CONTRIBUTIONS TO THE PETROGRAPHY, GEOCHEMISTRY AND GEOCHRONOLOGY OF VOLCANIC ROCKS FROM ALONG AND NEAR THE WESTERN HAWAIIAN RIDGE AND KAULA ISLAND, HAWAIIAN CHAIN

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ABSTRACT

Dredged volcanic rocks from six locations along the Hawaiian Ridge and from four off-ridge seamounts were examined petrographically and geochemically and compared with lavas from the principal Hawaiian Islands. Results from the Hawaiian Ridge samples show that tholeiitic basalts recovered from the northern edge of Gardner Pinnacles probably represent shield-building lavas from the volcanic center at the location. Other samples recovered from Gardner Pinnacles, Brooks Bank, and an unnamed seamount 200 km south-east of Necker Island have compositions transitional between tholeiitic and alkalic basalts. These samples may represent late stage shield-building lavas from these volcanic centers. A second sample recovered from Brooks Bank, samples from two unnamed seamounts 300 km west of Midway Islands and halfway between Necker and Nihoa Islands are hawaiites similar in composition to volcanic rocks of the alkalic-cap stage of development on Hawaiian volcanoes.

Conventional K-Ar age determinations yielded ages of 13.4 $\pm$ 0.8 m.y., 15.9 $\pm$ 1.0 m.y. and 16.2 $\pm$ 1.3 m.y. for Gardner Pinnacles, 17.6 $\pm$ 0.6 m.y. for Brooks Bank and 10.12 $\pm$ m.y. for the unnamed seamount halfway between Necker and Nihoa Islands. These ages are consistent with the general trend of increase in age to the northwest away from Kilauea volcano as predicted by the 'hot spot' hypothesis. The age progression, however, is not exactly linear and there is scatter of the ages northwest of French Frigate Shoal.

Off-ridge samples recovered from an unnamed seamount located 500 km northwest of Midway Island and from two unnamed seamounts located 200 km north and 625 km northeast of Pearl and Hermes Reef are hawaiites. Two samples recovered from an off-ridge seamount 140 km southwest of Salmon Bank are hornblende benmoreites, differentiated rocks, unlike any lavas from the Hawaiian Islands.

Conventional K-Ar age determinations on the hornblende benmoreite as well as on a hawaiite from the unnamed seamount 500 km northwest of Midway Island yield ages of 110.3 ± 3.1 m.y. and 111.7 ± 2.7 m.y. respectively. These ages are much older than ages predicted by the 'hot spot' hypothesis for these locations. These seamounts were built at nearly the same time as the underlying oceanic crust and are not part of the Hawaiian Ridge.

New petrologic and chemical analyses are presented on the virtually unstudied Kaula Island (Hawaiian chain). It is an eroded remnant of a tuff cone built on a submarine shield volcano. Accidental blocks embedded in the tuff include: basanitoids similar in composition to some post-erosional lavas of the Koloa Group on Kauai; biotite phonolites, post-erosional rocks previously unreported among the lavas of the principal Hawaiian Islands; and mantle-derived lherzolites and a garnet websterite. The occurrence of garnet websterite has only been reported from one other area in the Pacific basin (Oahu, Hawaii). Conventional K-Ar whole-rock age determination on two biotite phonolites and one age determination on biotite phenocrysts in the second sample yielded ages of 4.00 ± 0.09 m.y., 4.22 ± 0.25 m.y. and 3.98 ± 0.7 m.y. respectively. These ages probably represent the age of post-erosional volcanism on Kaula Island. The age is older than expected for this location as predicted by the 'hot spot' hypothesis.

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INTRODUCTION

The 'hot spot' hypothesis, first proposed by Wilson (1963a, 1963b), and later modified by Morgan (1971, 1972a, 1972b), suggests that linear volcanic chains in the Pacific basin, such as the Hawaiian - Emperor Chain, are formed as the Pacific plate moves over a magma source located deep in the mantle. One corollary which has developed from the 'hot spot' hypothesis states that lavas from different volcanic edifices along each chain should be petrographically and chemically similar (Dalrymple et al., 1974). Another corollary states that volcanic edifices should increase in age along the chain away from the youngest, volcanically active end of the chain (Dalrymple et al., 1974).

Previous Work

Abundant data on the principal Hawaiian Islands support the 'hot spot' hypothesis for at least this section of the Hawaiian Ridge. Fewer data exist for the portion of the Hawaiian Ridge northwest of Kauai, herein defined as the Western Hawaiian Ridge. Clague (1974) provided a comprehensive report which included detailed petrography and geochemistry of 36 samples along the Western Hawaiian Ridge and K-Ar age determinations for Pearl and Hermes Reef and two unnamed seamounts 160 and 380 km west of Midway Islands. Dalrymple et al. (1974) presented petrologic and geochemical data for Nihoa Island, Necker Island, La Perouse Pinnacle (French Frigate Shoal), Gardner Pinnacles and Midway Islands along with K-Ar ages for Nihoa, Necker, La Perouse Pinnacle and Midway. Additional contributions have been made for Necker Island and Wentworth Seamount (Clague and Dalrymple, 1975), Midway (Dalrymple et al., 1977), and Laysan Island and Northampton Seamount (Dalrymple et al., in prep.).

Purpose

This study presents new petrologic, geochemical and K-Ar data on new samples along the Western Hawaiian Ridge and evaluates the data in terms of the 'hot spot' model. The specific objectives for the thesis are threefold:

1) to report the petrography, major and mineral chemistry on samples from six locations along the Western Hawaiian Ridge and four unnamed off-ridge seamounts, and determine if these rocks are similar to or different from the volcanic rocks from the principal Hawaiian Islands;

2) to present new K-Ar age determinations on six previously undated volcanic edifices: four along the Western Hawaiian Ridge and two from off-ridge seamounts, and compare the ages to the age progression predicted by the 'hot spot' hypothesis; and

3) to present new petrographic, major and mineral chemistry and K-Ar age determinations on the virtually unstudied Kaula Island and determine its relationship to the Hawaiian Ridge.

REGIONAL GEOLOGIC SETTING

Regional Geology

The Hawaiian Islands form the southeastern extension of a quasilinear chain of volcanic islands, atolls and seamounts which cap a topographic high called the Hawaiian Ridge (Figure 1). The Hawaiian Ridge is one of several linear volcanic chains located in the Pacific basin. Beginning at Kilauea Volcano, on the island of Hawaii, the Hawaiian Ridge extends approximately 3500 kilometers northwest to Kure Island. Near Kure Island an abrupt bend in the chain marks the beginning of the Emperor Seamount Chain which continues to the north to the Aleutian Trench near Kamchatka Peninsula (Figure 1). Although the two chains are apparently related (Christofferson, 1968; Jackson et al., 1972; Clague, 1974), only the Hawaiian Ridge will be discussed here. For additional information on the Emperor Seamount Chain, the reader is referred to Jackson et al. (in press).

The Hawaiian Ridge, capped by approximately 107 distinct volcanic edifices, trends obliquely to the underlying structures of the Pacific Ocean floor (Figure 2). Large east-west trending fracture zones of the Pacific basin intersect the ridge, yet have no apparent affect on the ridge (Dalrymple et al., 1973; Clague, 1974). Jackson et al. (1972) showed that while the pattern of the chain as a whole is linear, individual volcanic edifices lie on short sigmoidal, en echelon loci which may represent extensional features in the crust and upper mantle. K-Ar age dates on volcanic rocks along the Hawaiian Ridge show it to be younger (Tertiary to Quaternary) than the Cretaceous ages of the surrounding Pacific Ocean floor (Jackson et al., 1972, Hilde et al., 1976; Jarrard and Clague, 1977).

Recent volcanic activity is concentrated at the southeastern end of the Hawaiian Ridge at Mauna Loa and Kilauea volcanoes on the island of Hawaii. Proceeding to the northwest, the volcanoes become increasingly more dissected by erosion. On the basis of these observations, early workers proposed that the islands increase in age to the northwest (Dana, 1849;

Figure 1. Index map showing the location of the Hawaiian Islands and Hawaiian Ridge. Small inset shows relation of Hawaiian Ridge and Emperor Seamount Chain to the Pacific basin. Modified from Dalrymple et al. (1973).

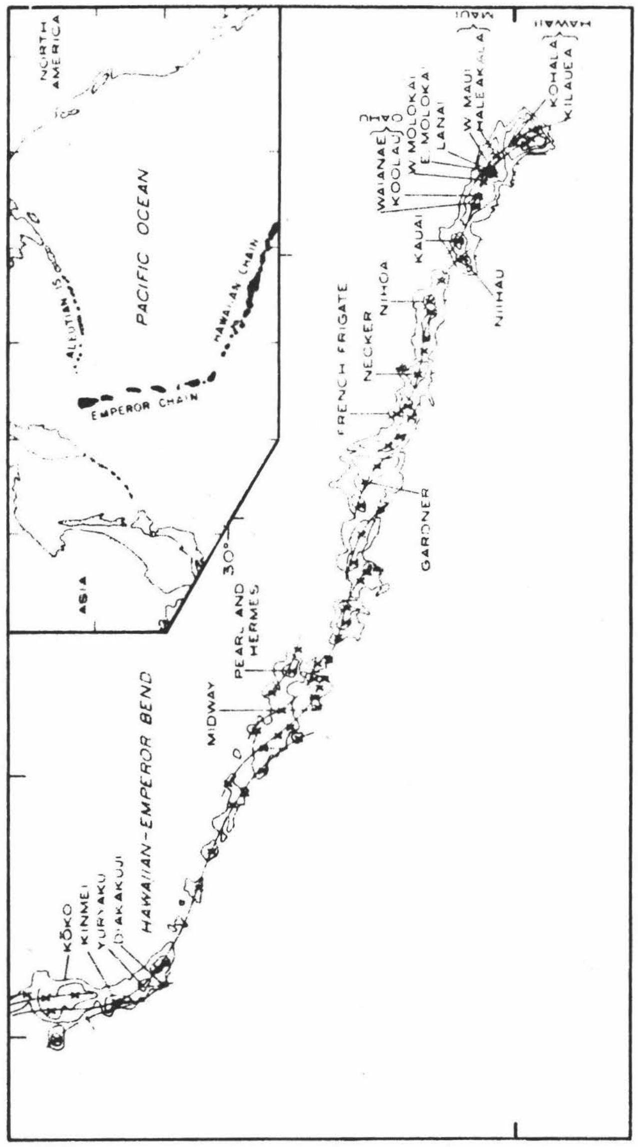
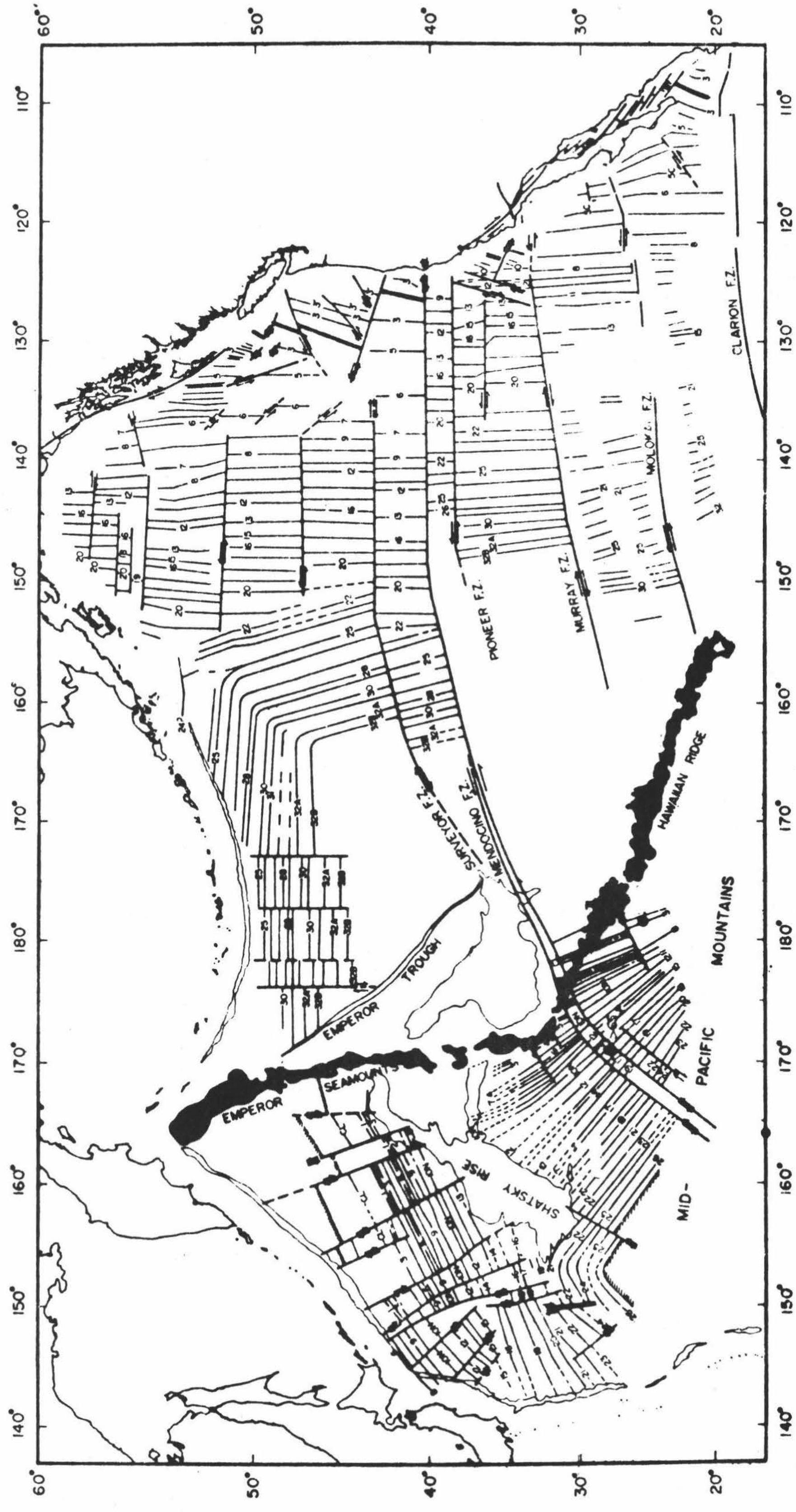

NORTH AMERICA
PACIFIC OCEAN
ALEUTIAN IS.
HAWAIIAN CHAIN
EMPEROR CHAIN
ASIA
30°
HAWAIIAN-EMPEROR BEND
KŌKO
KINMEI
YURYAKU
MIDWAY
PEARL AND HERMES
GARDNER
FRENCH FRIGATE
NECKER
NIHOA
KAUAI
NIIHAU
WAIANAE
KOOLAU
OAHU
W MOLOKAI
E MOLOKAI
LANAI
W MAUI
HALEAKALA
MAUI
KOHALA
KILAUEA
HAWAII

Figure 2. Map showing the Hawaiian - Emperor Chain and its orientation to other structural features in the Pacific basin. Modified from Clague (1974).


EMPEROR TROUGH
EMPEROR SEAMOUNTS
SHATSKY RISE
MID-PACIFIC MOUNTAINS
HAWAIIAN RIDGE
SURVEYOR F.Z.
MENDOCINO F.Z.
PIONEER F.Z.
MURRAY F.Z.
CLARION F.Z.

1890; Stearns, 1946; 1966). K-Ar radiometric dating on lavas from the principal Hawaiian Islands (McDougall, 1963; 1964; 1969; 1979; Funkhouser et al., 1968; Dalrymple, 1971; McDougall and Swanson, 1972; Doell and Dalrymple, 1973; Bonhommet et al., 1977; Porter et al., 1977) as well as ages on lavas dredged from the Western Hawaiian Ridge (Clague, 1974; Dalrymple et al., 1974; Clague et al., 1975; Dalrymple et al., 1977) show increasing ages to the northwest and confirm the earlier observations.

Origin of the Hawaiian Islands

Wilson (1963a, 1963b) first suggested that volcanoes along the Hawaiian Ridge were formed as the result of a fixed 'hot spot' located in the mantle and that the volcanoes are rafted along on the Pacific plate as it moves northwest. After a volcano has moved away from the 'hot spot" volcanic activity ceases and a new volcano forms southeast of the former volcano. Morgan (1971, 1972a, 1972b) expanded Wilson's theory to include other linear island chains and proposed that the 'hot spot' resulted from hot mantle plumes originating deep within the mantle due to convection currents. Morgan (1971) further proposed that the convection currents and mantle plumes, together, were the main driving force moving the Pacific plate.

Subsequent workers have attempted to explain the mechanism(s) responsible for the 'hot spot,' but no theory has yet been able to adequately explain the chemistry, timing and sequence of rock types (Jackson et al., in press). Some of the current hypotheses include:

1) propagating fracture which repeatedly taps fresh mantle material (Jackson and Wright, 1970) caused by the movement of the Pacific plate over an imperfect sphere (Green, 1971), a thermal high located in the low velocity zone resulting in diapiric upwelling and volcanism (McDougall, 1971), or fracturing the lithosphere due to stress corrosion (Anderson and Grew, 1977).

2) thermal plumes of material rising from the deep mantle (Morgan, 1972a, 1972b) or plumes arising from a chemically heterogeneous mantle (Anderson, 1975).

3) shear melting between the lithosphere and asthenosphere coupled with thermal feedback (Shaw, 1973) and possibly stablized by gravitational downwelling of melt residua (Shaw and Jackson, 1973).

Characteristics of Hawaiian Volcanoes

The Hawaiian Islands consist of a series of dome-shaped shield volcanoes built on the floor of the Pacific Ocean. Some of the larger volcanoes (e.g. Mauna Kea and Mauna Loa) have attained heights of over 3900 meters above sea level. Volcanic eruptions are commonly confined to a summit region and along narrow, well-defined rift zones which intersect at the summit (Macdonald, 1956). Both pahoehoe and aa type lavas are present; pahoehoe lavas predominate near the vents, and aa lavas are more prevalent on the slopes (Macdonald and Abbott, 1977). Pyroclastic rocks comprise less than 1% of the mountain mass (Macdonald and Abbott, 1977).

Geologic work on the subaerial portions of Hawaiian volcanoes has led to the recognition of a succession of stages in their development (Macdonald and Katsura, 1964; Macdonald, 1968; Macdonald and Abbott, 1977) which can be summarized as follows:

Shield-Building Stage

Repeated eruption of thin (1 to 5 meters thick) flows of fluid lavas which build the main mass (>98%) of the volcano (Macdonald and Abbott, 1977). The lavas of this stage mainly belong to the tholeiitic suite of rocks (Macdonald, 1968). Porphyritic textures are common with phenocrysts of magnesium-rich olivine predominately, rarely bytownite, augite and hypersthene grains are present (Macdonald, 1968; Wright, 1971; Keil et al., 1972; Macdonald and Abbott, 1977). Olivine is generally rounded or embayed, indicating disequilibrium with the magma (Macdonald and Katsura, 1964; Macdonald, 1968). Groundmass minerals include labradorite, pigeonite, accessory magnetite, ilmenite and locally interstitial silica-rich glass (Macdonald and Katsura, 1964; Macdonald, 1968; Keil et al., 1972; Macdonald and Abbott, 1977). Olivine is absent from the groundmass except where present as xenocrysts (Macdonald, 1968).

During the shield-building stage volcanic activity is accompanied by repeated collapse of the summit area forming a caldera (Macdonald and Abbott, 1977). Eruptions continue along the rift zones and within the caldera, gradually filling it (Macdonald and Abbott, 1977). Toward the end of the shield-building stage the eruptions become less frequent, slightly more explosive and the lavas become alkalic (Macdonald and Abbott, 1977).

Alkalic-Cap

Lavas of this stage of Hawaiian volcanic activity represent less than 1% of the total volume of a volcano. They cap most of the volcanoes of the Hawaiian Islands (e.g. Kohala, Haleakala, Mauna Kea, and West Maui) and are distinctly different than lavas of the shield-building stage (Macdonald and Katsura, 1964; Macdonald, 1968). The rocks typically belong to the alkalic suite of rocks: alkalic basalts, ankaramites hawaiites, mugearites, and trachytes (Macdonald, 1968; Macdonald and Abbott, 1977). Phenocrysts are common and include olivine, plagioclase, and augite (Macdonald and Katsura, 1964; Keil et al., 1972; Fodor et al., 1975; 1977). The olivines are subhedral to euhedral and unresorbed (Macdonald and Katsura, 1964). Rare inclusions of dunite and wehrlite are present (Macdonald, 1968; Jackson, 1968). Groundmass minerals include plagioclase, olivine, augite, interstitial alkali feldspar, accessory magnetite, and ilmenite (Macdonald and Katsura, 1964; Macdonald, 1968; Keil et al., 1972; Fordor et al., 1975; 1977).

During the alkalic-cap stage Hawaiian volcanoes develop in two distinct styles (Macdonald and Katsura, 1964; Macdonald and Abbott, 1977). Volcanoes of the "Kohala-type" (e.g. Kohala and West Maui) are composed of a cap of alkalic lavas separated from underlying shield-building lavas by an erosional unconformity and commonly a bed of ashy soil (Macdonald and Abbott, 1977). Typical lavas of "Kohala-type" volcanoes include mugearites, trachytes, some hawaiites, and alkalic olivine basalts (Macdonald and Katsura, 1964; Macdonald, 1968; Macdonald and Abbott, 1977). On volcanoes of the "Haleakala-type" (e.g. Haleakala and Mauna Kea) the upper most part of the shield-building lavas grade upward and are interbedded with the alkalic lavas. No erosional unconformity exists. Dominant lavas found on "Haleakala-type" volcanoes include hawaiites, alkalic olivine basalts and ankaramites (Macdonald and Katsura, 1964; Macdonald, 1968; Macdonald and Abbott, 1977).

