker, 1984) or simply by

<u>Figure 21.</u> First published outline of Waianae caldera, from Macdonald and Abbott, 1970.

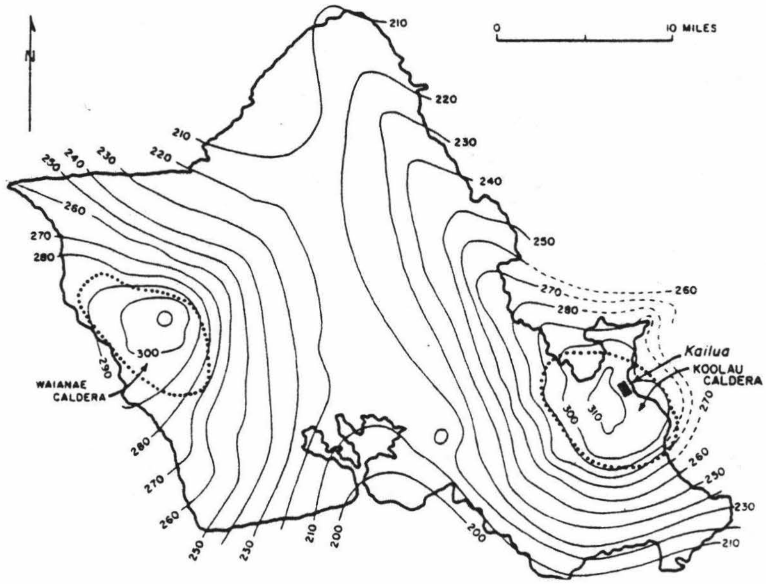
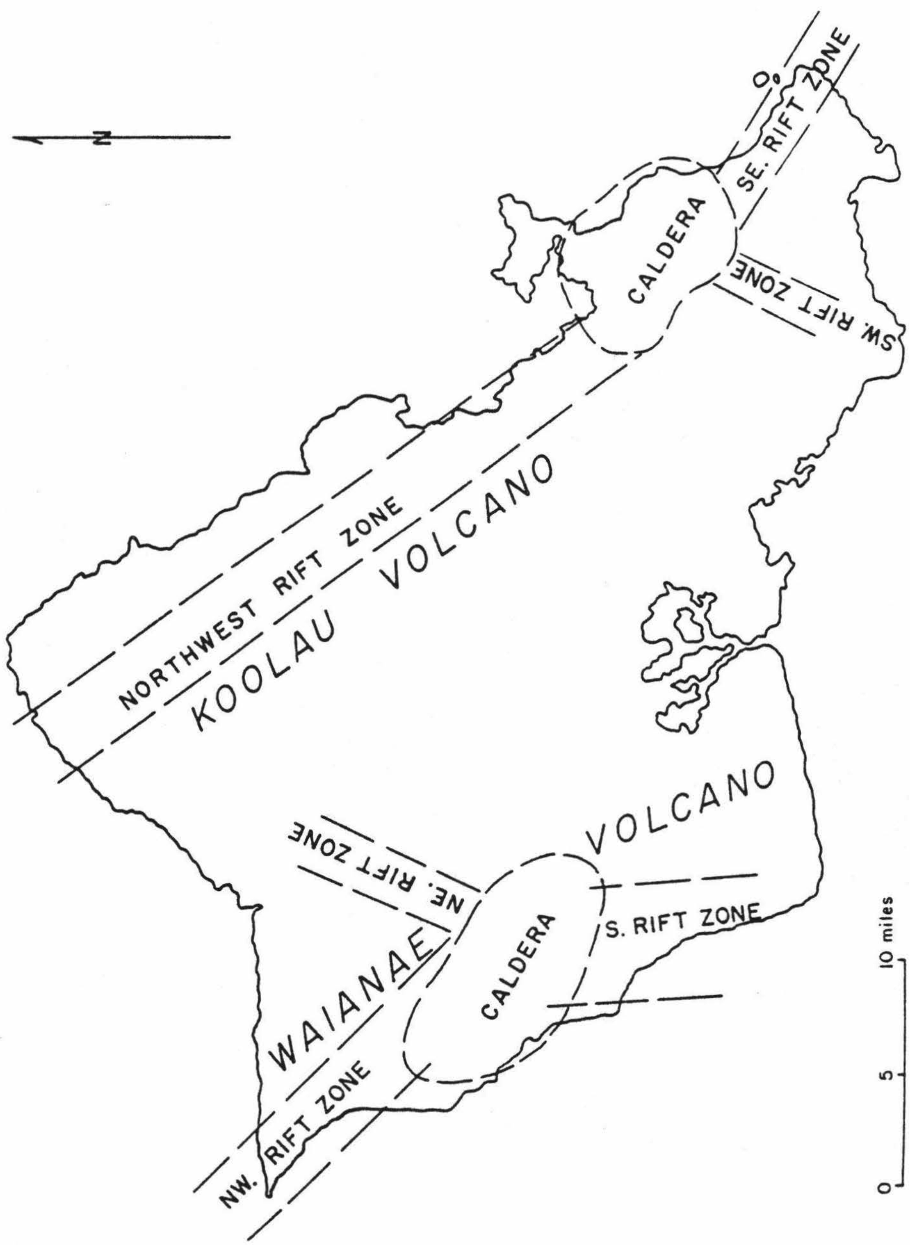

N
0
10 MILES
210
220
230
240
250
260
270
280
290
300
310
200
WAIANAE CALDERA
Kailua
KOOLAU CALDERA

Figure 22. Waianae caldera and rift zones. From Macdonald, 1972.


N
SE. RIFT ZONE
CALDERA
SW. RIFT ZONE
NORTHWEST RIFT ZONE
KOOLAU VOLCANO
NE. RIFT ZONE
WAIANAE VOLCANO
CALDERA
S. RIFT ZONE
NW. RIFT ZONE
0
5
10 miles

gradual erosion. It may fill to overflowing with lava and cease to exist (Holcomb, 1980; Stearns, 1940b). A new caldera may form when underlying support is once more removed (Holcomb, 1980; Powers, 1948). There may be more than one locus of support (de Saint Ours, 1979; Ryan et al., 1983) and so the center of the new caldera would not necessarily coincide with the center of the old one. Likewise, the boundaries would shift. Thus the flat-lying massive "caldera-filling" lavas of Waianae may occupy an area 14 x 7 km, and it is not necessary that, at any given time, a caldera of that size existed. The volcano may have had a series of smaller calderas and adjoining pit craters which formed by collapse, then filled; new ones formed in slightly different spots from the old ones.

If this is true, then the areas of aligned or random dike orientation listed above can be divided into rift zone or caldera areas. Koleaiiilii and Nanakuli Ridge are inside the larger caldera, yet the dikes in those areas have distinctly preferred orientation. Those dikes emplaced at a time when the areas were beneath a rift zone and not beneath a caldera or a pit crater.

The caldera-bounding faults mapped by Sinton (1979) along the east side of Lualualei Valley are also within the larger caldera; they must have bounded one of the series of calderas.

Those regions listed above as having dikes with little or no preferred orientation, were within a caldera at some time during the activity of the volcano. Those regions which have dikes of clear preferred orientation were in a rift zone at the time the dikes were emplaced. The positions of calderas and rift zones may have changed through time, as explained in the next two sections; thus a given region may have been within a caldera at one time and in a rift zone at another time. Nanakuli Ridge is possibly an example of this: flatlying flows accumulated inside a caldera depression; collapse created a new caldera somewhat north or west of the previous one; the rift zone extended through the location of the old caldera to meet the new one, emplacing well-aligned dikes through the old caldera-filling flows. It is also possible that Nanakuli Ridge is the site of a former pit crater, as suggested by Sinton (1979), and was in a rift zone through its entire history.

2. Rift zones

Waianae has two major rift zones, trending south and northwest, and a minor rift zone trending northeast

The northwest rift zone (NWRZ) is eroded, so its location is identified chiefly by the outcrop of the dike swarm. Supporting this are the observations that the edifice and the gravity anomaly are both elongated in that direction.

The location of the northeast rift zone is based on topography (slight outbuilding of the edifice), the impounding of groundwater under Schofield Plateau, and a few dikes cropping out in Kaukonahua Gulch. Some authors (e.g. Fiske and Jackson, 1972) do not recognize its existance. There are at least 14 dikes exposed in the gulch (Stearns, 1939; Takasaki, 1971), too many to dismiss as offshoots of the other rifts well to the south of the gulch.

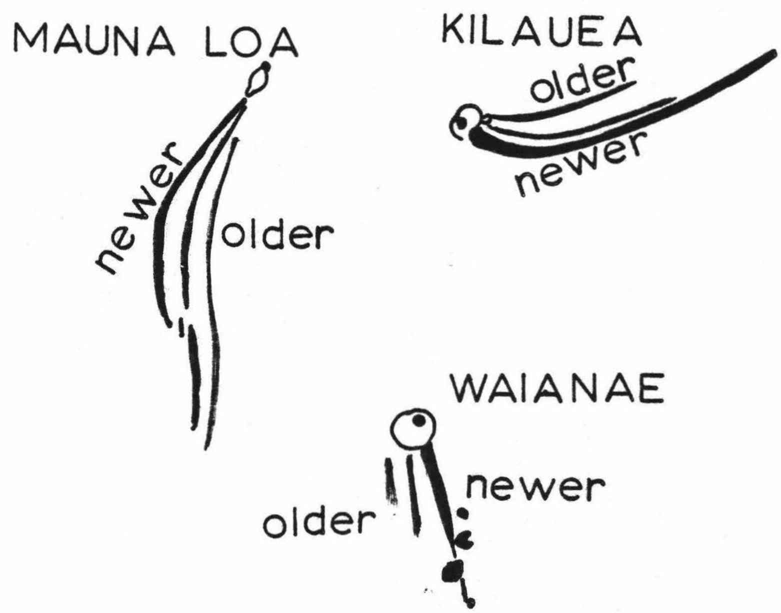
The location of the south rift zone (SRZ) is less certain. A curved line of cinder cones from Puu Kuua to Puu Kapolei (fig. 1) lies on a little-eroded portion of the shield. If the cones overlie a dike swarm, it is not exposed. Five cinder cones are evidence of at least five eruptions, and considering their position on trend with the elongation of the edifice, it is easy to believe that they delineate a south rift zone. However, west of this ridge are Puu o Hulu and Puu Heleakala, which bear abundant dikes with distinct preferred orientation and may be considered to be part of a rift zone. Then where is the south rift zone? Possibilities: a) The rift zone does not underlie the line of cinder cones, but does extend through Puu O Hulu and Puu Heleakala. b) The SRZ has shifted over time. c) There is a previously unidentified minor rift trending SSW from Puu Kailio/ Kolekole Pass. d) The rift zone underlies the line of cinder cones, and the dike swarm lies outside of it. e) the rift zone is wide enough to include both Puu o Hulu at the west and Puu Kapuai to the east. f) The rift zone dips gently, so that at lower elevations it is farther west than at higher elevations

Possibilities (a) and (d) may imply that a line of cinder cones is not a good criterion to identify a rift zone. This implication conflicts with the definition of rift zone offered in this paper (a curvilinear fissure zone along which eruptions tend to be concentrated). Possibility (a) may alternatively imply that a fortuitous alignment of five eruptions has no structural significance. This implication is less unbelievable than the first. Possibility (c) would be a cumbersome and contrived explanation of the observations, since topographical and geophysical evidence do not support the existance of another rift zone. Possibility (f) conflicts with current understanding of behavior of Hawaiian volcanoes. Possibility (e) would outline a rift zone which occupies half the volume of the volcano. Available evidence does not permit a choice to be made from these various possibilities.

