THE GEOLOGY OF THE LOWER SOUTHWEST RIFT OF HALEAKALA, HAWAII

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Abstract

A geologic map of the lower southwest rift of Haleakala with chemical and microscopic analysis of rock specimens shows that the most recent volcanic eruptions along the rift have occurred around four main centers. Five formations have been mapped: 1) The Mahoe Formation is titanaugite and olivine-bearing picrite basalts and alkalic olivine basalts; 2) The Makua Formation ranges from a relatively felsic picrite basalt through alkalic basalt to a felsic alkalic olivine basalt; 3) The Pimoe Formation is a complex series of flows and pyroclastics, the most recent of which is an alkalic olivine basalt with microphenocrysts of titanaugite and olivine; 4) The Kaloi Formation is several recent flows ranging from relatively silica-rich alkalic olivine basalt to picrite basalts containing olivine phenocrysts and titanaugite microphenocrysts, and a mafic picrite basalt; 5) The Keoneoio Formation consisting of three flows, the two most recent of which are the lavas of the 1790(?) eruption, of picrite basalt transitional to ankaramite.

Chemical analyses of eight samples shows that the lavas are undersaturated in silica, and that there is a notable distinction in the amounts of silica between Hana Series and Kula Series lavas. The rocks are typical of late-stage eruptions of Haleakala in the their alkali-silica ratios, their titaniferous augite, and normative but not modal nepheline.

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I. INTRODUCTION

Purpose and Scope

Late stage volcanic activity on the lower part of the southwest rift zone of Haleakala Volcano has not previously been studied in detail. Earlier investigations have been concerned with general descriptions of scattered rock specimens. Most study of late stage volcanism of Haleakala has been centered around the summit depression. The southwest rift zone was chosen for detailed investigation because of the numerous volcanic features and good exposures, the relatively undisturbed state of the terrain, and a fondness for the area from past experience. The stratigraphy and surface features were mapped in detail and are described in the report. Rock specimens were collected for laboratory study.

General Description of the Area

The Hawaiian Islands are located in a tectonically stable part of the Pacific Basin. The island of Maui, the second largest of the Hawaiian Islands, is composed of two volcanoes joined by a narrow isthmus of alluvium, colluvium, and shallow marine sediments. The West Maui volcano (Fig. 1) is the older of the two. The eastern part of the island is Haleakala, a volcanic mountain rising more than 3000 m above sea level.

The southwest rift zone is one of three intersecting rift zones of Haleakala along which volcanic eruptions have

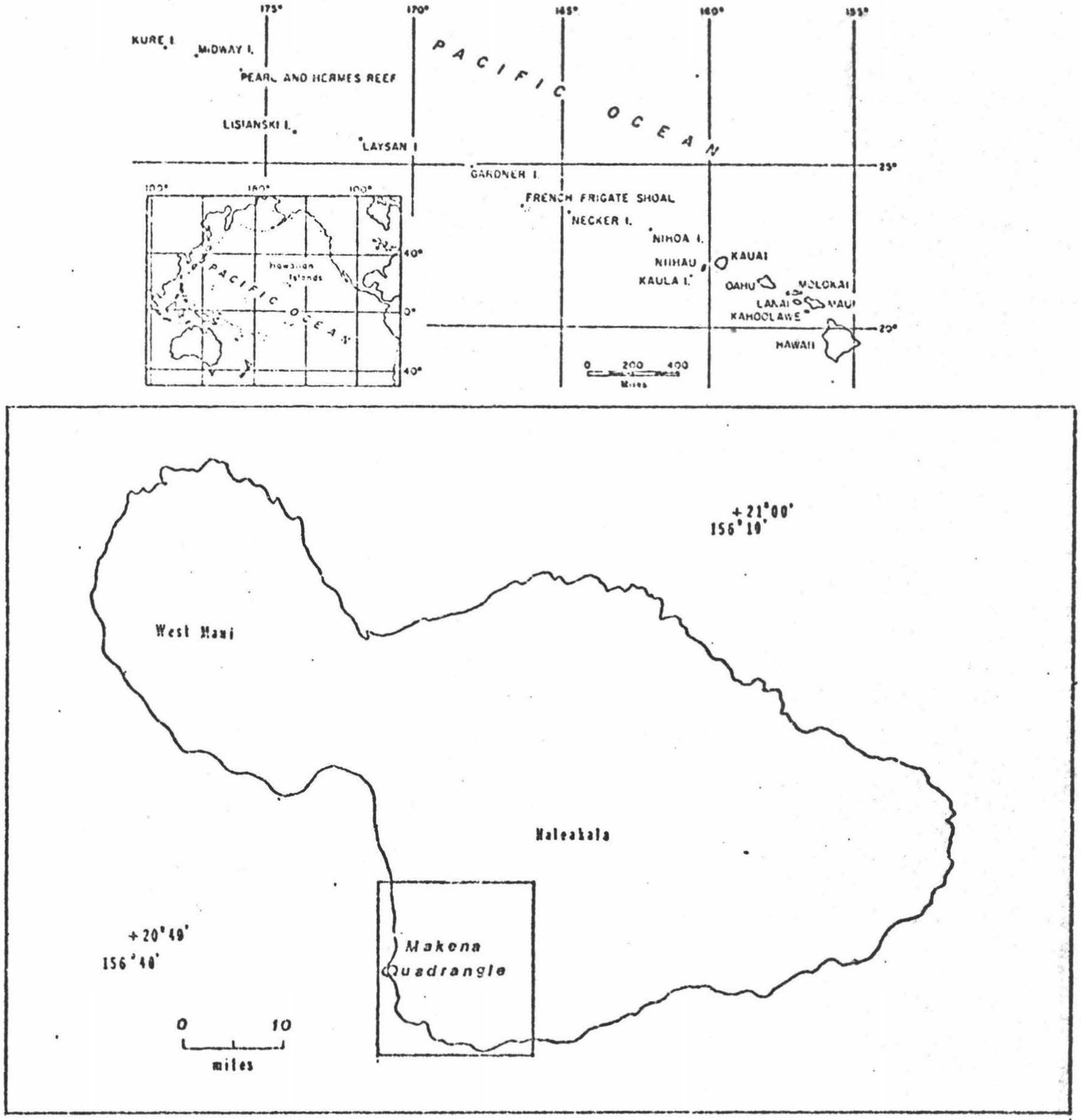

Figure 1. Location of Makena Quadrangle

occurred. The three rift zones intersect within the summit depression 12 km to the northeast. Each of the rift zones consists of numerous subparallel fractures and volcanic vents over a belt as much as 3 km wide. However for the sake of brevity hereafter in this report each will be referred to simply as a "rift". The southwest rift is marked by numerous cinder and spatter cones, eruptive fissures which are nearly co-linear, and lava flows.

The mapped area comprises part of the southeastern corner of United States Geological Survey Makena topographic quadrangle map, published in 1954. It is a sector of approximately 75 km^2 which includes the lower southwest rift from sea level to 1830 meters (6000 feet). It is bounded by a line extending due north from the center of Kanaloa Peninsula, and a line bearing N60^{o}E from Kanahena, 3.6 km northwest of La Perouse Bay. The vast majority of the land is owned or leased by Ulupalakua Ranch, Inc., and is used for cattle grazing. The area is accessible from Kahului by State Route 37 in about an hour's driving time.

Previous Investigations

Early geological investigators of the island of Maui include the French explorer, La Perouse, who, in 1786, anchored offshore in a bay which now bears his name; Drayton and Pickering (Dana, 1849), and Dutton (1884). Cohen (1880) described rock specimens sent to him from East Maui; E. S. Dana (1889) described eight additional specimens from Haleakala, collected by J. D. Dana. Mohle (1902) described another, but his specimen was probably from West Maui. The first systematic study was done by Cross (1915) who published petrographic descriptions and chemical analyses of several samples. Sidney Powers (1920) also gave analyses of several samples and outlined differences between rocks from different localities. Washington and Merwin (1922) published chemical analyses of augite crystals from Haleakala lavas. H. A. Powers (1935) systematically compared variations in rocks of Haleakala to those of other Hawaiian volcanoes. Stearns and Macdonald (1942) published details of surface and subsurface geology, groundwater and petrography. Several of the specimens described were from the lower southwest rift. Six new chemical analyses and corresponding petrography were published by Macdonald and Powers (1946) but were generally samples from earlier rock series. Reeber (1959) attempted to determine absolute ages of several recent lava flows within the map area by radiocarbon methods. Macdonald and Katsura (1964) added nearly 150 new chemical analyses of Hawaiian lavas, of which only one was from the lower southwest rift of Haleakala. Oostdam (1965) reported a new determination of the date of the historic eruption at La Perouse Bay. Macdonald and Powers (1968) published 15 new analyses of late-stage lavas of Haleakala.

Field Methods

A total of eighteen days was spent in the field during January 1974 and January 1975. Data were plotted on the

Makena Quadrangle map at a scale of 1:24,000. Samples were collected when outcrops were encountered on traverses, or when contacts were found. A total of 61 samples was collected and hand specimen descriptions and locations were noted. Locations were by compass resection or intersection where map correlatable landmarks could be seen. In heavy brush, when vision was obscured, distances, paced or estimated, and topography and bearing gave approximate locations. The car odometer was used to measure distances along the highway. Aerial photographs at an approximate scale of 1:24,000 were carried in the field, but conditions were seldom suitable for stereoscopic viewing. When possible, control points were located in the field and on the map and photographs, to facilitate correlation of data in the laboratory.

More obvious contacts can be followed by eye for some distance, and except for a small gently sloping terrace northwest of Pimoe cone the entire area can be seen at a distance from some point. Hand specimen correlation is possible to a degree in the field, but there is relatively little petrographic variation and many of the lava flows span considerable distance and climate so that there may be a wide variation in surface texture, vegetation and mineralogy between the source and terminus of a single long lava flow.

Relative ages were determined by superposition where possible and by comparisons of the degree of weathering and differences in the succession of vegetation. Degree of weathering and surface color are related to age (Macdonald, 1971), but differences in climatic conditions at the time of extrusion and cooling, as well as the permeability and roughness of the surface, are also factors. Succession depends on many factors which are difficult to quantify (Forbes, 1912; MacCaughey, 1917; Clements, 1928; Tansley, 1929; Hartt, 1940; Skottsberg, 1941; Mueller-Dombois and Krajina, 1966).

Laboratory Methods

In the laboratory aerial photographs were studied stereoscopically. Contacts were drawn on the photographs with a soft pencil, and transferred to an overlay of the base map. Lines were erased from the photographs and redrawn without reference to the first overlay. A second overlay was compared to the first and studied with reference to the photographs and the field map.

Several of the more recent lava flows showed features in more detail than could be drafted; some features are generalized in Plate 1. Several contacts were inferred from the photographs and were not apparent in the field. These are dashed or queried on Plate 1. A total of 33 specimens were studied in thin section. Modal percentages are given for 24 of these in Table 3. Descriptions are given under the headings "Stratigraphy" and "Petrography".

Acknowledgments

Air fare to and from Maui, car rental, and chemical analyses were paid by the T. A. Jaggar Volcano Research Fund of the University of Hawaii. Permission to enter Ulupalakua Ranch land, and keys to gates were given by Mr. Pard Erdman and Mr. James Armitage of Ulupalakua Ranch, Inc., who also provided information about locations, routes, and travel times to points of possible interest. Ms. Amy Sims assisted in the field on one occasion.

II. PHYSICAL CONDITIONS

Topography

The topography of the lower southwest rift is determined by volcanic features, which include pyroclastics, lava flows, pit craters, and lava tubes. The general trend of the rift is S60^{O}W. The average ground slope is 145 m/km, and is as high as 500 m/km on some of the pyroclastic cones. The highest of the cones is Puu Makua, elevation 1608 m (6000 ft), which rises 185 m above the surrounding slopes. At least 15 large cones are spread along the rift, becoming slightly smaller and occurring with less frequency towards the sea. The cones are either nearly circular or crescentic in plan, with the horns of the crescents pointing downslope. The arcuate cones usually have lava flows demonstrably associated with them.

Above 800 m (2600 ft) the topography becomes more irregular and hummocky with several rounded ridges up to 200 meters high trending generally parallel to the rift. Puu Kaeo, just out of the mapped area to the west is one, and is probably an older pyroclastic cone which has been buried by lava or pyroclastics from subsequent eruptions along the rift. Pohakea and Puu Ouli are buried except for the top few meters, which protrudes through the lava.

Several linear topographic features above 975 m (3200 ft) are lines of vents or pit craters which follow the trend of the rift en echelon out of the map to the northeast.

Eruptions from some of the vents built cinder cones or spatter cones, in some cases followed by the extrusion of lava. Others built spatter ramparts along an eruptive fissure.