Post-Erosional Stage

Following a period of volcanic quiescense, accompanied by extensive dissection of the islands by erosion, several Hawaiian volcanoes have experienced renewed volcanic activity (Macdonald and Katsura, 1964; Macdonald, 1968; Jackson and Wright, 1970; Macdonald and Abbott, 1977). Lavas of this stage of development include undersaturated alkalic basalts, (i.e. basanitoids, basanites), nephelinites, and melilite nephenlinites (Macdonald and Katsura, 1964). Porphyritic textures are common with olivine as the dominate phenocryst (Macdonald, 1968). Groundmass mineralogy is similar to basalts of the alkalic suite except that nepheline and melilite may be present. Rare inclusions of dunites, wehrlites, and lherzolites occur, including rare garnet-bearing varieties. Most noteworthy are lherzolites and garnet pyroxenites found at Salt Lake Crater on the island of Oahu, which are thought to represent mantle material (Jackson and Wright, 1970).

Not every Hawaiian volcano has followed the simplified growth pattern outlined above. For example, Koolau volcano apparently skipped the alkalic-cap stage of volcansim whereas Lanai volcano ended its volcanic activity before completing its shield-building stage (Macdonald and Abbott, 1977).

Previous Work

Brief descriptions of volcanic rocks from the Hawaiian Islands first appeared in the early to middle 19th century (Silliman, 1829; 1831; Jackson, 1846). Dana (1849) published the first comprehensive descriptions on Hawaiian volcanic rocks, but this was limited to megascopic features as were earlier reports (Macdonald, 1949). Systematic studies of the Hawaiian Islands were initiated in 1920 by the United States Geological Survey and since that time there has gradually emerged a general picture of the areal geology of the islands (Stearns, 1946; Macdonald, 1949; Macdonald and Abbott, 1977). Recent workers have extended the data base to include the Western Hawaiian Ridge and Emperor Seamount Chain (Clague, 1974; Dalrymple et al., 1974; Clague et al., 1975; Dalrymple et al., 1977; Jackson et al., in press).

METHODS OF STUDY

Samples from the Hawaiian Ridge were recovered from dredge hauls taken by the research vessel Kana Keoki during Hawaii Institute of Geophysics Cruise 72-07-02 Leg 2 (1972, chief scientist – J. F. Campbell), Cruise 76-08-06 (1976, chief scientist – Fritz Theyer), Cruise 76-11-08 Leg 1 (1976, chief scientist – James Andrews) and Cruise 77-03-17 Leg 1 (1977, chief scientist – Roger Larson). Samples from Kaula Island were collected by the author on March 6-8, 1979 in conjunction with a two day environmental assessment of the island by the U.S. Department of Commerce, NOAA, Marine Fishery Service; U.S. Department of the Interior, Fish and Wildlife Service; State of Hawaii, Department of Land and Natural Resources, Division of Fish and Game; Hawaii Institute of Marine Biology and the U.S. Military.

The freshest samples were sawed into slabs about 4.5 cm by 1 cm by 2.5 cm for detailed petrography and chemical analysis. Each sample chemically analyzed or dated by the potassium-argon method was first carefully examined for alteration under the petrographic microscope. Selected samples were crushed to a very fine powder utilizing a shatterbox and tungsten carbide grinder and stored in plastic vials.

Chemical major-element analyses were made by Ken Ramlal at the Department of Earth Sciences of the University of Manitoba, Canada. A summary of the analytical methods used can be found in APPENDIX A. Internal control basalt standards used were from the United States Geological Survey (BCR-1; Flanagan, 1973) and from the Hawaii Institute of Geophysics (HIGS-6 and HIGS-8; Macdonald et al., 1973). Standards were prepared using the same methods as the unknown samples.

REE abundances were determined in the laboratory of J. A. Philpotts at the Hawaii Institute of Geophysics by mass spectrometric, stable isotope dilution techniques (Schnetzer et al., 1967a; 1967b).

Microprobe mineral analyses were made using a Cameca-MBX electron microprobe, with natural and synthetic mineral standards. Both internal and external standards were used; the internal standards consisted of well analyzed chromite, magnetite, olivine, orthopyroxene, plagioclase, rhodenite and rutile. Instrument operating conditions were usually 15 kV and 18 nA sample current. Each analysis is an average of six to eight points from a small area and four to six grains per sample. Core and rim analyses were made to check for zoning and overall homogeneity. Raw data were corrected for dead time of detectors, instrument current drift and spectrometer background. Mineral analyses were then obtained by the correction methods of Henoc and Tong (unpublished manuscript). Accuracy is estimated to be 1-2% for major elements and 5-10% for minor elements, on the basis of replicate microprobe analyses compared with wet chemical analyses.

Conventional K-Ar measurements were made in the laboratory of J. J. Naughton at the Hawaii Institute of Geophysics using isotope dilution mass spectrometry methods described by Dalrymple and Lanphere (1969; 1971) and Gramlich (1970).

HAWAIIAN RIDGE

Petrography

The samples selected for study from along the Hawaiian Ridge and from off-ridge seamounts were all obtained from dredge hauls. Consequently the stratigraphic relationships of the lavas are unknown. The majority of the samples were covered by a coating of manganese oxide 2-9 mm thick.

A total of 44 thin sections were made of the freshest samples as determined by hand specimen examination. Of these, 19 were chosen for detailed petrographic study, 13 from along the Hawaiian Ridge and seven representing four off-ridge seamounts. The locations of each dredge site is shown in Figure 3. The specific geographic location for each dredge site is found in APPENDIX B.

Rock Types

The samples obtained from along the Hawaiian Ridge include 20-AA, and 20-CC, 6-7-A, 6-7-B, 6-7-D and 6-7-F, 37-A and 37-C, 41-A and 41-B, 51-A and 51-D, and 9-11. Samples from selected off-ridge seamounts are 65-24-A and 65-24-D, 33-17-A, 34-18-B and 34-18-C, and 20-8-J and 20-8-O. Modes for nine thin sections were determined by point counting 500 points per section (Table 1). Modes for the other thin sections were estimated by visual examination. Petrographic descriptions of samples from each dredge station can be found in APPENDIX C.

The samples dredged from along the Hawaiian Ridge are all basalts with vesicularities of 1-9%, rarely up to 40% (samples 20-AA and 20-CC). The majority of the samples are porphyritic; the main phenocryst phase is olivine, rarely clinopyroxene or plagioclase (An_{54-60}). The groundmass consists of plagioclase (An_{43-70}), clinopyroxene,and commonly olivine. Magnetite is an ubiquitous phase. Groundmass textures are intergranular to subophitic,

Figure 3. Index map showing the location of dredge sites along the Hawaiian Ridge. Modified from Dalrymple et al. (1977).

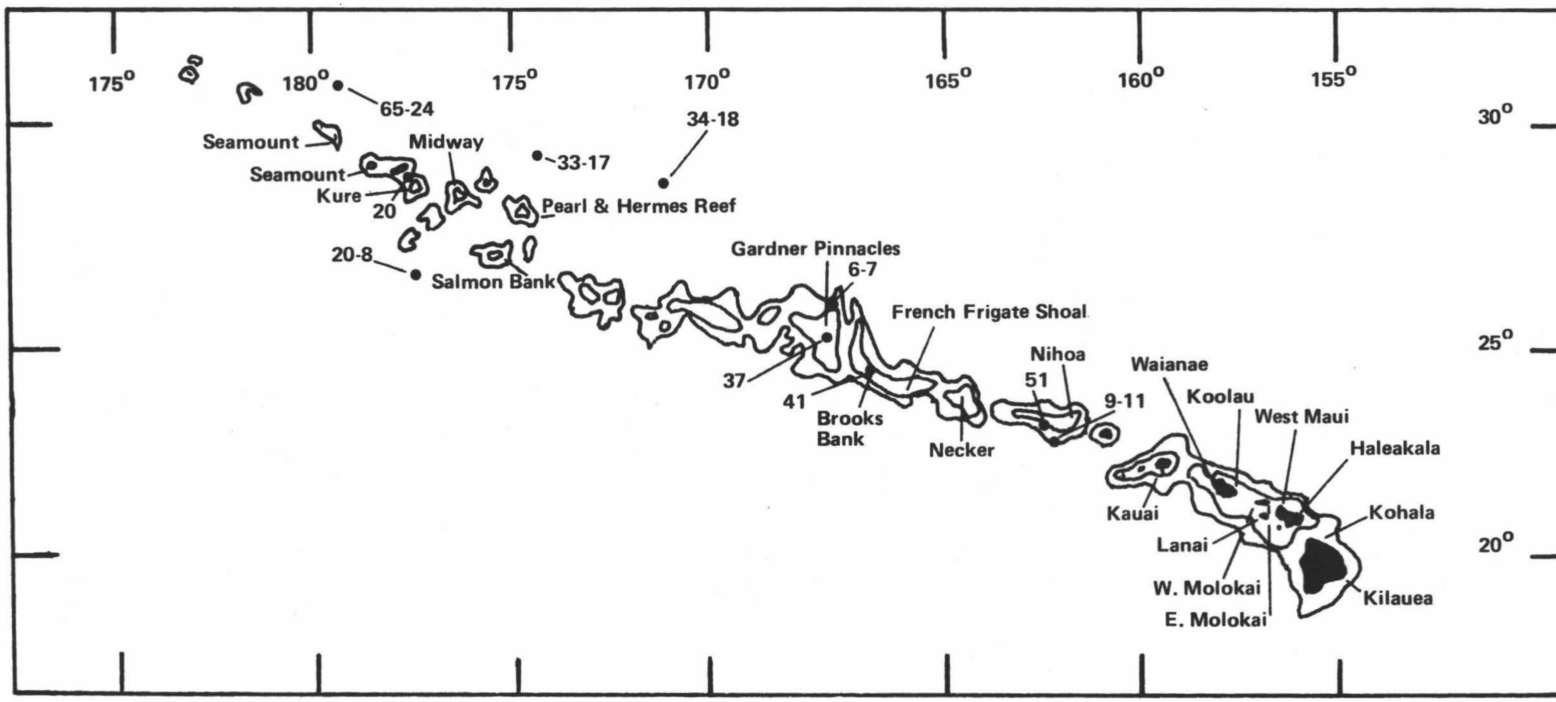

175°
180°
175°
170°
165°
160°
155°
30°
25°
20°
65-24
34-18
33-17
Seamount
Seamount
Midway
Kure
20
Pearl & Hermes Reef
20-8
Salmon Bank
Gardner Pinnacles
6-7
French Frigate Shoal
37
41
Brooks Bank
Necker
Nihoa
51
9-11
Waianae
Koolau
West Maui
Haleakala
Kohala
Kauai
Lanai
W. Molokai
E. Molokai
Kilauea

Table 1

Modal Point Count Analyses for Selected Samples from along the Hawaiian Ridge and Selected Off-Ridge Seamounts. Based on 500 Points Counted Per Sample.

SAMPLE	20-AA	6-7-A	37-A	41-B	51-A	33-17-A	34-18-B	65-24-A	20-8-J
PHENOCRYSTS									
Plagioclase	21.6%	1.2%	1.6%	1.4%	–	8.2%	–	<1%	7.9%
Olivine	<1%	13.4%	9.2%	9.6%	–	2.2%	–	–	–
Clinopyroxene	<1%	–	<1%	<1%	–	–	–	–	1.4%
Opaques	–	–	–	<1%	–	–	<1%	<1%	1.2%
Hornblende	–	–	–	–	–	–	–	–	11.3%
GROUNDMASS									
Plagioclase	26.2%	33.2%	35.6%	37.6%	43.0%	44.3%	43.3%	61.4%	44.8%
Olivine	4.2%	–	16.8%	11.8%	15.6%	3.6%	–	–	–
Clinopyroxene	14.0%	44.0%	15.6%	16.2%	10.8%	10.6%	7.8%	7.0%	6.1%
Opaques	13.0%	8.2%	20.4%	15.6%	25.6%	22.0%	39.4%	14.0%	6.7%
Hornblende	–	–	–	–	–	–	–	–	5.9%
Interstitial very fine grained undetermined material	–	–	–	4.8%	4.4%	8.9%	11.1%	6.0%	–
VESICULARITY	20.4%	–	<1%	2.6%	<1%	<1%	6.2%	11.0%	9.4%

rarely intersertal or pilotaxitic.

Except for the samples dredged from an unnamed seamount 140 km southwest of Salmon Bank, all off-ridge seamounts are petrographically similar to the samples from along the Hawaiian Ridge. The anamolous samples from the seamount southwest of Salmon Bank (samples 20-8-J and 20-8-O) are quite fresh. In hand specimen the rocks are dominated by prismatic hornblende phenocrysts up to 7 mm in length in a gray, fine grained groundmass. Vesicularity ranges from 7-10%. Under the microscope subhedral brown hornblende, commonly as glomerocrysts intergrown with plagioclase (An_{30-35}), clinopyroxene and/or iron oxides are set in a groundmass consisting of plagioclase (An_{26-32}), anhedral brown hornblende, clinopyroxene, iron oxides and minor apatite. Such mineralogy is rare for Hawaiian lavas.

Mineral Composition

Mineral analyses were made on olivine phenocrysts, groundmass plagioclase and clinopyroxene grains for two samples dredged from the northern edge of Gardner Pinnacles (sample 6-7-A and 6-7-F) utilizing an electron microprobe. Results of the analyses are presented in Tables 2, 3 and 4. In general compositions for groundmass plagioclase grains fall within the range of values determined for tholeiitic basalts from Haleakala volcano on Maui (Keil et al., 1972). Plagioclase microphenocrysts in sample 6-7-A slightly increase in percent from core to rim. Plagioclase microphenocrysts in sample 6-7-F display normal zoning. For each sample, the groundmass grains are the most sodic grains analyzed. Groundmass clinopyroxene compositions for the Gardner Pinnacles samples are similar to Hawaiian tholeiitic basalt compositions (Fodor et al., 1975). Olivine phenocryst compositions decrease in forsterite content from core to rim, although overall forsterite content is slightly higher than the forsterite contents found for Haleakala tholeiitic basalts by Fodor et al. (1977).

Table 2

Plagioclase Compositions from Basalts Dredged from Gardner Pinnacles, Hawaiian Chain

	6-7-A			6-7-F			
	Core mph-3	Rim mph-3	Gm-4	Core mph-4	Rim mph-3	Core mph-3	Gm-4
SiO_2	50.89	51.33	52.12	51.32	51.15	49.89	52.15
Al_2O_3	30.58	30.43	29.91	30.03	30.20	31.25	29.63
FeO	0.77	0.71	0.96	0.77	0.76	0.71	1.01
CaO	14.02	14.46	13.25	14.57	14.30	15.17	13.51
Na_2O	3.44	3.31	3.91	3.36	3.44	2.94	3.75
K_2O	0.12	0.11	0.16	0.13	0.14	0.07	0.16
Total	99.82	100.35	100.31	100.18	99.99	100.03	100.21
				Based on Eight Oxygens			
Si	2.327	2.335	2.369	2.342	2.337	2.283	2.374
Al	1.648	1.632	1.603	1.615	1.627	1.686	1.590
Fe	.030	.027	.036	.029	.029	.027	.039
Ca	.687	.705	.645	.713	.700	.744	.659
Na	.305	.292	.345	.297	.305	.261	.331
K	.007	.007	.009	.007	.008	.004	.009
Total	5.004	4.998	5.007	5.003	5.006	5.005	5.002
An%	68.8	70.2	64.6	70.1	69.1	73.7	66.0
Ab%	30.5	29.1	34.5	29.2	30.1	25.9	33.1
Or%	0.7	0.7	0.9	0.7	0.8	0.4	0.9

Analyst: M. Garcia

Table 3

Groundmass Clinopyroxene Compositions from Basalts Dredged from Gardner Pinnacles, Hawaiian Chain

	6-7-F		6-7-A	
	1	1	3	3
SiO_2	49.76	49.50	50.87	52.01
TiO_2	1.37	1.22	0.96	0.58
Al_2O_3	4.97	5.40	4.22	2.24
Cr_2O_3	0.75	0.75	0.60	0.39
FeO	7.32	8.06	7.54	8.05
MnO	0.13	0.18	0.17	0.21
MgO	15.90	16.83	16.85	18.41
CaO	19.92	18.09	19.05	17.52
Na_2O	0.30	0.31	0.28	0.22
K_2O	0.03	0.04	0.03	0.22
Total	100.45	100.38	100.57	99.65
Si	1.833	1.823	1.865	1.919
Al	.167	.177	.135	.081
Al	.049	.057	.048	.017
Ti	.038	.034	.027	.016
Cr	.022	.022	.017	.011
Fe	.226	.248	.231	.248
Mn	.004	.006	.005	.006
Mg	.873	.924	.921	1.012
Ca	.786	.714	.748	.692
Na	.022	0.22	.020	.015
K	.001	.002	.001	.001
Total	4.021	4.029	4.019	4.018
Ca:Fe:Mg	42:12:46	38:13:49	40:12:48	35:13:52

Analyst: M. Garcia

Table 4

Olivine Phenocryst Compositions from Basalts Dredged from Gardner Pinnacles, Hawaiian Chain

	6-7-F					6-7-A			
	Ph-Core 3	Strongly Inner	Zoned Rim Outer	Ph-Core 1	Ph-Rim 5	Ph-Rim 3	Ph-Core 3	Ph-Rim 3	Ph-Core 3
SiO_2	40.99	40.73	38.50	41.27	37.75	40.61	40.64	39.89	40.43
FeO	9.90	13.01	22.06	9.97	24.54	10.99	10.30	16.71	11.34
MnO	0.13	0.23	0.32	0.12	0.33	0.13	0.15	0.22	0.17
MgO	48.59	46.68	38.66	48.39	36.84	48.05	48.36	43.39	47.04
CaO	0.32	0.35	0.41	0.29	0.72	0.35	0.35	0.40	0.34
Total	99.93	101.00	99.95	100.04	100.18	100.13	99.80	100.61	99.32
					Based on Four Oxygens				
Si	1.005	1.002	1.001	1.010	.994	1.000	1.001	1.003	1.005
Fe	.203	.268	.480	.204	.540	.226	.212	.352	.236
Mn	.003	.005	.007	.002	.007	.003	.003	.005	.004
Mg	1.776	1.713	1.499	1.765	1.445	1.763	1.774	1.626	1.742
Ca	.008	.009	.011	.008	.020	.009	.009	.011	.009
Total	2.995	2.997	2.998	2.989	3.006	3.000	2.999	2.997	2.996
Fo%	89.2	85.9	75.0	89.1	71.8	88.2	88.8	81.5	87.5

Analyst: M. Garcia

Geochemistry

A total of 20 of the least altered samples were selected for major element chemical analyses: 13 from along the Hawaiian Ridge and 7 from four off-ridge seamounts. These results, C.I.P.W. norms and differentiation indexes (D.I.) are presented in Table 5. Differentiation index is defined as normative q + or + ab + ne + lc + kp + nl + c + z + th + nc. C.I.P.W. normative values were calculated using the Graphic Normative Analysis Program of R. W. Bowen (1971). The analyses were recalculated to 100%, water free and with the Fe_2O_3/ FeO ratio adjusted to 0.2 (Macdonald, 1969).

Whole-Rock Major Element Analyses

In general, lavas dredged from along the Hawaiian Ridge display higher MgO and CaO values and lower Na_2O and K_2O values than do lavas from the off-ridge seamounts. Except for the samples dredged from station HR 20-8, Hawaiian Ridge and off-ridge samples are similar in chemical composition to lavas from the principal Hawaiian Islands (Macdonald, 1949; Macdonald and Katsura, 1964; Macdonald, 1968). Exception are the low K_2O values for samples from dredge station MN 6-7 and the high P_2O_5 values for samples from dredge station HIG 51 and in sample 20-CC. Sample 20-CC is also noticeably higher in total iron and TiO_2 while sample 20-AA is lower in MnO than are typical Hawaiian lavas (Macdonald, 1968). The rock chemistry for samples 20-8-J and 20-8-O confirms that they are certainly differentiated rocks. However, they are noticeably higher in Al_2O_3, CaO, K_2O and TiO_2 and lower in total iron and MnO than are Hawaiian lavas of similar silica content.