Possibility (b) merits some discussion. Puu O Hulu and Puu Heleakala are thoroughly eroded. Their flows are among the oldest exposed on the volcano. If any portion of the alkalic cap covered the area, it has long since worn away. The flows surrounding Nanakuli Valley are younger than those of the two puus; the Palehua area consists of cap rocks, and the problematical last-erupted cones are at the easternmost edge of Waianae outcrops. There is certainly a west-to-east decrease in age of the exposed rocks as well as a west-to-east decrease in degree of erosion. If the rift zone migrated, it probably did so in a west-to-east direction, that is, towards Koolau volcano.

Swanson, Duffield, and Fiske (1976) and Lipman (1980) presented models to explain migrating rift zones of Kilauea and Mauna Loa (fig. 23). The east rift zone of Kilauea is migrating south away from Mauna Loa; the southwest rift zone of Mauna Loa is migrating west, away from Kilauea. The authors compare rift zones to mid-ocean ridges. Whether dike emplacement is active or passive, the edifice must expand to accommodate added width, as an ocean basin expands to accommodated the crust added at its ridge. The two volcanoes buttress each other and so can expand on one side only. In general, new dikes are emplaced seaward of pre-existing ones, causing net migration of the spreading center--the active part of the rift zone--away from the buttressing neighbor. This model would not explain migration of Waianae's south rift zone which, if it moved, went towards neighboring Koolau.

Figure 23. Models for migrating rift zones: Mauna Loa after Lipman, 1980; Kilauea after Duffield et al., 1972; Waianae, this work.


MAUNA LOA
newer
older
KILAUEA
older
newer
WAIANAE
newer
older

An alternate suggestion better explains the observations on Waianae (fig. 23). The active portion of the rift zone did not move. New dikes were consistently emplaced in about the same position, and older ones had to move away to accommodate them. Older dikes would gradually move west, away from the Koolau buttress. Under this model the dikes at Puu o Hulu Kai and the last-erupted cinder cones define different stages of the same, stationary, rift zone. This model does not, however, explain why the dikes of Puu O Hulu Kai and Puu O Hulu Uka strike at an angle to the strike of the dikes in Nanakuli Ridge and the trend of the chain of cinder cones.

V. Summary

Dikes exposed in Waianae volcano are not evenly distributed. They are concentrated in a northwest rift zone, a south rift zone, and a caldera region. They may be concentrated in a northeast rift zone as well, but that is outside the field area of this work. The dikes show preferred orientation parallel to the rift zones, and random orientation in the caldera area. The dikes are generally within $20^{\circ}$of vertical and less than a meter thick. Most are virtually identical in texture, mineralogy, and composition to extrusive rocks. A few have an unusual low-magnesium silicic composition not observed so far in any flows.

Flat-lying lavas and dikes with little or no preferred orientation occupy an area 14 x 7 km. Puu Kailio/Kolekole Pass area is the only repeatedly used (polygenetic) vent found so far on the volcano, though the entire rift complex is in some sense a vent.

It is likely that, at any given time, the caldera was smaller than the 14 x 7 km, and more nearly circular with a diameter of about 7 km. The area now occupied by caldera-filling lavas is the time-integrated sum of several calderas and/or pit craters.

The south rift zone may have kept a stationary active portion, and the newly arriving magma pushed previously emplaced dikes out of the way to the west.

85 dikes were chemically analyzed. Of those, 79 are tholeiitic. The tholeiites show petrological evolution from basalt to andesite. The basalts can be divided into two subgroups, a more primitive

strongly tholeiitic and a more evolved mildly tholeiitic group. The tholeiitic andesites originated by differentiation from the basalts. The tholeiitic andesites have been found only as dikes, not as flows.

In a general way, the more primitive dikes are in the rift zones and the more evolved dikes are in the caldera area. Most of the analyzed rift zone dikes are strongly tholeiitic; most of the analyzed caldera dikes are mildly tholeiitic; all of the differentiated high-silica, low-magnesium dikes were found inside the caldera near the eruptive center.

APPENDIX I
X-RAY FLUORESCENCE ANALYSES OF WHOLE ROCKS, MAJOR ELEMENTS
(weight percent; Fe_2O_3/FeO set at 0.15)

	WD21	WD25	WD50	WD60	WD62	WD65	WD88	WD103
SiO2	51.43	48.74	51.65	49.23	49.35	51.22	51.64	48.63
TiO2	3.61	3.89	3.21	3.35	3.38	3.69	2.37	3.03
Al2O3	13.83	13.60	13.69	13.13	13.04	13.42	12.97	14.32
Fe2O3	1.23	1.62	1.35	1.64	1.66	1.54	1.45	1.40
FeO	8.17	10.79	9.01	10.89	11.05	10.28	9.62	9.29
MnO	0.14	0.17	0.17	0.17	0.18	0.20	0.18	0.16
MgO	4.75	5.19	5.23	5.84	5.75	3.50	6.71	6.18
CaO	9.75	9.32	9.36	9.75	9.85	8.04	10.02	10.95
Na2O	2.85	2.78	2.70	2.63	2.64	3.64	2.44	2.72
K2O	0.85	0.55	0.83	0.66	0.60	1.33	0.39	0.60
P2O5	0.56	0.77	0.48	0.51	0.52	0.79	0.29	0.51
H2O+	0.99	1.05	0.88	0.66	0.81	0.99	0.51	0.80
H2O-	1.16	1.13	0.45	1.18	1.85	0.74	0.50	1.30
CO2	0.13	0.20	0.15	0.23	0.13	0.20	0.15	0.26
SO3	0.00	0.00	0.00	0.10	0.10	0.00	0.00	0.10
SumOx	99.45	99.81	99.16	99.96	100.91	99.58	99.24	100.25
CIPW Norms								
Q	5.0	1.5	4.8	0.8	1.0	1.6	2.0	0.0
Or	10.0	6.5	9.8	7.8	7.1	15.7	4.6	7.1
Ab	48.2	47.0	45.7	44.5	44.7	61.6	41.3	46.0
An	22.4	23.0	22.8	22.1	22.0	16.4	23.3	25.1
Pl	70.7	70.0	68.5	66.6	66.6	77.9	64.6	71.1
DiCa	10.8	9.7	9.9	11.0	11.2	9.8	11.0	12.2
DiMg	5.9	4.6	5.1	5.4	5.4	4.0	5.2	5.7
DiFe	4.6	4.9	4.5	5.4	5.7	6.0	5.6	6.4
Di	21.3	19.3	19.5	21.8	22.3	19.7	21.9	24.3
HyMg	6.0	8.3	7.9	9.2	8.9	4.8	11.5	3.0
HyFe	4.7	8.8	7.0	9.3	9.4	7.2	12.4	3.3
Hy	10.7	17.1	15.0	18.5	18.3	11.9	23.8	6.3
OlMg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.7
OlFe	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.9
Ol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.6
Il	6.9	7.4	6.1	6.4	6.4	7.0	0.0	0.0
H2O	2.1	2.2	1.3	1.8	2.7	1.7	1.0	2.1
D.I.	63.3	55.1	60.3	53.1	52.7	78.9	47.9	53.1
An	31.7	32.8	33.3	33.2	33.0	21.0	36.1	35.3
Mg No	50.9	46.1	50.8	48.9	48.1	37.8	55.4	54.2
T Alk	3.700	3.330	3.530	3.290	3.240	4.970	2.830	3.320
	30	–	–	60	75	–	60	80
	1			3	3		75	3

	WD132	WD134	WD144	WD192	WD193	WD202	WD204	WD222
SiO2	50.12	49.79	50.13	50.06	49.96	49.51	49.16	51.59
TiO2	3.19	2.89	3.51	3.41	3.80	3.36	3.29	2.20
Al2O3	13.90	14.37	13.10	13.46	12.65	13.58	13.71	17.26
Fe2O3	1.49	1.41	1.63	1.34	1.69	1.70	1.70	1.12
FeO	9.92	9.39	10.87	8.91	11.27	11.31	11.28	7.48
MnO	0.16	0.16	0.17	0.15	0.22	0.19	0.19	0.17
MgO	5.01	5.81	5.26	5.05	5.03	4.76	4.72	2.27
CaO	10.15	10.74	9.54	9.92	9.11	10.07	9.87	4.97
Na2O	2.76	2.70	2.73	2.71	2.74	2.83	2.80	5.39
K2O	0.65	0.58	0.63	0.69	0.83	0.60	0.61	2.49
P2O5	0.50	0.45	0.56	0.51	0.61	0.46	0.46	1.51
H2O+	0.75	0.62	1.08	1.12	0.86	0.90	0.85	0.98
H2O-	0.64	0.50	0.80	1.56	0.67	0.77	0.95	1.12
CO2	0.15	0.05	0.05	0.20	0.24	0.15	0.05	0.22
SumOx	99.39	99.46	100.06	99.09	99.69	100.18	99.64	98.77
CIPW Norms								
Q	2.1	0.4	2.5	3.6	2.6	0.9	0.8	0.0
Or	7.7	6.9	7.4	8.2	9.8	7.1	7.2	29.4
Ab	46.7	45.7	46.2	45.9	46.4	47.9	47.4	84.6
An	23.6	25.4	21.6	22.5	19.8	22.6	23.0	15.5
Ne	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1
Pl	70.3	71.1	67.8	68.4	66.1	70.5	70.4	100.2
DiCa	11.2	11.6	10.7	11.1	10.6	11.4	10.8	3.8
DiMg	5.3	6.0	5.0	5.8	4.8	4.9	4.6	1.4
DiFe	5.7	5.3	5.6	5.1	5.7	6.5	6.2	2.5
Di	22.2	23.0	21.3	22.0	21.2	22.9	21.7	7.7
HyMg	7.1	8.4	8.1	6.8	7.7	6.9	7.1	0.0
HyFe	7.6	7.5	8.9	5.9	9.1	9.1	9.5	0.0
Hy	14.7	15.9	17.0	12.7	16.8	16.0	16.6	0.0
OlMg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
OlFe	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.1
Ol	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.1
Il	6.1	5.5	6.7	6.5	7.2	6.4	6.2	4.2
H2O	1.4	1.1	1.9	2.7	1.5	1.7	1.8	2.1
D.I.	56.5	52.9	56.2	57.6	58.7	55.9	55.4	121.2
An	33.6	35.7	31.9	32.9	29.9	32.0	32.7	15.5
Mg No	47.4	52.4	46.3	50.2	44.3	42.9	42.7	35.1
T Alk	3.410	3.280	3.360	3.400	3.570	3.430	3.410	7.880