Vegetation and Exposures

Upslope from Piilani Highway a pyroclastic blanket of undetermined thickness smoothes the topography, but leaves large-scale features of the underlying lava revealed. They are especially apparent on the aerial photographs. Exposures of the lava are limited by this cinder where it exists. Along the highway all but the most recent flows are covered by a thin layer of soil but there is no difficulty in obtaining unweathered samples. The most recent flows along the highway are relatively unweathered although they support a community of various shrubs and grasses, the most dominant of which is koahaole. Near the coast outcrops are well exposed and lack a cinder, soil, or vegetative cover, except northeast of La Perouse Bay, where vegetation is dense. The degree of exposure changes upslope within a single lava flow because of differences in vegetation and degree of weathering caused by climatic changes with changing elevation. The type and density of vegetation depends upon both the amount of rainfall and the age of the lava flow. Moss and lichen are followed by grass, and shrubs, or small trees, such as koahaole and keawe, and eventually by larger trees, such as eucalyptus or ohia.

The latter require relatively large amounts of water and cooler temperatures and are found only at the higher elevations.

Differences in vegetation often mark contacts, especially upslope from the highway where the cinder supports pasture grasses and recent flows are black and unvegetated. Below the highway differences in surface textures and colors mark the contacts, which can often be seen more clearly from a distance than close up. A flow may appear to be beheaded due to a change in vegetation and degree of weathering along its length.

Climate and Drainage

The climate is subtropical to temperate, depending on elevation. Rainfall varies from less than 25 cm/year in some places along the coast to more than 100 cm/year in the wettest upper regions. Near the coast most rainfall comes during the winter, associated with kona (southwesterly) winds. The upper elevations have rainfall associated with tradewinds in the summer and also with kona winds in the winter. Yearly and daily temperature extremes seldom exceed a few degrees near sea level but may be 25^{o} C. in the upper regions.

Both the lava flows and cinder are too permeable for the development of extensive surface drainage. Several small intermittent streams were observed in the field and can be recognized on aerial photographs, but most are too small to be recognizable on the 40-foot contour interval of

Plate 1. No water was observed in any of the streams although it rained quite hard for two days during one stay in the field. The drainage is controlled by topography. A small intermittent stream between Puu Naio and Puu Kalihi has carved a gorge 15 m deep by 60 m wide and 750 m long, beginning at a waterfall just below the trail. A small sub-parallel system is beginning to develop in a small colluvial plain north of Pimoe cone. A small intermittent stream course can be seen on Plate 1 at the eastern boundary.

III. GEOLOGICAL CONDITIONS

Regional Stratigraphy

Hawaiian volcanoes above sea level typically pass through a tholeiitic stage, followed by a post-caldera stage characterized by eruptions of lavas richer in alkalis and poorer in silica than the tholeiites. Post-caldera lavas may be either mugearite or hawaiite but usually one type is dominant for a particular volcano. Those characterized by mugearite are designated "Kohala Type" volcanoes, and those with hawaiite "Haleakala Type" (Macdonald and Katsura, 1964). Many Hawaiian volcanoes experience renewed eruptions after a relatively long quiescent period, in some cases allowing the development of large-scale erosional features. These post-erosional lavas are generally alkali-rich and undersaturated in silica, and contain several percent of nepheline in the norm (Macdonald, 1968).

Stearns and Macdonald (1942, Pl. 1) recognized three main geologic units on Haleakala. The Honomanu Volcanic Series of tholeiitic basalts is overlain, mostly conformably, by hawaiites, alkalic olivine basalts and picrite basalts and ankaramites of the Kula Volcanic Series. Honomanu lavas are exposed only in valleys and sea cliffs along the northeastern coast. Kula lavas were erupted along the three rifts mentioned above. Overlying the Kula lavas and commonly separated from them by an erosional unconformity, with canyons several hundreds of meters deep, are lavas of the

Hana Volcanic Series. The erosional unconformity may be absent locally. Most of the rocks can be assigned to one series or the other based on hand specimen petrographic differences, but within a transition zone 15 to 60 meters thick assignment may be uncertain (Stearns and Macdonald, 1942, p. 63). Hana lavas are similar to Kula lavas with more abundant alkalic olivine basalts and less abundant hawaiites. Rocks transitional from alkalic olivine basalts to ankaramites are common.

Kula lavas and pyroclastic cones are common along the northwest rift and along the upper southwest rift, above 1600 meters. Kula lavas have not been reported on the east rift much beyond the summit depression. Hana lavas are common along the east and lower southwest rifts and adventively on the south slope, and uncommon on the upper southwest rift. Hana lavas have not been reported on the northwest rift (Stearns and Macdonald, 1942, Pl. 1).

A lava flow which formed Cape Kinau northwest of La Perouse Bay in 1790(?) is the only eruption on Maui in historic times. A detailed account of the Hawaiian legend concerning the eruption was given by Stearns (Stearns and Macdonald, 1942, p. 102-107),and the probable date of the eruption was established by Oostdam (1965).

Local Stratigraphy

Five units have been separated during the present mapping, and are designated the Makua, Pimoe, Kaloi, Mahoe and Keoneoio formations. The formations are simply mappable

Table 1. Names of Lava Flows Assigned to Different Formations

KEONEOIO FORMATION	MAHOE FORMATION	KALOI FORMATION	PIMOE FORMATION	MAKUA FORMATION
Kalua o' Lapa				
Kanahena				
				Makuamakai
		Waiokawa		
Maukamahoe				
		Keonehunehune		
		Hanamanioa		
			Pimoekai	Makuamauka
	Mahiehie			
		Kaimaloo		
	Papaka			
		Kamanamana		
	Kalihi			Leia Kanaionui
	Earlier lavas			Wana Kamana

units, and the names are assigned to them only for convenience in discussion. They are not intended to be formal stratigraphic units. Time relationships were determined by superposition when possible and by degree of weathering and plant succession where superposition was not established. There is considerable temporal overlap between units but spatial distribution and petrographic character are similar within units. In general no attempt was made to determine a detailed pyroclastic sequence, due to heavy soil cover and lack of outcrops. Table 1 lists the lava flows assigned to each formation. Sample locations and an index to lava flows are shown in Figure 2 and sample locations are detailed in Table 2.

Makua Formation

The Makua lavas are several flows with wide spatial and temporal distribution originating from the vicinity of Puu Makua. Makuamakai is lateral, Makuamauka, Kamana and Wana are central; the other vents are co-linear with spatter cones and small pit craters extending to Keonehunehune at the southwest and out of the map to the northeast. Two of these vents are the sources of the Leia and Kanaionui lavas.

The oldest of the three flows originating in central Puu Makua is the Kamana lava. It is a picrite basalt transitional to alkalic olivine basalt containing 25 to 30% olivine and labradorite phenocrysts and microphenocrysts

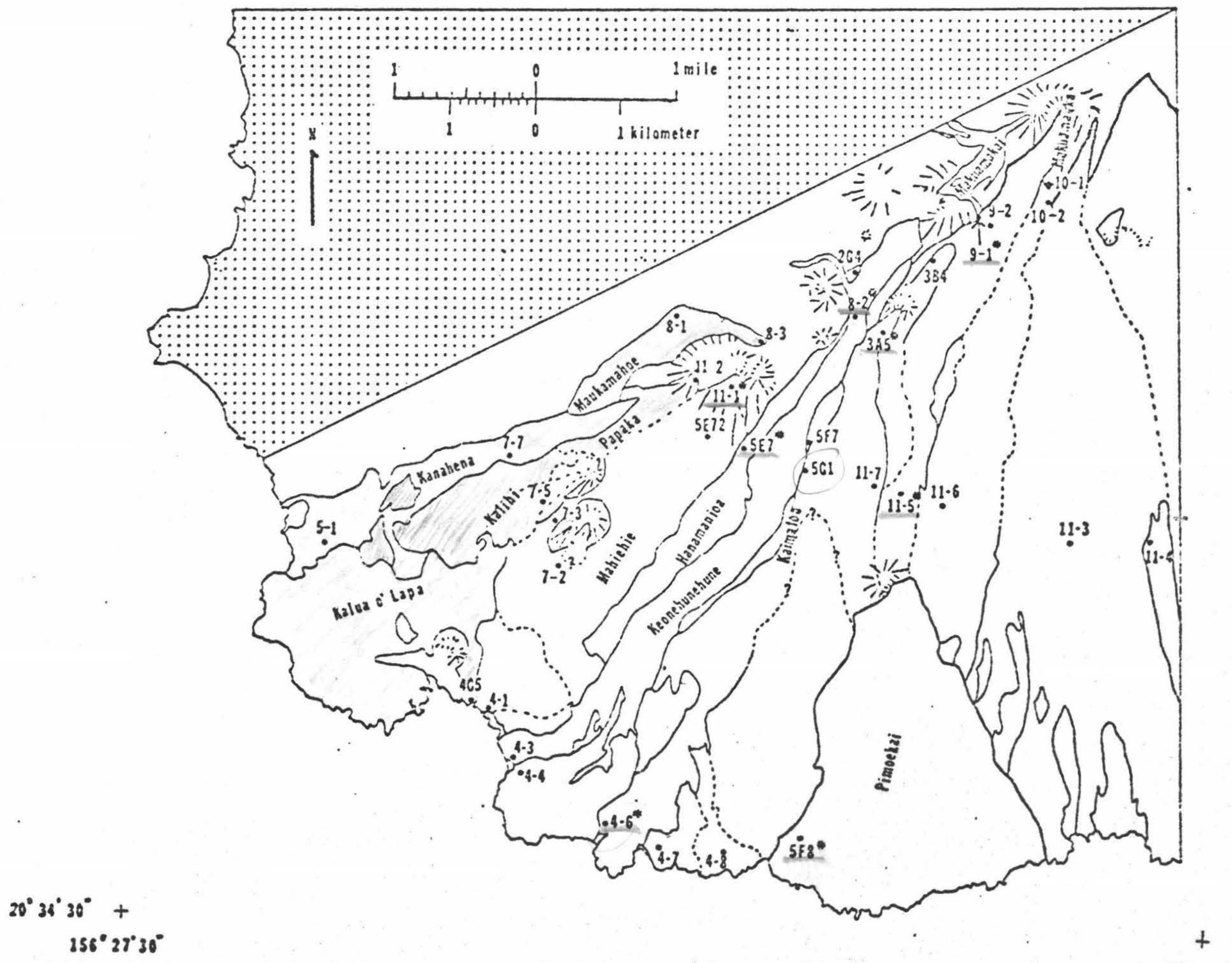

Figure 2. Sample Locations and Index to Lava Flows. Asterisks denote chemical analyses given in Table 5.

Table 2

Description of Sample Locations
(see Figure 2 for locations)

Sample	Locality
2G4	Pahoehoe toe of picrite basalt 10 m south of southernmost spatter cone.
3A5	Alkalic olivine basalt in massive aa in lava channel south of Kaimaloo, 20 m north of trail.
3B4	Cinder and Pele's tears at 1100 m elevation in small intermittent stream bed 250 m north of Maunanu, overlain by soil 25 cm thick.
4G5	Picrite basalt transitional to ankaramite at sea level, eastern lobe of 1790(?) flow.
4-1	Picrite basalt, pahoehoe along lower trail near center of La Perouse Bay.
4-3	Alkalic olivine basalt, top of aa flow, 12 m north of trail junction at east end of La Perouse Bay.
4-4	Picrite basalt, top of blocky aa flow 10 m east-northeast of rock wall east of trail junction at east end of La Perouse Bay.
4-6	Alkalic olivine basalt, old aa flow, 15 m east of contact, north side of lower trail 675 m north of Kamanamana.
4-7	Alkalic olivine basalt 5 m east of kiawe thicket on lower trail 350 m east of Kamanamana.
4-8	Picrite basalt transitional to alkalic olivine basalt along lower trail 1.2 km east of Kamanamana.
5E7	Picrite basalt, top of vegetated aa flow 15 m from contact, north side of Piilani Highway 950 m south of Puu Mahoe.
5E72	Picrite basalt transitional to alkalic olivine basalt. Aa exposed in roadcut 240 m east of junction of jeep trail with Piilani Highway.

Table 2 (continued)

Sample	Locality
5F7	Picrite basalt in kipuka 400 m north of Piilani Highway 1.2 km west of Kanaio Prison Road junction.
5F8	Alkalic olivine basalt, top of aa flow 400 m east of contact north side of lower trail 2.3 km east of Kamanamana.
5G1	Alkalic olivine basalt, front of lobe of aa. North side of Piilani Highway 1.1 km west of Kanaio Prison Road junction.
5-1	Picrite basalt transitional to ankaramite, aa transitional from pahoehoe, north side of Kihei road 2.4 km west of Keoneoio.
7-2	Alkalic olivine basalt, weathered flow at 185 m elevation southwest of Puu Naio.
7-3	Alkalic olivine basalt at dry stream, head of waterfall south side of trail between Puu Naio and Puu Kalihi.
7-5	Picrite basalt, eastern rampart of old lava channel along trail 720 m southwest of Puu Kalihi.
7-7	Picrite basalt transitional to ankaramite, east edge of aa transitional from pahoehoe west side of trail 1.2 km west of Puu Kalihi.
8-1	Picrite basalt, aa flow southwest of Piilani Highway near sign at junction of State Route 31.
8-2	Alkalic olivine basalt midway across aa flow along trail between Kulanapahu and Kaimaloo.
8-3	Picrite basalt at east edge of aa flow 250 m west of radiotelephone station northeast of Puu Mahoe.
9-1	Alkalic olivine basalt, lobe of aa flow at southwest base of Keonehunehune at 1150 m elevation.