Chemical analysis for Hawaiian Ridge and off-ridge seamount samples are plotted on an alkali-silica diagram (Figure 4) used to separate Hawaiian lavas of the tholeiitic and alkalic suites. Five of the samples from the Hawaiian Ridge (Points N, T, U, W and Z) plot near the boundary line dividing the two suites. Macdonald and Katsura (1962; 1964) and Beeson (1976) have noted that there appears to be a complete chemical gradation from lavas of the

Table 5

Whole-rock Major Element Analyses and C.I.P.W. Norms (Fe_2O_3 / FeO Adjusted to 0.2) for Selected Samples from Off-Ridge Seamounts

SAMPLE	34-18-B	34-18-C	65-24-A	65-24-D	33-17-A	20-8-J	20-8-O
SYMBOL	A	B	C	D	E	F	G
MAJOR ELEMENT ANALYSES							
SiO_2	45.65	46.90	49.70	50.10	46.75	57.65	57.35
Al_2O_3	17.90	17.26	17.57	16.80	16.98	18.67	18.28
Fe_2O_3	10.60	8.30	7.21	5.74	6.44	2.72	3.35
FeO	2.22	2.62	1.68	2.76	3.96	1.20	1.24
MgO	2.37	3.15	1.72	2.58	3.26	1.41	1.28
CaO	6.93	8.36	7.06	8.45	9.12	5.08	5.07
Na_2O	3.82	4.02	4.56	3.86	4.07	5.36	5.34
K_2O	1.89	1.39	2.94	3.70	2.10	4.63	4.49
TiO_2	3.44	2.96	2.56	3.19	2.66	1.09	1.10
P_2O_5	0.80	1.30	1.34	1.16	0.72	1.13	0.96
MnO	0.17	0.19	0.12	0.16	0.20	0.13	0.13
H_2O	3.88	3.06	3.27	0.97	3.23	0.55	0.87
CO_2	0.05	0.16	0.10	0.22	0.46	0.16	0.21
TOTALS	99.72	99.67	99.83	99.69	99.95	99.78	99.67
DRY ANALYSES NORMALIZED TO 100%							
SiO_2	47.65	48.61	51.53	50.85	48.57	58.19	58.17
Al_2O_3	18.69	17.89	18.22	17.06	17.64	18.85	18.54
Fe_2O_3	2.23	1.89	1.54	1.44	1.80	0.66	0.78
FeO	11.16	9.44	7.67	7.19	9.00	3.30	3.88
MgO	2.47	3.27	1.78	2.62	3.39	1.42	1.30
CaO	7.23	8.67	7.32	8.58	9.47	5.13	5.14
Na_2O	3.99	4.17	4.73	3.92	4.23	5.41	5.42
K_2O	1.97	1.44	3.05	3.76	2.18	4.67	4.55
TiO_2	3.59	3.07	2.65	3.24	2.76	1.10	1.12
P_2O_5	0.84	1.35	1.39	1.18	0.75	1.14	0.97
MnO	0.18	0.20	0.12	0.16	0.21	0.13	0.13
or	11.7	8.5	18.0	22.2	12.9	27.6	26.9
ab	32.2	35.3	35.9	26.4	23.9	44.9	44.9
an	27.3	25.8	19.5	17.8	22.7	13.4	12.8
ne	0.8	–	2.2	3.7	6.5	0.4	0.5
di wo	1.3	3.5	3.3	7.1	8.1	1.9	2.7
di en	0.4	1.5	1.1	3.4	3.5	0.9	1.1
di fs	0.9	2.0	2.2	3.6	4.5	1.0	1.6
hy en	–	–	–	–	–	–	–
hy fs	–	–	–	–	–	–	–
ol fo	4.0	4.7	2.3	2.2	3.4	1.8	1.5
ol fa	9.4	7.0	5.0	2.6	4.9	2.3	2.5
mt	3.2	2.7	2.2	2.1	2.6	1.0	1.1
il	6.8	5.8	5.0	6.1	5.2	2.1	2.1
ap	2.0	3.2	3.3	2.8	1.8	2.7	2.3
SALIC	71.94	96.64	75.64	70.14	65.92	86.35	85.13
FEMIC	28.06	30.36	24.36	29.86	34.08	13.65	14.87
D.I.	44.71	43.80	56.17	52.29	43.21	72.99	72.31

Table 5 (continued)

Whole-rock Major Element Analyses and C.I.P.W. Norms (Fe_2O_3/FeO Adjusted to 0.2) for Selected Samples from the Hawaiian Ridge

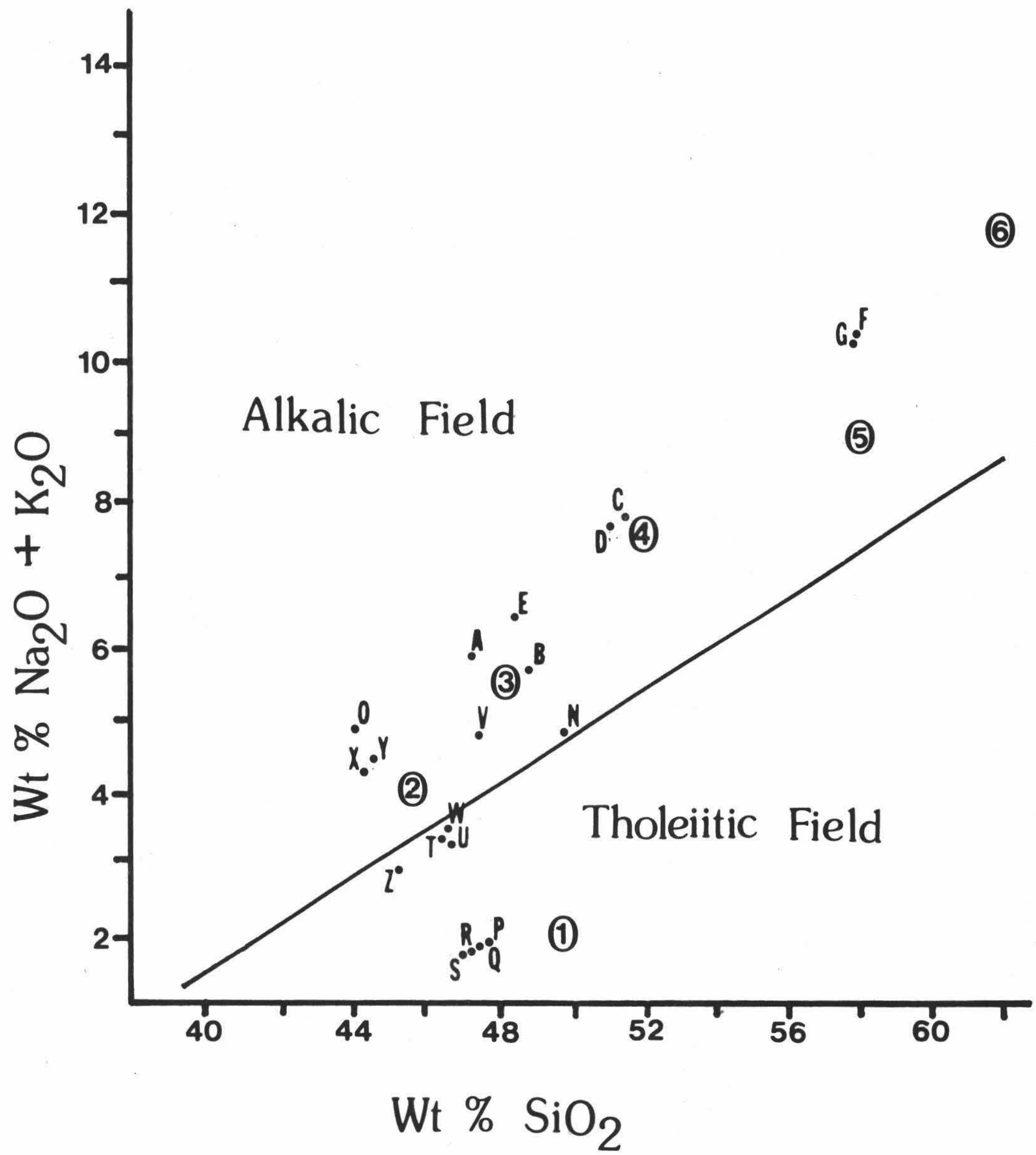
SAMPLE	20-AA	20-CC	6-7-A	6-7-B	6-7-D	6-7-F	37-A
SYMBOL	N	O	P	Q	R	S	T
MAJOR ELEMENT ANALYSES							
SiO_2	48.30	43.15	46.40	46.65	46.35	46.30	44.90
Al_2O_3	16.62	16.16	10.61	10.68	10.66	10.54	14.72
Fe_2O_3	7.67	14.28	2.67	2.81	2.79	2.22	4.28
FeO	2.92	1.60	8.74	8.88	9.16	9.42	7.64
MgO	3.95	2.78	16.05	16.05	15.80	16.95	9.60
CaO	9.45	8.64	8.70	8.92	8.89	8.77	9.76
Na_2O	3.43	3.45	1.74	1.76	1.74	1.73	2.53
K_2O	1.06	1.38	0.16	0.11	0.10	0.10	0.64
TiO_2	2.59	4.69	1.68	1.70	1.65	1.66	2.32
P_2O_5	0.42	1.30	0.26	0.14	0.12	0.19	0.36
MnO	0.07	0.29	0.17	0.17	0.18	0.17	0.17
H_2O	3.47	1.89	2.73	2.01	2.17	1.70	2.96
CO_2	0.03	0.06	0.01	0.01	–	0.04	0.04
TOTALS	99.98	99.67	99.92	99.89	99.61	99.79	99.94
DRY ANALYSES NORMALIZED TO 100%							
SiO_2	50.06	44.16	47.75	47.68	47.58	47.24	46.31
Al_2O_3	17.23	16.54	10.92	10.91	10.94	10.75	15.21
Fe_2O_3	1.83	2.71	1.96	1.99	2.04	1.98	2.05
FeO	9.15	13.54	9.95	10.22	9.89	10.25	10.55
MgO	4.09	2.84	16.52	16.40	16.22	17.29	9.90
CaO	9.79	8.84	8.95	9.11	9.12	8.94	10.07
Na_2O	3.56	3.53	1.79	1.80	1.79	1.76	2.61
K_2O	1.10	1.41	0.16	0.11	0.10	0.10	0.66
TiO_2	2.68	4.80	1.73	1.74	1.69	1.69	2.39
P_2O_5	0.44	1.33	0.27	0.14	0.12	0.19	0.37
MnO	0.07	0.30	0.17	0.10	0.18	0.17	0.18
or	6.5	8.3	1.0	0.6	0.6	0.6	3.9
ab	30.1	26.7	15.2	15.2	15.1	14.9	21.5
an	27.8	25.1	21.3	21.4	21.5	21.1	27.8
ne	–	1.7	–	–	–	–	0.3
di wo	7.5	4.2	8.9	9.6	9.6	9.2	8.2
di en	3.5	1.4	6.1	6.5	6.5	6.3	5.0
di fs	3.8	3.0	2.1	2.3	2.3	2.1	2.8
hy en	3.3	–	13.7	12.5	12.2	11.5	–
hy fs	3.5	–	4.6	4.3	4.4	3.7	–
ol fo	2.4	4.0	14.9	15.3	15.2	17.7	13.8
ol fa	2.8	9.5	5.5	5.8	6.1	6.4	8.3
mt	2.7	3.9	2.8	2.9	3.0	2.9	3.0
il	5.1	9.1	3.3	3.3	3.2	3.2	4.5
ap	1.0	3.1	0.6	0.3	0.3	0.4	0.9
SALIC	64.41	61.86	37.38	37.24	37.26	36.62	53.56
FEMIC	35.59	38.14	62.62	62.76	62.74	63.38	46.44
D.I.	36.62	36.74	16.09	15.88	15.74	15.48	25.72

Table 5 (continued)

Whole-rock Major Element Analyses and C.I.P.W. Norms (Fe_2O_3/FeO Adjusted to 0.2) for Selected Samples from the Hawaiian Ridge

SAMPLE	37-C	41-A	41-B	51-A	51-D	9-11
SYMBOL	U	V	W	X	Y	Z
MAJOR ELEMENT ANALYSES						
SiO_2	45.20	45.95	45.10	42.60	43.30	44.40
Al_2O_3	14.53	15.26	14.48	13.32	13.14	10.56
Fe_2O_3	4.42	6.79	4.46	4.40	5.42	3.86
FeO	7.82	6.34	7.58	10.38	9.36	9.14
MgO	9.44	4.70	9.55	5.72	5.43	16.63
CaO	9.51	8.58	9.76	8.91	9.24	7.13
Na_2O	2.42	3.41	2.56	3.29	3.27	2.09
K_2O	0.58	1.27	0.65	0.86	1.08	0.68
TiO_2	2.28	3.92	2.32	3.84	3.78	2.40
P_2O_5	0.35	0.63	0.36	2.97	2.91	0.41
MnO	0.17	0.21	0.18	0.20	0.21	0.19
H_2O	2.87	2.82	2.70	3.17	2.52	2.67
CO_2	0.15	0.05	0.08	0.07	0.12	0.02
TOTALS	99.74	99.93	99.78	99.73	99.78	100.18
DRY ANALYSES NORMALIZED TO 100%						
SiO_2	46.73	47.34	46.49	44.15	44.56	45.55
Al_2O_3	15.02	15.72	14.93	13.80	13.53	10.83
Fe_2O_3	2.11	2.26	2.07	2.55	2.54	2.22
FeO	10.55	11.27	10.34	12.77	12.68	11.12
MgO	9.76	4.84	9.85	5.93	5.59	17.06
CaO	9.83	8.84	10.06	9.23	9.51	7.31
Na_2O	2.50	3.51	2.64	3.41	3.37	2.14
K_2O	0.60	1.31	0.67	0.89	1.11	0.70
TiO_2	2.36	4.04	2.39	3.98	3.89	2.46
P_2O_5	0.36	0.65	0.37	3.08	3.00	0.42
MnO	0.18	0.22	0.19	0.21	0.22	0.19
or	3.5	7.7	4.0	5.2	6.5	4.1
ab	21.1	29.7	22.0	28.8	28.5	18.1
an	28.0	23.3	26.9	19.7	18.5	17.9
ne	–	–	0.2	–	–	–
di wo	7.7	6.8	8.6	2.5	3.8	6.5
di en	4.6	3.3	5.2	1.2	1.8	4.5
di fs	2.7	3.4	2.9	1.2	1.9	1.6
hy en	3.1	0.2	–	4.9	3.9	4.0
hy fs	1.8	0.2	–	5.0	4.3	1.4
ol fo	11.6	6.0	13.5	6.1	5.7	23.8
ol fa	7.4	6.9	8.3	6.9	6.9	9.2
mt	3.1	3.3	3.0	3.7	3.7	3.2
il	4.5	7.7	4.5	7.5	7.4	4.7
ap	0.9	1.5	0.9	7.3	7.1	1.0
SALIC	52.69	60.71	53.03	53.83	53.59	40.12
FEMIC	47.31	39.29	46.97	46.17	46.41	59.88
D.I.	24.70	37.44	26.12	34.11	35.08	22.24

Figure 4. Alkali-silica diagram of selected samples from along the Hawaiian Ridge and selected off-ridge seamounts. Symbols are from Table 2. 1 = Tholeiite, 2 = Alkalic Basalt, 3 = Hawaiite, 4 = Mugearite, 5 = Benmoreite, 6 = Soda Trachyte. Modified from Macdonald and Katsura (1964).


Wt % Na_2O + K_2O
14
12
10
8
6
4
2
Alkalic Field
Tholeiitic Field
40
44
48
52
56
60
Wt % SiO_2
G
F
⑥
⑤
C
D
④
E
A
B
③
O
V
N
X
Y
②
W
T
U
Z
R
P
S
Q
①

tholeiitic suite to those of the alkalic suite and rocks transitional between the two suites commonly occur.

Differentiation within the alkalic suite is illustrated by the Coombs and Wilkinson (1969) diagram of differentiation index versus normative plagioclase composition (Figure 5). Samples from the Hawaiian Ridge and off-ridge seamounts (except for Points P, Q, R and S which plot well within the tholeiitic field on Figure 4) have been plotted on this diagram. Except for N, which plots in the hawaiite field, samples which plotted near the tholeiitic-alkalic boundary line on Figure 4 plot in a separate area than the remaining alkalic samples. Samples F and G, which plot near the trachyte-benmoreite boundary, are the anomalous samples from the off-ridge seamount southwest of Salmon Bank.

REE Analyses

Five samples were selected for REE, Li, K, Rb, Sr and Ba analysis: four from along the Hawaiian Ridge and one from the off-ridge seamount 140 km southwest of Salmon Bank. The results of these analyses are presented in Table 6. Chondrite-normalized REE abundances for each sample are plotted against atomic number in Figure 6.

The sample dredged from the northern edge of Gardner Pinnacles (6-7-F) has REE distributions similar to those of tholeiites from other recent Hawaiian volcanoes (e.g. Mauna Loa and Kilauea), although the sample has less relative fractionation of the light and middle REE Ce to Tb (Dalrymple et al., 1977; Leeman et al., 1977, 1979). Except for samples 51-A and 20-8-J, the remaining samples have REE distribution patterns which fall within the range of values for Hawaiian lavas of the alkalic and nephelinic suites (Jackson et al., in press; Clague et al., 1977). Sample 51-A has slightly higher middle to heavy REE values than do most Hawaiian lavas whereas sample 20-8-J shows strong enrichment in the light REE Ce through Sm.

Figure 5. Diagram of differentiation index versus normative plagioclase composition showing differentiation within the alkalic suite. Symbols are from Table 2. Modified from Coombs and Wilkinson (1969).

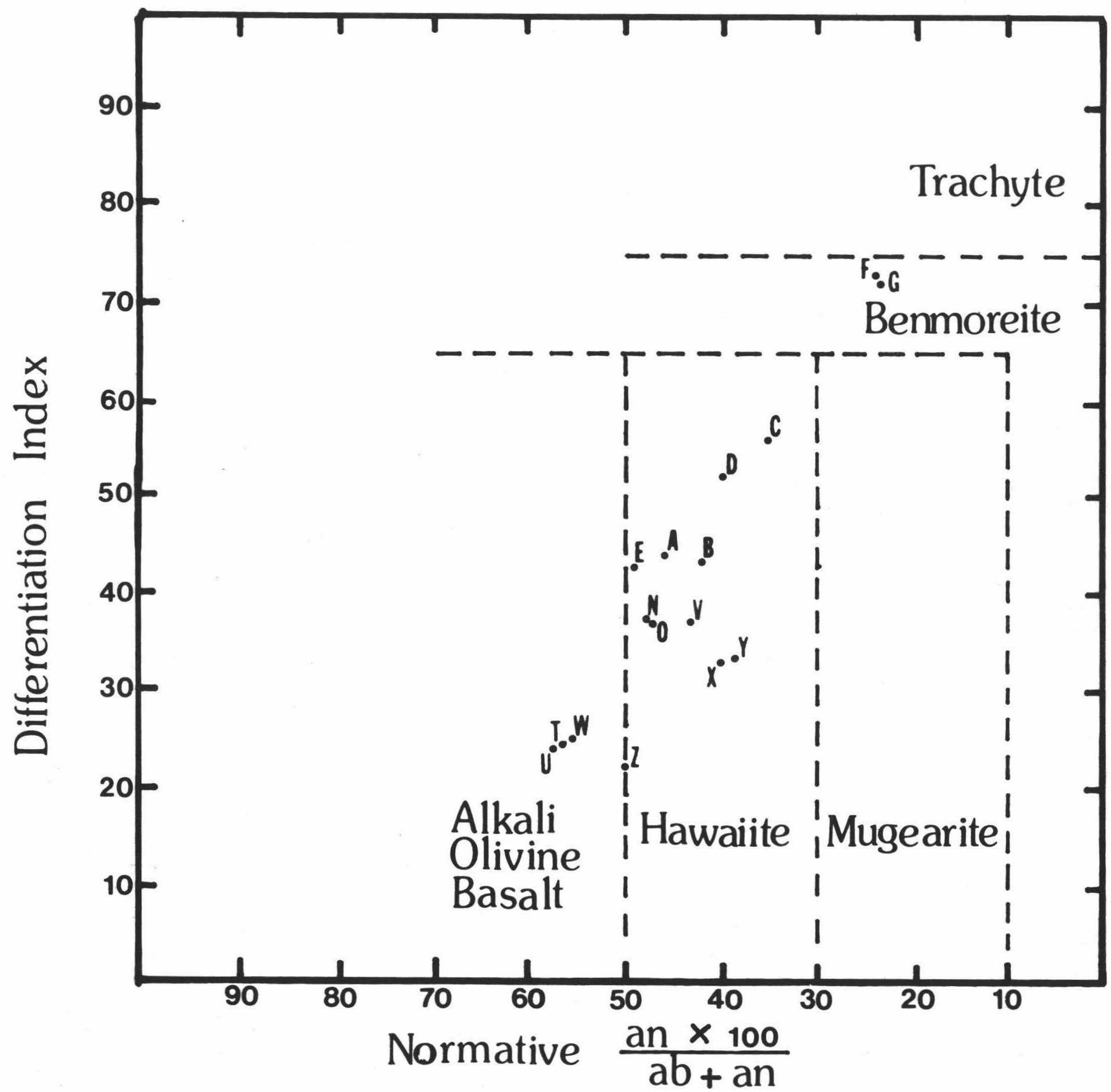

Trachyte
Benmoreite
Alkali Olivine Basalt
Hawaiite
Mugearite
Differentiation Index
Normative $\frac{an \times 100}{ab + an}$
F G C D E A B N O V X Y T W U Z
90 80 70 60 50 40 30 20 10

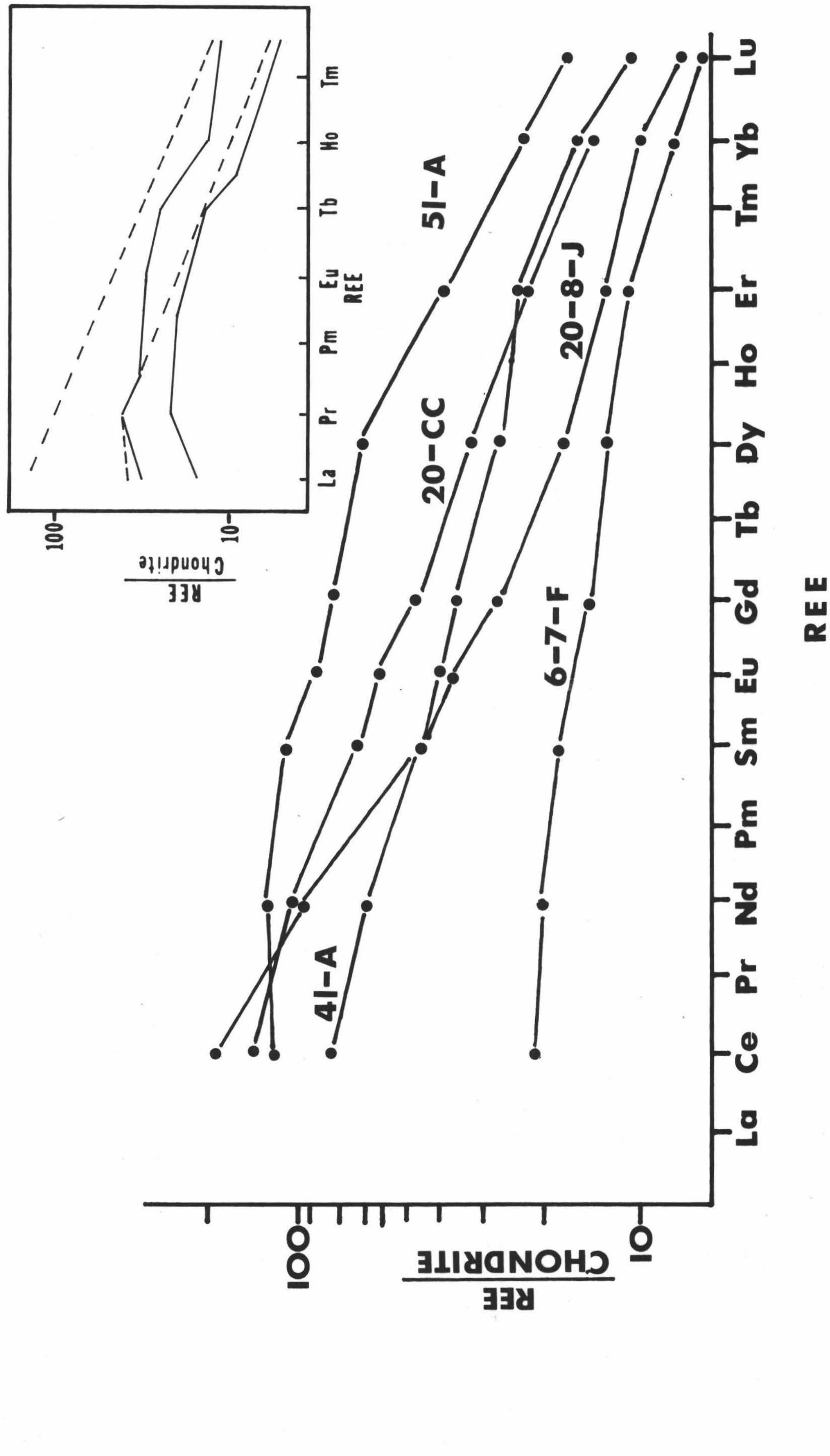
Table 6

REE Abundances of Dredged Volcanic Rocks from along the Hawaiian Ridge (ppm by wt.)