	WD235	WD240	WD241	WD265	WD304	305WR	305MX	315WR
SiO2	48.92	49.67	49.07	50.00	51.22	47.56	50.14	51.05
TiO2	3.45	3.49	2.84	4.40	2.57	1.89	2.75	2.45
Al2O3	12.94	14.67	13.55	12.28	13.79	10.68	12.29	15.36
Fe2O3	1.70	1.46	1.69	1.90	1.44	1.56	1.58	1.38
FeO	11.30	9.71	11.24	12.63	9.60	10.36	10.54	9.16
MnO	0.08	0.16	0.20	0.21	0.18	0.18	0.19	0.16
MgO	5.18	4.97	5.98	4.86	6.93	16.01	7.83	5.62
CaO	9.76	9.72	10.30	8.86	10.73	8.35	10.20	10.39
Na2O	2.72	2.74	2.65	2.79	2.34	1.75	2.19	2.90
K2O	0.65	0.67	0.51	0.71	0.36	0.23	0.39	0.50
P2O5	0.54	0.71	0.37	0.70	0.32	0.22	0.33	0.39
H2O+	0.88	0.94	0.54	0.71	0.44	0.68	0.62	0.38
H2O-	1.12	0.64	0.56	0.51	0.42	0.36	0.48	0.36
CO2	0.15	0.14	0.14	0.10	0.16	0.19	0.19	0.07
SumOx	99.39	99.69	99.63	100.66	100.50	100.02	99.72	100.16
CIPW Norms								
Q	0.9	2.1	0.0	2.8	0.6	0.0	0.0	0.9
Or	7.7	7.9	6.0	8.4	4.3	2.7	4.6	5.9
Ab	46.0	46.4	44.8	47.2	39.6	29.6	37.1	49.1
An	21.2	25.8	23.6	18.9	26.1	20.6	22.6	27.4
Pl	67.2	72.1	68.4	66.1	65.7	50.2	59.6	76.5
DiCa	11.4	9.4	11.5	10.5	11.3	8.7	11.7	10.1
DiMg	5.2	4.6	5.4	4.5	5.5	5.5	5.7	5.1
DiFe	6.1	4.6	5.9	6.0	5.7	2.7	5.8	4.8
Di	22.7	18.6	22.8	21.0	22.5	16.8	23.2	19.9
HyMg	7.7	7.8	8.1	7.6	11.8	11.0	12.8	8.9
HyFe	9.1	7.8	8.8	10.3	12.3	5.3	12.9	8.3
Hy	16.8	15.5	16.9	17.9	24.0	16.4	25.7	17.2
OlMg	0.0	0.0	1.0	0.0	0.0	16.4	0.7	0.0
OlFe	0.0	0.0	1.2	0.0	0.0	8.8	0.8	0.0
Ol	0.0	0.0	2.2	0.0	0.0	25.1	1.5	0.0
Il	6.6	6.6	5.4	8.4	0.0	0.0	0.0	4.7
H2O	2.0	1.6	1.1	1.2	0.9	1.0	1.1	0.7
D.I.	54.6	56.4	50.9	58.4	44.4	32.3	41.7	55.9
An	31.5	35.7	34.5	28.6	39.7	41.0	37.8	35.8
Mg No	45.0	47.7	48.7	40.7	56.3	73.4	57.0	52.2
T Alk	3.370	3.410	3.160	3.500	2.700	1.980	2.580	3.400

	315MX	WD354	WD335	WD342	WD375
SiO2	50.28	52.23	51.61	51.70	51.55
TiO2	3.27	3.83	2.50	2.53	2.88
Al2O3	12.97	13.16	13.54	13.63	13.69
Fe2O3	1.80	1.27	1.40	1.49	1.52
FeO	12.01	8.48	9.30	9.93	10.14
MnO	0.19	0.17	0.17	0.18	0.16
MgO	6.18	4.81	6.73	6.04	5.88
CaO	9.80	8.90	10.24	9.96	10.08
Na2O	2.65	3.00	2.46	2.77	2.86
K2O	0.57	0.98	0.49	0.38	0.56
P2O5	0.43	0.77	0.35	0.32	0.45
H2O+	0.28	1.17	0.80	0.57	0.58
H2O-	0.31	0.54	0.59	0.51	0.47
CO2	0.10	0.18	0.47	0.29	0.10
SumOx	100.84	99.49	100.65	100.30	100.93
CIPW Norms					
Q	0.0	5.7	1.2	0.9	1.8
Or	6.7	11.6	5.8	4.5	6.6
Ab	44.8	50.8	41.6	46.9	48.4
An	21.8	19.5	24.5	23.6	22.9
Pl	66.7	70.3	66.1	70.5	71.3
DiCa	11.2	10.3	11.0	10.8	11.3
DiMg	4.6	5.5	5.3	4.8	5.6
DiFe	6.7	4.4	5.5	5.9	5.5
Di	22.5	20.2	21.8	21.5	22.4
HyMg	7.7	6.5	11.4	10.2	9.0
HyFe	11.2	5.2	11.9	12.6	8.7
Hy	19.0	11.6	23.3	22.9	17.7
OlMg	2.2	0.0	0.0	0.0	0.0
OlFe	3.5	0.0	0.0	0.0	0.0
Ol	5.6	0.0	0.0	0.0	0.0
Il	0.0	7.3	0.0	0.0	5.5
H2O	0.6	1.7	1.4	1.1	1.0
D.I.	51.6	68.1	48.6	52.3	56.8
An	32.7	27.8	37.0	33.5	32.1
Mg No	47.8	50.3	56.3	52.0	50.8
T Alk	3.220	3.980	2.950	3.150	3.420

APPENDIX II
X-RAY FLUORESCENCE ANALYSES OF WHOLE ROCKS, TRACE ELEMENTS (in ppm)

	WD21	WD25	WD50	WD60	WD62	WD65	WD88	WD103
Cr	66	38	28	77	74	0	284	182
V	393	352	324	382	356	314	316	349
Sc	23	23	24	22	23	21	24	22
Ni	76	65	57	87	85	22	104	100
Cu	110	61	74	87	84	18	118	92
Zn	126	124	131	118	124	146	88	98
Rb	15	2	10	9	3	21	4	4
Sr	557	592	547	513	516	555	357	648
Y	47	44	48	34	38	52	31	30
Zr	256	339	239	246	275	398	145	267
Nb	13	24	16	13	17	35	6	21
Ba	204	152	256	121	131	390	68	183

	WD132	WD134	WD144	WD192	WD193	WD202	WD204	WD222
Cr	119	256	52	52	56	50	52	0
V	355	304	364	396	342	394	406	114
Sc	22	22	24	21	23	22	23	9
Ni	83	105	85	124	168	59	58	0
Cu	104	97	80	115	117	111	117	3
Zn	106	101	124	121	133	122	122	123
Rb	8	8	5	18	20	6	6	31
Sr	553	546	519	583	486	543	533	791
Y	36	33	65	38	37	39	36	59
Zr	242	198	287	255	337	248	238	611
Nb	18	18	12	20	21	18	17	54
Ba	206	156	214	180	208	164	157	638

	WD235	WD240	WD241	WD265	WD304	305WR	305MX	315MX
Cr	65	94	44	50	262	614	551	78
V	388	300	344	394	326	304	406	292
Sc	21	18	22	23	24	19	23	26
Ni	67	53	66	54	104	721	202	79
Cu	92	75	99	123	118	101	110	96
Zn	120	108	104	140	92	84	97	84
Rb	9	9	5	9	4	6	11	7
Sr	541	608	438	494	376	306	374	578
Y	44	35	32	48	34	32	40	33
Zr	265	319	181	346	182	133	193	205
Nb	19	20	13	14	16	9	14	12
Ba	226	164	170	246	102	77	96	168

	315MX	WD354	WD335	WD342	WD375
Cr	91	56	257	110	144
V	393	387	314	340	306
Sc	23	24	25	23	23
Ni	89	49	105	70	93
Cu	113	76	90	119	80
Zn	114	136	83	91	102
Rb	12	21	8	2	16
Sr	502	592	442	411	547
Y	34	56	35	39	35
Zr	200	328	188	185	236
Nb	22	24	9	8	12
Ba	214	481	142	120	173

APPENDIX III
ELECTRON MICROPROBE ANALYSES OF GLASSES
(weight percent; Fe_2O_3/FeO set at 0.15)

	WD03	WD06	WD10B	WD10C	WD28	WD29	WD37	WD41
SiO2	49.83	52.18	51.80	52.64	50.53	49.86	51.97	51.78
TiO2	3.43	3.31	2.84	2.77	3.38	3.37	3.20	2.72
Al2O3	13.59	13.50	13.79	14.01	13.55	12.66	13.44	13.86
Fe2O3	1.68	1.66	1.56	1.42	1.73	1.74	1.62	1.47
FeO	11.16	11.07	10.37	9.48	11.53	11.61	10.78	9.78
MnO	0.18	0.20	0.22	0.16	0.16	0.16	0.15	0.14
MgO	5.68	5.05	5.55	5.74	5.60	4.96	5.03	5.74
CaO	9.70	8.91	9.71	10.69	9.87	9.25	8.84	9.95
Na2O	2.67	2.74	2.62	2.61	2.65	2.96	2.71	2.78
K2O	0.72	0.89	0.66	0.66	0.69	0.82	0.75	0.58
P2O5	0.40	0.34	0.32	0.33	0.37	0.39	0.36	0.30
SumOx	99.04	99.85	99.44	100.52	100.07	97.79	98.85	99.10
CIPW Norms								
Q	0.8	4.1	3.5	3.6	1.3	0.8	4.8	2.8
Or	8.5	10.5	7.8	7.8	8.2	9.7	8.9	6.9
Ab	45.2	46.4	44.3	44.2	44.8	50.1	45.9	47.0
An	23.0	21.9	23.9	24.6	23.0	18.8	22.3	23.6
Pl	68.2	68.3	68.3	68.7	67.9	68.9	68.2	70.7
DiCa	10.5	9.3	10.1	11.9	10.8	11.3	9.0	10.7
DiMg	5.0	4.2	4.8	6.0	5.0	4.9	4.1	5.4
DiFe	5.4	5.1	5.2	5.6	5.7	6.4	4.8	5.2
Di	20.9	18.6	20.1	23.5	21.5	22.6	17.9	21.3
HyMg	9.1	8.4	9.0	8.2	8.9	7.4	8.4	8.9
HyFe	9.8	10.2	9.6	7.6	10.2	9.7	9.9	8.6
Hy	19.0	18.5	18.6	15.8	19.1	17.1	18.4	17.5
Il	6.5	6.3	5.4	5.3	6.4	6.4	6.1	5.2
D.I.	54.5	61.0	55.6	55.6	54.3	60.6	59.5	56.7
An	33.7	32.1	35.0	35.7	33.9	27.3	32.7	33.4
Mg No	47.6	44.8	48.8	51.9	46.4	43.2	45.4	51.1
T Alk	3.390	3.630	3.280	3.270	3.340	3.780	3.460	3.360