Table 2 (continued).

Sample	Locality
9-2	Alkalic olivine basalt, outcrop overlain by soil and cinder 100 m southeast of sample 9-1.
10-1	Picrite basalt, top of weathered aa flow 1.3 km south of Puu Makua at 1335 m elevation.
10-2	Glassy alkalic olivine basalt 225 m south of sample 10-1, outcrop through grass-covered cinder.
11-1	Alkalic olivine basalt, grass-covered aa flow just north of State Route 31 (upper Kanaio Road) near center of Puu Mahoe.
11-2	Picrite basalt, thin aa flow overlying cinder, 100 m wouth of cinder quarry on Puu Papaka.
11-3	Alkalic olivine basalt north of parking area on north side of Piilani Highway 1.6 km east of Kanaio Prison Road junction.
11-4	Alkalic basalt in kipuka, Kanaio Homesteads 800 m west of intermittent stream, north side Piilani Highway.
11-5	Picrite basalt transitional to alkalic olivine basalt in roadcut just west of Kanaio Prison Road junction on north side Piilani Highway.
11-6	Alkalic olivine basalt in roadcut just east of junction with Kanaio Prison Road, north side Piilani Highway.
11-7	Alkalic olivine basalt near east edge of contact south of Kanaio church, north side of Piilani Highway.

in a barely resolvable interstitial groundmass of labradorite and clinopyroxene. The olivine phenocrysts are euhedral to subhedral with magnetite inclusions in a glassy, colorless reaction rim which has, in some cases, completely pseudomorphed the olivine. Sample 11-5 contains a few rounded grains of pleochroic, purple to yellow titanaugite which appear to be xenocrysts. Similar grains were not found in sample 4-8 which is otherwise virtually identical. The chemical analyses of samples 11-5 and 4-8 is given in Table 5. The Kamana lavas are covered by a thin layer of cinder from Pimoe cone, especially where they are exposed near the highway. The surface textures of the flows are obscurred by the cinder and by weathering.

The Wana and Kanaionui lavas are alkalic olivine basalts with phenocrysts of olivine and microphenocrysts of labradorite and pale brown clinopyroxene with a high positive optic axial angle ($2V_z$), in an intersertal to subophitic groundmass of clinopyroxene, labradorite and magnetite. The modal amount of magnetite is higher than in the picrite basalt of the older Kamana lavas. Plagioclase microphenocrysts are usually of a markedly different size and texture than groundmass plagioclase but in a few cases grade into microlites. Interstitial plagioclase is largely unresolvable, but refractive index measurements indicate that it is labradorite.

A single sample of alkalic basalt (sample 11-4) has a groundmass which is virtually identical in texture and mode to the alkalic olivine basalts, but lacks olivine phenocrysts, and contains a few percent of olivine in the groundmass. The picrite basalts of the Kamana lavas are relatively high in modal feldspar and do not contain the titanaugite microphenocrysts of the alkalic olivine basalts.

Sample 10-2 contains 40% pale yellow-brown glass, both interstitially and as rare blebs up to 0.8 mm. The blebs are rounded; the interstitial patches are sub-angular. Both contain randomly oriented clinopyroxene microlites, and are slightly anisotropic.

The Wana lavas show a wide variation in the degree of weathering between the upper elevations and the coast, and contacts are obscured above the highway, although large-scale features show through the cinder and soil mantle.

The Makuamauka lava was extruded from the central part of Puu Makua and extends downslope about 1 kilometer. The flow is 2 to 3 meters thick near the terminus and of undetermined thickness near the vent. The surface is aa with much of the spinose clinker weathered away. Moss, lichen, and scraggly grass are the only vegetation on it. Thin cinder occurs in patches on it and is probably colluvial. Sample 10-1 is a picrite basalt with phenocrysts of titanaugite and a few of olivine in a fine-grained, intersertal groundmass of brown clinopyroxene, sodic labradorite, magnetite, and a few percent of olivine. Modally it resembles the Kamana lavas, which apparently were extruded from the same vent in earlier eruptions.

The Makuamakai lavas were erupted from a fissure which opened in the southwest side of Puu Makua. The lava flowed down Puu Makua and divided at a small ridge northwest of Keonehunehune. One lobe flowed west and out of the map area, the other flowed southwest, ponding in the central crater of Keonehunehune and eventually flowing down the southeast slope. The surface is very rough, clinkery aa, with small spinose clinker. It is of undetermined thickness where it is ponded and less than 2 meters elsewhere. The contact with the cinder over which it lies is striking in its contrast; the flow is black, and the only vegetation on the flow is moss, lichen, and a single scraggle ohia tree. The adjacent cinder is overgrown with bright green grass up to one meter high. The vent appears to have been the site of several eruptions, but the lava flows of all but the latest have been buried except at the vent, higher on the same fissure.

The stratigraphic relationship between the Makuamauka amd Makuamakai lavas cannot be determined by superposition, although it is obvious that they both postdate Kamana lavas. Climatic conditions are similar for the two flows; Makuamakai probably gets a little more rain, but it is much less weathered than the Maukamahoe flow, 550 meters lower in elevation on the rift. Based on degree of weathering Makuamakai is stratigraphically above both Makuamauka and Maukamahoe, and may be nearly contemporaneous with the Kanahena and Kalua o' Lapa lavas. There is, however, no record of an eruption that high on the rift in Hawaiian legend and it is unlikely that it would go unnoticed, although the flow cannot be seen except from a few locations, and the eruption appears to have been a relatively quiet one. Good absolute age determinations should shed more light on this question. For this work, Makuamakai is assigned a date earlier than Kanahena but later than Maukamahoe and Makuamauka.

Sample 9-1, from Makuamakai, is an alkalic olivine basalt and contains abundant phenocrysts to microphenocrysts of labradorite with lesser magnetite and olivine in a partly glassy groundmass of labradorite (?), magnetite, and olivine. No pyroxene was found, either in the groundmass or as phenocrysts, but the groundmass is extremely fine-grained, about 0.004 mm. The glass is slightly anisotropic in places and may be slightly devitrified. The lava contains an unusually high modal amount of magnetite (25% total, 35% in groundmass) and little resembles other samples collected within the map area. The chemical analysis with calculated norm is shown in Table 5.

Pimoe Formation

The Pimoe Formation is a complex series of lava flows, spatter, cinder, and ash, and includes lava flows from Pimoe and Pohakea cones. Pohakea cone is buried by Kanaionui lavas except for the westernmost peak of what was formerly a crescentic cinder cone, and it may properly belong to the

Kula Series. No samples were collected from Pohakea for study.

Pimoe lavas were erupted from the center of Pimoe cone in a complex series of eruptions widely separated in time. A spatter rampart up to 30 meters high at the eastern margin of the flow extends southward to Pohakea, and served as a barrier to divert later flows, and probably prevented the complete burial of Pohakea. At least four different flows from the Pimoe vents are visible, but the latest of them, the Pimoekai flow, very nearly buried the others except near the vent. The surface of Pimoekai lava is extremely rugged, with large, spinose aa clinker and numerous ridges, lava channels, spatter ramparts and pinnacles. The flows total at least 15 meters thick where they are exposed in sea cliffs; Pimoekai lava is 5 to 6 meters of the total.

The stratigraphic position of the most recent flow cannot be determined accurately because of the lack of superposition with other formations and the slow weathering rate. It overlies Kaimaloo lava to the southwest of Pimoe and probably postdates, or is contemporaneous with, the cinder which overlies the Kaimaloo lava along the highway. The same cinder is not present on Hanamanioa lavas to the west of Pimoe, and thus establishes a time succession.

Sample 5F8, from Pimoekai lava, is similar to a sample from the Pimoe flow analyzed in the mode by Macdonald (Stearns and Macdonald, 1942, p. 302). The chemical analysis is given in Table 5. It is an alkalic olivine basalt containing abundant laths of labradorite up to 0.1 x 0.01 mm grading into an unresolvable intergranular to intersertal groundmass of pale to light brown clinopyroxene and labradorite(?) with accessory olivine and magnetite. Groundmass andesine was not recognized. Microphenocrysts are labradorite laths, light brown titanaugite with $2V_z = 60^o$ and strong dispersion $r > v$, equant subhedral to euhedral grains of colorless olivine, and a few angular magnetite grains.

Kaloi Formation

The Kaloi Formation is a series of recent lavas exposed near the center of the map area from sea level to the central rift. The rocks are dark grey to black and contain varying amounts of phenocrysts of olivine and clinopyroxene. They are alkalic olivine basalts, with the exception of the Hanamanioa lava, which is picrite basalt. The flows were all erupted from either the Keonehunehune or Kaimaloo vents. Outcrops are well exposed, but the surface appearance of the flows changes from source to terminus because of climatic differences. Near the coast all flows are remarkably unweathered, with only subtle differences in surface color to distinguish one from another.

The lava exposed to the east of Kamanamana Peninsula consists of several thin flows of both pahoehoe and aa. It is covered by later Kaloi lavas except at the coast and in a kipuka north of Kamanamana Peninsula. It is a rather feldspar-poor alkalic olivine basalt containing phenocrysts of olivine. It is assigned to the Kaloi lavas rather than those of Makua because of petrographic similarities to other Kaloi lavas.

The Kaimaloo lavas were erupted from Kaimaloo cone at a late stage in its history. The flow, which is at least 10 meters thick, formed Kamanamana Peninsula. It is aa through its entire length, but the surficial clinker has been weathered away at the higher elevations. Near the vent the lava is mantled by a thin layer of cinder probably erupted from the same vent. A lava channel 10 meters wide, 3 meters deep and 300 meters long extending from the vent contains thick colluvial soil and high grass with a few outcroppings of lava. Near Piilani Highway the flow is obscured by cinder from Pimoe and by complex surface relationships with the Keonehunehune and Hanamanioa lavas. Chemical (Table 5) and modal (Table 4) analysis, and the petrographic character of samples 3A5 and 4-6 indicate that the lava of Kamanamana Peninsula is the same as that from Kaimaloo. Near sea level the surface consists of spinose aa clinker fragments up to several meters in diameter, and averaging more than 40 centimeters. Spatter pinnacles stand 3 to 20 meters high. The eastern lobe at Kamanamana Peninsula is 15 meters thick where the flow stopped just short of the sea and overlies loosely consolidated calcareous sand.

Sample 3A5 is an alkalic olivine basalt containing phenocrysts of labradorite, olivine, and magnetite in a fine groundmass of labradorite laths, intergranular clinopyroxene, several percent of magnetite, and a trace of olivine. A single subhedral crystal of oxyhornblende 10 x 3 mm is described in the section on petrography. No oxyhornblende was found in other specimens of Kaimaloo lavas. Samples 5G1, 4-6, and 11-7 are virtually identical both in hand specimen and in thin section, although 4-6 was collected 6.7 kilometers from 3A5.

The Hanamanioa lava is picrite basalt with phenocrysts of olivine and titanaugite with $2V_z = 55^{\circ}$, in a fine groundmass of clinopyroxene, labradorite, magnetite, and olivine. The feldspar laths are intersertal with the clinopyroxene and range in size from 0.004 x 0.02 mm to large microlites. Groundmass pyroxene is pale brown and largely unresolvable, but is without doubt monoclinic. The titanaugite phenocrysts are concentrically zoned with up to 36° difference in extinction angles. They are light brown with purple edges. The olivine is rarely euhedral and generally equant. Some olivine crystals contain hourglass-shaped magnetite grains as cores. The hourglass shape is probably due to the attitude of the section, as other grains contain square magnetite grains.

The source of the Hanamanioa lavas is a fissure high on the southwest slope of Keonehunehune, from a vent which is co-linear with the source of Keonehunehune lavas. It is covered by a thin cinder mantle, probably from Kaimaloo, between Kulanapahu and Kaimaloo. Where it exists, this cinder cover defines the contact with Keonehunehune lavas.

where the flow crosses Piilani Highway the contact is marked by a change in the density and size of koahaole. Below 100 meters elevation the two flows are delineated by a sharp contact, a more weathered surface, and differences in surface texture. The surface of the Hanamanioa flow is blocky and spinose, but less so than that of the Kaimaloo flow, with blocks three or more meters in diameter. A pinnacled ridge 15 meters high at about 60 meters elevation diverted later Keonehunehune lavas and protected a small kipuka of older aa which has not been correlated with any other lava.