	Sample				
Element	**6-7-F**	**41-A**	**20-CC**	**51-A**	**20-8-J**
Li	6.44	10.1	13.2	11.3	14.3
K	1,060	10,600	10,900	6,800	34,800
Rb	0.915	24.7	20.3	10.5	95.6
Sr	217	736	1,210	828	965
Ba	74.6	340	470	230	9,400
Ce	18.4	70	108	104	157
Nd	12.8	41.6	61.7	81.4	60.3
Sm	3.54	9.5	12.2	22.3	9.52
Eu	1.24	3.21	4.16	7.17	2.84
Gd	3.99	–	11.2	–	7.5
Dy	4.16	8.9	9.25	22.0	5.7
Er	–	4.4	3.7	–	2.53
Yb	1.67	3.02	2.4	4.0	2.12
Lu	0.230	0.38	–	0.56	0.273

Analyst: C. Noble

Figure 6. Chondrite-normalized rare-earth element distribution for selected volcanic rocks from along the Hawaiian Ridge and one off-ridge seamount. Symbols are from Table 6. Insert shows fields for Hawaiian tholeiitic rocks (solid lines) and alkalic rocks (dashed lines). Modified from Hubbard (1969).



REE / Chondrite
100
10
La
Pr
Pm
Eu
Tb
Ho
Tm
REE
51-A
20-CC
20-8-J
6-7-F
41-A
REE / CHONDRITE
100
10
La
Ce
Pr
Nd
Pm
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
REE

Geochronology

Seven samples were chosen for conventional potassium-argon age determinations: five samples representing four locations along the Hawaiian Ridge and two samples from two selected off-ridge seamounts. All age determinations were calculated using the new ^{40}K decay and abundance constants recommended by the IUGS Subcommission of Geochronology (Steiger and Jager, 1977) and all other ages referenced to or utilized in this thesis have been converted to these new constants (Dalrymple, 1979).

Previous Work

A total of 21 volcanic shields along the Hawaiian Ridge have been dated by conventional potassium-argon and/or argon-argon dating methods. McDougall (1963; 1964; 1969; 1979) pioneered the work on the principal Hawaiian Islands and provided dates for Haleakala, West Maui, East and West Molokai, Waianae, and Kauai. Other volcanic shields thus far dated include Kohala (McDougall and Swanson, 1972), Lanai (Bonhommet et al., 1977) and Koolau (Doell and Dalrymple, 1973). Dalrymple et al. (1974) provided ages for Nihoa and Necker Islands and French Frigate Shoal along the Western Hawaiian Ridge. Dalrymple et al. (1977) dated alkalic basalts from Midway Island and Clague et al. (1975) presented dates for Pearl and Hermes Reef and two unnamed seamounts northwest of Midway Island. Dalrymple et al. (in prep.) dated lavas from Northampton and Laysan Island. A summary of available K-Ar age data pertaining to the Hawaiian Ridge is presented in Table 7.

New Work

This work reports new K-Ar age determinations for four previously undated volcanic centers along the Hawaiian Ridge and from two unnamed off-ridge seamounts 500 km northwest of Midway Islands and 140 km southwest of Salmon Bank. Results of the potassium-argon calculations are summarized in Table 8. The two samples from the off-ridge seamounts

Table 7

Summary of the Potassium-Argon Data for the Shield-Building Phase of Volcanism along the Hawaiian Ridge

Volcano	Distance From Kilauea (km)	Average Age of Shield-Building Volcanism (m.y.)	Source
Kilauea	0	0	–
Kohala	90	0.39 ± 0.04	McDougall and Swanson (1972)
Mauna Kea	54	0.375 ± 0.05	Porter (1977)
Haleakala	180	$>$0.89	McDougall (1964)
West Maui	220	1.32 ± 0.02	McDougall (1964)
Lanai	235	1.33 ± 0.06	Bonhommet et al. (1977)
East Molokai	255	1.52	McDougall (1964)
West Molokai	280	1.89	McDougall (1964)
Koolau	360	2.31 ± 0.29	McDougall (1964 Doell and Dalrymple (1973)
Waianae*	375	3.35 ± 0.31	McDougall (1964, 1979) Doell and Dalrymple (1973)
Kauai	530	4.43 ± 0.45	McDougall (1964, 1979)
Niihau	565	5.5 ± 0.2	Dalrymple (in press)
Nihoa	800	7.2 ± 0.3	Dalrymple et al. (1974)
Necker	1080	10.3 ± 0.4	Dalrymple et al. (1974)
La Perouse Pinnacles (French Frigate Shoal)	1240	12.0 ± 0.4	Dalrymple et al. (1974)
Northampton	1935	26.6 ± 2.7	Dalrymple et al. (in prep.)
Laysan	2129	19.9 ± 0.3	Dalrymple et al. (in prep.)
Pearl and Hermes Reef	2260	20.6 ± 0.5	Clague et al. (1975)
Midway	2430	27.7 ± 0.6	Dalrymple et al. (1977)
Unnamed Seamount	2585	28.0 ± 0.4	Clague et al. (1975)
Unnamed Seamount	2820	27.4 ± 0.5	Clague et al. (1975)

**Lower and middle members only.*

Table 8

Potassium-Argon Age Measurements on Samples from the Western Hawaiian Ridge and Selected Off-Ridge Seamounts*

Sample	K_2O (Wt. %)**	Argon: Wt. (grams)	Argon: ^{40}Ar (Rad) (10^{-11} mol/gram)	Argon: $\frac{^{40}Ar\ (Rad)}{Ar\ (Total)} \times 100$	Calculated Age (m.y.)***
6-7-F	0.0793 ± 0.0002	4.003	1.964	8.0	15.9 ± 1.0
37-A	0.3940 ± 0.0091	4.002	9.901	20.9	16.2 ± 1.3
37-C	0.453 ± 0.0005	4.006	9.437	18.9	13.4 ± 0.8
41-A	0.895 ± 0.014	4.007	24.50	38.1	17.6 ± 0.5
51-A	0.6566 ± .0013	3.012	89.2	19.8	10.12 ± 0.6
65-24-A	2.550 ± 0.38	1.002	19.5	84.2	111.7 ± 2.7
20-8-J	3.775 ± 0.72	1.003	72.4	96.3	110.3 ± 3.1

* Analyses made in the laboratory of J. J. Naughton, Hawaii Institute of Geophysics.

** Mean and range of two measurements.

*** Data has been converted to new decay constants $\lambda_{\epsilon} = 0.581 \times 10^{-10}\ yr^{-1}$; $\lambda_{\beta} = 4.962 \times 10^{-10}\ yr^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$ mol. Errors are estimates of standard deviation of precision.

(samples 65-24-A and 20-8-J) yielded ages of 111.3 $\pm$ 2.7 m.y. and 110.3 $\pm$ 3.1 m.y. respectively. These ages are considerably older than are ages predicted by the 'hot spot' hypothesis for volcanic centers of similar distances from Kilauea volcano. The ages are consistent, however, with Mesozoic magnetic anomaly ages obtained for the oceanic crust of the Pacific basin in those areas (Larson and Chase, 1972; Larson and Pitman, 1972; Clague, 1974).

The K-Ar ages for samples dredged from along the Hawaiian Ridge are plotted as a function of distance from Kilauea in Figure 7 along with all available data on ages for volcanic centers along the Hawaiian Ridge. In general the age of individual volcanic centers along the Hawaiian Ridge increases to the northwest, although the increase in age is not exactly linear and the scatter of the ages becomes more noticeable northwest of French Frigate Shoal. The sample from Brooks Banks (sample 41-B) yielded an age noticeably older than would be predicted by the 'hot spot' hypothesis for that location.

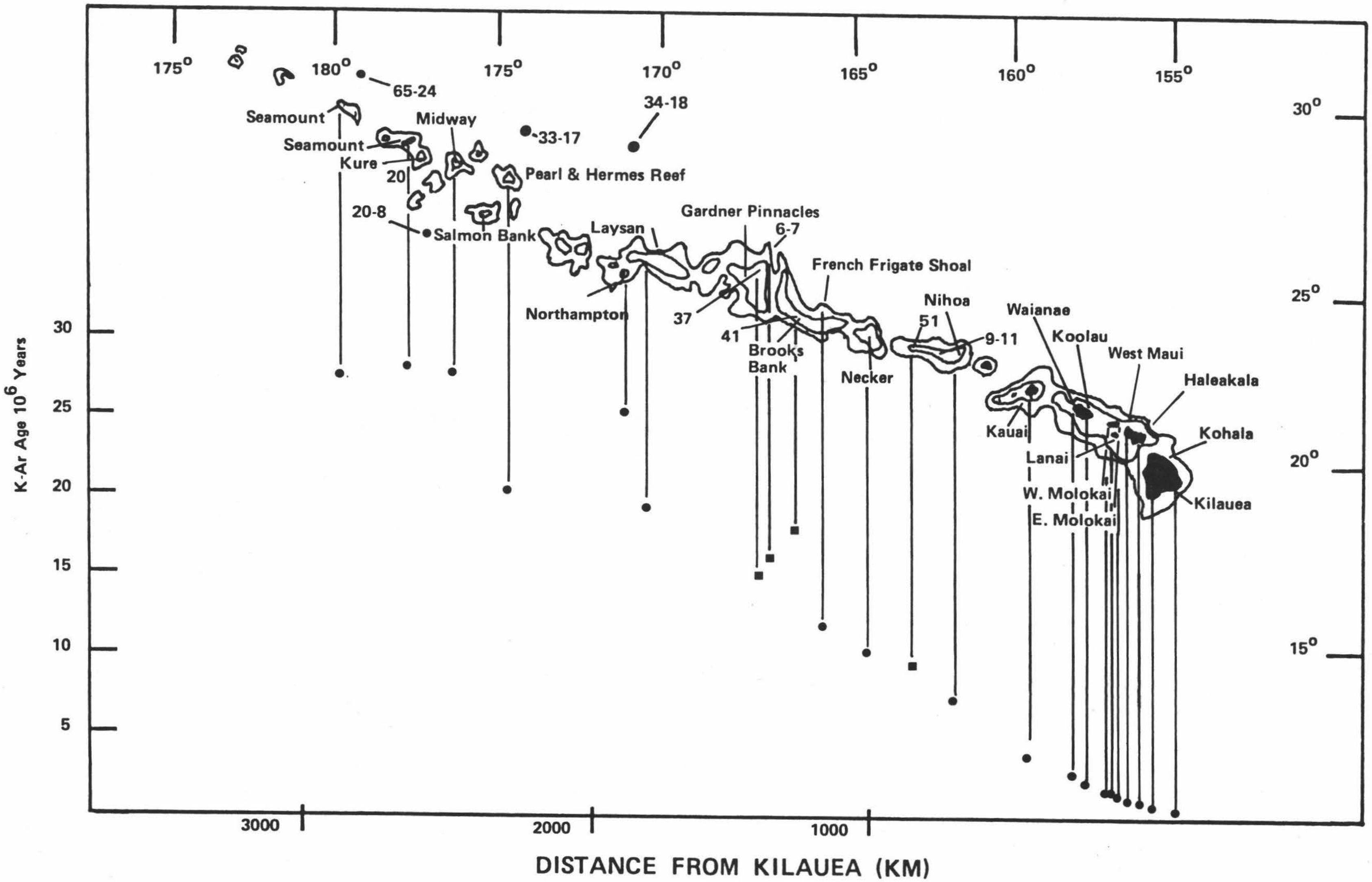
Discussion

Off-Ridge Seamounts

The two samples dredged from the off-ridge seamount 140 km southwest of Salmon Bank (Station HR 20-8) are differentiated rocks but are not similar to lavas found on Hawaiian volcanoes. On the basis of petrography and rock chemistry (Figure 5) the samples are classified as hornblende benmoreites. The volcanic rocks dredged from the remaining off-ridge seamounts (Stations KK 65-24, HR 33-17 and HR 34-18) are hawaiites based on rock chemistry (Figure 5) and petrography. These samples are similar to Hawaiian lavas of the alkalic-cap stage of volcanism.

Radiometric age determinations show that samples 20-8-J and 65-24-A are 110.3 $\pm$ 3.1 and 111.7 $\pm$ 2.7 m.y. in age, much older than ages predicted for volcanic edifices at these locations by the 'hot spot' hypothesis. Magnetic anomaly studies and paleontologic evidence

Figure 7. Map showing age distribution along the Hawaiian Ridge as a function of distance from Kilauea. Ages represented by solid circles are from McDougall (1979) and Dalrymple et al. (in prep.). Ages represented by solid squares are new data.



175°
180°
175°
170°
165°
160°
155°
65-24
34-18
Seamount
Seamount
Midway
33-17
Kure
20
Pearl & Hermes Reef
20-8
Salmon Bank
Laysan
Gardner Pinnacles
6-7
French Frigate Shoal
Northampton
37
41
Brooks Bank
Nihoa
51
9-11
Necker
Waianae
Koolau
West Maui
Haleakala
Kohala
Kauai
Lanai
W. Molokai
E. Molokai
Kilauea
30°
25°
20°
15°
K-Ar Age 10^6 Years
30
25
20
15
10
5
3000
2000
1000
DISTANCE FROM KILAUEA (KM)

from sediments directly overlying basalt basement show the surrounding ocean floor of the Pacific basin near the extreme western portion of the Hawaiian Ridge to be 116 to 144 m.y. old (Larson and Chase, 1972; Larson and Pitman, 1972; Scientific staff, 1973). Two samples dredged from Wentworth Seamount 60 km northwest of Midway Island yielded minimum K-Ar ages of 71 $\pm$ 5.0 m.y. in that area (Clague and Dalrymple, 1979). Therefore, the most likely interpretation for samples from dredge stations HR 20-8 and KK 65-24 is that the lavas are from seamounts constructed on the floor of the Pacific basin more than 100 m.y. ago and are not part of the Hawaiian Ridge. Based on their distance from the Hawaiian Ridge, a similar origin for the remaining two off-ridge seamounts (Stations HR 33-17 and HR 34-18) might be hypothesized. Rocks from these stations, however, were too altered for K-Ar age determinations. Therefore, the relation of these seamounts to the Hawaiian Ridge is uncertain.

Hawaiian Ridge Seamounts

The thirteen samples dredged from along the Hawaiian Ridge are from six volcanic centers. Four samples collected from the northern edge of Gardner Pinnacles (Station MN 6-7) are tholeiitic olivine basalts based on groundmass clinopyroxene compositions (Table 3), petrography, rock chemistry (Figure 4) and REE patterns (Figure 6). K_2O contents for these samples are the lowest ($<$0.17%) of any tholeiitic basalt yet recovered from along the Western Hawaiian Ridge and are near the range of values for ocean floor tholeiites (Hubbard, 1969). Tholeiitic basalts of similar K_2O contents, however, have been reported among the older, exposed, lower shield-building lavas of the Pololu Group on Kohala volcano (Macdonald and Katsura, 1964). Dalrymple et al. (1974) reported alkalic basalts from Gardner Pinnacles and interpreted them as representing an alkalic capping on a tholeiitic shield. The samples from dredge station MN 6-7, reported in this work, confirm the presence of tholeiites at Gardner Pinnacles.

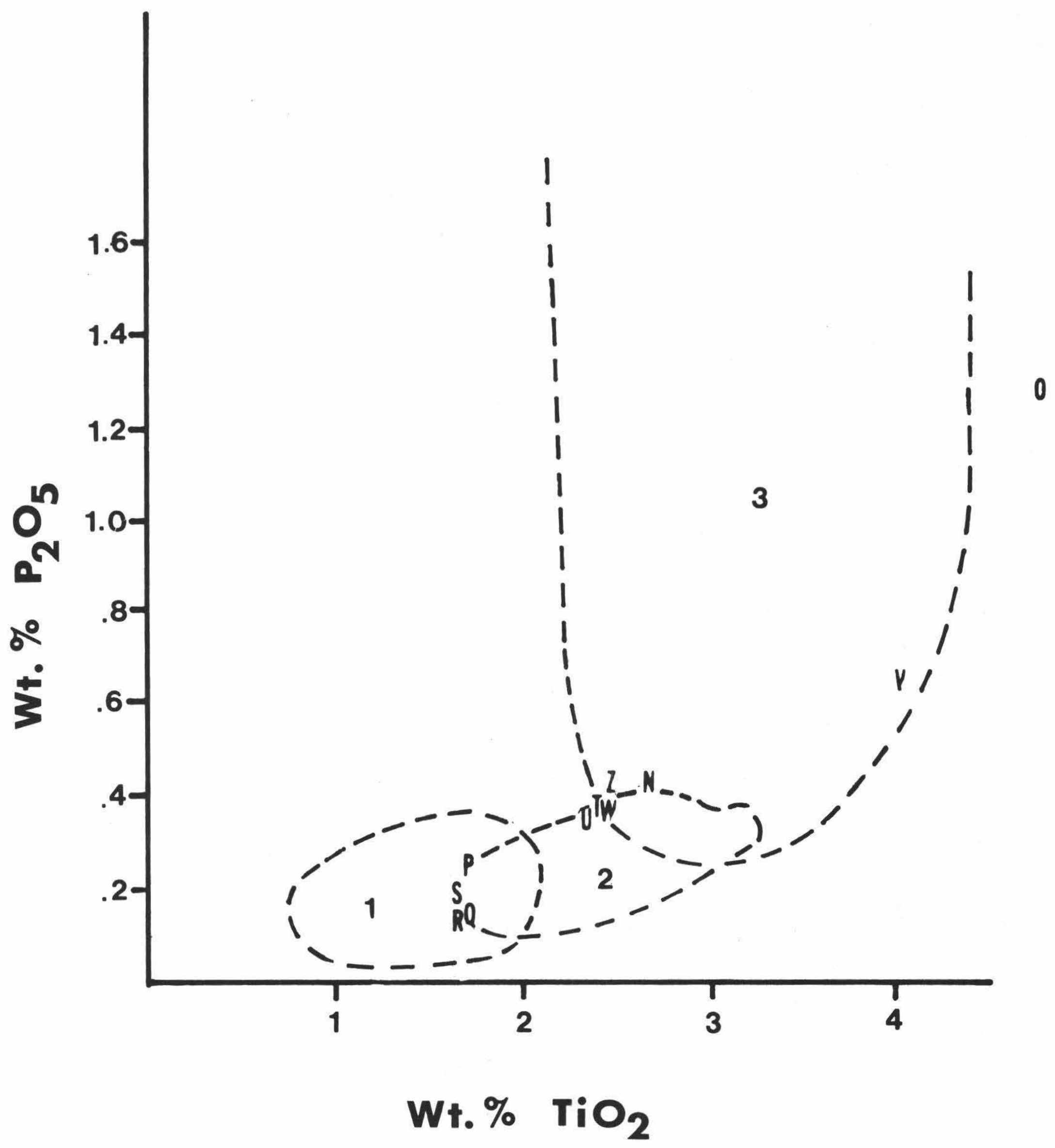
Two additional samples were recovered from Gardner Pinnacles (Station HIG 37). On an alkali-silica diagram, these samples plot just within the tholeiitic field (Points T and U on Figure 4). Sample 37-C (U) contains normative hypersthene but sample 37-A (T) has 0.3% normative nepheline. Both samples contain titaniferous augite and modal andesine rather than labradorite which suggests that the lavas have alkaline affinities. Both of these samples are somewhat altered and contain almost 3wt% H_2O.

Certain stable minor elements preserve their primary concentrations and ratios even in altered volcanic rocks, and these elements can be of assistance in identifying basaltic suites (Kay et al., 1970; Hart, 1971; Floyd and Winchester, 1975; Pearce and Cann, 1973; Bass et al., 1973). One such discriminant plot is that of P_2O_5 versus TiO_2 in weight percent (Figure 8). The fields in Figure 8 are from Bass et al. (1973). The magmatic affinity of the samples from station HIG 37 cannot be confirmed as both samples plot very near the boundary separating the two suites. Macdonald and Katsura (1964) have noted that there is a complete chemical gradation between rocks of the tholeiitic and alkalic suites in Hawaiian lavas. Beeson (1976) confirmed that such a gradation from transitional tholeiitic to alkalic to strongly alkalic lavas does exist in lavas of the East Molokai Group. Therefore, in the absence of more definitive criteria, samples from dredge station HIG 37 are classified as transitional basalts, i.e. basalts which display characteristics of both tholeiitic and alkalic basalts.