	WD49	WD52	WD53A	WD55	WD95	WD96	WD99	WD101
SiO2	51.60	50.69	48.97	49.62	48.75	52.04	49.82	56.45
TiO2	3.18	2.72	3.50	3.57	3.58	2.29	3.06	2.60
Al2O3	13.16	14.04	13.78	13.60	13.93	13.89	13.96	14.52
Fe2O3	1.67	1.51	1.69	1.87	1.70	1.46	1.63	1.29
FeO	11.09	10.04	11.26	12.45	11.34	9.69	10.83	8.56
MnO	0.18	0.11	0.21	0.17	0.15	0.16	0.17	0.21
MgO	5.29	6.09	5.47	5.18	5.50	7.06	6.03	3.28
CaO	9.40	10.46	10.05	10.01	9.91	10.78	10.95	6.58
Na2O	2.66	2.74	3.10	2.94	2.82	2.10	2.53	3.97
K2O	0.79	0.69	0.93	0.84	0.87	0.33	0.65	2.09
P2O5	0.53	0.30	0.37	0.36	0.38	0.24	0.36	1.08
SumOx	99.55	99.38	99.33	100.61	98.93	100.04	99.99	100.62
CIPW Norms								
Q	3.4	0.0	0.0	0.0	0.0	2.3	0.0	4.7
Or	9.3	8.2	11.0	9.9	10.3	3.9	7.7	24.7
Ab	45.0	46.4	52.5	49.7	47.7	35.5	42.8	67.2
An	21.6	24.0	20.9	21.4	22.8	27.5	24.8	15.6
Pl	66.6	70.3	73.4	71.2	70.5	63.0	67.6	82.8
DiCa	10.4	11.7	12.1	11.8	11.0	10.8	12.3	7.1
DiMg	4.8	5.2	5.6	5.0	5.2	5.3	5.3	2.9
DiFe	5.6	6.4	6.3	6.8	5.7	5.4	7.1	4.2
Di	20.8	23.3	24.0	23.6	21.9	21.5	24.7	14.3
HyMg	8.4	6.8	2.5	5.1	5.6	12.3	5.4	5.2
HyFe	9.9	8.3	2.8	6.9	6.2	12.7	7.2	7.6
Hy	18.3	15.1	5.4	12.0	11.7	25.0	12.6	12.8
OlMg	0.0	2.2	3.8	1.9	2.1	0.0	3.1	0.0
OlFe	0.0	3.0	4.7	2.8	2.5	0.0	4.6	0.0
Ol	0.0	5.2	8.6	4.7	4.6	0.0	7.7	0.0
Il	6.0	0.0	6.6	6.8	6.8	0.0	0.0	4.9
D.I.	57.8	54.5	63.4	59.7	58.0	41.7	50.5	96.5
An	32.5	34.1	28.5	30.1	32.3	43.6	36.7	18.9
Mg No	45.9	52.0	46.4	42.6	46.4	56.5	49.8	40.6
T Alk	3.450	3.430	4.030	3.780	3.690	2.430	3.180	6.060
		200	20	36	35	30	20	300
		3	3	3	2.5	2.5	2.5	3

	WD129	WD131	WD133	WD136	WD141	WD142	WD147	WD160
SiO2	50.83	50.48	50.47	51.64	51.40	48.92	53.68	52.26
TiO2	2.46	3.45	3.44	3.42	2.97	3.27	3.21	3.28
Al2O3	14.04	13.22	13.75	13.58	13.30	15.67	13.55	13.45
Fe2O3	1.43	1.64	1.53	1.65	1.63	1.51	1.59	1.63
FeO	9.50	10.93	10.15	10.97	10.86	10.05	10.61	10.85
MnO	0.20	0.19	0.15	0.15	0.15	0.13	0.18	0.19
MgO	6.29	5.51	5.84	5.43	5.32	5.03	4.93	5.02
CaO	10.65	9.51	10.07	9.87	9.71	9.70	8.87	8.71
Na2O	2.92	3.05	2.82	2.95	2.83	3.00	2.68	2.87
K2O	0.60	0.81	1.08	0.74	0.70	1.36	0.87	0.99
P2O5	0.27	0.40	0.40	0.36	0.32	0.43	0.36	0.35
SumOx	99.19	99.19	99.70	100.76	99.19	99.07	100.53	99.60
CIPW Norms								
Q	0.0	0.2	0.0	1.6	2.3	0.0	6.5	3.7
Or	7.1	9.6	12.8	8.7	8.3	16.1	10.3	11.7
Ab	49.4	51.6	47.7	49.9	47.9	50.8	45.4	48.6
An	23.4	20.0	21.7	21.6	21.5	25.3	22.4	20.9
Pl	72.8	71.6	69.4	71.5	69.4	76.0	67.7	69.5
DiCa	12.3	11.4	11.8	11.4	11.1	9.5	9.0	9.3
DiMg	5.7	5.4	6.0	5.4	5.1	4.6	4.1	4.2
DiFe	6.5	5.8	5.5	5.9	5.9	4.8	4.9	5.0
Di	24.4	22.5	23.3	22.7	22.2	18.9	18.0	18.6
HyMg	5.7	8.3	8.0	8.1	8.1	2.2	8.2	8.3
HyFe	6.4	8.9	7.3	8.9	9.4	2.3	9.7	9.8
Hy	12.1	17.2	15.2	17.0	17.5	4.4	17.8	18.1
OlMg	3.0	0.0	0.4	0.0	0.0	4.1	0.0	0.0
OlFe	3.8	0.0	0.4	0.0	0.0	4.8	0.0	0.0
Ol	6.8	0.0	0.7	0.0	0.0	8.8	0.0	0.0
Il	0.0	6.6	6.5	6.5	5.6	6.2	6.1	6.2
D.I.	56.5	61.4	60.5	60.2	58.5	66.8	62.1	63.9
An	32.2	27.9	31.2	30.2	31.0	33.2	33.0	30.1
Mg No	54.1	47.3	50.6	46.9	46.6	47.1	45.3	45.2
T Alk	3.520	3.860	3.900	3.690	3.530	4.360	3.550	3.860

	WD162A	WD162	WD163	WD164	WD168	WD173	WD177	WD179
SiO2	52.64	51.28	51.70	49.94	50.36	50.33	51.06	50.73
TiO2	3.22	3.06	3.22	3.58	3.58	3.49	3.37	3.99
Al2O3	13.59	13.24	13.27	13.06	13.39	13.45	13.33	13.04
Fe2O3	1.66	1.60	1.63	1.73	1.73	1.58	1.67	1.80
FeO	11.05	10.62	10.83	11.51	11.51	10.55	11.11	11.99
MnO	0.15	0.16	0.13	0.18	0.17	0.13	0.16	0.20
MgO	5.03	5.23	5.19	5.38	5.84	5.97	5.77	4.75
CaO	9.01	8.84	9.21	9.71	9.75	10.06	9.81	8.84
Na2O	2.84	2.82	2.77	2.76	2.70	2.52	2.72	2.98
K2O	0.90	0.85	0.86	0.77	0.77	0.82	0.76	1.22
P2O5	0.36	0.35	0.41	0.45	0.40	0.39	0.40	0.47
SumOx	100.45	98.04	99.22	99.07	100.20	99.29	100.16	100.01
CIPW Norms								
Q	3.9	3.1	3.4	0.9	0.7	1.6	1.6	1.0
Or	10.6	10.0	10.2	9.1	9.1	9.7	9.0	14.4
Ab	48.1	47.7	46.9	46.7	45.7	42.6	46.0	50.4
An	21.7	21.0	21.2	21.0	22.1	23.0	21.9	18.6
Pl	69.7	68.7	68.1	67.7	67.8	65.6	67.9	69.0
DiCa	9.6	9.6	10.2	11.4	11.0	11.2	11.2	10.5
DiMg	4.3	4.4	4.7	5.2	5.2	5.7	5.4	4.5
DiFe	5.3	5.0	5.4	6.0	5.6	5.3	5.6	6.0
Di	19.2	19.0	20.3	22.6	21.7	22.2	22.2	21.1
HyMg	8.2	8.6	8.2	8.2	9.3	9.2	9.0	7.3
HyFe	10.0	9.7	9.4	9.5	10.0	8.5	9.5	9.8
Hy	18.2	18.3	17.6	17.7	19.3	17.7	18.5	17.1
Il	6.1	5.8	6.1	6.8	6.8	6.6	6.4	7.6
D.I.	62.6	60.9	60.4	56.7	55.5	53.9	56.6	65.8
An	31.1	30.5	31.2	31.0	32.6	35.0	32.3	26.9
Mg No	44.8	46.7	46.1	45.4	47.5	50.2	48.1	41.4
T Alk	3.740	3.670	3.630	3.530	3.470	3.340	3.480	4.200

	WD185	WD187	WD190	WD193G	WD210	WD228	WD230	WD250
SiO2	51.07	52.25	50.52	51.23	51.52	52.15	51.47	50.55
TiO2	3.30	2.30	3.92	3.96	3.31	3.28	3.12	3.80
Al2O3	13.40	13.74	12.67	12.75	13.13	13.45	13.48	12.81
Fe2O3	1.56	1.42	1.76	1.83	1.70	1.70	1.59	1.86
FeO	10.35	9.48	11.72	12.18	11.31	11.30	10.57	12.39
MnO	0.15	0.15	0.12	0.16	0.18	0.17	0.14	0.19
MgO	5.36	6.02	5.09	4.66	3.36	5.26	5.64	4.19
CaO	10.05	10.63	9.48	9.12	7.65	9.23	9.68	8.44
Na2O	2.65	2.57	2.82	2.92	3.70	2.51	2.51	3.10
K2O	0.79	0.50	0.86	0.87	1.49	0.86	0.78	1.07
P2O5	0.34	0.24	0.48	0.45	0.62	0.35	0.35	0.44
SumOx	99.02	99.31	99.44	100.13	97.97	100.26	99.33	98.84
CIPW Norms								
Q	2.7	1.7	1.9	2.7	0.8	4.5	3.5	1.6
Or	9.3	5.9	10.2	10.3	17.6	10.2	9.2	12.6
Ab	44.8	43.5	47.7	49.4	62.6	42.5	42.5	52.5
An	22.3	24.5	19.4	19.1	14.8	22.9	23.2	17.9
Pl	67.2	68.0	67.1	68.5	77.4	65.4	65.7	70.3
DiCa	11.5	11.8	11.5	10.9	9.7	9.6	10.4	10.0
DiMg	5.6	5.4	5.2	4.6	3.4	4.3	5.0	3.9
DiFe	5.8	6.3	6.3	6.4	6.4	5.2	5.2	6.3
Di	22.8	23.5	23.0	21.9	19.5	19.1	20.6	20.2
HyMg	7.8	9.6	7.5	7.0	4.9	8.8	9.0	6.5
HyFe	8.1	11.3	9.0	9.8	9.2	10.5	9.3	10.6
Hy	15.9	21.0	16.5	16.8	14.1	19.3	18.4	17.1
Il	6.3	0.0	7.4	7.5	6.3	6.2	5.9	7.2
D.I.	56.9	51.1	59.8	62.4	81.0	57.1	55.2	66.7
An	33.2	36.0	28.9	27.9	19.1	35.0	35.3	25.4
Mg No	48.0	53.1	43.6	40.5	34.6	45.3	48.7	37.6
T Alk	3.440	3.070	3.680	3.790	5.190	3.370	3.290	4.170
	5	20	16		35	100	100	
	1.5	1.5	1.5		1.5	4.3	4.3	