The Keonehunehune lavas were erupted from a series of vents cutting the southwest flank of Keonehunehune cone. The main vent is 30 meters deep with an asymmetrical spatter cone-rampart. It is the southernmost of, and nearly contemporaneous with, other vents on a line trending N50^{o}E for about 750 meters, roughly co-linear with the fissures of the Makua vents. Just north of a line from Kulanapahu to Kaimaloo the lava is ponded to a thickness of about 10 meters. Southeast of Waiokawa the lava is covered by a thin layer of cinder. A small lobe, 25 meters wide, extends 1.2 km down the north side of Kulanapahu. The more voluminous portion of the lava flowed southwestward over Hanamanioa lavas and near Cape Hanamanioa was diverted towards La Perouse Bay by a high portion of the Hanamanioa lava. Another small lobe flowed towards Hanamanioa lighthouse over Hanamanioa lavas, but stopped 800 m short of the sea.

It appears that several small flows were erupted in rapid succession from the same vent, or nearly contemporaneously from several closely-spaced vents. No field evidence was found to indicate that the flows are composite. A lava channel in a collapsed lava tube near 30 meters elevation exposes 10 to 15 thin pahoehoe flow units in the side of the channel. Many small kipukas of differing degrees of weathering and vegetation, as well as the spatial relationships of recent-appearing pahoehoe and aa suggest the complexity of eruptive history. Most of the features are too small to be shown on Plate 1.

The aa surface is rough, spinose clinker with fragments 3 to 30 centimeters in diameter. The pahoehoe surfaces are ropy and generally more weathered than the aa with small patches of light-yellow-brown grasses beginning to take a foothold.

Sample 8-2, from near the vent, is an alkalic olivine basalt transitional to picrite basalt with phenocrysts and microphenocrysts of pale brown subhedral to euhedral titanaugite, lath-shaped labradorite, colorless subhedral olivine, and a few crystals of sub-angular magnetite. The groundmass is fine-grained, usually about 0.05 mm, and intergranular. It is light to medium brown, due to titanium in the pyroxene, and brown glass. Labradorite laths are partly enclosed by pyroxenes. Olivine and magnetite occur in small quantities in the groundmass.

The Waiokawa lava was erupted from two small spatter cones 500 meters south of Waiokawa. The spatter cones are each 3 meters high and have weathered surfaces. The flow is small, about 0.03 km^2. It is younger than the Keonehunehune lavas since the latter are covered by cinder, presumably from the same eruption that built the spatter cones. Extensive bulldozing has obliterated the contacts but exposed the cinder, which is small in aerial extent. Keonehunehune lavas support ohia trees, while the Waiokawa lava is unvegetated except for moss, lichens, and small bushes.

Sample 2G4 is a mafic picrite basalt composed of titanaugite microphenocrysts in a fine groundmass of pale brown titanaugite, lesser plagioclase and small amounts of olivine and magnetite. The microphenocrysts are both concentrically and hourglass zoned and show strong inclined dispersion. The titanaugite often occurs as glomerocrysts, sometimes surrounding a grain of magnetite.

Mahoe Formation

The Mahoe Formation is a series of several flows of both pahoehoe and aa. It is of undetermined thickness, with the surface slightly weathered but with surface textures generally preserved although partly obscured by koahaole and low grasses. The rocks are slightly vesicular, dark grey, olivine and titanaugite-bearing picrite basalts with lesser amounts of alkalic olivine basalt erupted from Puu Mahoe, Puu Naio(?), hill 1369 (herin called Puu Kalihi), and hill

2229 (herein called Puu Papaka).

The lavas exposed along the coast at La Perouse Bay appear to be the oldest, based on the degree of weathering and vegetation. Their source is unknown. The Kalihi lavas, erupted from Puu Kalihi, may overlap the Mahiehie lavas in time. The two most recent Kalihi lavas were erupted nearly contemporaneously from vents separated by approximately 300 meters. Both flows are mantled by a thin veneer of soil and cinder a few centimeters to 1 meter thick. A lava channel 75 meters wide with spatter ramparts a few meters high can be seen both in the field and in aerial photographs. Sample 7-5 is a picrite basalt containing abundant phenocrysts of titanaugite with $2V_z$ of 60^o, microphenocrysts and phenocrysts of sodic labradorite and lesser amounts of olivine in a fine-grained interstitial to intergranular groundmass of clinopyroxene and plagioclase, with accessory olivine and magnetite. Sample 7-6 is virtually identical. The contact between the two flows is not apparent in the field and was inferred from aerial photographs.

A small flow erupted from the south central portion of Puu Naio is the only evidence of recent activity of the cone. The flow is pahoehoe near the vent, but all that remains is a small lava channel a few meters wide and equally deep, with a spatter rampart about 1 meter high on either side. Sample 7-1, collected from the spatter rampart, is glassy with a few microphenocrysts of labradorite and titanaugite. Sample 7-2 from 450 meters to the south is an alkalic olivine basalt which closely resembles Mahiehie lavas with a few more labradorite microphenocrysts, a matrix of more variable texture and iddingsite rims on the olivine phenocrysts. It contains a small amount of pale brown glass with a refractive index of 1.55. It is not certain whether 7-2 is from Puu Naio or represents older Mahoe lavas. The lower contact with the Mahiehie lavas, as well as lateral contacts, could not be located in the field.

The lavas from Puu Papaka were erupted from a vent just east of radiotelephone tower 2229. It is pahoehoe near the vent and changes to aa downslope. Its maximum thickness is less than one meter. In hand specimen the lava is similar to Mahiehie lavas, but with fewer and smaller phenocrysts. The Papaka lava represents a late-stage eruption from a dissected cinder cone, the center of which is now occupied by Puu Mahoe.

The Mahiehie lavas are a thick series of flows, the latest of which was erupted from the southwest center of Puu Mahoe. Near the vent it is mantled with a thin soil and pasture grass. The top clinker zone has been weathered away, leaving dense, dark grey outcrops. Several outcrops are exposed where the flows cross Piilani Highway, but generally it is vegetated with low density koahaole and lesser kiawe. One roadcut reveals superposition above

Papaka lava. The western contact with Papaka lava is well exposed just south of the highway where it turns northward around Puu Mahoe. A change in topography in aerial photographs implies the location of several contacts with older Mahiehie lavas. The eastern contact with Kaloi lavas is marked by a sharp change in the density of vegetation. The latest of the flows is seen to have been constricted when it flowed between Puu Naio and Puu Kalihi.

Sample 7-3 is an alkalic olivine basalt containing abundant microphenocrysts of labradorite and phenocrysts of tatanaugite and lesser olivine in a fine-grained intergranular to intersertal groundmass of labradorite and clinopyroxene with accessory magnetite and olivine. Sample 11-1, from nearer the vent, is similar to 7-3 but has a finer groundmass with less plagioclase and glomerocrysts of poikilitic plagioclase, titanaugite and magnetite.

Keoneoio Formation

The Keoneoio Formation includes the 1790(?) flow(s) (Stearns and Macdonald, 1942, p. 102-107) and one other, which were erupted from three nearly co-linear vents bearing S50^{o}W. The rocks are picrite basalts and are virtually identical in hand specimen and very similar in thin section.

The Maukamahoe lava was erupted from a small fissure trending slightly south of due west at the north base of Puu Mahoe. The eruption built a small spatter rampart at the vent. The flow is aa its entire length and has a rather uniform thickness of less than 2 meters. The lava flowed west-northwest for about 700 meters around the base of Puu Mahoe, then turned southwestward. It is completely covered by Kanahena lava 700 meters southwest of Piilani Highway. Near the vent the vegetation on the flow is limited to moss and lichen but below the highway it is partly covered by low-density koahaole and young eucalyptus trees.

Sample 8-3, from near the vent, is a picrite basalt with concentrically zoned pheoncrysts of titanaugite with $Z \wedge C = 44$ to 50^{o} and a $2V_{z}$ of 55^{o}, showing strong dispersion, along with a few olivine phenocrysts and microphenocrysts of labradorite, in a partly glassy, mostly intergranular groundmass of clinopyroxene, labradorite, and magnetite. The titanaugite phenocrysts often occur as glomerocrysts enclosing magnetite grains. Sample 8-1, collected just below the highway, contains more glass and has a finer groundmass, but is virtually identical otherwise.

The Kanahena lava was erupted from a vent 700 meters below the highway at an altitude of about 400 meters from a fissure trending S65^{o}W. It is the upper vent of the 1790(?) lavas mapped by Stearns and Macdonald (1942, Pl. 1). In hand specimen it is dark and moderately vesicular with numerous phenocrysts of pyroxene and olivine. Near the vent it is transitional from pahoehoe to aa and changes to the latter downflow. The flow is a little more than 1 meter thick at the coastal terminus. Its stratigraphic position overlying the Maukamahoe and under the Kalua o' Lapa lava is obvious at the contacts. The surface is slightly less weathered than that of the Maukamahoe flow near the contact with the latter and the vegetation is much less dense. The flow is well exposed along its entire length and the flow margins are well delineated because of the relative freshness of the surface.

Sample 5-1 is very similar in the mode to other Keoneoio lavas, but contains a little more olivine and a little less pyroxene than the Maukamahoe lava, and is coarser grained. The titanaugite phenocrysts show reaction rims with magnetite pseudomorphs. Sample 7-7 contains a little glass, is finer grained, and shows a wider variation between the size of the labradorite laths and the groundmass pyroxene. The labradorite laths are similar in size to those in sample 5-1, but the groundmass pyroxenes are much smaller.

The Kalua o' Lapa lava was erupted from a spatter cone at about 170 meters elevation, from which it gets its name. The cone is about 50 meters high with a central fissure trending S55^{o}W. The lava is pahoehoe transitional to aa near the vent, and is aa downflow. It is similar in appearance and thickness to the Kanahena lava. The two flows can barely be distinguished where the Kihei Road crosses the contact 2.4 kilometers northwest of Keoneoio. The lava diverged at Puu o' Kanaloa and left a kipuka southwest of the hill. The lava has been analyzed modally (Stearns and

Macdonald, 1942, p. 302), and chemically (Macdonald and Katsura, 1964, Table 7, spec. 8. The lava was analyzed earlier by Washington and Merwin, 1928). A chemical analysis (#C-129) is included in Table 5. It is similar to other Keoneoio lavas but contains less augite and more olivine. The olivine phenocrysts are larger and more munerous, and olivine is less abundant in the groundmass.

Stearns (Stearns and Macdonald, 1942, p. 103) cites evidence that the two flows (Kalua o' Lapa and Kanahena) are nearly contemporaneous, a feature common with Hawaiian eruptions. No evidence from this work directly refutes that conclusion, but there is a noticeable difference in the degree of weathering and vegetation, which may be accountable by other factors. It is likely that the Maukamahoe lava is not contemporaneous with the others, as it is much more weathered. The eruptions may be separated by a few hundred years.

Pyroclastic Rocks

The approximate distribution of pyroclastic rocks is shown in Plate 1. Above Luapelani pyroclastics form a nearly continuous blanket 3 to 4 kilometers wide extending out of the map area to the northeast and west. Several small cuts along the rift reveal cinder up to 2 meters thick with up to 1 meter of soil on top. The cinder encountered at various locations on traverses of the middle portion of the rift is indistinguishable from a sample (3B4) collected 500 meters north of Maunanu. 3B4 is slightly weathered, dark brown to black cinder and Pele's tears typically 1 centimeter in length. The glass has a refractive index of 1.62 and contains microphenocrysts of olivine, labradorite laths and a little clinopyroxene. A series of roadcuts on the side of Puu Mahoe reveal a sequence 25 meters thick consisting of several layers of cinder representing several eruptions.

Several of the pyroclastic cones have no visible associated lava flows, but their crescent shapes suggest that flows may have been covered by subsequent pyroclastics. On the aerial photographs, traces of the surface texture of underlying lava adjacent to the cones can be seen clearly, but contacts and lava channels can be followed only for short distances. The outlines of several buried crescentic cinder cones can be inferred from the topography in the vicinity of Keonehelu. Puu Kaeo, just out of the map area to the northwest, is one such, possibly a cone of the Kula Volcanic Series. Puu Ouli, southeast of Puu Makua, was mapped by Stearns and Macdonald (1942, Pl. 1) as belonging to the Kula Series.

Sand

Most lava flows which entered the sea are not sufficiently eroded at the shoreline to have allowed for extensive beach development. A few small sand pockets in embayments or shoreward of kipukas are the only beaches observed. They are too small to be shown in Plate 1. The largest of them is

Table 3. Pyroclastic Stratigraphy Exposed in Roadcuts in the Side of Puu Mahoe

Description	Thickness (meters)
PAHOEHOE (Source of Sample 11-2)	0.3 - 1.5
Altered, layered red-brown cinder	2.0
Unlayered black cinder	6.0
Unlayered brown cinder yielding a goethite-colored streak	4.5
Alternating black-brown layers of cinder each a few centimeters thick	3.0
Thin brown soil	0.02
Alternating red-black cinder in layers each about 60 cm thick	8.5

at La Perouse Bay, where the sand is clastic, biogenic, calcareous, and medium to fine-grained. It contains some olivine and augite, small amounts of other dark mineral grains, and smaller amounts of clay and limonite. The sand varies in thickness from a thin veneer to dunes a few meters high near the eastern contact of the Kalua o' Lapa lava. Another small beach seaward of the easternmost lobe of the Kaimaloo aa at Kamanamana Bay is overlain by the aa. Several small, arcuate sandpockets are scattered along the coastline.