Two samples dredged from station HIG 20 (Figure 3) are classified as alkalic basalts based on petrography and REE abundances (Figure 6). On Figure 5 the samples plot just within the hawaiite field (Points N and O). They are alkalic basalts, however, on the basis of modal labradorite over andesine. Sample 20-CC is anomalously higher in total iron ($>$16%), TiO_2 (4.8%) and P_2O_5 (1.33%) and noticeably lower in MgO (2.8%) than typical Hawaiian alkalic lavas (Macdonald, 1968).

Two samples were dredged from station HIG 41 (Figure 3). Sample 41-A is a hawaiite

Figure 8. Plot of P_2O_5 versus TiO_2 for selected samples along the Hawaiian Ridge. Symbols are from Table 5. Fields are as follows: 1 = Ocean Floor Basalts, 2 = Ocean Island Tholeiites, 3 = Alkalic Basalts. Modified from Bass et al., 1973.


1.6
1.4
1.2
1.0
.8
.6
.4
.2
Wt. % P_2O_5
1
2
3
4
Wt. % TiO_2
0
3
V
Z
N
D
T
W
P
S
R
Q
1
2

based on petrography and rock chemistry (Figure 5). REE abundances (Figure 6) confirm that the sample is alkalic. Sample 41-B has characteristics of both tholeiitic and alkalic basalts as do samples from dredge station HIG 37. It plots just within the tholeiitic field on an alkali-silica diagram (Point W on Figure 4) yet contains titaniferous augite and groundmass olivine in the mode. On a P_2O_5 versus TiO_2 diagram (Figure 8), sample 41-B plots at the same point as sample 37-A. Thus, utilizing the same criteria as used to classify the samples from dredge station HIG 37, sample 41-B is transitional basalt.

Two samples dredged from station HIG 51 (Figure 3) are classified as hawaiites based on petrography and rock chemistry (Figure 5). REE abundances (Figure 6) confirm that the samples are alkalic. Both samples are noticeably higher in total iron, probably due to the high (>20%) magnetite content, and in P_2O_5 (>3wt%) than are typical lavas of the Hawaiian alkalic suite. Macdonald (1968) has noted that, within the alkalic suite, phosphorus tends to reach maximum concentrations in mugearites. These samples, however, are hawaiites on the basis of modal andesine over oligoclase and the P_2O_5 values for station HIG 51 samples are much higher than phosphorus values for any Hawaiian mugearite (Macdonald, 1968). More than likely, the extremely high P_2O_5 values for station HIG 51 samples result from the fact that the small islets along the Hawaiian Ridge in this area are popular resting places for birds (Dalrymple et al., 1974).

The single analyzed sample dredged from station MN 9-11 is classified as transitional basalt. On an alkali-silica diagram the sample plots within the tholeiitic field (Point Z on Figure 4). However, the sample contains groundmass olivine and titaniferous augite. On a plot of P_2O_5 versus TiO_2, the sample plots just within the alkalic field near the tholeiitic boundary. The unusually high MgO content is probably due to the abundance of olivine pseudomorph in the sample.

The Hawaiian Ridge samples selected for K-Ar age determinations include tholeiitic basalts, hawaiites, and transitional basalts. The age difference between the tholeiitic shield-building climax and the alkalic-cap stage of volcanism is on the order of 2×10^5 yr. for Hawaiian volcanoes (McDougall, 1964; Funkhouser et al., 1968; McDougall and Swanson, 1972; Doell and Dalrymple, 1973; and Porter et al., 1977). Thus all of the age determinations for alkalic and transitional basalts presented in this study probably date upper shield-building lavas for each volcanic center within analytical uncertainties of the age measurements.

The ages obtained from Gardner Pinnacles (Stations HIG 37 and MN 6-7) and from the unnamed seamount halfway between Necker and Nihoa Islands (Station HIG 51) are generally consistent with the age progression northwest along the Hawaiian Ridge as predicted by the 'hot spot' hypothesis (Figure 7). The age determination for Brooks Bank (Station HIG 41) is noticeably older than would be expected for the volcanic center at that location. Although the samples were selected on the basis of freshness, the possibility still exists that some radiogenic argon has been lost and/or absorption of potassium from sea water has occurred (Dalrymple and Lanphere, 1969; Jarrard and Clague, 1977).

The age data presented in this thesis and plotted on Figure 7 fill in some of the gaps which existed in the data along the Hawaiian Ridge and generally support a quasi-linear trend of increasing age with distance from Kilauea volcano at least as far northwest as French Frigate Shoal. Nevertheless, there is considerable scatter of ages from a simple linear trend for volcanic centers northwest of French Frigate Shoal. Whether this implies a non-linear trend of volcanism along the Hawaiian Ridge or is the result of alteration of the dated samples is uncertain.

KAULA ISLAND

Regional Geologic Setting

Kaula Island, a crescent shaped eroded remnant of a tuff cone, is located approximately 33 km west-southwest of the island of Niihau, Hawaiian Volcanic Chain (Figure 9). Situated near the southeast edge of a 43 km^2 shoal, the island occupies approximately 55 ha and reaches a maximum elevation of 165 meters above sea level (Palmer, 1936). The shoal forms the southwest end of a west-southwest trending ridge which includes the islands of Niihau and Kauai (Figure 10). This ridge trends obliquely to the west-northwest trend of the Hawaiian Ridge. Uninhabited, except for numerous large bird colonies, the island is currently being used by the U.S. Navy and U.S. Marine Corps as a target for bombing.

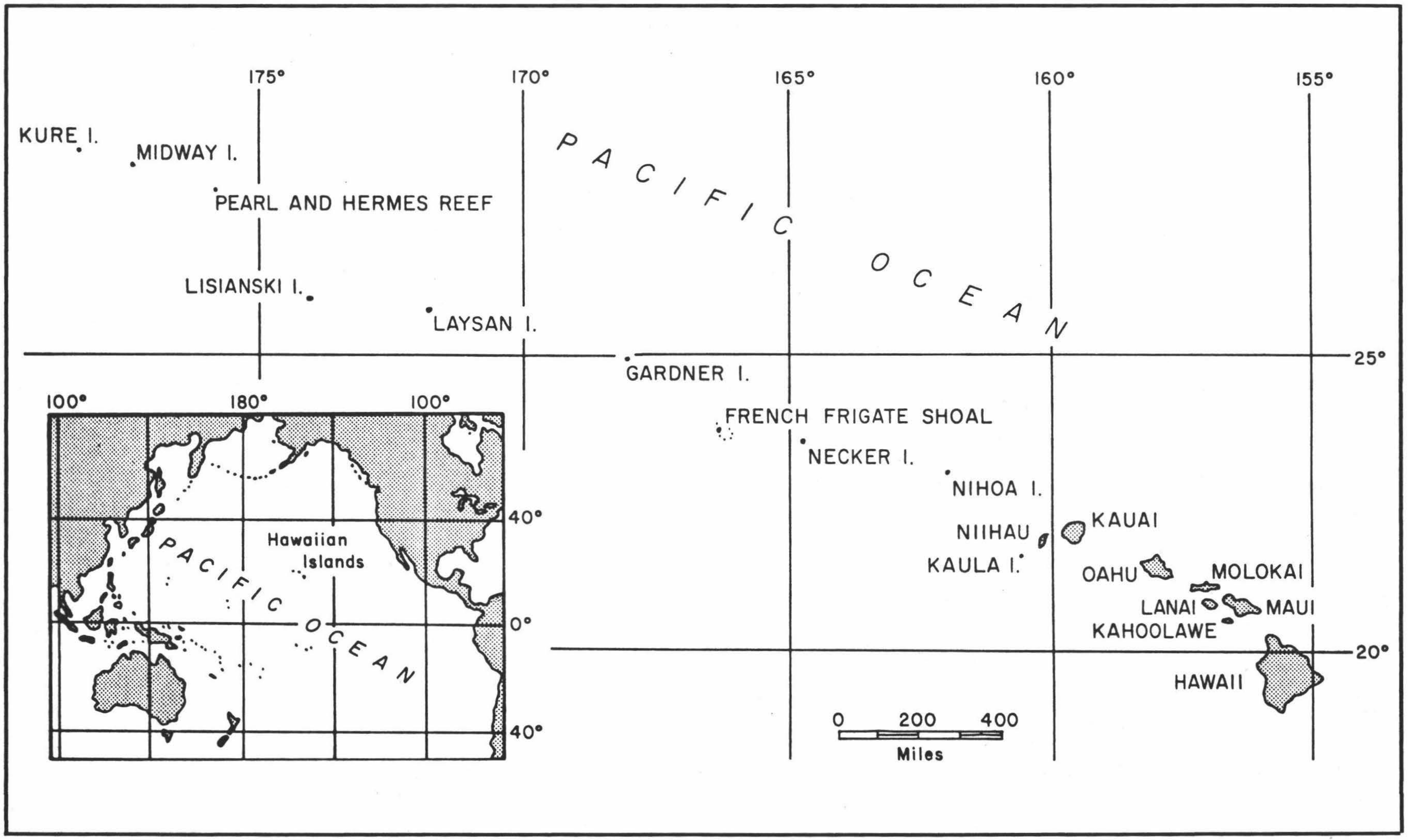
Previous Work

Relatively little information exists on the geology of Kaula Island. Palmer (1927, 1936) published the first general descriptions of Kaula based on circumnavigation of the island by boat and concluded that it was a secondary tuff structure built on an older shield volcano which had been truncated by the sea. Petrographic descriptions by Palmer (1927, 1936) were based on rock samples given to him by others and were largely megascopic in nature. No chemical analysis of the rocks or K-Ar age determinations were made. Stearns (1947), Macdonald (1949), and Macdonald and Abbott (1977) briefly mention Kaula, but their discussions are based largely on the previous work by Palmer.

Field Work

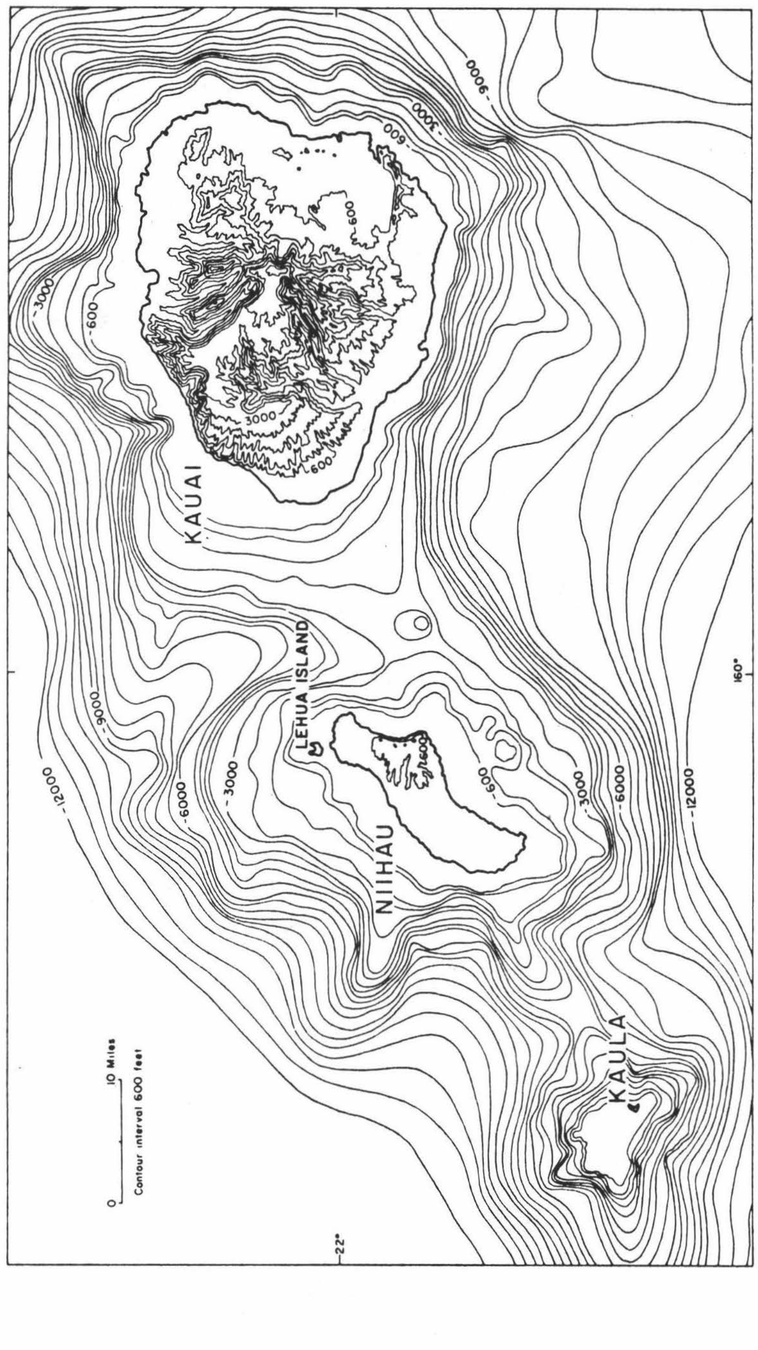
Field work was completed over a three day period during March 6-8, 1979. Transportation to the island was provided by U.S. military helicopters in conjunction with a semiannual environmental assessment of the island. Unexploded ordinance and extremely

Figure 9. Map showing the location of Kaula Island in relation to the Hawaiian Ridge. Small inset shows the location of the Hawaiian Islands in the Pacific Ocean. Modified from Macdonald and Abbott (1977).



175°
170°
165°
160°
155°
KURE I.
MIDWAY I.
PEARL AND HERMES REEF
LISIANSKI I.
LAYSAN I.
PACIFIC OCEAN
25°
GARDNER I.
FRENCH FRIGATE SHOAL
NECKER I.
NIHOA I.
NIIHAU
KAUAI
KAULA I.
OAHU
MOLOKAI
LANAI
MAUI
KAHOOLAWE
20°
HAWAII
0
200
400
Miles
100°
180°
100°
40°
Hawaiian Islands
PACIFIC OCEAN
0°
40°

Figure 10. Map showing the relationship of Kaula, Niihau and Kauai and the northeast-trending ridge connecting them. The submarine contours are generalized. Modified from Macdonald and Abbott (1977).


KAUAI
LEHUA ISLAND
NIIHAU
KAULA
0
10 Miles
Contour interval 600 feet
22°
160°
600
3000
6000
9000
12000

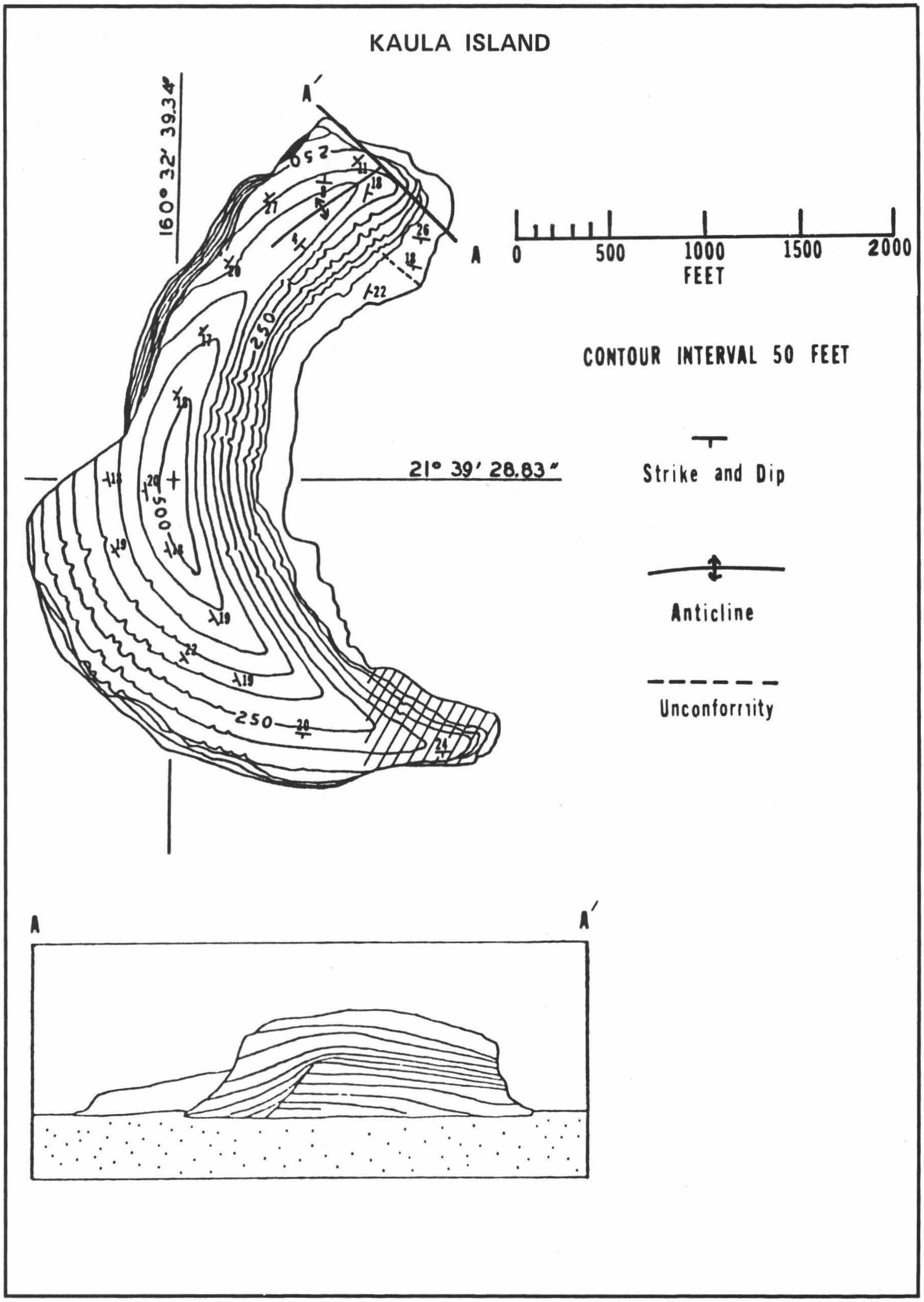
numerous bird nests made sample collection both hazardous and difficult. A sea cliff, which surrounds the island, limited the area which could effectively be studied to the upper slopes. Only one access, down a steep stream cut valley, could be found to a wave-cut bench which partially surrounds the island. Examination of a large erosional unconformity exposed in the northern seacliff and described by Palmer (1927, 1936) was not possible due to high wave action. Sample locations and structural attitudes (strike and dip of bedding) were determined by correlation of topographic field map and aerial photograph, Brunton compass, and pace.

Areal Geology

Kaula Island is a crescent shaped tuff cone which has been breached on its eastern side by the Pacific Ocean (Figure 11). A wave-cut cliff surrounds the island, locally separated from the sea by a wave-cut bench 2.5 m to 3.0 m above sea level. The island rests on the southeastern edge of a broad submarine base that is almost certainly an older shield volcano. This submarine platform is part of an elongate submarine ridge which includes the shield volcanoes on Niihau and Kauai (Figure 10).

The exposed portion of Kaula Island consists of approximately 150 meters of well bedded, palagonitic tuff (Figure 11). No lava flows are present. The tuff is composed of lapilli size, altered volcanic glass, lava fragments, magnetite, olivine, fragments of bird bone and augite (Palmer, 1936). Embedded in the tuff, often forming bomb sags, are accidental angular blocks of volcanic rocks, coral fragments and ultramafic nodules up to 0.5 m. in size. The sequence of tuffs is interrupted by an unconformity best exposed in the sea clift on the northern end of the island. High surf during the visit to the island made access to the unconformity along the wave-cut bench impossible.

Figure 11. Map showing areal geologic features of Kaula Island. Strike and dip of beds indicated. Diagonal lines indicate target area. Modified from Palmer (1936).


KAULA ISLAND
160° 32' 39.34"
21° 39' 28.83"
A
A'
250
500
0 500 1000 1500 2000
FEET
CONTOUR INTERVAL 50 FEET
Strike and Dip
Anticline
Unconformity

Petrography

A total of 41 samples from Kaula Island were collected during the course of this study. All of these samples are accidental volcanic blocks or ultramafic nodules from the tuff. None of the coral fragments in the tuff were collected. Of these, 34 samples were chosen for detailed petrographic study on the basis of freshness. Modes for eight of the thin sections were determined by point-counting 500 points per section whereas modes for the remaining thin sections were estimated by visual examination (Table 9). Petrographic descriptions for Kaula Island samples are given in APPENDIX D.

Rock Types

Accidental blocks recovered from Kaula Island can be grouped into four categories according to their mineralogy. Rock samples belonging to Group I include: KA-11, KA-15, KA-17, KA-19, KA-24, KA-25, KA-28, KA-31, KA-34, KA-35, KA-38, KA-39, KA-40 and KA-42. Group II samples include: KA-10, KA-12, KA-13, KA-33, KA-36, KA-37, KA-41 and KA-45. Samples of Group III include: KA-23, KA-26, KA-27, KA-32, KA-43, KA-44, KA-47 and KA-48. Group IV samples include: KA-14, KA-29 and KA-30.

Group I lavas are basanitoids. They are light to dark gray in color and commonly porphyritic. Common phenocrysts are augite and olivine along with xenocrysts of clinopyroxene. Rare xenocrysts of anorthoclase are present (KA-15 and KA-39). Ultramafic xenoliths are not uncommon. Vesicularity ranges from 10-45%. In thin section, olivine and augite phenocrysts, clinopyroxene xenocrysts, microphenocrysts of olivine, titaniferous augite and rarely green spinel are set in a groundmass consisting of minute augite prisms, iron oxides and interstitial glass. Groundmass textures are generally hylopilitic, rarely variolitic (KA-24). Two thin sections were stained for nepheline. None was detected.