	WD252	WD256	WD257	WD258	WD259	WD260	WD267	WD273
SiO2	50.98	49.98	50.35	51.26	50.74	50.22	50.74	50.26
TiO2	3.84	3.15	2.99	3.93	2.95	2.97	3.57	3.50
Al2O3	12.82	13.63	14.07	12.91	14.09	14.46	13.00	13.43
Fe2O3	1.86	1.77	1.55	1.76	1.52	1.52	1.72	1.73
FeO	12.35	11.75	10.29	11.75	10.09	10.12	11.42	11.49
MnO	0.14	0.18	0.15	0.27	0.19	0.14	0.17	0.16
MgO	4.52	5.68	5.99	4.96	6.11	6.13	5.38	5.04
CaO	8.44	10.01	10.49	9.18	10.57	10.49	9.64	9.75
Na2O	3.06	2.77	2.83	2.77	2.61	2.64	2.70	2.61
K2O	1.12	0.72	0.72	0.88	0.73	0.75	0.79	0.80
P2O5	0.46	0.32	0.32	0.66	0.33	0.35	0.37	0.39
SumOx	99.59	99.96	99.75	100.33	99.92	99.78	99.49	99.16
CIPW Norms								
Q	1.7	0.0	0.0	3.1	0.0	0.0	2.1	2.1
Or	13.2	8.5	8.5	10.4	8.6	8.9	9.3	9.5
Ab	51.8	46.9	47.9	46.9	44.2	44.7	45.7	44.2
An	17.9	22.6	23.6	20.2	24.6	25.4	21.0	22.6
Pl	69.7	69.5	71.5	67.1	68.7	70.1	66.7	66.7
DiCa	10.0	11.3	11.9	10.6	11.6	11.1	11.2	10.8
DiMg	4.1	5.1	6.0	4.7	5.2	5.0	5.2	4.8
DiFe	6.0	6.1	5.7	5.9	6.4	6.1	5.9	6.0
Di	20.1	22.5	23.5	21.1	23.2	22.2	22.3	21.5
HyMg	7.2	8.0	7.8	7.7	7.3	6.1	8.2	7.8
HyFe	10.6	9.4	7.4	9.7	9.1	7.5	9.5	9.7
Hy	17.8	17.4	15.2	17.4	16.4	13.6	17.7	17.4
OlMg	0.0	0.7	0.8	0.0	1.9	3.0	0.0	0.0
OlFe	0.0	0.9	0.9	0.0	2.6	4.0	0.0	0.0
Ol	0.0	1.6	1.7	0.0	4.5	7.0	0.0	0.0
Il	7.3	6.0	5.7	7.5	0.0	0.0	6.8	6.6
D.I.	66.7	55.4	56.4	60.4	52.8	53.5	57.1	55.7
An	25.7	32.6	33.0	30.1	35.7	36.2	31.5	33.8
Mg No	39.5	46.3	50.9	42.9	51.9	51.9	45.6	43.9
T Alk	4.180	3.490	3.550	3.650	3.340	3.390	3.490	3.410

	WD282	WD294	WD310	WD319	WD320	WD323	WD328	WD341
SiO2	49.79	51.46	52.98	49.81	55.85	51.61	58.12	51.93
TiO2	3.32	2.72	2.34	3.95	2.44	2.62	1.93	2.27
Al2O3	13.53	14.05	13.63	13.18	14.18	13.83	15.08	13.80
Fe2O3	1.78	1.51	1.36	1.77	1.19	1.59	1.14	1.41
FeO	11.88	10.02	9.02	11.78	7.89	10.61	7.58	9.36
MnO	0.23	0.18	0.09	0.18	0.13	0.19	0.17	0.19
MgO	5.09	5.98	6.07	4.91	3.13	5.76	2.22	6.87
CaO	9.51	10.67	10.11	9.05	6.25	10.17	5.07	10.24
Na2O	3.07	2.58	2.62	2.77	4.37	2.62	4.56	2.54
K2O	0.91	0.65	0.48	1.05	1.98	0.64	2.07	0.46
P2O5	0.35	0.34	0.27	0.46	0.76	0.29	0.51	0.23
SumOx	99.46	100.15	98.97	98.91	98.17	99.93	98.45	99.29
CIPW Norms								
Q	0.0	1.8	3.2	1.2	3.8	2.2	6.8	0.8
Or	10.8	7.7	5.7	12.4	23.4	7.6	24.5	5.4
Ab	51.9	43.7	44.3	46.9	73.9	44.3	77.2	43.0
An	20.5	24.8	24.0	20.4	13.2	24.1	14.6	24.9
Pl	72.4	68.5	68.3	67.3	87.2	68.4	91.7	67.9
DiCa	11.2	11.7	10.9	10.2	7.4	11.0	4.4	10.8
DiMg	4.8	5.9	5.1	4.5	3.1	5.2	1.5	5.3
DiFe	6.4	5.6	5.7	5.7	4.3	5.6	3.0	5.4
Di	22.3	23.2	21.7	20.4	14.9	21.9	9.0	21.5
HyMg	5.6	9.0	10.0	7.7	4.7	9.1	4.0	11.9
HyFe	7.4	8.6	11.1	9.8	6.4	9.9	8.0	12.2
Hy	12.9	17.6	21.1	17.5	11.1	19.0	12.0	24.0
OlMg	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OlFe	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ol	3.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Il	6.3	5.2	0.0	7.5	4.6	5.0	3.7	0.0
D.I.	62.7	53.1	53.2	60.5	101.1	54.1	108.4	49.2
An	28.2	36.3	35.1	30.4	15.2	35.2	15.9	36.7
Mg No	43.3	51.5	54.5	42.6	41.4	49.2	34.3	56.7
T Alk	3.980	3.230	3.100	3.820	6.350	3.260	6.630	3.000

	WD369	WD370	WD372	WD388	1.1.42
SiO2	51.19	50.87	53.12	50.44	58.28
TiO2	2.51	3.16	2.37	3.42	2.11
Al2O3	14.13	14.27	13.87	13.08	15.17
Fe2O3	1.50	1.58	1.55	1.66	1.05
FeO	9.98	10.54	10.33	11.08	6.96
MnO	0.15	0.15	0.09	0.14	0.12
MgO	6.18	5.65	5.39	5.31	2.62
CaO	11.04	9.27	9.66	10.00	5.47
Na2O	2.69	2.77	2.69	2.69	4.31
K2O	0.57	0.93	0.64	0.80	2.15
P2O5	0.26	0.35	0.27	0.33	0.50
SumOx	100.20	99.54	99.98	98.95	98.74
CIPW Norms					
Q	0.0	1.1	4.6	1.7	7.5
Or	6.7	11.0	7.6	9.5	25.4
Ab	45.5	46.9	45.5	45.5	72.9
An	24.8	23.8	23.9	21.3	15.7
Pl	70.3	70.6	69.4	66.8	88.6
DiCa	12.5	9.3	10.0	11.8	4.8
DiMg	5.6	4.5	4.7	5.5	2.0
DiFe	6.8	4.6	5.3	6.2	2.9
Di	25.0	18.4	20.0	23.6	9.6
HyMg	7.1	9.6	8.8	7.7	4.6
HyFe	8.6	9.8	9.9	8.7	6.7
Hy	15.7	19.4	18.7	16.5	11.2
OlMg	1.8	0.0	0.0	0.0	0.0
OlFe	2.5	0.0	0.0	0.0	0.0
Ol	4.3	0.0	0.0	0.0	0.0
Il	0.0	6.0	4.5	6.5	4.0
D.I.	52.3	59.0	57.6	56.7	105.8
An	35.3	33.6	34.4	31.8	17.7
T Alk	3.260	3.700	3.330	3.490	6.460
	60	50	50		
	1.5	1.5	10		

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APPENDIX V

LOCATION, ORIENTATION, THICKNESS, CROSSCUTTING RELATIONS, AND PETROGRAPHY FOR ALL WAIANAE DIKE SAMPLES

Key:

Columns 1-6= Sample number

Columns 10-11= LOCATION
- 1=KAUAOPUU
- 2=KOLEALIILII
- 3=KOLEKOLE ROADCUT
- 4=PUU O HULU UKA
- 5=PUU O HULU KAI
- 6=KUNIA
- 7=PUU KAILIO
- 8=KOLEKOLE PASS MEADOW
- 9=MAUNA KUWALE
- 10=PAHEEHEE RIDGE
- 11=LUALUALEI RIDGE
- 12=HONOULIULI 1
- 13=HONOULIULI 2
- 14=HONOULIULI 3
- 15=HONOULIULI 4
- 16=NANAKULI RIDGE
- 17=KAENA POINT
- 18=PUU HELEAKALA
- 19=MAKUA FRONT
- 20=MAKUA CENTER
- 21=KUAOKALA FOREST RESERVE
- 22=KAMAILEUNU
- 23=KOLEKOLE PASS, KAALA SIDE

Columns 15-19=PHENOCRYSTS
- 0= not present, 1= present
- C15=PLAGIOCLASE
- C16=AUGITE
- C17=OLIVINE
- C18=ORTHOPYROXENE
- C19=OXIDES

Columns 21-23=MATRIX
- 0= not present, 1= present
- C21=OLIVINE
- C22=SEGREGATION VESICLES
- C23=ORTHOPYROXENE

Column 25 PETROGRAPHIC GROUPS
- A= PLAGIOCLASE + AUGITE
- B= PLAGIOCLASE + AUGITE + OLIVINE
- C= PLAGIOCLASE
- D= TRACHYTIC
- E= MAGNETITE
- F= ORTHOPYROXENE
- G= APHYRIC
- H= OLIVINE
- I= OTHER
- J= SAMPLED, BUT NO THIN SECTION
- K= NO SAMPLE

Columns 29-31= STRIKE:
all measured with reference to north.

Columns 33-35= DIP

Columns 36-38= THICKNESS, IN CENTIMETERS

ROCK	THIN SECTION				FIELD			COMMENTS
1	10	15	21	25	29	33	36	41
WD1	01	00000	110	G	30E	57N	060	50 yards up from volleyball court at Camp Waianae. Dip varies
WD2	01			K			200	At sharp angle to WD-1, perhaps cuts it. Cuts WD3 and WD15.
WD3	01	11000	000	A	52W	42N	050	Mildly tholeiitic basalt. Is cut by WD-2.
WD4	01			K				Roughly horizontal; penetrates rhyodacite, maybe 480ft alt.
WD5	01	11101	000					A sample of the rhyodacite, near 724ft alt.
WD6	01	10000	000	C			015	Strongly tholeiitic basalt. Cuts rhyodacite, anastamosing fingers.
WD7	01			K			006	Cuts rhyodacite.
WD8	01	00000	000	G	40W	82S	020	Above rhyodacite, in dark grey flows.
WD9a	01	11000	000	A	60E	56E		Above rhyodacite, just below 9b
WD9b	01	10000	000	C	20W	30E	020	Above rhyodacite.
W10	01	11000	000	A	30E	35E	050	At summit of Kauaopuu peak
W10a	01	11000	000	A	55W	45S	065	NE of Kauaopuu peak
W10b	01	11000	000	A	55W	45S		Strongly tholeiitic basalt. May be continuous with 10a; also may continue across gulch.
W11	01			K	46E	53S		Accross the gulch from 10a and 10b.
W12								Ash or tuff, weathers out to form the gulch.
W13	01	10000	010	C	20W	81S	100	Dike makes a small crevice in the ridge.
W14	01	11000	000	A	70W	48S	075	Intersects WD13. Relative ages not clear.
WD15	01	11000	000	A	85E	80N		Back at beginning by Camp Waianae. Cut by WD2; close above WD3. Cuts WD17.
WD16								Pinkish flow.
WD17	01	11001	000	E				Cut by WD15, 50ft or so above WD2 and WD3.