Beachrock

At La Perouse and Kamanamana Bays, and at several other locations along the coast, the intertidal zone is a pitted, irregular bench of beachrock 1 meter thick sloping from about 1 meter above low water to low water. The rock is an easily friable conglomerate comprising wave-rounded basalt pebbles and shell fragments. The cement is grey and slimy and supports a community of unidentified worms and snails.

Petrography

Twenty-four thin sections were examined in detail, including at least one specimen from each mapped unit. In some instances two or more specimens from different locations within the same flow were compared for textural and mineralogical variations. The names of textures follows the usage of Moorhouse (1959). Modes are given in Table 4. The rocks were classified on the basis of amounts of feldspar, pyroxene, and olivine in the mode as suggested by Macdonald

Table 4. Point Count Modes of Rocks of the Lower Southwest Rift

SAMPLE	4G5	5-1	8-3	9-1
FORMATION Member	KEONEOIO Kalua o' Lapa	KEONEOIO Kanahena	KEONEOIO Maukamahoe	MAKUA Makuamakai
ROCK NAME	Picrite Basalt	Picrite Basalt	Picrite Basalt	Alkalic Olivine Basalt
MODE				
Phenocrysts				
Plagioclase	2	-	1	34
Clinopyroxene	17	18	47	-
Olivine	21	12	2	2
Iron Ore	tr	-	-	4
Glass	-	-	-	-
Groundmass				
Plagioclase	19	25	18	27
Clinopyroxene	32	35	19	tr.
Olivine	3	3	1	9
Iron Ore	6	7	11	18
Glass	tr	tr	2	6

Table 4 (continued). Modes of Rocks of the Lower Southwest Rift

SAMPLE	10-1	5F8	2G4	8-2
FORMATION Member	MAKUA Makuamauka	PIMOE Pimoekai	KALOI Waiokawa	KALOI Keonehunehune
ROCK NAME	Picrite Basalt	Alkalic Olivine Basalt	Picrite Basalt	Alkalic Olivine Basalt
MODE				
Phenocrysts				
Plagioclase	2	21	-	16
Clinopyroxene	8	2	10	20
Olivine	5	12	-	2
Iron Ore	1	tr	-	2
Glass	-	-	-	-
Groundmass				
Plagioclase	21	26	22	15
Clinopyroxene	47	26	63	27
Olivine	4	4	1	3
Iron Ore	13	8	4	6
Glass	-	1	-	9

Table 4 (continued). Modes of Rocks of the Lower Southwest Rift

SAMPLE	5E7	3A5	4-7	7-3
FORMATION Member	KALOI Hanamanioa	KALOI Kaimaloo	KALOI Kamamana	MAHOE Mahiehie
ROCK NAME	Picrite Basalt	Alkalic Olivine Basalt	Alkalic Olivine Basalt	Alkalic Olivine Basalt
MODE				
Phenocrysts				
Plagioclase	-	36	20	18
Clinopyroxene	5	-	-	6
Olivine	10	7	20	2
Iron Ore	-	2	-	-
Glass	-	-	-	-
Groundmass				
Plagioclase	17	28	18	21
Clinopyroxene	51	16	30	39
Olivine	tr	tr	-	6
Iron Ore	13	11	12	8
Glass	4	tr	tr	tr

Table 4 (continued). Modes of Rocks of the Lower Southwest Rift

SAMPLE	5E72	7-2	7-5	4-1
FORMATION Member	MAHOE Mahiehie	MAHOE Mahiehie	MAHOE Kalihi	MAHOE Earlier lava
ROCK NAME	Picrite Basalt	Alkalic Olivine Basalt	Picrite Basalt	Picrite Basalt
MODE				
Phenocrysts				
Plagioclase	13	20	15	8
Clinopyroxene	2	20	19	11
Olivine	1	5	4	12
Iron Ore	-	-	-	-
Glass	-	-	-	-
Groundmass				
Plagioclase	17	17	13	11
Clinopyroxene	43	21	36	42
Olivine	-	3	tr	3
Iron Ore	17	14	13	11
Glass	8	tr	tr	3

Table 4 (continued). Modes of Rocks of the Lower Southwest Rift

SAMPLE	11-4	4-8	11-3	11-5
FORMATION Member	MAKUA Kanaionui	MAKUA Kamana	MAKUA Leia	MAKUA Kamana
ROCK NAME	Alkalic Basalt	Picrite Basalt	Alkalic Olivine Basalt	Picrite Basalt
MODE				
Phenocrysts				
Plagioclase	-	20	42	13
Clinopyroxene	-	-	-	-
Olivine	-	5	8	17
Iron Ore	-	-	-	-
Groundmass				
Plagioclase	50	9	12	13
Clinopyroxene	30	31	31	33
Olivine	3	1	1	2
Glass	5	8	tr	4
Iron Ore	12	26	6	18

Table 4 (continued). Modes of Rocks of the Lower Southwest Rift

SAMPLE	9-2	11-6	10-2	11-2
FORMATION Member	MAKUA Kamana	MAKUA Wana	MAKUA Wana	MAHOE Papaka
ROCK NAME	Alkalic Olivine Basalt	Alkalic Olivine Basalt	Picrite Basalt	Picrite Basalt
MODE				
Phenocrysts				
Plagioclase	20	23	8	-
Clinopyroxene	6	4	-	17
Olivine	14	9	11	3
Iron Ore	-	-	1	-
Glass	-	-	tr	-
Groundmass				
Plagioclase	27	26	12	24
Clinopyroxene	18	26	20	40
Olivine	tr	tr	-	tr
Iron Ore	15	10	8	8
Glass	tr	3	40	8

and Katsura (1964):

Alkalic Olivine Basalt--more than 30% total feldspar, more than 5% olivine.

Alkalic Basalt--more than 30% total feldspar, less than 5% olivine.

Picrite Basalt--less than 30% total feldspar. Ankaramite if abundant phenocrysts of both augite and olivine.

Establishing whether a particular lava is alkalic or tholeiitic in the mode is difficult, but the presence of a purplish clinopyroxene with a high $2V_z$, strong inclined dispersion, and high extinction angles allows those rocks studied here to be assigned unhesitantly to the alkalic suite (Macdonald and Katsura, 1964, p. 90). A plot of alkali against silica (Figure 3) supports this.

As a group, the rocks show a relatively small range of variation both in modal composition and in texture. All are fine-grained, with groundmasses ranging from unresolvable to an average grain size of 0.1 millimeters, typically from 0.004 to 0.06 millimeters. Some are truly porphyritic. The Mahoe and Keoneoio lavas all contain phenocrysts of pyroxene and olivine up to 5 millimeters long, and are considered transitional to ankaramite. Others are microporphyritic with microphenocrysts of olivine, titanaugite, or plagioclase.

Plagioclase

Most of the specimens contain plagioclase both in the matrix and as microphenocrysts. Interstitial plagioclase grains are typically 0.004 millimeters or smaller, generally anhedral (although largely unresolvable), and can be distinguished from pyroxene by their low birefringence, low to moderate relief and lack of color. Phenocrysts and microphenocrysts are lath-shaped to platy, average about ten times longer than wide and typically range from 0.04 x 0.004 to 0.4 x 0.04 millimeters. In a few specimens the plagioclase varies through the entire size range, but in most the range is small or bimodal.

Albite, Carlsbad, and pericline twinning are common. Twinning is complex, and all three may be present within a single lath. Flow deformation of twin lamellae is common, to a small degree. Some of the platier crystals show a small degree of poorly defined normal zoning.

Compositions of plagioclase were determined by various methods, including the Michel-Levy statistical method (Heinrich, 1965, p. 360), when appropriately oriented albite twins were recognized. Where twin planes were obscured, or not present, the beta refractive index was approximated by comparing the index of randomly oriented grains with that of oils. Where interference figures could be found the optic axial angle was determined by the Kamb method (Bloss, 1961, p. 180) and the values compared with compositional curves in Heinrich (1965, p. 358). The latter method is less accurate than the other two and was used only as a cross-check.

In all the samples studied the feldspar is labradorite. Several samples contain sodic labradorite and one (11-6) contains microphenocrysts of calcic labradorite. The range of composition is An_{53} to An_{65}. Interstitial andesine, as reported by Macdonald (Stearns and Macdonald, 1942, p. 302) was not observed. The laths are generally randomly oriented in thin section, but sample 11-4, a nonporphyritic alkalic basalt, has a tendency toward a poorly defined flow structure.

Pyroxenes

The pyroxene in all samples is augite, occurring both in the groundmass and as phenocrysts or microphenocrysts of purplish-brown titanaugite. As phenocrysts it is subhedral to euhedral, with a majority of grains showing rims of dusty magnetite inclusions. Glomerocrysts are uncommon, but where present enclose magnetite or plagioclase. Phenocrysts and microphenocrysts range from 0.01 to greater than 3 millimeters in length. They are notably absent from the Kamana, Wana and Leia lavas and the two lower Kaloi lavas. In the groundmass the pyroxene grains are small, usually less than 0.01 millimeters long and interstitial to intersertal to subophitic in relation to plagioclase. Sample 10-2 contains augite as unoriented microlites in glass.

Many augites are slightly pleochroic, pale purple-brown to yellow-brown; the purple is the fast ray. The optic axial angle (2V) is as high as 63° and is usually 55 to 60°. Extinction angles, measured from flash figures, show $\gamma \wedge C$ as high as 58° in sample 7-2, but it is usually around 45 to 50°. Most phenocrysts are zoned, either concentrically or in an hourglass structure, with the extinction angle varying as much as 36° on the concentrically zoned crystals. Purple tint, high 2V, large extinction angles, and hourglass aoning are probably due to titanium cation substitution (Heinrich, 1965, p. 217), and are common in the pyroxenes of the alkalic suite of Hawaiian lavas (Macdonald and Powers, 1968, p. 878).

Olivine

Olivine is found in all specimens, the grains ranging from 0.08 to greater than 3 millimeters long. It is colorless with a 2V very close to 90^{o}, and a beta refractive index of 1.69, corresponding to Fo_{88} (Heinrich, 1965, p. 145). It occurs mainly as elongate to equant, subhedral to euhedral crystals which may be slightly embayed. Many crystals contain magnetite grains as cores and have rims of dusty magnetite pseudomorphs. In a few samples the magnetite dust had completely pseudomorphed an euhedral olivine form. Groundmass olivine is common, and in many cases appears to be remnants of resorbed phenocrysts, a feature more common in tholeiites than in alkalic basalts (Macdonald and Katsura, 1964, p. 91). The crystals are fresh in appearance, with the exception of sample 7-2 in which the phenocrysts have iddingsite rims. A few crystals are unbroken, but most are fractured and have adjacent sections displaced along the fractures.

Magnetite

Magnetite is common in all the lavas. It is present in the groundmass as dust or as small crystals, as square, euhedral microphenocrysts up to 0.2 millimeters across, and as angular to herring-bone microphenocrysts of about the same size. It occasionally is included in glomerocrysts of titanaugite and occurs as dusty inclusions in olivine, titanaugite, and plagioclase.

Amphibole

A single crystal of oxyhornblende 10 by 3 millimeters in size was found in sample 3A5. In thin section it is elliptical in outline, with magnetite inclusions in a rim about 0.04 millimeters wide. Cleavage traces forming angles of 56° and 124° are obvious. It is pleochroic with α yellow to pale brown, γ dark brown to black. Dispersion is $r > v$ moderate. Refractive indices, determined by immersion methods are: $\alpha = 1.685$, $\beta = 1.698$, $\gamma = 1.719$. No oxyhornblende was found in other lavas of the same unit, or anywhere in the map area. It is similar in appearance to basaltic hornblende from near the summit of Haleakala described by Macdonald and Powers (1946, p. 121). The reaction rim on the single crystal, as well as its rarity, suggest it is probably a xenocryst.

Glass

Glass is common but its total volume is small. It is usually in the groundmass and is largely unresolvable with the microscope. In a sample of cinder (3B4) the glass has a refractive index of 1.62, corresponding to a silica percentage of about 47% (George, 1924, p. 365) whereas the glass in sample 10-2, which is more crystalline, has a refractive index of about 1.59, corresponding to about 50% silica, and indicating a slight silica enrichment in the residual liquid during crystallization. The appearance of nepheline in the norms (Table 5) but not in the modes (Table 4) may indicate that the silica deficiency is retained in the glass, or it may be in the pyroxene (Macdonald, 1968, p. 487).