Samples belonging to Group II are phonolites. They are light gray to brown gray in color and biotite phyric. The phenocrysts of biotite range up to 4 mm in size. Samples KA-10,

Table 9

Modal Point Count Analysis for Selected Samples from Kaula Island. Based on 500 Points Counted.

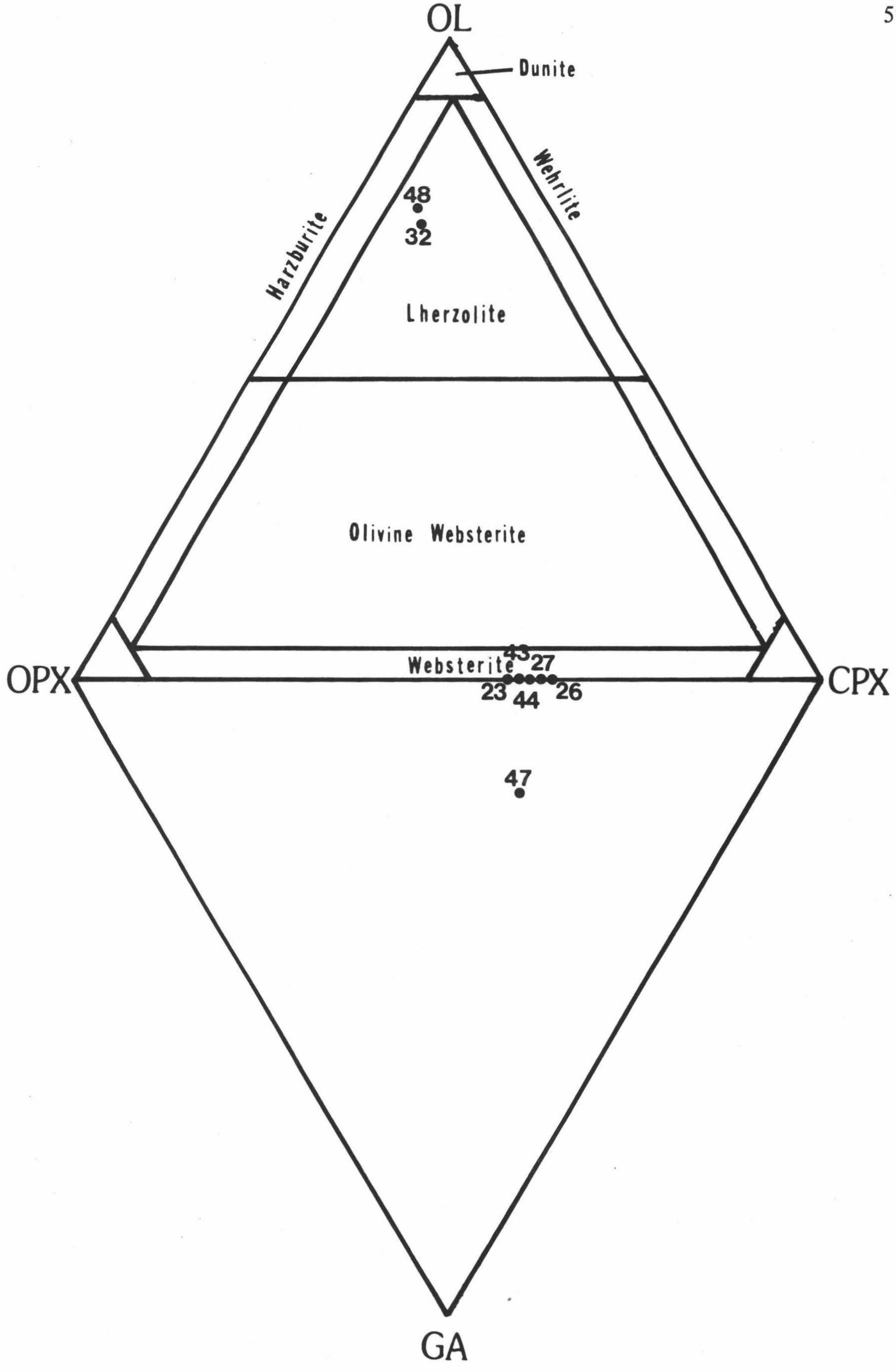
SAMPLE	KA-19	KA-23	KA-24	KA-29	KA-30	KA-32	KA-33	KA-43
PHENOCRYSTS								
Olivine	14.4%	–	12.8%	8.1%	2.7%	55.4%	–	–
Clinopyroxene	3.1%	51.3%	7.4%	2.1%	–	15.9%	–	52.3%
Plagioclase	–	–	–	–	5.3%	–	–	–
Biotite	–	–	–	–	–	–	7.8%	–
Spinel	1.2%	6.1%	–	–	–	1.8%	–	5.3%
Orthopyroxene	–	42.3%	–	–	–	26.9%	–	42.4%
XENOCRYSTS	3.1%	–	4.1%	–	–	–	–	–
GROUNDMASS								
Olivine	8.1%	–	9.3%	11.8%	–	–	–	–
Clinopyroxene	18.4%	–	40.3%	23.2%	29.1%	–	–	–
Plagioclase	–	–	–	32.9%	27.9%	–	–	–
Biotite	–	–	–	–	–	–	2.4%	–
Apatite	–	–	–	0.8%	–	–	8.4%	–
Zircon	–	–	–	–	–	–	2.2%	–
Magnetite	10.1%	–	10.1%	8.3%	7.3%	–	6.3%	–
Glass	5.3%	–	5.7%	–	5.1%	–	–	–
Alkali Feldspar	–	–	–	–	–	–	67.5%	–
VESICLES	26.2%	–	10.3%	12.8%	22.6%	–	5.4%	–

KA-13 and KA-45 have vesicularity ranging from 3-10% whereas the remaining samples are nonvesicular. In thin section, phenocrysts of partially resorbed brown biotite are surrounded by microphenocrysts of magnetite, apatite and rarely zircon (Samples KA-36 and KA-41). These minerals are set in a trachytic matrix of alkali feldspar (sanidine?) microlites, iron oxides, apatite and anhedral, brown biotite.

Rock samples belonging to Group III are predominately lherzolites and websterites (Figure 12). The lherzolite samples are massive and show no evidence of layering. Olivine grains are commonly kink-banded. Green spinel is a common accessory. Websterite samples are composed of approximately equal amounts of clinopyroxene and orthopyroxene grains with minor green spinel. Two varieties of websterites dominate the Kaula Island samples. One variety is composed of irregular clinopyroxene grains which have exsolved orthopyroxene. The exsolved orthopyroxene in these samples occurs as exsolution plates or blebs, but more commonly in simplectic intergrowths. Sample KA-48 contains porphyoblasts of pyrope-rich garnet. The occurrence of garnet websterite has only been reported from one other location in the Pacific basin, namely Oahu, Hawaii (Jackson, 1968; Beeson and Jackson, 1970; Jackson and Wright, 1970). The second variety of websterite is composed of approximately equal amounts of clinopyroxene and orthopyroxene, but the clinopyroxene in these samples shows no exsolution phenomena and the orthopyroxene occurs as irregular shaped grains. Green spinel in minor amounts is always present.

Group IV samples KA-29 and KA-30 are light gray in color, vesicular and contain rare ultramafic xenoliths. Except for the presence of feldspar they resemble samples of Group I. Vesicularity ranges from 3-25% and is present in two sizes: larger (2-8 mm) vesicles, irregular in shape make up 3-5%; whereas smaller (0.5-1 mm) vesicles make up 7-20%. The larger vesicles are commonly filled with zeolites. In thin section these rocks are dominated by suhedral olivine phenocrysts, rarely as glomerocrysts, set in a groundmass consisting of plagioclase (An_{50-55}) lathes, olivine, titaniferous augite, dendritic magnetite and interstitial

Figure 12. Plot of modal mineral % of ultramafic nodules from Kaula Island. 0L = Olivine, OPX = Orthopyroxene, CPX = Clinopyroxene and GA = Garnet. Modified from Jackson (1968).


OL
Dunite
Wehrlite
Harzburite
48
32
Lherzolite
Olivine Websterite
Websterite
43
27
23
44
26
OPX
CPX
47
GA

alkali feldspar. Groundmass textures are intergranular. Sample KA-14 is gray in color has vesicularity of 45-50%. The vesicles are commonly lined with red iron oxides or zeolites. In thin section, subhedral to anhedral olivine phenocrysts completely altered to reddish brown iddingsite and glomerocrysts of plagioclase (An_{55-58}) are set in a subophitic groundmass consisting of plagioclase (An_{50-55}), augite and magnetite. Olivine is absent from the groundmass.

Mineral Composition

Sample KA-47 was chosen for mineral composition analyses utilizing an electron mircroprobe. The results of the analysis are presented in Table 10.

In general, mineral compositions for the Kaula Island sample are similar to garnet pyroxenite xenoliths found at Salt Lake Crater, Oahu (Table 10) (Beeson and Jackson, 1970; Wilkinson, 1976). Garnet compositions are slightly higher in total iron and lower in MnO and clinopyroxene compositions are slightly lower in Cr_2O_3. The composition of orthopyroxene exsolution blebs and of discrete orthopyroxene grains are similar, both phases have slightly higher total iron than Salt Lake Crater samples. Spinel compositions are noticeably higher in Al_2O_3 and lower in Cr_2O_3 than Salt Lake Crater spinels.

Geochemistry

Nine of the least altered samples from Kaula Island were chemically analyzed for major elements, six from Group I and three from Group II. These results, C.I.P.W. norms and differentiation indexes (D.I. = normative q + or + ab + lc + ne + kp + hl + c + z + th + nc) are presented in Table 11. Analyses were recalculated to 100% water free and with the Fe_2O_3/FeO ratio adjusted to 0.2 (Macdonald, 1969).

Except for slightly higher values for K_2O, TiO_2, and P_2O_5, rock samples belonging to Group I are similar to lavas intermediate between basanites and picrite basalts of the mimo-

Table 10

Mineral Compositions of Garnet Websterite from Kaula Island

	Garnet	Clinopyroxene	Orthopyroxene*	Spinel
SiO_2	40.59	49.13	51.25	0.16
Al_2O_3	23.91	7.95	6.06	62.19
FeO	13.43	6.86	12.24	18.79
MgO	17.12	14.33	28.34	18.91
CaO	3.66	18.11	0.52	–
Na_2O	0.04	2.02	0.17	0.01
TiO_2	0.24	0.78	0.24	0.30
Cr_2O_3	0.01	0.08	0.04	0.27
MnO	0.40	0.12	0.15	0.19
TOTALS	99.40	99.38	99.01	100.97

NUMBER OF IONS

	Based on 24 oxygens	*Based on 6 oxygens*	*Based on 6 oxygens*	*Based on 32 oxygens*
Si	5.90	1.82	1.84	0.03
Al^{IV}	1.92	0.16	0.12	7.39
Al^{VI}	2.19	0.19	0.13	7.79
Cr	–	–	–	0.04
Ti	0.03	0.02	–	0.03
Mg	3.73	0.79	1.52	5.83
Fe	1.64	0.21	0.37	3.25
Mn	0.05	–	–	0.03
Ca	0.57	0.72	0.02	–
TOTALS	16.03	4.06	4.00	24.39
	Almandine 27.1% Grossular 9.6% Pyrope 62.3% Spessartine 1.0%	Ca 41.8% Fe 12.3% Mg 45.9%	Ca 1.0% Fe 19.3% Mg 79.7%	Fe 35.8% Mg 64.2%

**Exsolved from clinopyroxene*

Table 11

Whole-rock Major Element Analyses and C.I.P.W. Norms (Fe_2O_3 / FeO Adjusted to 0.2) for Selected Kaula Island Samples

SAMPLE	KA-15	KA-17	KA-19	KA-28	KA-31	KA-34	KA-36	KA-37	KA-41
SYMBOL	1	2	3	4	5	6	7	8	9
MAJOR ELEMENT ANALYSES									
SiO_2	42.35	40.60	40.75	42.05	40.95	39.20	54.40	54.25	54.55
Al_2O_3	11.58	11.68	11.54	12.44	12.02	11.42	17.98	17.86	17.35
Fe_2O_3	3.94	5.22	6.16	4.04	4.51	5.74	3.22	4.47	2.76
FeO	9.40	7.84	6.44	9.40	8.72	7.56	2.00	0.92	1.98
MgO	13.43	12.14	12.10	10.35	12.82	11.38	2.05	1.85	1.90
CaO	10.48	11.16	10.98	10.58	10.84	12.10	1.65	1.29	2.36
Na_2O	3.32	3.28	1.67	3.72	3.74	2.42	8.23	7.88	6.75
K_2O	1.16	1.19	1.21	1.48	1.23	1.29	4.38	5.09	4.09
TiO_2	2.74	2.56	2.60	2.81	2.83	2.71	0.55	0.51	0.54
P_2O_5	0.70	1.11	0.66	0.73	0.86	0.83	0.66	0.63	0.63
MnO	0.22	0.24	0.19	0.22	0.23	0.32	0.35	0.28	0.32
H_2O	0.56	2.91	5.31	1.56	0.83	4.85	4.12	4.52	6.34
CO_2	0.09	0.10	0.04	0.35	0.19	0.11	0.17	0.18	0.19
TOTALS	99.97	100.03	99.65	99.73	99.77	99.93	99.76	99.73	99.76
DRY ANALYSES NORMALIZED TO 100%									
SiO_2	42.65	41.85	43.13	42.99	41.46	41.29	56.98	57.09	58.51
Al_2O_3	11.66	12.04	12.21	12.72	12.17	12.02	18.83	18.79	18.61
Fe_2O_3	2.24	2.24	2.22	2.29	2.23	2.33	0.91	0.95	0.85
FeO	11.19	11.22	11.11	11.45	11.17	11.67	4.55	4.72	4.23
MgO	13.52	12.51	12.80	10.58	12.98	11.98	2.15	1.95	2.04
CaO	10.55	11.50	11.62	10.82	10.98	12.74	1.73	1.36	2.53
Na_2O	3.34	3.38	1.77	3.80	3.79	2.55	8.62	8.29	7.24
K_2O	1.17	1.23	1.28	1.51	1.25	1.36	4.59	5.36	4.39
TiO_2	2.76	2.64	2.75	2.87	2.87	2.85	0.58	0.54	0.58
P_2O_5	0.70	1.14	0.70	0.75	0.87	0.87	0.69	0.66	0.68
MnO	0.22	0.25	0.20	0.22	0.23	0.34	0.37	0.29	0.34
or	6.91	7.26	7.56	8.92	3.82	–	27.12	31.67	25.94
ab	3.03	0.64	5.13	2.97	–	–	38.49	34.21	46.73
an	13.36	14.04	21.59	13.19	12.50	17.33	–	–	5.31
lc	–	–	–	–	2.79	6.30	–	–	–
ne	13.66	15.14	5.33	15.81	17.37	11.68	17.77	17.66	7.87
ac	–	–	–	–	–	–	1.43	2.74	–
ns	–	–	–	–	–	–	–	0.05	–
di wo	14.36	14.84	13.14	14.85	15.15	16.64	1.70	1.02	1.16
di en	9.34	9.41	8.45	8.99	9.78	10.32	0.70	0.38	0.50
di fs	4.03	4.49	3.82	5.05	4.34	5.33	1.01	0.65	0.66
hy en	–	–	–	–	–	–	–	–	–
hy fs	–	–	–	–	–	–	–	–	–
ol fo	17.05	15.23	16.41	12.16	15.79	13.67	3.26	3.13	3.20
ol fa	8.12	8.00	8.17	7.52	7.73	7.79	5.20	5.91	4.69
mt	3.25	3.24	3.22	3.32	3.23	3.37	0.59	–	1.23
il	5.24	5.01	5.22	5.45	5.45	5.41	1.10	1.02	1.10
ap	1.65	2.70	1.65	1.77	2.09	2.06	1.63	1.56	1.61
SALIC	36.98	37.11	39.94	40.89	36.49	35.33	83.39	83.55	85.86
FEMIC	63.02	62.89	60.06	59.11	63.51	64.67	16.61	16.45	14.14
D.I.	23.62	23.06	18.03	27.70	23.99	17.99	83.39	83.55	80.55

site type (Macdonald, 1968). In Hawaii the latter lavas are only found among the post-erosional lavas of the Koloa Volcanic Series on the island of Kauai. Sample KA-19 is lower in Na_2O than are the other samples in Group I and sample KA-17 shows high P_2O_5.

Major element compositions for samples belonging to Group II are similar to alkalic lavas intermediate between benmoreites and soda trachytes except for slightly higher Al_2O_3, K_2O and TiO_2 contents (Macdonald, 1968). The high normative nepheline values for these rocks, however, confirm that Group II samples are undersaturated with respect to silica and, in this respect, similar to post-erosional Hawaiian lavas. On the alkali-silica diagram (Figure 13), samples belonging to Group I plot in the field outlined by the solid line which represents the field boundary for Hawaiian post-erosional lavas of the nephelinie suite (Macdonald, 1968). Except for sample KA-41, samples belonging to Group II plot just outside the field boundary for Hawaiian alkalic rocks represented by the dashed line (Macdonald, 1968).

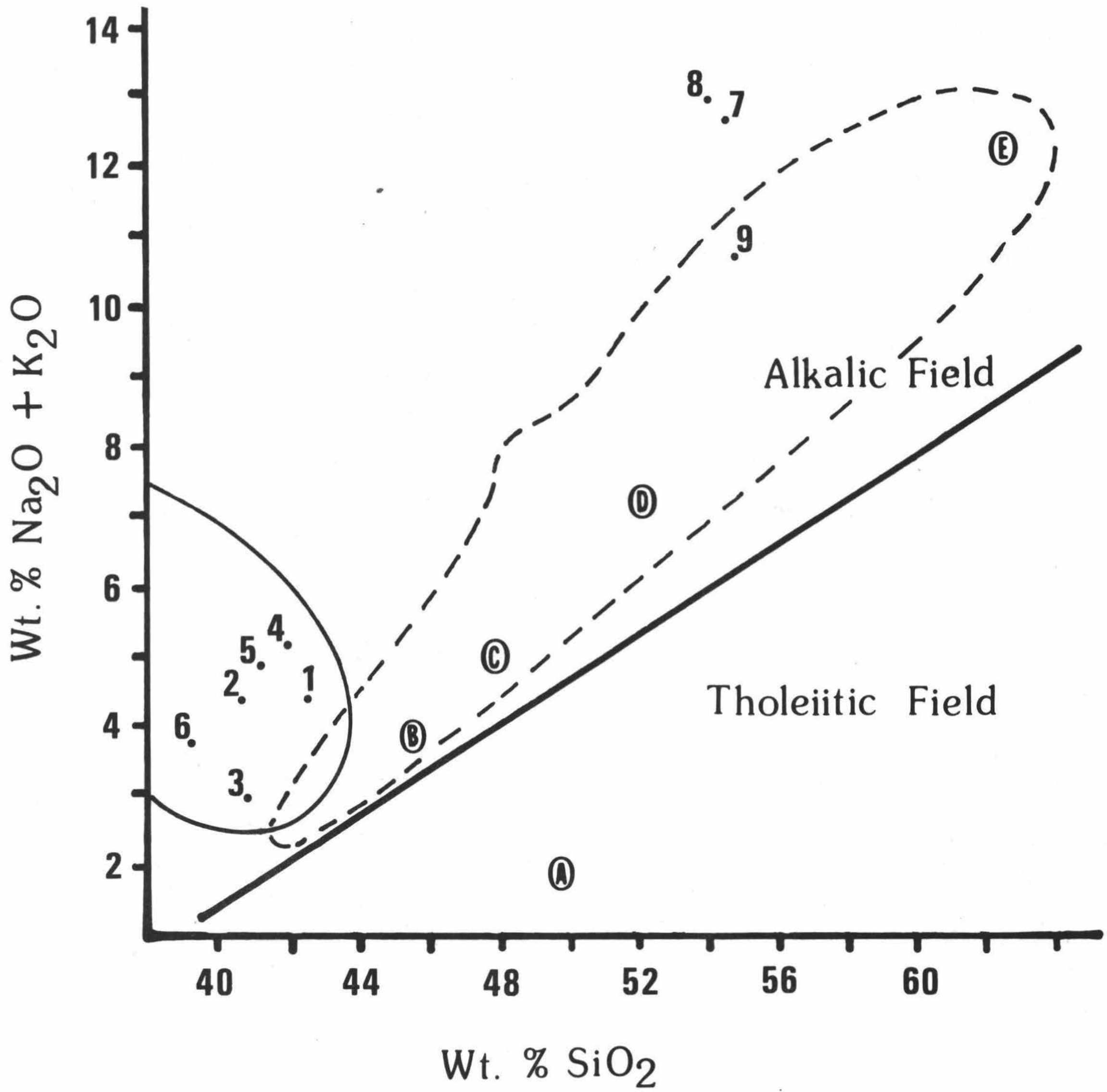
Figure 14 is a modified ternary classification diagram for volcanic rocks suggested by the IUGS Subcommission on the Systematics of Igneous Rocks (Streckeisen, 1979). Fields for Hawaiian rock types have been added. On this diagram, the samples from Kaula Island can be subdivided into two distinct groups. Samples belonging to Group I plot in the basanite field, typical of Hawaiian post-erosional lavas (Macdonald, 1968). Group II samples are phonolites according to this classification and plot outside fields for Hawaiian alkalic rocks.

Geochronology

Conventional potassium-argon age measurements were conducted to obtain an absolute age for the volcanic edifice that underlies Kaula Island and to compare the age of the Kaula volcanic edifice with other volcanoes along the Hawaiian Ridge.