WD18	01	11000 000 A	36E 60S 012	Around ridge to right from WD17. (South side of ridge.)
WD19	01	K	80E 76N 050	Continuing around ridge to right. Is cut by WD20.
WD20	01	00000 110 G	44W 75S 050	Cuts WD19. Makes crevice in ridge.
WD21	01	10000 000 C	70E 40N 030	Strongly tholeiitic basalt. Rock fence crosses it. Width varies 30cm-1m.
WD22	02	11000 000 A	65W 88S 065	First dike when approaching Kolealiilii from mauka trail.
WD23	02	11000 010 A	60W 48S 050	10 ft uphill from WD22.
WD24	02	11100 100 B	62W 43S 076	Another 10 ft makai from WD23.
WD25	02	11010 010 F	62W 43S	Mildly tholeiitic basalt. At northern (mauka) edge of top "plateau" of Kolealiilii.
WD26	02	11000 000 A	32W 80S 040	At south (makai) edge of Kolealiilii plateau.
WD27	01	11000 100 A	46W 020	Beginning at Camp Waianae again, taking left (north) side of ridge. Zigzags, so strike is an average.
WD28	01	11000 000 A		Mildly tholeiitic basalt. Just above WD27, veinlet mostly glass.
WD29	01	11000 000 A	70E 60S 010	Mildly tholeiitic basalt. Into rhydacite. Thin, but continuous.
WD30	01		66W 65N 075	In rhyodacite. Olivine-phyric; no sample
WD31	01		E-W 68N 006	In rhyodacite. Feldspar concentrated in center of dike.
WD32	01	10000 000 C	70E VRT 020	Dike stands out from cliff. Feldspar crystals concentrated to one side.
WD33e	01	10000 000 C	050	Thick, dish-shaped. Flow above top surface is weathered out to make overhang.
WD33m	01	11000 000 C	050	"e", "m" = edge and middle. 60 cm is narrower end, widens a bit at the bottom.
WD34	01	10101 110 D	30W 70S 020	
WD35	01	K	80W 60S 015	Above rhyodacite.
WD36e	01	00000 000 G	80W 060	A meter downhill from WD35 and parallel to it. Still beyond rhyodacite.
WD37	01	10000 000 C	83W 35S 020	Strongly tholeiitic basalt. Some has squeezed up into cracks in surrounding flows.
WD38	01	10001 100 D	56W 70S 115	Next to a gully. Light color; weathers reddish.
WD39	01	11000 000 A	80E 75S 015	Accross the gully from WD38.
WD40	01	K	70E 60S 050	
WD41	01	11000 000 A	80W 70S 020	Strongly tholeiitic basalt. Runs down small precipice. Continues around ridge.
WD42	01	11000 010 A	75W 70S 035	Farther down same precipice--mauka (north) end of Kauaopuu.
WD43	01	11110 000 F	40E 30S 200	Compound dike: rubble (aa clinker?) in middle and along both sides; massive in two parallel bands between the rubble.
WD44	01	11000 000 A	68E 45E 030	
WD45	01	11000 010 A	005	
WD46	01	11010 000 F	60E 40S 035	
WD47	01	11000 000 A	80E 70S 040	At mauka end of Kauaopuu, just before dropoff.
WD48	02	10000 000 C		Waianae Kai Forest Reserve, starting on trail by people's house (not on the fork with the hunting sign). WD48 crosses trail where two silky oak trees straddle trail.
WD49	02	11000 000 A	52W 31S	Strongly tholeiitic basalt. Surrounded by cactus. Bifurcates.
WD50	02	11000 000 A	56W 36S	Strongly tholeiitic basalt. Crosses trail branch towards water tunnel and streams.
WD51	02	010		Boulder beside trail. Light colored, with darker blotches.
WD52	03	11000 010 A	50W 75S 200	Mildly tholeiitic basalt. Roadcut of Kolekole Pass, most obvious dike directly accross road from overlook.
WD53A	03	11100 000 B	10W 61W 020	Alkalic basalt. Downhill from WD52 near traffic warning sign. Guides WD53b.
WD53B	03	11000 000 A	05W 62W 030	Guided by WD53a. Much more jointed and weathered than WD53a, but seems to be later (younger). Both a and b feldspar phyric but less so than surrounding flows.
WD54	03	11000 010 A	53W 60S 025	3m downhill from WD53. It crosses a sill about 20ft up.
WD55	03	10000 010 C	65E 78S 030	Mildly tholeiitic basalt. Forms face of roadcut, undulating.
WD56	03	10000 000 C	70E 69S 015	Parallel to and downhill from WD55.
WD57	03	K	88W 70S 040	Third in a row. Narrows upward.
WD58e	03	11000 010 A	68E 75S 065	Around a curve from WD57. Cuts WD59, and causes offset.
WD58m	03	00000 010 A	68E 75S 065	Middle of WD58
WD59	03	11100 000 B	30W 30N 080	Cut and offset by WD58.
WD60	03	11000 000 A	N-S 73W 060	Mildly tholeiitic basalt. Twenty ft past falling rocks sign.
WD61	03	11100 010 B	20E 46E 100	Runs into WD60; relative age not clear.
WD62	03	00000 010 G	20E 84W 025	Mildly tholeiitic basalt. Just past falling rocks sign.
WD63	03	11100 000 B	49W 75S 100	3m downhill from WD62.

WD64	03	11100 000	B		Hidden behind scrub at roadside.
WD65	03	11101 000	E	28E 60E	Evolved tholeiitic basalt. High on roadcut by upper outcrop of picrite, cut by WD66.
WD66	03	11000 010	A	16E 63N	Intersection w/WD65 is above eye level so relative age may be wrong.
WD67A	04	11100 100	B	20E 80W 100	Puu O Hulu, starting at water tank and walking mauka.
WD67B	04	11100 110	B	N-S 79W 100	Western branch from WD67.
WD68	04	11010 010	F	20E 84W 125	
WD69	04	11110 000	F	07E 70W 125	Eroded a bit deeper than surrounding flows.
WD70	04	00000 100	D	30E VRT 095	Level with surrounding ground.
WD71	04	00100 110	H	05E 75W 030	Nearly hidden by grass
WD72	04	11000 010	A	37E 75E 110	Outcrop is a slope break.
WD73	04			25E 75W 040	
WD74	04			05E 73W 090	Farthest dike mauka on this hill.
WD75	04	11000 110	A	21E VRT 080	On the way back toward water tank.
WD76	04	00000 110	G	20E 85W 090	Again on the way back. This one stands up a bit from surrounding flows.
WD77	05	11000 100	A	03E 75W 040	Directly behind water tank fence.
WD78	05	00000 000	G	22E 85W 100	Puu O Hulu Kai, walking makai. Just before 6m high cliff.
WD79	05	11100 000	B	03W 73W 150	Lower than surrounding flows. At the cliff.
WD80	05		K	10E 83W	Maybe iron-rich: affects compass needle. Strike estimated. Past the cliff.
WD81	05	00100 100	H	13E 70W 090	Cut by WD82.
WD82	05	11110 000	F	35E 85W 080	Graffiti: "dinan" painted on it. Cuts WD81.
WD83	05	00100 100	H	22E 65W 075	Just in front of a small precipice.
WD84	05	11000 000	A	11E 75W 080	Level with surrounding flows.
WD85	05	10100 000	H	20E 73W	10 steps uphill from WD84.
WD86	05	00110 011	F	18E 70W 040	Lower than surrounding flows--makes small gully.
WD87	05	00100 100	H	12E	Narrow and indistinct.
WD88	05	00100 100	H	05E 83W 060	Strongly tholeiitic basalt. Level with surrounding flows. No chilled margin.
WD89	05			12E 79W 030	
WD90	05			15E 65W 025	Just below WD84.
WD91	06			65E 75W	Behind Kunia pineapple field. Weathered.
WD92	06			65E ~~163~~ 75W 080	Five steps to the left of WD91. Slightly less weathered.
WD93	07	11000 010	C	72W 72S 020	Puu Kailio, first dike off road on uphill side. Cuts WD94.
WD94	07	11000 000	A	18E 74W 028	Cut by WD93; cuts WD95.
WD95	07	11000 000	A	15W 47W 035	Alkalic basalt. Cut by WD94. Sends glassy stringers into surrounding breccia.
WD96	07	11110 000	F	28W 65W 030	Strongly tholeiitic basalt. Five steps farther from road from WD95.
WD97	07	11000 000	A	08E 74W 080	Crossed and slightly displaced by (thinner)WD99.
WD98	07	11000 000	A	32E 67W 010	Doesn't extend very far.
WD99	07	11000 010	A	47W 84E 020	Mildly tholeiitic basalt. Cuts WD97.
WD100	07	11000 010	A	04E 63E 030	Still in Puu Kailio, no more than maybe 10 m from road.
WD101	03	11001 100	E	N-S 74W 300	Tholeiitic andesite. Kolekole roadcut, between Puu Kailio and overlook.
WD102	03	00000 010	G	55W 72S 100	9 or 10 m uphill from WD101.
WD103	03	11100 010	B	10W 73E 080	Mildly tholeiitic basalt
WD104	08	11000 010	A	65W 40S 110	Weathered zone around the meadow at Kolekole Pass.
WD104f	08	11000 010	A	65W 40S 110	Sampled fresher and more weathered parts of dike.
WD105	08		K	27W 60S 005	Crosses WD-106. This and several following highly weathered--Not sampled.
WD106	08		K	85W 65S	One branch has this strike, another branch not measured. Cuts WD107, is cut by WD105, WD108, and WD109.
WD107	08		K	40W 77S	Is cut and offset by WD106.
WD108	08		K	43W 55S	Cuts WD106, is cut by WD109.
WD109	08		K	80W 74S	Cuts WD106 and WD108.
WD110	08	11100 100	B	77W 60S 040	Less feldspar than last 5, center is reasonably fresh.
WD111	08		K	58W 70S 110	
WD112	08		K	40W 65S	
WD113	08		K	10W 62W 080	Just east (far side) of post in meadow.
WD114	08		K	10W 66W	Looking back from post toward road.

WD115	08	11000 010 C	66E 65S 020	Farthest dike out on small spur before steep drop.
WD116	08	11100 110 B	46E 66S	
WD117	08	11100 000 B	65E 80N 150	On the very steep end beyond WD115.
WD118	08	K	86W 85S 030	A meter downhill from WD117
WD119	08	K	60E 66S	3m uphill from 116 in red soil. Strike is an average of many small turns.
WD120	08	K	E-W 45S 035	A meter uphill from WD119.
WD121	08	11100 010 B	80W 85N	Again strike is an average. Dike seems to have been squeezed into joints in flows.
WD122	08	10000 010 C	46W 70S 150	
WD123	08	K	60W 65S 100	
WD124	08	K	60W 75S	
WD125	08	K	85E	In heavily eroded jeep track. Cuts WD126.
WD126	08	K	75W 45S	Cut by WD125.
WD127	08	10001 000 E	66W 75N	Outcrop quite steep, makes a vertical gully.
WD128	08	K	84W 70S	Stands up from surrounding outcrop, but still highly weathered.
WD129	09	11000 000 A	80E 77S 017	Mildly tholeiitic basalt. Mauna Kuwale behind the cowbarn. Intrudes the lower side of rhyodacite, right accross the trail up.
WD130	09	11000 000 A	56W 13N	Sill, concordant in flow planes of rhyodacite. Dip is a maximum; it's flatter in places. On trail uphill, behind inclusion-bearing boulder.
WD131	09	00000 000 G	36W 20W	Mildly tholeiitic basalt. Another sill.
WD132	09	11000 000 A	10W 53W 080	Mildly tholeiitic basalt. Above rhyodacite, cutting feldspar-rich flow.
WD133	09	11101 000 E	10W 30W 030	Mildly tholeiitic basalt. 2m above WD132.
WD134	09	11100 010 B	60W 45S 080	Mildly tholeiitic basalt. Off summit toward NW corner of Mauna Kuwale triangle.
WD135	09	11100 100 B	80W 83N	Along cliff face at base of slope break. Thin, inconspicuous.
WD136	09	11000 000 A	74W 31S	Tholeiitic basalt. A lot of glassy stringers clustered together; strike is from one of those stringers.
WD137	09	11000 010 A	87E 31S 100	Another sill, on main trail behind cowbarn.
WD138	09	00000 100 D	31W 54S 005	
WD139	10	11100 010 B	58E 60S 020	Approaching Mauna Kuwale from Paheehee Ridge side, in feldspar-rich flow above rhyodacite.
WD140	10	11100 100 B	81E 80S 050	2m above WD139.
WD141	09	00000 000 G	16W 70N 010	Mildly tholeiitic basalt. Twists through rhyodacite.
WD142	09	00100 000 H	06E 60E 010	Alkalic basalt. Cuts rhyodacite.
WD143	09	00100 100 H	26W 070	It looks like a cement-cased drill hole set in this dike.
WD144	10	00000 100 G	60E 58N 060	Mildly tholeiitic basalt. Down at the level of Paheehee Ridge, walking makai (west).
WD145	10	10000 100 C	84E	Nearly hidden in grass.
WD146	10	10000 000 C	E-W 65S	Level with country rock.
WD147	10	11010 000 F	76E 62S 030	Strongly tholeiitic basalt.
WD148	10	11100 100 B	60W 31N 040	Sill, above WD149, visible on both sides of ridge.
WD149	10	11100 110 B	85W 36N 040	Sill, below WD148, also visible on both sides of ridge.
WD150	10	11101 000 E	70E 30S 050	
WD151	10	11100 100 B	15E 18E 030	
WD152	10	10101 110 E	29E 44E 050	Stands up from country rock.
WD153	10	10100 110 I	38E 70N 040	
WD154	10	00000 010 G	30E 60W	Several en echelon segments.
WD155	10	11100 110 B	E-W 45S	
WD156	10	10010 010 F	66W 45S	
WD157	10	11100 100 B	HRZ	Sill, where Paheehee Ridge thickens into Puu Paheehee.
WD158	11	K	43W VRT 120	Navy Ridge. Dike weathered deeper than surrounding flows.
WD159	11	11000 000 A	63E 30S 020	
WD160	11	10000 000 C	63E 30S 020	Strongly tholeiitic basalt. A few steps above WD159.
WD161	11	K	73W 78N 020	Again a few steps above WD159 and WD160. Cut by WD162.
WD162	11	11000 000 A	61E 55N 010	Strongly tholeiitic basalt. Crosses WD161.
WD163	11	11000 000 A	72E 08S 010	Strongly tholeiitic basalt.
WD164	11	10000 000 C	48W 65S 010	Mildly tholeiitic basalt