Chemical Analyses

Eight samples were analyzed chemically. The results, with calculated CIPW norms, are shown in Table 5. An analysis of an additional sample collected within the map area (Macdonald and Powers, 1968, table 2 sample 6) is also shown. It (sample C-129) represents the Keoneoio Formation (Kalua o' Lapa lava); sample 9-1 is from the Makuamakai lava; sample 5F8 is from the Pimoekai lava; samples 8-2 and 5E7 are from the Keonehunehune and Hanamanioa lavas of the Kaloi Formation; 3A5 and 4-6 are from source and terminus region of the Kaimaloo lavas; 11-1 is from Mahoe (Mahiehie) lavas; 11-5 is from the Makua (Kamana) Formation. Detailed locality descriptions are given in Table 2.

The analysis was done by X-ray fluorescence quantometer in the Department of Agronomy and Soil Science, College of Tropical Agriculture, University of Hawaii. Recent studies have shown this method to give results comparable in reliability to wet-chemical methods (Gribble, 1974). The analyses are done on an ignition basis, and thus give total iron as Fe_2O_3 and do not give either + or - H_2O. To produce values for FeO and Fe_2O_3 to be used in normative calculations, average FeO/FeO + Fe_2O_3 ratios were determined from pub-

Table 5

Chemical Analyses and Norms of Lavas of the Lower Southwest Rift

	3A5	4-6	5E7	5F8	8-2	9-1	11-1	11-5	C-129
SiO_2	46.36	46.36	42.92	43.98	42.38	47.87	43.35	43.16	42.53
Al_2O_3	16.48	16.54	12.75	14.81	12.27	16.74	14.22	14.60	12.43
Fe_2O_3	4.50	4.50	5.09	4.99	4.99	4.21	5.40	5.51	2.68
FeO	8.94	8.94	10.10	9.92	9.90	8.35	10.71	10.94	11.23
MgO	4.20	4.30	8.18	6.64	8.80	3.41	7.98	6.94	12.17
CaO	8.33	8.26	12.50	10.24	12.62	7.88	11.64	10.70	11.80
Na_2O	5.27	5.19	3.41	3.97	3.27	5.47	3.04	3.47	2.35
K_2O	1.79	1.69	1.70	1.29	1.14	1.82	0.84	1.04	0.81
TiO_2	3.03	3.04	3.54	3.18	3.52	2.62	3.31	3.59	2.92
P_2O_5	0.93	1.12	0.56	0.63	0.54	1.01	0.47	0.50	0.55
MnO	0.20	0.19	0.18	0.18	0.17	0.21	0.17	0.18	0.16
	100.03	100.13	100.45	99.84	100.59	99.60	101.15	100.64	99.63

Norms (CIPW)

		3A5	4-6	5E7	5F8	8-2	9-1	11-1	11-5	C-129
or		10.57	10.02	6.67	6.07	6.68	10.57	4.95	6.12	5.00
ab		24.38	27.79	6.29	14.68	5.24	30.41	12.53	13.80	5.24
an		16.02	16.97	15.85	18.91	15.30	15.85	22.81	21.14	20.89
ne		10.94	8.52	12.20	10.22	12.22	8.52	7.13	8.38	7.95
di	wo	8.03	6.97	17.70	11.70	18.20	6.79	13.35	12.19	14.27
	en	2.87	3.81	11.50	7.13	12.00	3.50	8.31	7.32	9.10
	fs	5.35	2.90	5.01	3.95	4.75	3.29	4.24	4.08	4.22
ol	fo	2.10	4.85	6.19	6.61	6.89	3.51	8.14	6.97	14.91
	fa	5.34	3.97	3.06	4.67	3.06	3.66	4.56	4.48	7.44
mt		6.52	6.48	7.40	7.17	7.17	6.02	7.87	7.87	3.94
il		5.75	5.76	6.67	6.07	6.67	5.00	6.22	6.82	5.47
ap		2.03	2.03	1.24	1.24	1.24	2.17	1.02	0.93	1.34

Table 6

Chemical Analyses and Norms of Lavas of the Hana Series
(After Macdonald and Powers, 1968, Table 2)

	1*	2*	3*	4*	5*
SiO_2	42.81	42.46	41.55	41.46	42.86
Al_2O_3	14.55	12.57	14.13	14.11	16.20
Fe_2O_3	4.92	4.90	3.99	6.05	7.55
FeO	10.94	9.98	11.36	10.22	6.62
MgO	5.66	9.37	6.04	6.74	7.24
CaO	9.96	11.77	11.79	10.56	10.77
Na_2O	3.78	2.96	3.84	3.36	3.19
K_2O	1.54	1.27	1.67	1.33	1.55
TiO_2	3.91	3.08	4.10	4.24	1.84
P_2O_5	0.57	0.45	0.63	0.52	0.56
MnO	0.19	0.17	0.19	0.21	0.19
	99.54	99.42	99.57	99.68	99.54

Norms (CIPW)

		1*	2*	3*	4*	5*
or		8.90	7.78	10.01	7.78	8.90
ab		14.15	5.76	2.10	11.53	12.58
an		18.07	17.24	16.12	19.46	25.30
ne		9.66	10.51	16.47	9.09	7.95
di	wo	11.60	16.01	16.24	12.30	10.21
	en	6.50	10.60	9.00	8.10	7.70
	fs	4.62	4.22	6.60	3.30	1.45
ol	fo	5.39	8.96	4.27	6.09	7.28
	fa	4.08	3.98	3.57	2.96	1.43
mt		7.19	7.19	5.80	8.82	10.90
il		7.45	5.93	7.75	8.06	3.50
ap		1.34	1.01	1.34	1.34	1.34

* Locality descriptions given in Macdonald and Powers (1968)

Table 7

Chemical Analyses and Norms of Lavas of the Kula Series
(After Macdonald and Powers, 1968, Table 1)

	2*	3 *	4*	5*	6*	7*	8*	9 *	10 *	11*
SiO_2	44.72	46.31	51.90	44.76	47.78	45.66	46.00	44.54	44.46	40.51
Al_2O_3	13.86	15.29	17.10	15.22	16.32	17.01	14.48	16.51	13.97	13.80
Fe_2O_3	5.69	4.02	3.38	3.96	6.18	4.96	4.50	2.88	6.14	5.73
FeO	9.82	8.84	6.64	10.34	6.82	7.73	8.85	10.58	8.95	10.30
MgO	5.07	4.86	2.26	5.74	3.96	4.60	4.90	5.64	5.41	6.32
CaO	10.89	9.76	5.70	8.40	7.34	8.09	8.44	8.31	10.28	12.02
Na_2O	3.07	3.72	6.65	3.71	4.00	5.01	4.89	4.46	3.07	3.53
K_2O	1.09	1.47	2.72	1.13	1.41	1.55	1.84	1.57	1.17	1.50
TiO_2	3.96	3.67	2.11	4.63	3.50	3.41	3.63	3.68	4.08	4.15
P_2O_5	0.61	0.74	0.84	0.56	0.71	0.75	0.72	0.62	0.72	0.56
MnO	0.23	0.19	0.17	0.20	0.21	0.20	0.21	0.21	0.20	0.19
	99.74	99.64	100.10	99.63	99.81	99.74	99.61	99.57	99.80	99.50

* Locality descriptions given in Macdonald and Powers (1968)

Norms (CIPW)										
	2	3	4	5	6	7	8	9	10	11
Q	-	-	-	-	0.24	-	-	-	-	-
or	6.67	8.90	16.12	6.67	8.34	8.90	10.56	9.45	7.23	8.90
ab	23.06	25.15	37.73	17.25	34.06	26.20	24.10	18.86	24.63	3.14
an	20.85	20.57	8.90	21.41	22.24	19.46	12.23	20.29	20.57	17.51
ne	1.42	3.41	9.94	2.27	-	8.80	9.37	10.22	0.85	14.20
di wo	12.41	9.74	5.80	6.96	3.94	6.73	10.44	7.19	10.90	16.01
di en	7.50	5.50	2.70	4.20	3.00	4.40	6.30	3.80	7.30	10.10
di fs	4.22	3.83	3.04	2.38	0.53	1.85	3.36	3.17	2.77	4.88
hy en	-	-	--	-	6.90	-	-	-	-	-
hy fs	-	-	-	-	1.32	-	-	-	-	-
ol fo	3.57	4.69	2.03	7.14	-	4.97	4.13	7.21	4.34	3.71
ol fa	2.14	2.86	2.45	4.59	-	2.24	2.65	6.32	1.73	2.14
mt	8.35	5.80	4.87	5.80	9.05	7.19	6.50	4.18	8.82	8.35
il	7.60	5.93	3.95	8.82	6.69	6.54	6.84	6.99	7.75	7.90
ap	1.34	1.68	2.02	1.34	1.68	1.68	1.68	1.34	1.68	1.34

lished wet-chemical analyses of Hana Volcanic Series lavas of similar composition, reproduced here as Table 6. Only 7 analyses were available for comparison. $FeO + Fe_2O_3$ values showed a small range but the ferrous iron to total iron ratio showed a wide range and the calculated value of 0.665 may not be the best for all samples. Since the values ultimately affect normative amounts of Mt, Di, Ol, Hy, Ab, and Ne, future analyses by this method should include an independent wet-chemical determination of FeO and Fe_2O_3.

Discussion of Chemical Analyses

The composition of the Hana Series lavas shown in Table 4 are similar to those given by Macdonald and Powers (1968), and reproduced here as Table 6. The post-caldera and post-erosional lavas of Hawaiian volcanoes are notably richer in alkalis and poorer in silica than the tholeiitic lavas and the two plot in two distinct regions on a graph of total alkalis against silica (Macdonald and Katsura, 1964). A further segregation occurs between the lavas of the Kula Series and those of the Hana Series within the alkalic field. Figure 3 shows plots of both Kula Series and Hana Series lavas shown in Tables 5, 6, and 7. The Hana Series lavas are not generally richer in alkalis, but they are notably poorer in silica than those of the Kula Series, although there is some overlap between the two.

In Figure 4 total alkalis are plotted against lime. The Hana Series lavas are notably richer in lime and poorer in alkalis, although there is again some overlap. In vari-