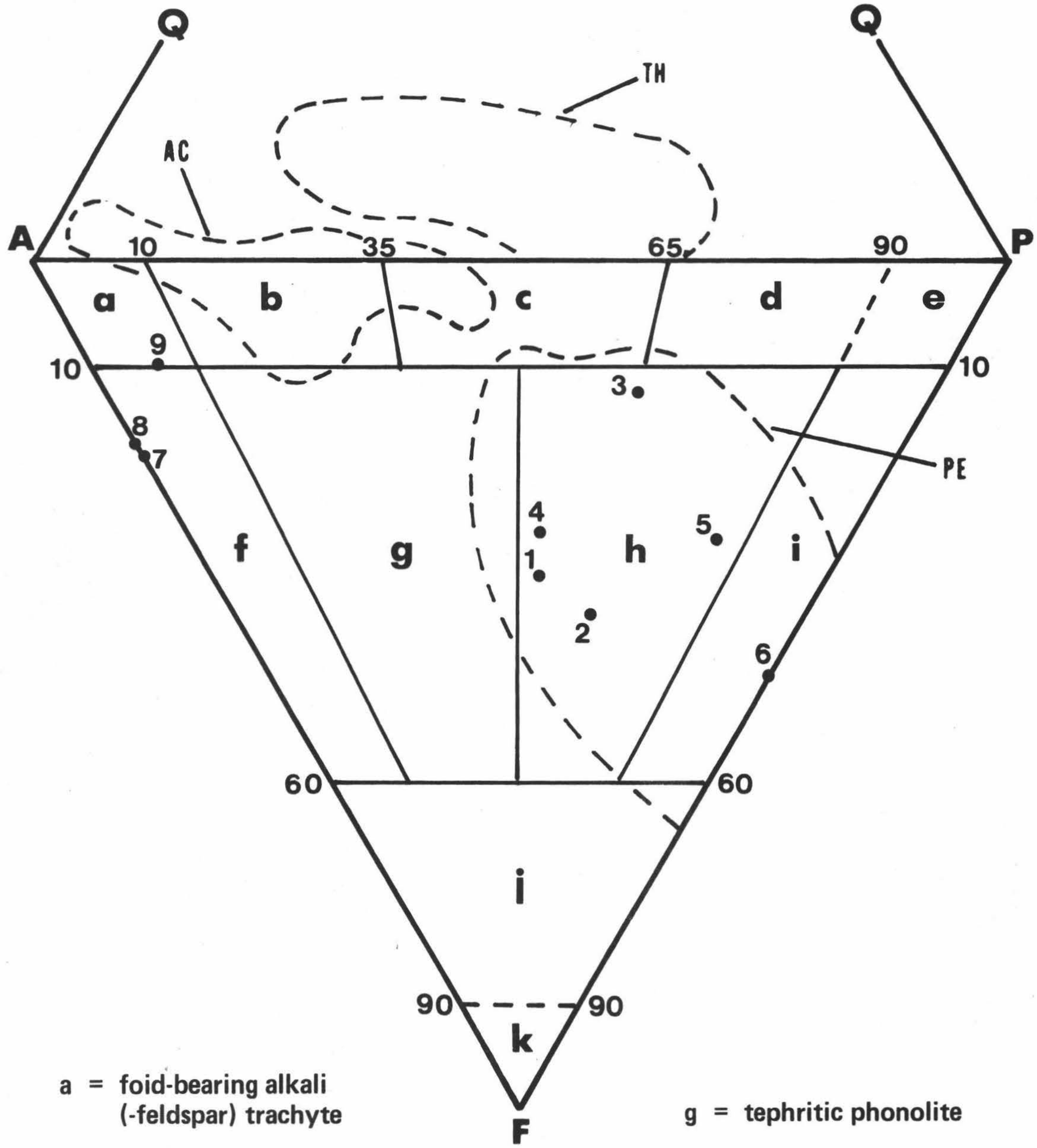
No published age data exist for Kaula Island. McDougall (1964, 1979) used K-Ar age determinations to demonstrate that lavas of the Waimea Canyon Group on Kauai range in

Figure 13. Alkali-silica diagram of selected samples from Kaula Island. Data from Table 11. A = Tholeiite, B = Alkalic Basalt, C = Hawaiite, D = Mugearite, E = Soda Trachyte. Solid line represents approximate field boundary for Hawaiian post-erosional lavas. Dashed line represents approximate field boundary for alkalic-cap lavas. Modified from Macdonald (1968).



Wt. % $Na_2O + K_2O$
14
12
10
8
6
4
2
40
44
48
52
56
60
Wt. % SiO_2
Alkalic Field
Tholeiitic Field
A
B
C
D
E
1
2
3
4
5
6
7
8
9

Figure 14. Modified QAPF diagram for selected samples from Kaula Island. A = normative or + ab, P = normative an, F = normative ne + lc, and Q = normative q. Symbols from Table 9. Dashed lines represent approximate field boundaries for Hawaiian suites: Th = Tholeiitic, AC = Alkalic-Cap, PE = Post-Erosional. Modified from Streckeisen (1979).



a = foid-bearing alkali (-feldspar) trachyte

b = foid-bearing trachyte

c = foid-bearing latite

d = alkalic basalts

e = alkalic basalts

f = phonolite

g = tephritic phonolite

h = phonolitic tephrite (basanite)

i = tephrite, basanite

j = phonolitic / tephritic foidite

k = foidite

age from 3.81 m.y. to 5.14 m.y. Ages of tholeiitic lavas from Niihau yield 5.5 m.y. for main shield-building lavas (Dalrymple et al., in prep.).

Radiometric ages for Kaula Island reported here are based on two samples, both accidental blocks of biotite phonolite embedded in tuff. Results of the potassium-argon calculation are summarized in Table 12. Two whole-rock age determinations yield ages of 4.00 $\pm$ 0.09 and 4.22 $\pm$ 0.25 m.y. A third age determination on the biotite phenocrysts from the second sample (KA-36) yielded an age of 3.98 $\pm$ 0.7 m.y. The results of the potassium-argon age determinations for Kaula Island, along with available ages for volcanic centers from the principal Hawaiian Islands, are plotted on Figure 15 as a function of distance from Kilauea. Ranges of ages for each stage of volcanic development at each volcano have been plotted rather than average shield-building ages to demonstrate the time span over which the volcanoes grow and the variability in the data.

Discussion

The Group I samples may be classified as basanitoids based on normative nepheline (>5%) and the lack of modal nepheline. Basanitoids are virtually restricted to the post-erosional stage of Hawaiian volcanism (Macdonald, 1968). The most striking features about the mineralogy of the rocks are the abundance of mafic minerals and the lack of feldspar. With the exception of Sample KA-42, no feldspar was identified in the thin sections examined. Macdonald (1949) and Macdonald et al. (1960) noted a rare variety of basanite in which mafic minerals are quite abundant, modal nepheline constitutes about 5-10% and feldspar may be completely absent. Macdonald (1949) described a complete gradation from basanites to these highly mafic, undersaturated rocks. These latter rock types have only been reported among the post-erosional lavas of the Koloa Group on the island of Kauai (Macdonald, 1949; Macdonald et al., 1960). Their origin is uncertain.

Table 12

Potassium-Argon Age Measurements on Samples from Kaula Island*

Sample	K_2O (Wt. %)**	Argon: Wt. (grams)	Argon: ^{40}Ar (Rad) (10^{-11} mol/gram)	Argon: $\frac{^{40}Ar (Rad)}{^{40}Ar (Total)} \times 100$	Calculated Age (m.y.)***
KA-100**** (whole-rock)	3.89 ± 0.02	4.343	2.71	94.2	4.00 ± 0.09
KA-36 (whole-rock)	3.79 ± 0.04	3.007	2.77	37.5	4.22 ± 0.25
KA-36 (biotite)	5.58 ± 0.16	0.1545	3.84	15.9	3.98 ± 0.70

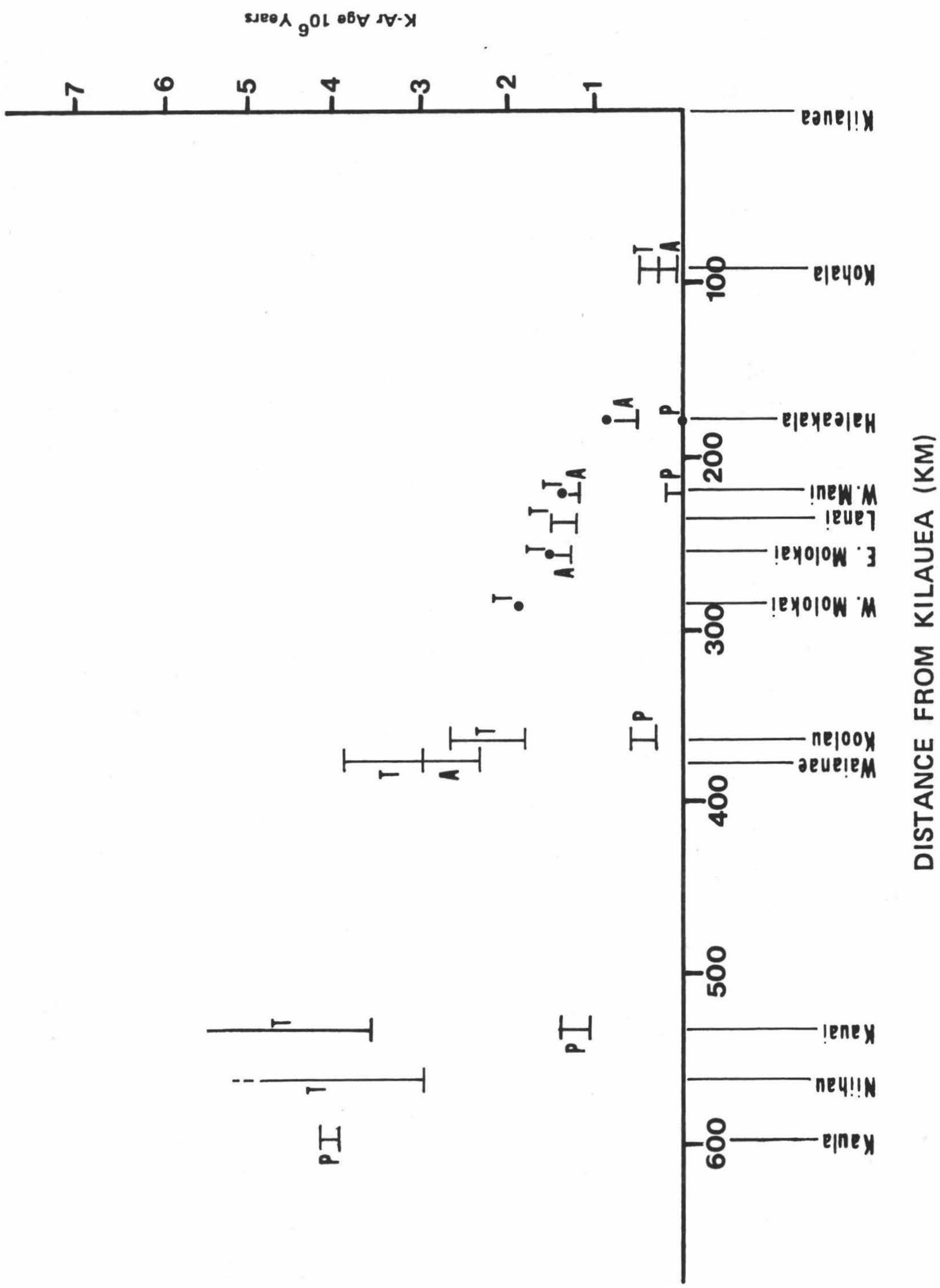
* Analyses from the laboratory of J. J. Naughton, Hawaii Institute of Geophysics.

** Mean and range of two measurements.

*** Data has been converted to new decay constants $\lambda_\epsilon = 0.581 \times 10^{-10}\ yr^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10}\ yr^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol. Errors are estimates of standard deviations of precision.

**** Sample collected by Dr. Robert J. Homman.

Figure 15. Plot of K-Ar ages relative to distance from Kilauea for lavas of the principal Hawaiian Islands. T = Shield-Building Lavas, A = Alkalic-Cap Lavas and P = Post-Erosional Lavas. Ages from McDougall (1979) and Clague (1974). Ages for Kaula Island from this work.


K-Ar Age 10^6 Years
1
2
3
4
5
6
7
Kilauea
Kohala
Haleakala
W. Maui
Lanai
E. Molokai
W. Molokai
Koolau
Waianae
Kauai
Niihau
Kaula
100
200
300
400
500
600
DISTANCE FROM KILAUEA (KM)

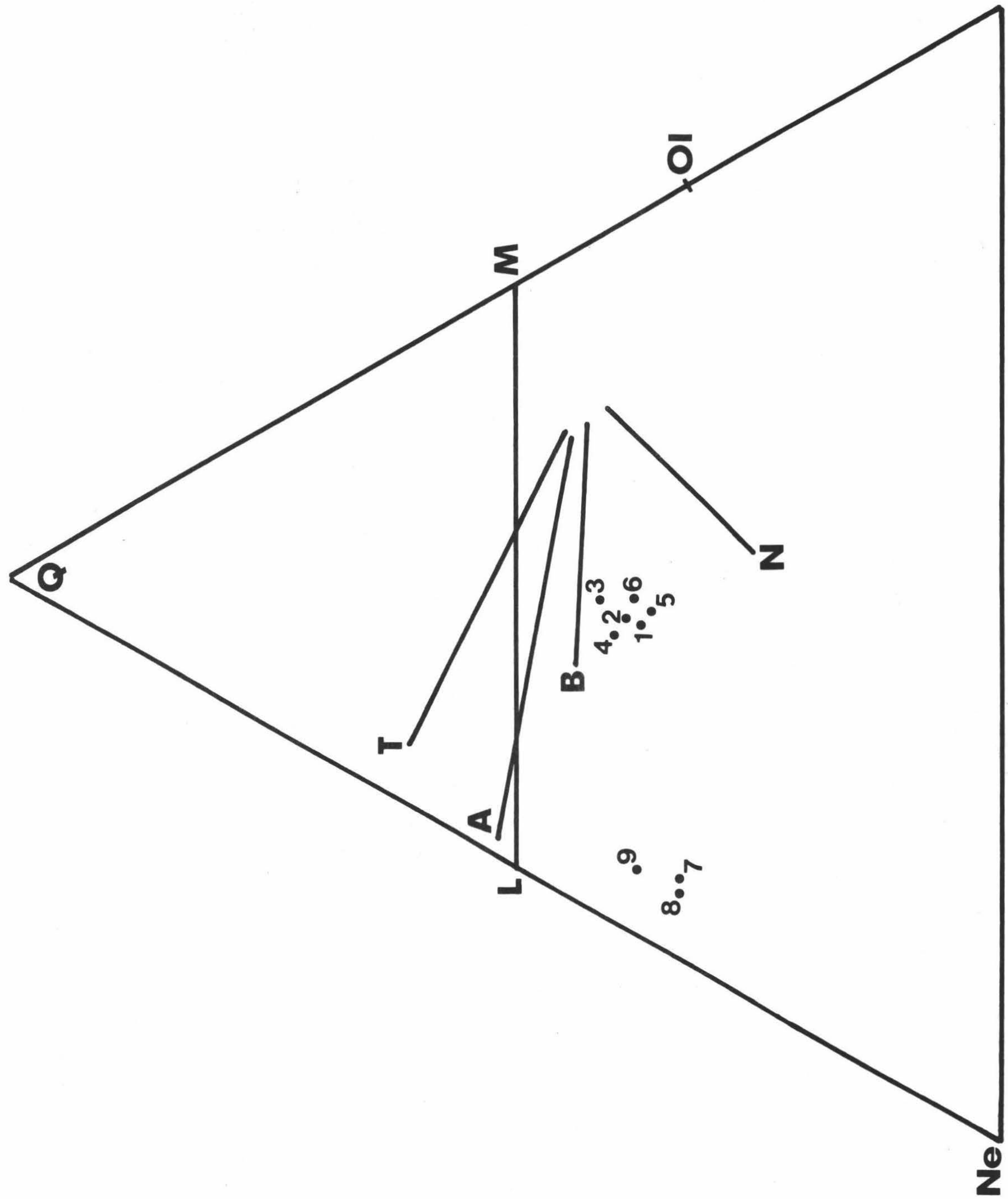
Samples belonging to Group II are biotite phonolites based on petrography and rock chemistry (Figure 14). Phonolites are unknown among the lavas of the principal Hawaiian Islands, but they have been recovered from Pearl and Hermes Reef and from the southern end of the Emperor Seamount Chain (Clague, 1974; Clague et al., 1975). Comparison of major element chemistry of samples from Group II with average chemical compositions of lavas from both the alkalic-cap and post-erosional stage of Hawaiian volcanism shows that Group II samples are certainly differentiated rocks (Macdonald and Katsura, 1964; Macdonald, 1968). The noticeably high percent of normative nepheline suggests that the samples are more characteristic of the undersaturated post-erosional lavas.

Baker (1969) suggested that the late, silica-undersaturated phonolitic lavas from Saint Helena were derived from undersaturated trachytic liquids by processes including volatile transfer and migration of alkali-rich late crystallizing fluids. These trachytes were, in turn, derived from undersaturated basalts by crystal fractionation as are the differentiated members of the Hawaiian alkalic series. Two lines of evidence appear to preclude such an origin of Kaula Island phonolites from Hawaiian trachytes. Differentiation within the Hawaiian alkalic suite is accompanied by a relative decrease in MgO values (Macdonald, 1968). Saint Helena samples decrease in MgO with differentiation. The phonolites are the most differentiated rocks and contain the least amount of MgO (Baker, 1969). In contrast, the phonolites from Kaula Island have MgO values in excess of 2%, higher than MgO values for typical Hawaiian trachytes 0.4-0.6 (wt % MgO) (Macdonald and Katsura, 1964; Macdonald, 1968; Verde, 1978).

An examination of Baker's (1969) data on Saint Helena lavas shows that the parental trachytes were undersaturated with respect to silica. Undersaturated trachytes in Hawaiian lavas are rare (Macdonald, 1968). In fact, all but one of three analyzed trachytes contain normative quartz (Macdonald and Katsura, 1964; Macdonald, 1968; Verde, 1978). Therefore, to derive highly undersaturated rocks such as the phonolites from Kaula Island (15% normative Ne) from typical Hawaiian trachytes (1-3–% normative Q) of the alkalic cap stage of development would require the modification of oversaturated liquids to an undersaturated condition. Though not impossible, this process appears difficult to achieve (Macdonald, 1974). Bailey and Schairer (1966) have suggested a possible mechanism, based on observations in the synthetic system Na_2O-Al_2O_3-Fe_2O_3-SiO_2, namely substitution of Fe^{3+} for Al in feldspar. The effect is to use Fe to make $NaFe^{3+}Si_3O_8$ rather than acmite $NaFe^{3+}Si_2O_6$, thereby using more silica. A trachytic magma plotting just on the silica-rich side of a natural crystallization barrier, such as Ab-Or-Ac-Alkali Disil., might be pushed through the plane towards the SiO_2 undersaturated side by separation of alkali feldspar carrying small amounts of Fe in its structure. However, Hawaiian groundmass feldspar compositions for trachytes from West Maui volcano (Keil et al., 1972; Verde, 1978) contain virtually no iron.

Macdonald (1968) utilized a Von Wolff diagram (Figure 16) and noted that Hawaiian lavas of the post-erosional stage of development seemed to display two differentiation trends. One trend includes alkalic olivine basalts, basanitoids and basanites and is nearly parallel to that of the main alkalic suite. The second includes nephelinites and melilite nephenilites and trends well away from that of the main alkalic suite. Samples belonging to Group I and Group II from Kaula Island have been plotted on Figure 16 along with the trends recognized by Macdonald (1968). An examination of the diagram shows that the phonolites from Kaula Island (Points 7, 8 and 9) plot within a field separated from the trend of the alkalic suite. What is interesting is that an approximated straight line connecting the Group II and Group I samples extends back to the region of alkalic basalts. This suggests that the phonolites from Kaula Island may have been derived from the basanitoids of Group I and, together, the rocks may represent a new differentiation trend within Hawaiian post-erosional lavas.

Figure 16. Modified Von Wolff diagram of volcanic rocks from Kaula Island. Q = Quartz, L = Feldspar, M = Mafic Minerals, Ol = Olivine, Ne = Nepheline, T = Tholeiitic Trend for Hawaiian Lavas, A = Alkalic Trend for Hawaiian Lavas, B = Basanitic Trend for Post-Erosional Hawaiian Lavas and N = Nephelinitic Trend for Post-Erosional Hawaiian Lavas. Data from Table 9. Modified from Macdonald (1968).


Q
M
Ol
N
B
T
A
L
Ne
1
2
3
4
5
6
7
8
9

The ultramafic samples of Group III are classified as lherzolites and websterites based on modal mineralogy (Figure 12). Sample KA-47 is a garnet websterite. The occurrence of garnet websterite has only been reported from one other area in the Pacific basin, Salt Lake Crater, Oahu, Hawaii (Jackson, 1968; Beeson and Jackson, 1970; Jackson and Wright, 1970; Wilkinson, 1976). Ultramafic xenoliths are not uncommon among the lavas of the principal Hawaiian Islands but are more abundant in lavas of the alkalic and nephelinic suites than in lavas of the tholeiitic suite (Jackson, 1968). Generally two origins for the ultramafic xenoliths have been proposed: 1) the xenoliths represent crystal cumulates or, 2) the xenoliths originated in the upper mantle and were transported to the surface with ascending lavas (Jackson, 1968; Jackson and Wright, 1970).

The metamorphic textures and mineral compositions of garnet-pyroxenite and lherzolite xenoliths in Hawaiian basaltic lavas has led to the idea that these xenoliths have been derived from the upper mantle (Jackson, 1968; Beeson and Jackson, 1970; Jackson and Wright, 1970; Reid and Frey, 1971; Wilkinson, 1976). The metamorphic textures and mineralogy of the lherzolites and websterites from Kaula Island suggest that they may have had a similar origin.