WD165	11	10000	000	C	75W	70S	015	
WD166	11	11110	000	F	70E	42S	050	At 1222ft peak (see USGS topo map)
WD167	11	11000	000	A	65W	05S	030	Like a sill
WD168	11	11000	000	A	17E	40W		Mildly tholeiitic basalt. Downhill along the strike of WD166.
WD169	11			K				Couldn't get across a gully to this dike.
WD170	11	10000	000	C	61W	20E		Flows below this are eroded, so it is the roof to a small cave.
WD171	11	11100	100	B	75E	35N	040	Below rock fence in gully.
WD172	11	11000	000	A	05E	68W	050	
WD173	11	11100	000	B	35W	68W	015	Mildly tholeiitic basalt. Feldspar phenos make snowflake-shaped clusters.
WD174	10	00000	100	G	25E	50W		Paheehee Ridge, starting at base of Puu, by fence.
WD175	10	00000	110	G	62W	25N	030	Steep outcrop makai of fence.
WD176	10	10101	000	E			050	Sill, nearly horizontal. Above WD175.
WD177	10	00000	100	G	42E	24N	040	Mildly tholeiitic basalt. Near WD175 and WD176. Bifurcates.
WD178	10	10000	100	C	15E	44E		By itself--not near other outcrop.
WD179	10	11000	100	A		HRZ		Mildly tholeiitic basalt.
WD180	10	10100	100	D	07E	78W	030	
WD181	10	00000	100	G	35E	70W		At 125ft altitude. Near starting point, makai of fence.
WD182	10	11100	100	B		HRZ		Sill, below outcrop of WD181, in family with WD175,176,177.
WD183	11	11100	000	B	78E	20N	030	Navy ridge.
WD184	11	11100	010	B			050	
WD185	11	11000	000	A	65E	40N	005	Mildly tholeiitic basalt. Nearly back to WD173
WD186	11	11100	000	B	38E	62N	030	
WD187	11	11000	010	A	12W	76E	020	Strongly tholeiitic basalt. Next to WD186.
WD188	11	11100	000	A	30W	80N	080	Weathered below surrounding flows, making gully.
WD189	11	10001	000	E	30W	70E		6m from WD188.
WD190	11	11100	000	B	40E	35N	015	Mildly tholeiitic basalt. 3m uphill from WD189.
WD191	11	11100	000	B	10E	50W	030	One step up from WD190.
WD192	11	11000	000	A	10E	35E	050	Strongly tholeiitic basalt. Cuts WD193.
WD193	11	11100	000	B	60E	20N		Mildly tholeiitic basalt. Cut by WD192.
WD194	11	11100	000	B	22E	40W	030	Downhill from WD193.
WD195	12	11100	100	B	60E	65S	100	Kolekole Pass, start of Honouliuli Trail. Past heavily weathered zone into fresher flows.
WD196	12	10001	100	E	45E		100	Weathered much deeper than flows, even shows up on the topo map.
WD197	12	11100	110	B	65E	60S	080	Intersects WD196, but relative age unclear.
WD198	12			K	40E	65S		Between WD195 and WD196.
WD199	12	10000	000	C	70W	70N		Where trail crosses first dry stream channel.
WD200	12	11000	000	A	50E	85N	025	Up the streambed, a family of dikes making a scarp. Would be a waterfall if wet.
WD201	12	11100	100	B	75W	30S	025	A few steps upstream, taking the right fork.
WD202	12	11100	010	B	85E		060	Mildly tholeiitic basalt. 15yds up the channel.
WD203	12	11100	110	B	72W	52S	050	Anastamosing set of dikes,
						80W	61S	030 with two sets of measurements.
WD204	12	11100	100	B	80E	30S	040	Mildly tholeiitic basalt. Back down stream, then up the left fork.
WD205	11	11100	100	D	32E	VRT	030	Navy Ridge, high on the ridge in a grove of guava trees.
WD206	11	11000	010	A	70W	75N	170	Downhill from 205, on an especially narrow part of ridge.
WD207	11	11000	000	A	65W	88S	050	Weathers deeper than the surrounding flows.
WD208	11	11001	010	E	N-S	73W	110	Barely downhill from WD207
WD209	11	00000	010	G	05E	70W	030	Level with surrounding rock.
WD210	11	11000	000	A	80W	80S	035	differentiated tholeiitic basalt. Twenty steps downhill from WD209.
WD211	11	11000	000	A	68W	62S		Is a small scarp. Cuts WD212 and WD213.
WD212	11	11000	000	A	67E	38S	030	Cut by WD211; cuts WD213. One face exposed.
WD213	11	00000	010	G	40W	75W	040	Cut by WD211 and WD212. Eroded below surrounding rocks.
WD214	11	11000	010	A	85E	70S		
WD215	11	11000	010	A	65E	42N	025	Dark grey; surrounding rocks have red lichens.
WD216	16	11000	110	A	10W	56W	050	On the way up to Nanakuli Ridge, from Lualualei. Dike is next to wire fence, makes a watercourse if it rains.

WD217	16	10101 100 D	66W 35S 03	This area has had a brush fire recently. Stands up a little from country rock. First dike after reaching top of ridge; not far from Survey marker.
WD218	16	10101 100 D	86W 78S	About 6m up from WD217.
WD219				not a dike
WD220	16	10101 100 D	26W 88S 500	Past the burned-out area, past fresh vegetation, and into burned area again. This one is so big it's easy to miss.
WD221	16	00001 100 D	60W 75S 150	
WD222	16	10101 100 D	26W 78W 100	Mugearite.
WD223	16	00000 100 D	20W 80W	26 steps uphill from WD222. Quite magnetic.
WD224	16	00000 100 D	43W 85W	Walked past it at first. Between WD221 and WD223.
WD225	16	00000 100 D	16W 75E 150	Another one on the way back downhill.
WD226	13	J	65W 72S 020	Beginning Honouliuli 2. Dike crosses trail.
WD227	13	10100 010 I	70E 62N	In another stream channel, parallel to stream. Below the trail, crossed by WD240.
WD228	13	11000 100 A	26E 29W 100	Strongly tholeiitic basalt. Accross the stream, cuts WD229.
WD229	13	10000 100 C	40E 80S 100	Again parallel to stream, cut by WD228 and WD230.
WD230	13	11100 110 B	64W 62N 100	Strongly tholeiitic basalt. Cuts WD229, crossing the stream. On bottom half, phenos stand out in relief from groundmass.
WD231	13	10000 000 C	10E 26E 010	
WD232	13	10000 010 C	06E 44W 100	To the left of stream channel.
WD233	13	01100 100 I	07W 65W 100	Like WD232: Outcropping along face of hill beside trail.
WD234	13	00000 110 G	04E 62W 075	
WD235	13	11000 110 A	66W 60S	Mildly tholeiitic basalt.
WD236	13	10101 100 E	60E 72E 033	
WD237	13	01100 110 I		Above and left of WD236; dike has a kink, changing sharply from concordant to discordant.
WD238	14	11000 000 A	E-W 34S 100	Persists for several meters parallel to trail.
WD239	14	11000 000 A	16W 40W 050	Visible in gully perhaps a meter vertically above trail.
WD240	14	11000 010 A	60W 62W	Mildly tholeiitic basalt. Below trail; crosses WD227.
WD241	14	11000 010 A	47W 38W 100	Mildly tholeiitic basalt. 3m below WD241.
WD242	14	10000 010 C	82W 35S 060	A meter and a half below WD241.
WD243	14	11000 010 A	78W 28S 090	Another meter and a half downhill, on other side of gully from WD242.
WD244	14	10000 100 D	62E 60S	Around a corner, less than two meters below WD243.
WD245	14	11000 100 A	68W 30W	Slants up the face between level of WD244 and the trail. Is cut by WD246.
WD246	14	11000 000 A	42W 32W 090	Fatter than WD245, and cuts it.
WD247	14	10000 100 C	66E 12S	Along face above WD245 and WD246.
WD248	14	11100 110 B	060	At level of trail again.
WD249	14	11000 110 A	88W 64S	On the trail.
WD250	03	11000 010 A	76W 66S	Mildly tholeiitic basalt. Kolekole Pass roadcut, uphill from overlook. First dike downhill from contact with Kolekole Pass Conglomerate.
WD251	03	K	83W 85S	Runs into and is diverted by WD252.
WD252	03	J	44W 60S	Mildly tholeiitic basalt.
WD253	03	11000 000 A	68E 48S	
WD254	03	11100 110 B	60W 80S 090	Crosses WD255, above road (and eye) level.
WD255a	03	11000 010 A	88W 52S 080	Lowest segment of compound dike or of 3 dikes together.
WD255b	03	11000 000 A	88W 52S	Middle one of "set"; has large feldspar "polkadots".
WD255c	03	11000 010 A	88W 52S 030	Upper one of set; perhaps oldest.
WD256	03	11000 000 A		Mildly tholeiitic basalt.
WD257	03	11000 010 A	64W 62S	Mildly tholeiitic basalt. Offset en eschelon. Cuts WD258.
WD258	03	11100 000 B	HRZ	Mildly tholeiitic basalt. Runs into WD257 and ends. Is cut and offset by WD259.
WD259	03	11000 010 A		Mildly tholeiitic basalt. Offsets WD258, then runs into WD260 and quits. Orientation irregular.
WD260	03	11000 000 A	68W 64S 090	Mildly tholeiitic basalt.
WD261	03	11000 010 A	16W 70W	WD263 runs into this and quits.
WD262	03	11100 000 B		Has a loop in it, surrounds a portion of WD263.
WD263	03	10000 000 C		Several odd twists, then ends against WD261.