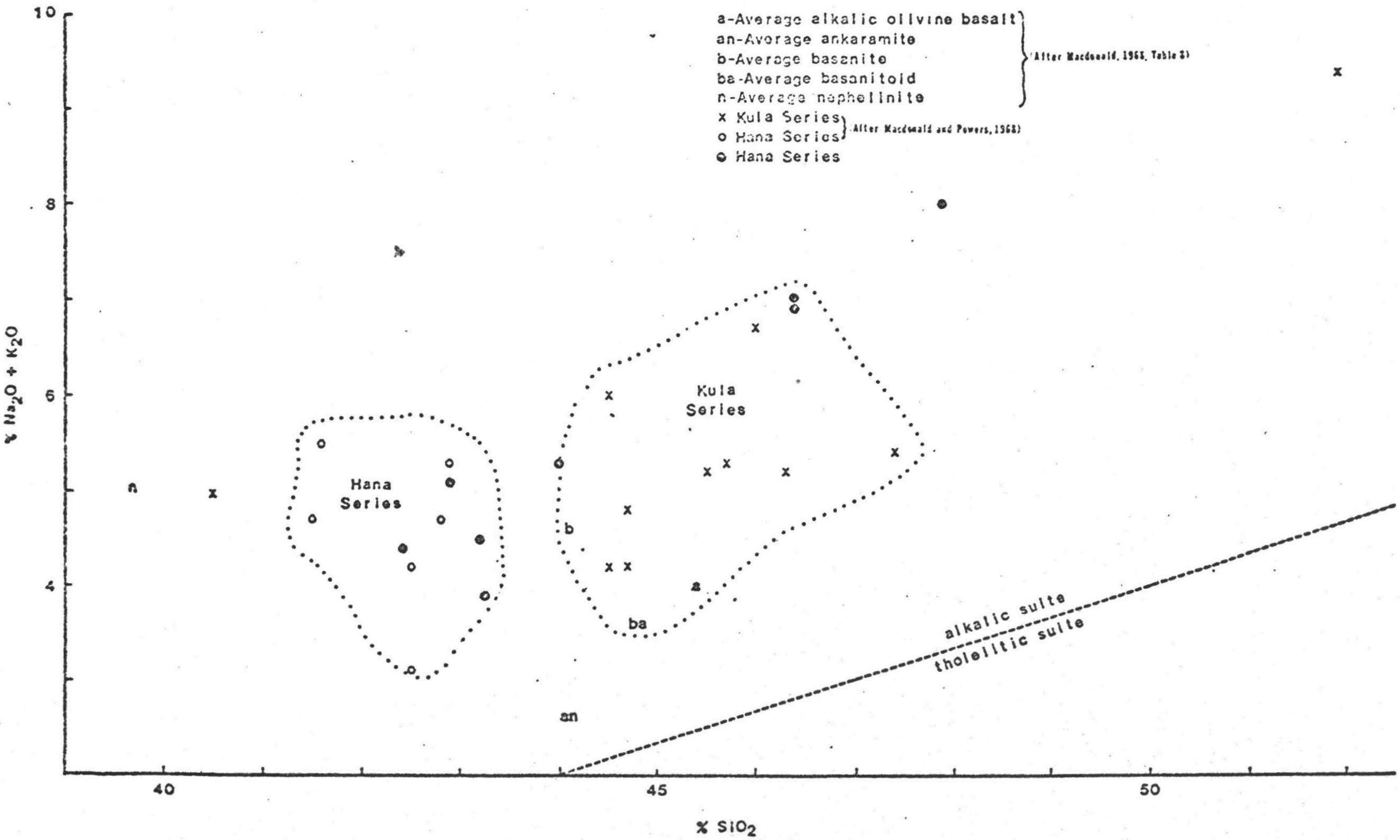

Figure 3. Alkali-Silica Diagram of Some Alkalic Hawaiian Lavas

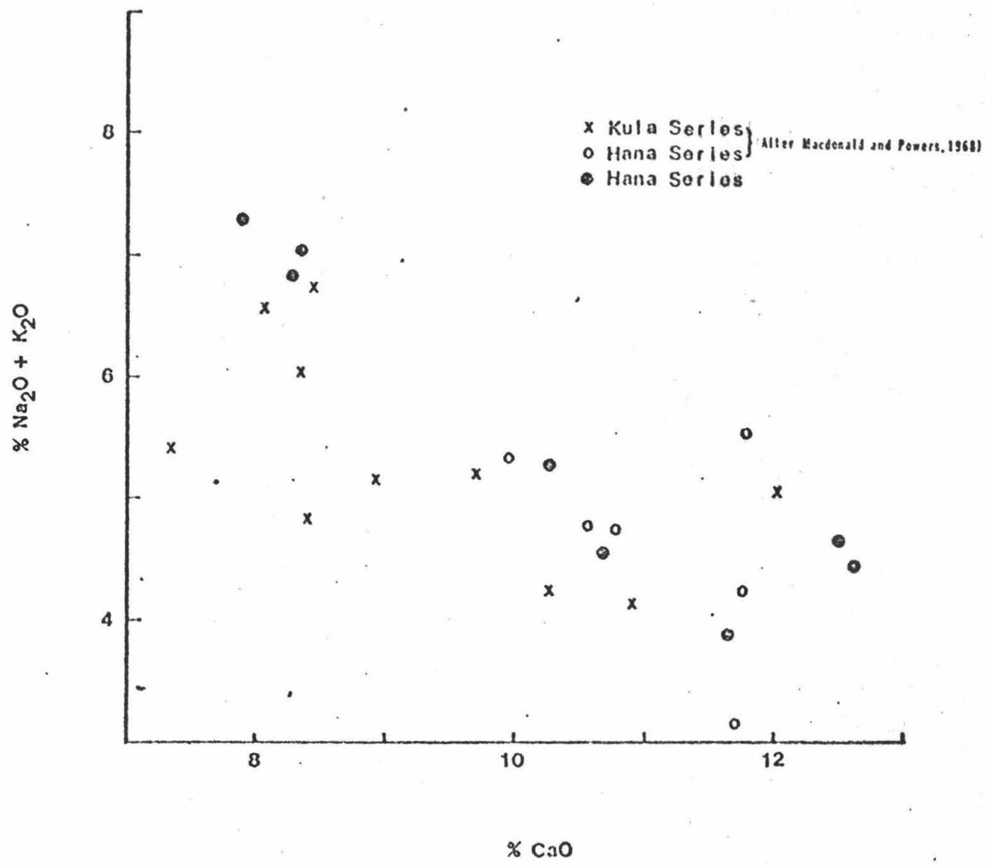

Figure 4. Alkali-Lime Diagram of Late-Stage Lavas of Haleakala

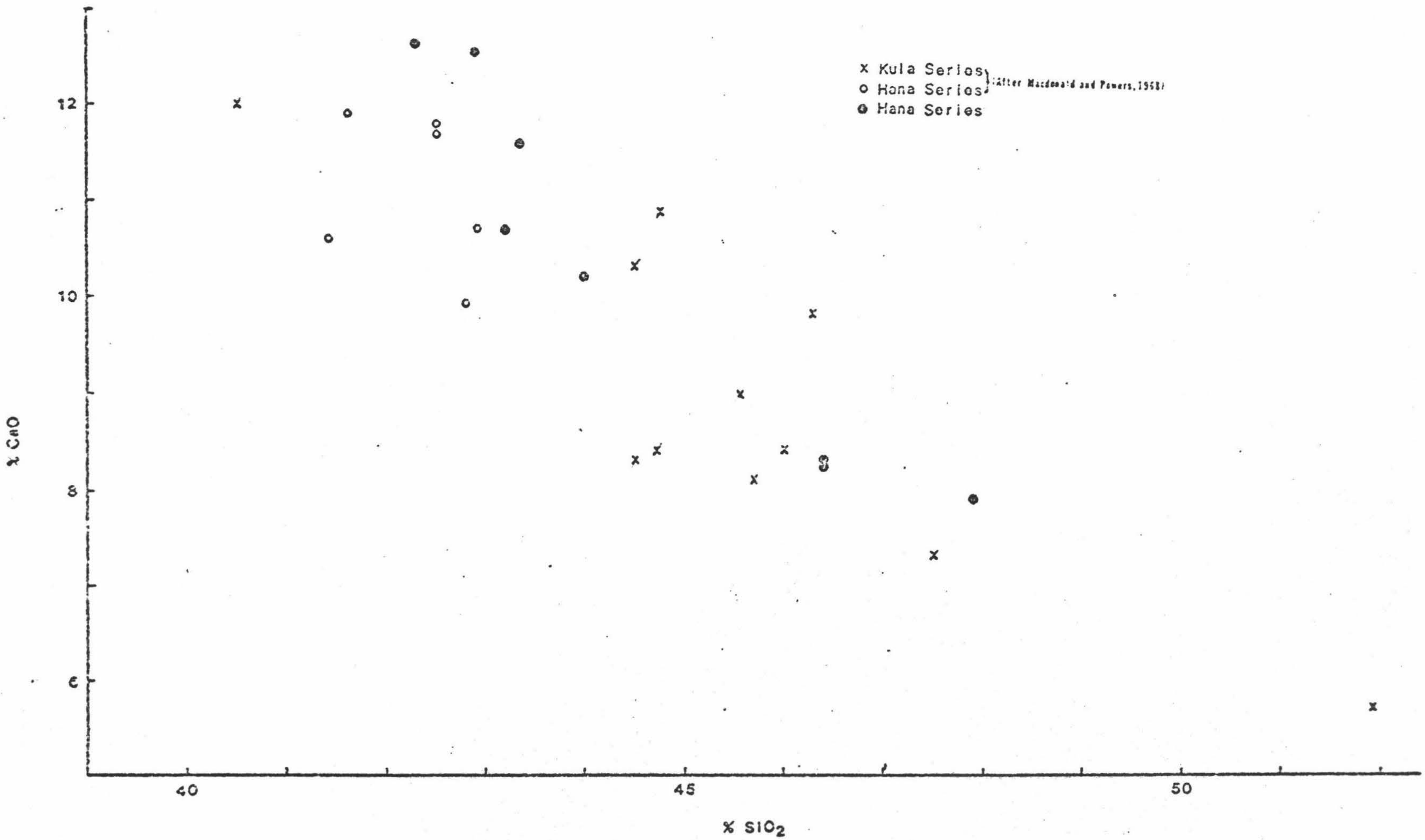

Figure 5. Lime-Silica Diagram of Late Stage Lavas of Haleakala

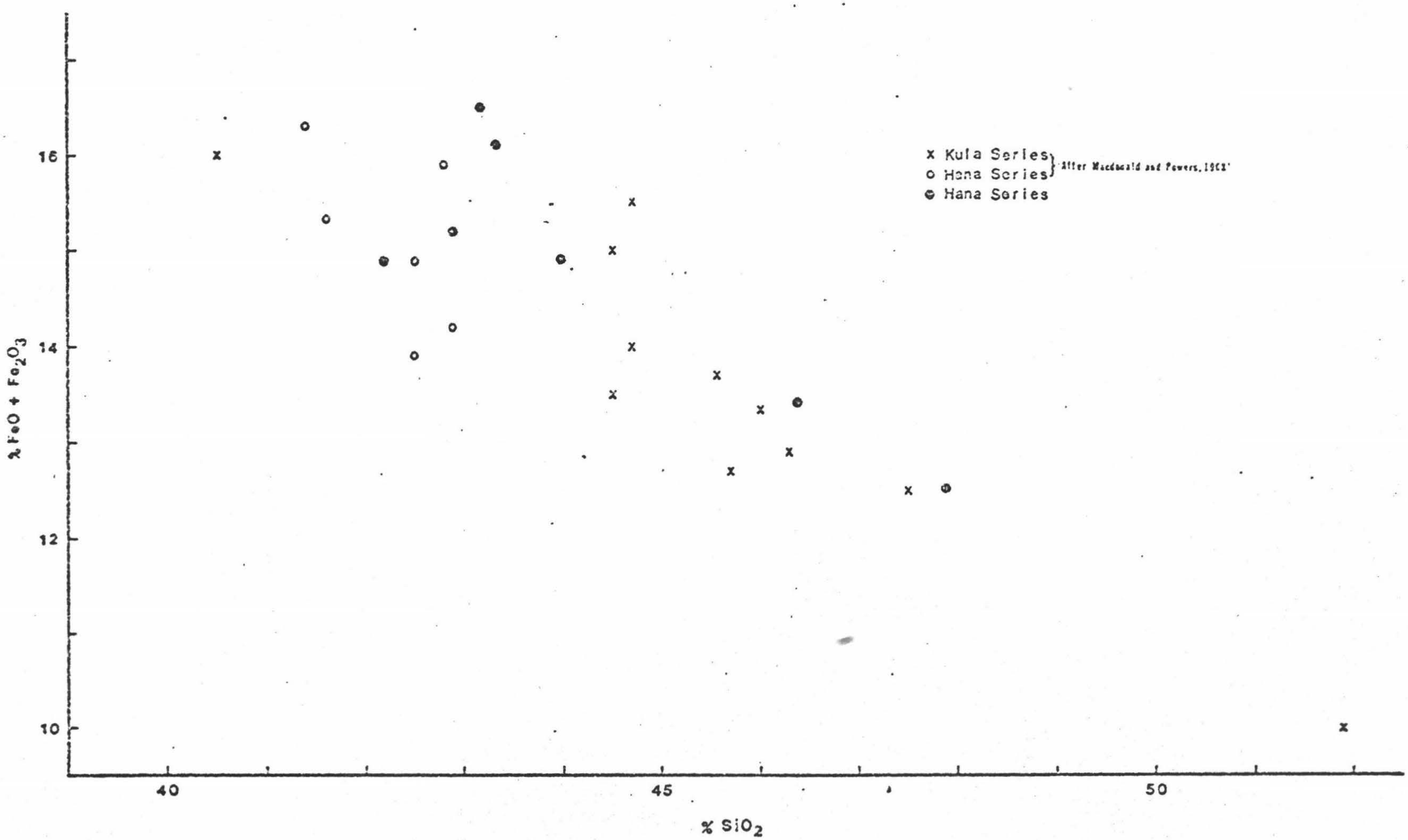

Figure 6. Total Iron-Silica Diagram of Late-Stage Lavas of Haleakala

ation diagrams of other oxides against silica (Figures 5 and 6) the same pattern is observed. There is a generally linear decrease of total iron and lime with increasing silica.

Three of the eight analyzed samples plot well within the Kula Series region in Figures 3 through 7. Two of the three samples (3A5, 4-6) have the same silica percentages and are from different portions of the Kaimaloo lava. The other (9-1) is from the Makuamakai flow. A sample from the Kula Series lavas plots well within the Hana Series region in all plots. The Pimoekai sample (5F8) plots within the transitional region in all plots.

A comparable trend is apparent in the AFM diagram (Figure 7). The trend of the two series as a unit follows the general variation trend of Hawaiian lavas (Macdonald and Powers, 1968, Fig. 1.) and the region of overlap marks a change from iron enrichment to iron depletion. The Kula Series rocks trend with the tholeiitic and nephelinitic suites, while the Hana Series lavas trend with the alkalic suite and a second trend of the nephelinitic suite (Macdonald, 1968, Fig. 4).