Three potassium-argon age determinations on the phonolite lavas from Kaula Island yield ages of 4.00 ± 0.90 m.y., 4.22 ± 0.25 m.y. and 3.98 ± 0.7 m.y. Based on petrography and rock chemistry of these samples, this date of about 4.0 m.y. may represent the age of post-erosional volcanism on Kaula volcano. However, considering the trend for post-erosional volcanism along the Hawaiian Islands, the age from Kaula Island is noticeably older than expected (Figure 15). The age is more consistent with the trend of alkalic-cap lavas (McDougall, 1964; Gramlich et al., 1971; Clague et al., 1975).

In summary, accidental blocks recovered from Kaula Island fall into three general categories: ultramafic nodules of mantle origin; mafic basanitoids, similar in composition to some post-erosional lavas of the Koloa Group on Kauai; and, biotite phonolites, extremely differentiated lavas possibly derived from the basanitoids.

It should be noted that the generally accepted pattern of volcanism for Hawaiian volcanoes is based on field relationships as well as on petrographic and geochemical evidence. Rejuvenated volcanism associated with the post-erosional stage of Hawaiian volcanism implies a profound period of erosion after the principal period of volcanism has ceased. The presence of a profound erosional period cannot be confirmed on Kaula Island as all of the rocks are accidental blocks embedded in tuff. Thus, any catagorization of Kaula Island samples as post-erosional is based strictly on petrographic and geochemical evidence.

CONCLUSIONS

The results of this study confirm that Gardner Pinnacles is a shield volcano similar in composition to those of the principal Hawaiian Islands. Transitional basalts from Brooks Bank and from an unnamed seamount 200 km southeast of Necker Island probably represent late shield-building lavas for these volcanic centers. A second sample from Brooks Bank, samples from two unnamed seamounts 300 km west of Midway Islands and halfway between Necker and Nihoa Islands are hawaiites. These lavas are similar in composition to volcanic rocks of the alkalic-cap stage of volcanism on Hawaiian volcanoes.

K-Ar age determinations yielded ages of 13.4 ± 0.8 m.y., 15.9 ± 1.0 m.y and 16.2 m.y. for Gardner Pinnacles, 17.6 ± 0.6 m.y. for Brooks Bank and 10.12 ± 0.6 m.y. for the unnamed seamount halfway between Necker and Nihoa Islands. These ages are consistent with the general trend of increase in age to the northwest, away from Kilauea volcano, as predicted by the 'hot spot' hypothesis. However, the age progression is not exactly linear and there is considerable scatter for the ages northwest of French Frigate Shoal.

Off-ridge volcanic rocks recovered from an unnamed seamount located 500 km northwest of Midway Islands and from two unnamed seamounts 200 km north and 625 km northeast of Pearl and Hermes Reef are hawaiites. Two samples from an off-ridge seamount located 140 km southwest of Salmon Bank are hornblende benmoreites, differentiated rocks unlike any lavas from the Hawaiian Islands.

K-Ar age determinations on the hornblende benmoreite and from the off-ridge seamount northwest of Midway Island yielded ages of approximately 110 m.y. These seamounts were built at nearly the same time as the underlying oceanic crust and are not part of the Hawaiian Ridge. Radiometric age determination were not made of samples from the other two off-ridge seamounts because no unaltered samples were available. The relation of these two seamounts to the Hawaiian Ridge is uncertain.

Kaula Island, located approximately 33 km southwest of Niihau, is an eroded remnant of a tuff cone built near the southeast edge of a submarine shield volcano. Accidental blocks from the tuff include: basanitoids similar in composition to some post-erosional lavas of the Koloa Group on Kauai; biotite phonolites, differentiated rocks previously unreported among the lavas of the principal Hawaiian Islands; some mantle-derived lherzolites and a garnet websterite. The occurrence of garnet websterite has only been reported from one other location in the Pacific basin: Oahu, Hawaii.

Whole-rock K-Ar age determinations on two biotite phonolites yielded ages of 4.00 $\pm$ 0.09 m.y. and 4.22 $\pm$ 0.25 m.y. A single age determination on biotite phenocrysts in the second sample yielded an age of 3.98 $\pm$ 0.7 m.y. These ages may represent the age of the post-erosional stage of volcanism on Kaula volcano. These ages, however, are noticeably older than ages expected for post-erosional lavas for that location and are more consistent with the trend for alkalic-cap volcanism.

APPENDIX A

Summary of Methods Used in the Analytical Laboratory Department of Earth Sciences, University of Manitoba*

Element	Method
Si Al Fe (Total) Mg (High) Ca K Ti Mn Zr	X-ray Fluorescence Spectrometry. Sample plus $Li_2B_4O_7$ and La_2O_3 are heated in a graphite crucible at about 1100 degrees celsius for one half hour. Resulting glass bead with H_3BO_3 (total weight, 2.1000 grams) ground to −200 mesh and then compressed to 50,000 p.s.i. Elements then simultaneously analyzed on multi-channel ARL X-ray Spectrometer.
Na_2O, MgO (Low)	Atomic Absorption Spectrophotometry. Rock dissolved with HF, H_2SO_4, and HNO_3 in platinum crucibles. Perkin-Elmer 303 A.A.S. used for determinations.
P_2O_5	Colorimetry. Solution as for Na_2O above. The absorption at 430 m of molybdivanadophosphoric acid complex. Unicam sp 500 spectrophotometer.
FeO	Rock decomposed with HF and 1:4 H_2SO_4 solution titrated with $K_2Cr_2O_7$ using Sodium Diphenylamine sulfonate as indicator.
H_2O^-	Determined by heating sample to constant weight at 1100 degrees celsius.
H_2O (Total)	Determined by heating sample in a stream of dry oxygen in an induction furnace (Temperature 1100 degrees celsius H_2O collected on Anhydrone and weighed.
H_2O^+	H_2O (Total) $-H_2O^-$.
CO_2	Sample decomposed by HCl and heat. Evolved CO_2 passed through drying train and collected on Ascarite.
CO_2 (Low S samples)	Determined simultaneously with H_2O (Total). CO_2 collected on Ascarite; small amounts of SO_2 removed on MnO (act).

**written communication by K. Ramlal (1979)*

APPENDIX A (continued)

Summary of Analytical Methods

Constituents, Concentration, Precision, and Accuracy of Major Element Determinations, Department of Earth Sciences, University of Manitoba*

Constituent	Concentration Percent	Instrument Precision	Accuracy of Replicates
SiO_2	59.60	.12	.20
Al_2O_3	9.34	.05	.13
Fe_2O_3 (Total)	10.08	.017	.03
MgO	.404	.04	.10
CaO	10.22	.02	.07
K_2O	2.69	.01	.01
MnO	.41	.01	.01
TiO_2	.48	.02	.02
Na_2O	4.20	.01	.05
H_2O (Total)	1.60	.03	.06
CO_2	1.15	.05	.12
P_2O_5	0.20	.01	.01
FeO	10.92	–	.04

**written communication by K. Ramlal (1979)*

APPENDIX B

Location of Dredge Sites along the Hawaiian Ridge and Number of Samples Analyzed

	Dredge	Latitude	Longitude	Depth (m.)	Name	No. of Analyzed Samples
1	HR 34-18	27°55.2'N	171°03.8'W	890	Unnamed Seamount	2
2	KK 65-24	31°08.5'N	179°44.8'W	2950	Unnamed Seamount	2
3	HR 33-17	29°11.7'N	174°06.0'W	1300	Unnamed Seamount	1
4	HR 20-8	26°27.2'N	177°51.6'W	930	Unnamed Seamount	2
5	HIG 20	28°48.6'N	178°53.5'W	1090-875	Unnamed Seamount	2
6	MN 6-7	25°41.0'N	167°41.8'W	1390-1290	Gardner Pinnacles	4
7	HIG 37	25°13.3'N	167°51.4'W	850-665	Gardner Pinnacles	2
8	HIG 41	24°02.9'N	166°33.6'W	1050-1040	Brooks Banks	2
9	HIG 51	23°15.0'N	163°06.1'W	730	Unnamed Seamount	2
10	MN 9-11	23°06.7'N	162°28.8'W	2080-1650	Unnamed Seamount	1

The dredges denoted by 'HIG' were taken by the research vessel Kana Keoki during Hawaii Institute of Geophysics Cruise 72-07-02 Leg 2. The dredges denoted by 'MN' were collected by the research vessel Kana Keoki during Hawaii Institute of Geophysics Cruise 76-11-08 Leg 1. The single dredge denoted by 'KK' was taken by the research vessel Kana Keoki during the Hawaii Institute of Geophysics Cruise 77-03-17 Leg 1. Dredges labeled 'HR' were made during the HIG Cruise 76-08-06.

APPENDIX C

Petrographic Descriptions of Selected Samples from the Hawaiian Ridge

Samples 20-AA, 20-CC:

Alkalic Basalts. Texture: Porphyritic subophitic. Vesicularity: 20-40%. Phenocrysts: Plagioclase (An_{54-60}), 15-22%, subhedral, normal zoning, combined albite, Carlsbad and pericline twinning. Olivine: 1%, locally altered to iddingsite, commonly resorbed. Augite: 1%, subhedral. Groundmass: Plagioclase (An_{52-55}), 25-30%, subhedral, albite twins. Augite: 12-17%, subhedral, locally sector zoned. Magnetite: 12-17%, subhedral. Olivine: 7-10%, subhedral, locally altered to iddingsite.

Samples 6-7-A, 6-7-B, 6-7-D and 6-7-F:

Tholeiitic Olivine Basalts. Texture: intergranular to intersertal, locally subophitic. Vesicularity: 1-3%. Phenocrysts: Olivine: 15-25%, subhedral and commonly partially resorbed, a few magnetite inclusions, locally altered to iddingsite along fractures, undulatory extinction; sample 6-7-B and 6-7-F have kink banding. Plagioclase (An_{68-72}), 1-3%, subhedral, locally altered to sericite, albite and pericline twinning. Groundmass: Plagioclase (An_{63-66}), 25-35%, subhedral, locally altered to sericite. Sample 6-7-A shows reverse zoning, other samples have normal zoning. Augite: 30-40%, subhedral to anhedral, sector zoned. Magnetite 8-12%, subhedral. Olivine: 1%, subhedral. Interstitial fine grained undetermined material: 0-5%.

Samples 37-A and 37-C:

Transitional Olivine Basalts. Texture: Porphyritic holocrystalline to subophitic, pilotaxitic. Vesicularity: 1-3%. Phenocrysts: Olivine: 9-11%, subhedral, altered to iddingsite. Plagioclase (An_{48-52}), 3-5%, subhedral, combined albite and pericline twinning. Augite: 1%, anhedral, poorly developed cleavage. Groundmass: Plagioclase (An_{44-49}), 33-36%, subhedral, locally altered to sericite, combined albite, pericline and Carlsbad twinning. Olivine: 17-19%, subhedral to anhedral, altered to iddingsite. Titaniferous augite: 15-18%, purplish pink, subhedral to anhedral. Magnetite: 17-20%. Interstitial very fine grained undetermined material, 0-5%.

Sample 41-A:

Hawaiite. Texture: Subpilotaxitic intergranular to intersertal. Vesicularity: 1%. Phenocrysts: none. Groundmass: Plagioclase (An_{43-49}), 55%, subhedral, locally altered to sericite, albite and pericline twinning. Magnetite: 20%, subhedral. Titaniferous augite: 15%, purplish, subhedral. Interstitial very fine grained undetermined material: 8%. Olivine: 2%, subhedral to anhedral, locally altered to iddingsite.

Sample 41-B:

Transitional Olivine Basalt. Texture: Porphyritic pilotaxitic. Vesicularity: 3%, commonly filled with brown and green chlorophaeite. Phenocrysts: Olivine, 9%, subrounded and altered to iddingsite. Plagioclase (An_{48-52}), 1%, subhedral, albite and Carlsbad twinning. Spinel: one grain, 0.1mm, brown, isotropic, partially resorbed. One clinopyroxene xenocryst, 1.0mm, rounded. Groundmass: Plagioclase (An_{46-48}), 38%, subhedral, albite and pericline twinning. Titaniferous augite: 16%, subhedral. Magnetite: 16%, subhedral. Olivine: 12%, subhedral to anhedral. Interstitial very fine grained undetermined material: 5%.

Samples 51-A and 51-D:

Hawaiites. Texture: Pilotaxitic intergranular to intersertial. Vesicularity: 1-3%, commonly filled with calcite and chlorophaeite. Phenocrysts: none. Groundmass: Plagioclase (An_{43-47}), 40-45%, subhedral, locally altered to sericite; albite and pericline twinning.

Magnetite: 24-26%, subhedral. Olivine: 14-16%, subhedral to anhedral. Titaniferous augite: 9-11%, subhedral. Interstitial very fine grained undetermined material: 4-7%.

Sample 9-11:

Transitional Alkalic Olivine Basalt. Texture: Porphyritic intergranular to intersertal. Vesicularity: 7-9%. Phenocrysts: Olivine, 15-20%, subrounded, as pseudomorphs, completely altered to red iron oxides. Groundmass: Plagioclase (An_{43-49}), subhedral, locally altered to sericite, albite and pericline twinning. Augite: 16-19%, subhedral. Magnetite: 10-12%, Olivine: 8-10%, subhedral, altered to iron oxide. Interstitial, very fine grained undetermined material, 7-10%.

Petrographic Descriptions of Selected Off-Ridge Seamount Samples

Samples 65-24-A and 65-24-D:

Hawaiites. Texture: Porphyritic intergranular to intersertal. Vesicularity: 7-20%. Phenocrysts: Plagioclase (An_{50-56}), 1-3%, subhedral, albite twinning, locally embayed. Clinopyroxene: 1-3%, subhedral. Magnetite, 1-3%, euhedral. Groundmass: Palgioclase (An_{48-55}), 45-60%, subhedral, locally altered to sericite, albite and pericline twinning. Magnetite: 10-15%, as scattered subhedral crystals and as dendritic growths around vesicles. Titaniferous augite: 20-35%, subhedral, locally sector zoned.

Sample 33-17-A:

Hawaiite. Texture: Porphyritic pilotaxitic. Vesicularity: 1%. Phenocrysts: Plagioclase (An_{48-55}), 8-10%, subhedral, albite and pericline twinning, normally zoned. Olivine: 3-5%, subhedral, altered to iddingsite. Groundmass: Plagioclase (An_{40-45}), 25-30%, subhedral, albite twinning. Magnetite: 22%, euhedral to subhedral. Clinopyroxene: 3%, subhedral. Olvine: 1%, subrounded, altered to iddingsite. Interstitial, very fine grained undetermined material: 42%.

Samples 34-18-B and 34-18-C:

Hawaiites. Texture: Subpilotaxitic, locally variolitic. Vesicularity: 5-7%, commonly lined with celadonite. Phenocrysts: Iron oxides: 1%, subhedral. Groundmass: Plagioclase (An_{30-35}), 35-40%, subhedral, albite twinning. Magnetite: 35-40%, embayed. Interstitial very fine grained undetermined material 12-15%.

Samples 20-8-J and 20-8-O

Hornblende Benmoreites. Texture: Porphyritic subtrachytic. Vesicularity: 7-10%, commonly lined with celandonite. Phenocrysts: Brown hornblende: 10-12%, subhedral, strongly pleochroic, locally intergrown with feldspar or clinopyroxene as glomerocrysts. Plagioclase (An_{30-35}), 7-10%, subhedral, albite twinning. Clinopyroxene: 1-3%, light green, subrounded, usually intergrown with hornblende. Iron oxides: 1-3%, subhedral, commonly intergrown with hornblende. Groundmass: Plagioclase (An_{30-35}), 40-45%, subhedral, locally slightly altered to sericite. Hornblende: 5-7%, subhedral, locally mantled with subhedral iron oxides. Clinopyroxene: 5-7%, yellow-green color, subhedral prisms. Magnetite: 5-7%, subhedral to euhedral. Minor apatite (1%).

APPENDIX D

Petrographic Description of Kaula Island Samples

Group I-A – Samples KA-19, KA-25, KA-31, KA-34, KA-35, KA-40:

Basanitoids. Texture: Porphyritic, intersertal. Vesicularity: 25-50%. Phenocrysts and microphenocrysts: Olivine, 15-30%, clear, subhedral to euhedral, elongate, skeletal structure. Titaniferous augite: 3-10%, pale green, sector zoning, anhedral with olivine inclusions and local orthopyroxene exsolution. Green spinel, 1-3%, rounded or embayed, commonly coated with magnetite. Groundmass: Very fine grained, monoclinic pyroxene (augite ?) microlites, 10-30%, pale green subhedral. Olivine: 7-10%, clear, anhedral. Magnetite: 10-17%, in two generations as crystals and as dendritic structures around vesicles. Volcanic glass: 5-10%. Xenocrysts: ultramafic inclusions, mainly composed of monoclinic and orthorhombic pyroxene, green gray spinel, 3-5%. Interstitial very fine grained undetermined material: 7-10%.

Group I-B – Samples KA-11, KA-15, KA-16, KA-17, KA-24, KA-28, KA-38, KA-39, KA-42:

Basanitoids. Texture: Porphyritic, intersertal. Vesicularity: 15-45%, commonly filled with zeolites. Phenocrysts and microphenocrysts: Olivine, 10-25%, clear, subhedral to euhedral, elongate, commonly displays skeletal structure. Titaniferous augite: 5-20%, pale green to pale pink, altered, sector zoning, anhedral. Sample KA-15 contains 1-3% green spinel, rimmed by individual magnetite grains. Sample KA-42 contains phenocrysts of plagioclase (An_{50-55}), 7-10%, subhedral, combined albite and Carlsbad twinning. Groundmass: Monoclinic pyroxene (augite ?) microlites, 30-60%, pale green to pale pink, subhedral. Sample KA-24 contains very abundant amounts of pyroxene, commonly displaying variolitic texture. Olivine: 5-10%, clear, anhedral. Magnetite: 10-30%. Volcanic glass: 5-10%.

Xenocrysts: ultramafic inclusions, mainly websterites with green gray spinel, 3-5%. Sample KA-39 contains one small grain of clear garnet included within an ultramafic xenolith. Interstitial very fine grained undetermined material: 7-15%.

Group II – Samples KA-10, KA-12, KA-13, KA-33, KA-36, KA-37, KA-41, KA-45:

Biotite phonolites. Texture: Porphyritic, intergranular to intersertal. Vesicularity: 3-25%, commonly filled with zeolites. Phenocrysts: Brown biotite, 5-10%, strongly pleochroic, embayed or rounded, local inclusions of apatite, commonly surrounded by magnetite, apatite, and rarely zircon. Groundmass: Trachytic texture, moderate to well developed flow structure. Alkalic feldspar, 65-75%, as curved laths. Apatite: 7-10%, commonly concentrated around biotite phenocrysts, subhedral, biaxial with small 2V (5-10^{o}). Magnetite: 5-7%, subhedral, commonly around biotites. Zircon, 1-3%, in samples KA-36 and KA-41, around biotites, subhedral. Biotite: 1-3%, anhedral, brown, pleochroic.

Group III-A – Samples KA-32 and KA-48:

Lherzolites. Texture: Coarse granular. Olivine: 50-60%, subhedral, commonly kink banded. Orthopyroxene: 23-27%, subhedral, non-pleochroic, 2V=76^{o}, rarely intergrown with olivines. Clinopyroxene: 12-16%, pale green, subhedral. Spinel: 1-2%, dark reddish brown, anhedral, rarely partial resorbed. Veins of calcite: 1%.

Group III-B – Samples KA-23, KA-26 and KA-27:

Websterites. Texture: Coarse granular. Clinopyroxene: 50-55%, subhedral, with exsolved orthopyroxene as blebs and as lamellae along cleavage planes. Orthopyroxene: 45-50%, commonly as exsolution blebs and exsolution lamellae along clinopyroxene cleavage planes, rarely as small (0.25-0.50 mm) discrete grains, pale yellow, slightly pleochroic. Spinel: 5-7%, green-gray to green, anhedral.

Group III-C – Samples KA-43 and KA-44:

Websterites. Textures: Coarse granular. Clinopyroxene, 50-55%, subhedral, no exsolution. Orthopyroxene, 45-50%, anhedral, as discrete grains, pale yellow, slightly pleochroic. Spinel: 5-7%, green-gray to green, anhedral.

Group III-D – Sample KA-48:

Garnet Websterite. Texture: Porphyroblastic granular. Porphyroblasts: Pyropic garnet, clear, anhedral, surrounded by crushed zone. Clinopyroxene: 30-35%, anhedral, with exsolution of orthopyroxene common. Orthopyroxene: 28-32%, as exsolution blebs in clinopyroxenes and also as exsolution along clinopyroxene cleavage planes. Spinel: 5-7%, gray-green to green, anhedral.

Group IV-A – Samples KA-29 and KA-30:

Basanitoids. Texture: Porphyritic intergranualr. Vesicularity: 10-30%, commonly filled with zeolites. Phenocrysts and microphenocrysts: Olivine, 7-10%, subhedral to anhedral, poorly developed skeletal structure, commonly as glomerocrysts. Titaniferous augite: 1-3%, purple, commonly as isolated microlites. Groundmass: Plagioclase (An_{50-55}), 25-35%, subhedral, combined albite and Carlsbad twinning, rare apatite inclusions. Augite: 15-30%, pale green to buff color, anhedral to subhedral, rarely sector zoned. Olivine: 10-15%, anhedral. Magnetite: 7-10%, as distinct subhedral crystals and in dendritic patterns around vesicles. Apatite: 1%.

Group IV-B – Sample KA-14:

Basalt. Texture: Porphyritic subophitic. Vesicularity: 25-30%, commonly lined with red iron oxides. Phenocrysts: Olivine, 1-3%, completely altered to iddingsite. Plagioclase (An_{55-58}), 5-7%, commonly as glomerocrysts, subhedral, concentric zoning, combined albite and Carlsbad twinning. Groundmass: Plagioclase (An_{50-55}), 25-28%, subhedral, combined albite and Carlsbad twinning. Augite: 26-30%, pale green, anhedral to subhedral. Interstitial, reddish brown clays and volcanic glass, 5-7%. Magnetite, 7-10%.

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