WD264	03	00100	100	H	53W	22E	200	The picrite dike, upper outcrop.
WD265	22	11100	100	B	65E	45S		Mildly tholeiitic basalt. Heading up to Kamaileunu, on the spur behind Angel's Junkyard. This one isn't too conspicuous.
WD266	22	11100	100	B	48E	65N	055	A few steps uphill from WD265. More obvious than WD265 as a dike.
WD267	22	11000	100	A			100	Mildly tholeiitic basalt. Just above WD266, nearly at closed contour on map.
WD268	22			K	10E	20W		
WD269	22	10101	100	D	65E	16N	200	Big dike, nearly a sill, visible from quite a distance
WD270	22	11101	100	E	67E	70S	115	
WD271	22	11000	110	A	80E	82S	025	Coming down makai ridge, past a lot of massive hawaiites, then into some thinner basalt.
WD272					38W	10S		This is a flow, orientation is of flow surface. T.H. wrote initials on it.
WD273	22	11000	110	A	70W	18S	015	Mildly tholeiitic basalt. Below "68" graffiti.
WD274	17	11100	100	B	32W	45N	080	Kaena Point; first dike on the way up from sand dunes.
WD275	17	11100	100	B	04W	VRT		Between highest bunker and flag.
WD276	17	11100	000	B	65W	80N	080	Just beyond flag.
WD277	17	11100	100	H	65W	85S	250	Waianae side of WD276.
WD278	17	10101	100	D	58W	85S	033	
WD279	17	10000	100	D				Orientation obscure--dip may be curved.
WD280	03	11100	010	B	15W	65W	100	Kolekole Roadcut, next to lower outcrop of picrite.
WD281	03	11000	110	A	22W	54E	100	9m downhill from WD280, still in breccia. Some breccia included in dike.
WD282	03	00000	010	G	65W	75S	080	Alkalic basalt. 3m downhill from WD281.
WD283	03	11100	000	B	03W	64W	125	Dike marked with White-out. (I'll bet it's worn off by now.)
WD284	03			K	55W	40S	050	3m downhill from WD283.
WD285	03			K	10W	80E	050	Still in breccia
WD286	03	11101	100	E	65W	80N	300	Bits of breccia included in dike.
WD287	03	11000	010	A	75E	45E	050	Below a curve.
WD288	03			K	30W	80N		6m down from WD287, next to a face that looks like it has slickensides.
WD289	03	11000	010	A	10W	68S	060	Next dike downhill from WD288.
WD290	07	11000	000	A	60E	70N	050	In Puu Kailio proper.
WD291	07			K	15W	80		Dike forms the face of outcrop here. Intrudes lava, not breccia.
WD292	07			K	20E	70S	040	Still in lava.
WD293	07			K	15E	VRT	150	Nearly parallel to roadcut. At contact betwee lava (uphill) and breccia (downhill).
WD294	07	11100	010	B	12E	15W	030	Mildly tholeiitic basalt. In breccia on side of hill that straddles road.
WD295	07			K	05E	VRT		At the curve, on Puu Kailio side, where the hill straddles road.
WD296	07	11001	010	E	50E	76N	055	100 yds downhill from WD295, next to a drainpipe that goes under road.
WD297	07	11100	010	B	20W	65S	050	Cut by WD298.
WD298	07	10100	000	I	73W	72N	040	Cuts WD297.
WD299	07			K	85W	VRT	025	Next to WD297 and WD298.
WD300	07			J	60E	65N		Cuts WD301.
WD301	07	11100	010	B	N-S	60W		Cut by WD300.
WD302	18	11000	100	A	N-S	65W		Starting up Puu Heleakala, on spur that points into Lualualei Valley. Near bottom in a cow pasture.
WD303	18	00100	000	H	07E	68W		About the same elevation as the cement stacks. 2 or 3 dikes together.
WD304	18	11100	100	H	20W	70W	050	Strongly tholeiitic basalt.
WD305	18	10100	100	H	05W	70W	060	Strongly tholeiitic basalt.
WD306	18	00100	000	H	85W	73N	060	
WD307	18			K	05E	65W	030	
WD308	18	11100	000	B	10E	15W	060	Intrudes aa. In segments, like boudinage.
WD309	18	11100	100	B	02E	80W	080	Cuts WD310. Clearly exposed.
WD310	18			J		HRZ	030	Strongly tholeiitic basalt. A sill. Cut by WD309.
WD311	18	11110	000	F	28E	70W		Inconspicuous, just uphill from WD311.
WD312	18	11100	110	B	25W	80W	080	
WD313	18	11100	100	B	05W	VRT	075	
WD314	18	00100	100	H	05E	VRT	060	Last dike before top.
WD315	18	11100	100	B	10W	75W		Mildly tholeiitic basalt. Coming down makai, this is the big dike visible from the road.

WD316	18			K	20W	VRT		
WD317	18	11110	000	F	23E	60W	060	Nearly at bottom, near houses.
WD318	07	11011	000	F	26E	76W	160	Puu Kailio, first dike below WD301, just downhill of Do Not Pass sign.
WD319	07	11000	000	A	38W	72S	026	Mildly tholeiitic basalt. Skipping one dike between WD318 and here. In two segments, offset en echelon.
WD320	07	10000	000	C	68E	VRT	016	Tholeiitic andesite. Flat and smooth-looking.
WD321	07	10000	000	C	22W	75W	060	Immediately downhill from WD320.
WD322	07	11001	010	E	76W	VRT		Roadcut face here looks yellow.
WD323	07	11000	000	A	10W	85W		Tholeiitic andesite. Still in yellow face, next to concrete drainage ditch.
WD324	07	11000	010	A	11E	75W		Intersects WD323 high above eye level, also intersects an unsampled dike.
WD325	07	11000	010	A	30E	70W	090	Close to notch in cliff.
WD326	07	11101	000	E	60W ~~030~~	83S		This is the notch in cliff. Skipped one between WD325 and here.
WD327	07	10100	000	H	32W	85W	060	Opposite fire lookout sentry box. Intrudes lava, not breccia.
WD328	07	11101	000	E	10E	74W		Tholeiitic basalt. Also intrudes lava.
WD329	07	11100	010	B	N-S	75W	060	Back into breccia, below culvert.
WD330	07	00000	010	G	18W	65E	060	
WD331	19	00000	011	F	48W	VRT	175	Outside edge of Makua valley. Forms stairsteps, surrounded by rushes.
WD332	19	11100	110	B	65W	70S	160	Still pretty low, in tall grass or rushes.
WD333	19	00000	000	G	60W	80S		Uphill and makai of ccement platform.
WD334	19	10000	100	C	60W	VRT	050	Just beyond "house".
WD335	19	00100	110	H	66W	70S	080	Strongly tholeiitic basalt. Measuring 2 segments of the same dike.
					43W	70S	080	
WD336	19	11100	110	B	30W	VRT		Big dike, standing out right at ridge crest.
WD337	19	11100	110	B	65W	80S	110	Half of a compound dike. Again, stands out clearly from surroundings.
WD338	19	10010	000	F	65W	80S	110	The other half, on Kaena Pt. side of WD337.
WD339	19	11100	100	B	46W	75S	110	Just beyond metal pipe survey marker.
WD340	19	10010	011	F	55W	VRT	125	
WD341	19	00100	100	H	60W	VRT		Strongly tholeiitic basalt. Lower of the two triangular faces.
WD342	19	11010	010	F	60W	VRT		Strongly tholeiitic basalt. Upper of the two triangular faces. Wide enough for two people to sit on.
WD343	19	11110	010	F	40W	VRT	080	Immediately above WD342.
WD344	19	11010	010	F	43W	VRT	060	Immediately above WD343.
WD345	19	11101	100	D	43W	53S	110	Skipping one in between, is still only 6m from WD344.
WD346	23			K	80E	65S	025	Kolekole Pass, on the weathered hillside where the flow with the xenoliths is.
WD347A	23			K	55E	25S	150	The above half of a pair. WD346-WD350 much weathered, not sampled.
WD347B	23			K	30W	55N	050	The below half of the pair; they cross but relative age not clear.
WD348	23			K	60E	25S	075	Directly above roadcut. Cuts WD349.
WD349	23			K	30E	80W	075	Cut by WD348.
WD350	23			K	60W	70S	175	
WD351	23	11000	000	A	45W	65S	100	On ridge leading toward Kaala.
WD352	23	11000	110	A	40W	70S	025	
WD353	23	11000	110	A	45W	80S	030	Past KUM1927 benchmark, and above graffiti rock.
WD354	23	11000	010	A	55W	68S	050	Strongly tholeiitic basalt. Forms a saddle bridge jus below Puu Kumakalii.
WD355	23	11000	000	A	60W	VRT		Oblique to trail.
WD356	23			K	80E	35S	040	Measured from a distance.
WD357	23			K	30W	80S		Also measured from a distance.
WD358	23	11101	100	E	35E	VRT	080	On the way back, past WD355, makes the ridge to walk on.
WD359	23	11000	110	A	40E	VRT	030	
WD360	16	11100	010	B	40W	30N	060	Honouliuli 2. In wet streambed.
WD361	16	11010	010	F	10W	60W	060	45m above WD360, in same stream channel.
WD362	16	11100	110	B	N-S	45W	075	6m or so above WD361.
WD363	16	11000	000	A	70E	55S	040	Back downhill, still in stream channel, 6m below trail.
WD364	16	11010	010	F	20W	35S	030	Along the trail.
WD365	16	11001	100	D	86E	75N		150-200m farther along trail, almost at a stream.

WD366	09	11100	000	B	85W	45N	040	Base of Mauna Kuwale, at mauka (east) end. Dike is right side of tuff exposure.
WD367	09	11100	000	B	60W	80S	040	In jeep track that goes around hill.
WD368	09							Tuff at end of Mauna Kuwale.
WD369	09	11100	000	B	60W	60S	060	Mildly tholeiitic basalt. Left side of tuff.
WD370	09	11100	000	B	83W	88N	050	Mildly tholeiitic basalt. Around the corner again, might connect with WD367.
WD371	20	10100	000	H	35W	68N	040	Makua Valley middle section.
WD372	20	11100	100	B	10W	VRT	050	Strongly tholeiitic basalt. Feldspar phenocrysts snowflake-shaped
WD373	20	00100	100	D	41W	VRT	075	
WD374	20	00000	110	D	30W	60S	080	
WD375	20	11100	100	B	47W	80S	060	Mildly tholeiitic basalt. On flank of ridge instead of crest, on the way back down.
WD376	20	00000	110	D	41W	80S	070	Downhill from WD375, makes sort of a wall.
WD377	20	10101	000	D	32W	75S	060	
WD378	20	10100	100	I	38W	75S	110	
WD379	20	00101	100	E	50W ~~45~~	80W	100	
WD380	21			K	60W	85N	100	Kuaokala forest reserve, starting by pumping station, but going as long way before any dikes. This one measured from a distance.
WD381	21			K	60W	80S	110	Walking makai on ridge that forms Kaena Pt side of Makua Valley. Weathered, no sample.
WD382	21			K	65W	VRT	250	Measured from maybe half a km away.
WD383	21	00001	110	D	50W	75W	080	Finally into rocks firm enough to sample--though still weathered.
WD384	21	10101	100	D	57W	75N	085	
WD385	21			K	49W	VRT	060	6m from WD384.
WD386	21			K	30W	75N	030	
WD387	21	11101	000	E	040	VRT	175	
WD388	19	10100		J				Mildly tholeiitic basalt. Glass only, sampled from dike on south side of Makua Cave.
1142		10101		E				Tholeiitic andesite. Dike collected by G.A. Macdonald. Also has some apatite crystals.