The Hana Series samples in table 5 contain normative orthoclase from 5 to 16%, and normative nepheline in excess of 5%. Neither was found in the mode. Macdonald (1968, p. 487) has stated that most, if not all, of the silica deficiency is in the pyroxene. This is substantiated in part by re- fractive index measurements of glass which indicates relative

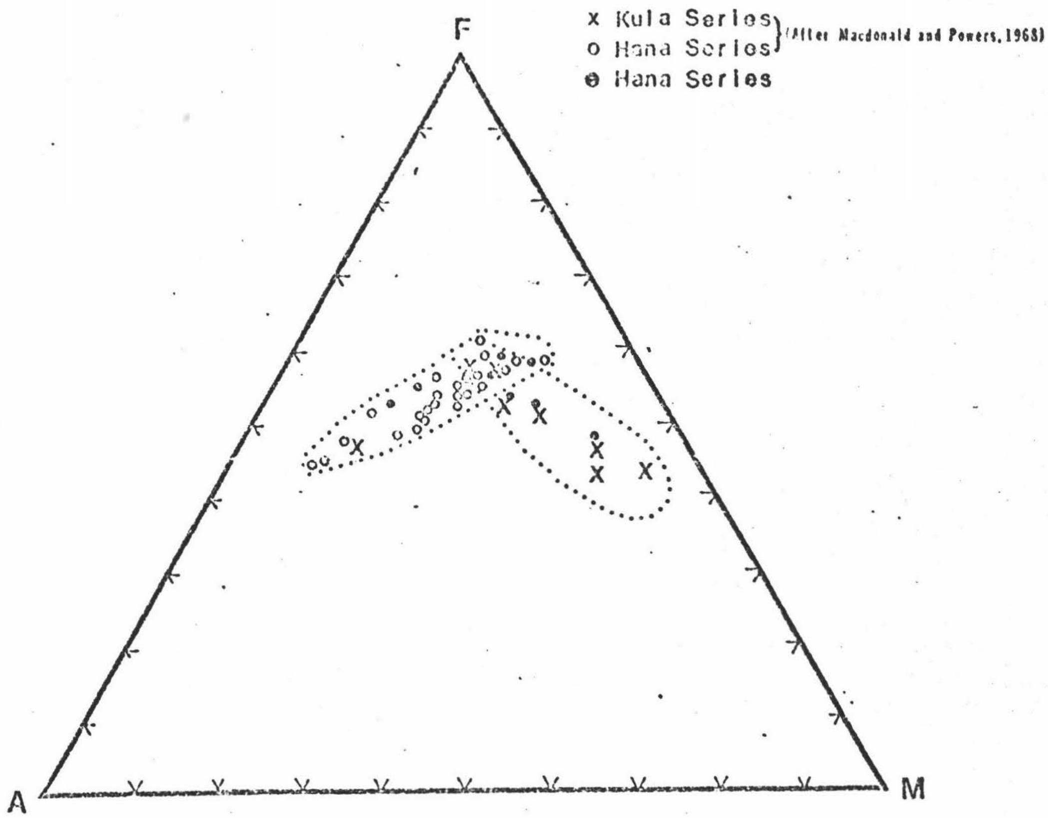

Figure 7. AFM Diagram of Late-Stage Lavas of Haleakala.
$A = Na_2O + K_2O$; $F = FeO + Fe_2O_3 + MnO$; $M = MgO$

silica enrichment in the glass. The presence of nepheline in the norms but not in the modes leads to the classification of these samples as basanatoids (Macdonald and Katsura, 1964, p. 89).

The Hana Series rocks are separated from those of the Kula Series by local unconformities (Stearns and Macdonald, 1942) and can therefore be considered post-erosional. When compared with post-erosional nephelinites of other Hawaiian volcanoes, the Hana Series lavas are less undersaturated in silica ("n" in Figure 3), and less enriched in magnesia (Macdonald and Powers, 1968, p. 884), but more undersaturated than the average basanites and average basanitoids. The Hana Series lavas are, however, more undersaturated in silica (Figure 3) and more mafic than the post-caldera Kula Series lavas. Macdonald and Powers (1968, p. 886) conclude that the same processes which produce the post-erosional lavas of other Hawaiian volcanoes also produce the Hana Series lavas of Haleakala, but have operated over a shorter period of time, and that the efficacy of the method depends on the time interval between eruption of the two series. The overlap of chemical trends for the rocks herein classified as Hana Series, based on stratigraphic position,with those of the Kula Series indicates that the interval between the two series is short along this portion of the rift, or that the lack of appreciable rainfall failed to produce large-scale erosional unconformities between the two series, and hence a lack of any definite criterion for separating them.

More chemical analyses of lavas of the two series are needed to determine the extent of overlap in other parts of the volcano.

Geologic Structure

The Hawaiian Islands are located in a tectonically stable part of the Pacific basin. Thus the minor geologic structures on the southwest rift are largely due to small scale effects of compaction and settling of pyroclastics and cooling of lava. Several roadcuts on Puu Mahoe reveal small normal faults, and at the coast where the aa interiors are exposed the lava flows are seen to be jointed.

Geologic History

Volcanic eruptions have undoubtedly occurred along the southwest rift throughout the time of the Kula Series eruptions which began during the middle Pleistocene, and continued with reduced frequency into the late Pleistocene. During the late Pleistocene great valleys were being carved into Kula lavas on the Northeast coast; evidence is lacking for Pleistocene quiescence along the southwest rift. Hana Series eruptions began in the late Pleistocene and have continued to the present along the southwest rift. It is likely that most, if not all, of the flows exposed along the lower southwest rift are Holocene, although some of the partly buried cinder cones may be earlier than Holocene. No evidence was found for sea level changes more recent than the earliest exposed lava along the coast.

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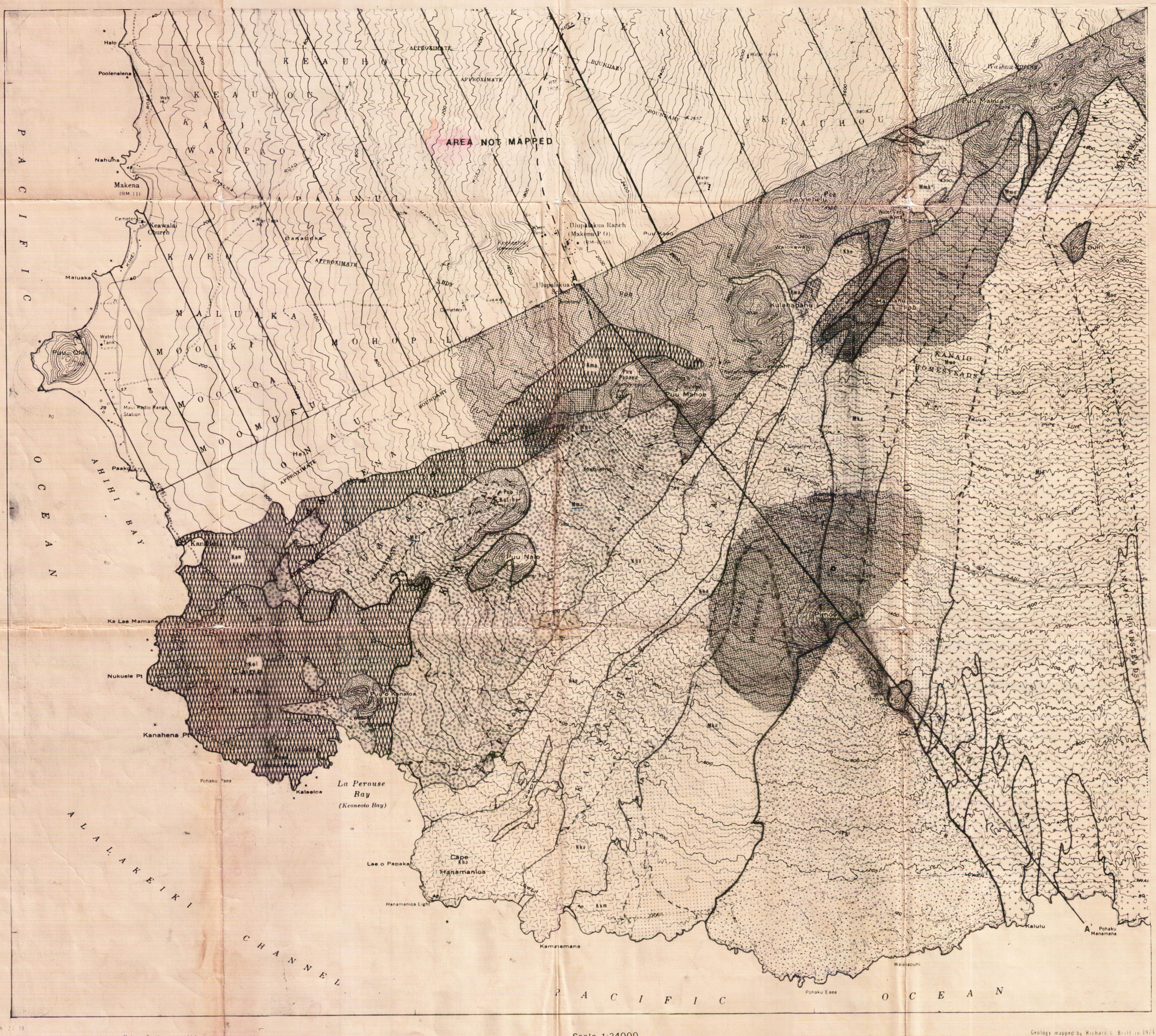


Geology mapped by Richard C. Brill in 1974–75

Scale 1:24000

1 — 5 — 1 miles

1000 — 0 — 5000 feet

1 — 0 — 1 kilometers

CONTOUR INTERVAL 40 FEET

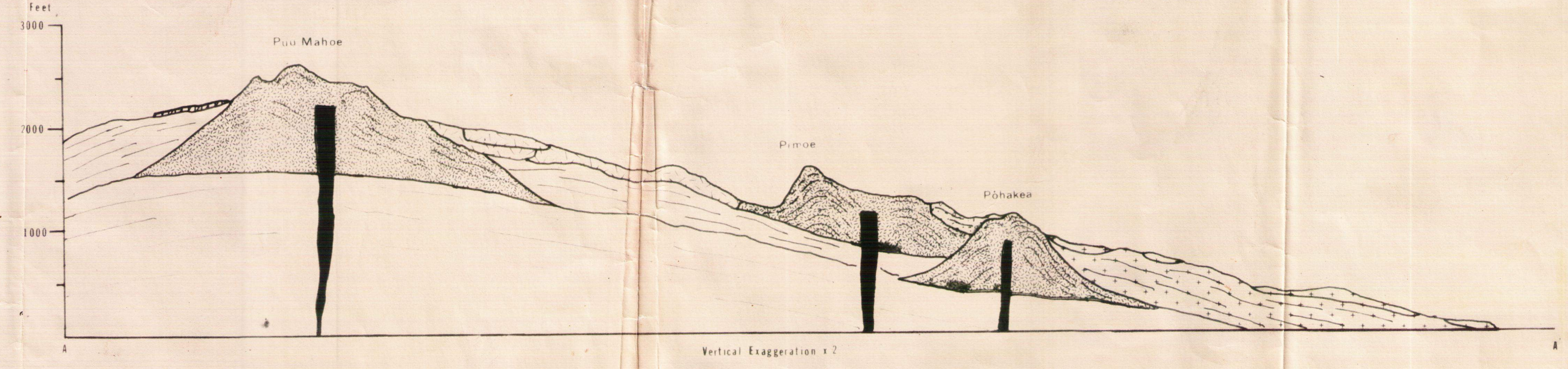
11.5° true north magnetic north

approximate mean declination 1975

HAWAIIAN ISLANDS

Location

PLATE 1. GEOLOGIC MAP OF THE LOWER SOUTHWEST RIFT OF HALEAKALA, HAWAII



EXPLANATION

QUATERNARY — Hana Volcanic Series

Keoneoio Formation

Historic

Kol – Kalua o' Lapa lava
Kan Kanahena lava
Olivine and augite bearing picrite basalts from the 1790(?) eruption

Prehistoric

Kma — Maukamahoe lava
Prehistoric(?) flow of olivine and augite bearing picrite basalt

Mahoe Formation

Lava flows of picrite basalt with plagioclase and augite phenocrysts

Mma — Mahiehie lava

Mpa — Papaka lava

Mkl — Kalihi lava

Mel — Earlier lava

Kaloi Formation

Kwa — Waiokawa lava
flow of augite bearing picrite basalt

Khe — Keonehunehune lava
flows of alkalic olivine basalt with plagioclase and augite phenocrysts

Kha — Hanamanioa lava
flow of picrite basalt with olivine and augite phenocrysts

Kka — Kaimaloo lava
flows of alkalic olivine basalt with plagioclase phenocrysts

Kkm — Kamanamana lava
flows of alkalic olivine basalt with plagioclase phenocrysts

Pimoe Formation

Ppi — Pimoekai lava
flow of alkalic olivine basalt with phenocrysts of olivine and augite

Makua Formation

Mmk — Makuamakai lava
flow of fe sic alkalic olivine basalt with plagioclase phenocrysts

Mmu — Makuamauka lava
flow of picrite basalt

Mle Leia and
Mnu Kanaionui
lava flows of alkalic olivine basalt with plagioclase phenocrysts

Mwa – Wana and
Mka – Kamana
lava flows of alkalic olivine basalt

Hel — *Older Hana Series lavas*

Pcc — *Cinder cones and spatter*

Ppb — *Approximate extent of pyroclastic blanket*

———— ---?--

Contact

Dashed where inferred
Queried where doubtful
Shown within some units to separate flows of different ages