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Petrology and geochronology of volcanic rocks from seamounts along and near the Hawaiian Ridge: Implications for propagation rate of the ridge

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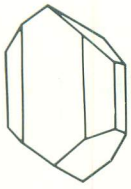

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Lavas from three seamounts along and three seamounts near the Hawaiian Ridge are petrographically and geochemically similar to lavas from the Hawaiian Islands. Rock types recovered include tholeiitic and alkalic lavas. The composition of these lavas is virtually identical to that of lavas from the Hawaiian Islands. This indicates that the source composition and petrogenesis of lavas along the Hawaiian chain are very consistent. The three along-ridge seamounts are in areas where there were gaps in the radiometric age data base. New ages further document the linear age progression along the chain and define a new propagation rate of 9.6 ± 0.4 cm/yr (which is identical to the present-day plate motion of the island of Hawaii). The near-ridge seamounts are Cretaceous in age (74–77 Ma) and are part of NNW-trending linear chains that predate and are unrelated to the NW- and N-trending Hawaiian and Emperor chains.

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Introduction

The Hawaiian-Emperor chain is the longest chain in the Pacific basin extending over 5800 km in length. Most of the chain consists of seamounts (87 of 107 volcanic edifices that comprise the chain and all but four of the edifices northwest of the Hawaiian Islands; Shaw et al., 1980). Despite the importance of these seamounts to understanding the origin of this chain and hotspot processes in general, relatively little is known of their petrology and geochronology. This is particularly the case for the submarine portion of the Hawaiian Ridge (northwest of Nihoa Island). No systematic dredging program of the Hawaiian Ridge seamounts has ever been undertaken. Rocks from only 8 of the 48 volcanic edifices between Nihoa Island and the bend in the Hawaiian-Emperor chain have been geochemically analyzed and dated by K-Ar.

Other seamounts along and near the Hawaiian Ridge (Fig. 1) are older than the Hawaiian Ridge. Samples dredged from Wentworth (28°54′N, 177°52′W) and Necker (23°48′N, 164°25′W) seamounts, which are morphologically part of the ridge, have yielded K-Ar ages of 71 and 78 Ma, respectively (Clague and Dalrymple, 1975). Two seamounts south of the Hawaiian Islands have been dated at about 86 Ma (Dymond and Windom, 1968). North of the Hawaiian Ridge, two seamounts from the Musicians were dated at 65 and 85 Ma (Clague and Dalrymple, 1975).

The purpose of this study was to better characterize the leeward section of the Hawaiian Ridge, which is a major portion of the type-example of a hotspot trace. We present petrographic, geochemical and geochronological data for volcanic rocks dredged from three seamounts along the Hawaiian Ridge (where there were gaps in the data base) and for

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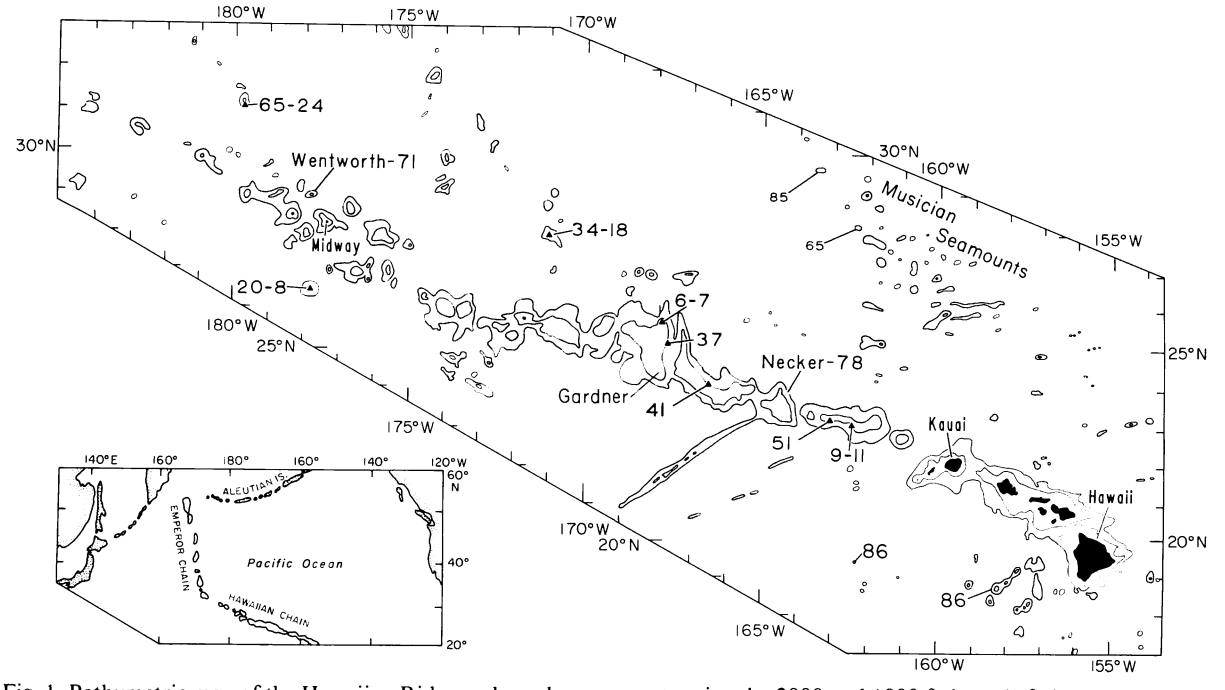

Fig. 1. Bathymetric map of the Hawaiian Ridge and nearby seamounts using the 2000 and 1000 fathom (1 fathom = 1.8288 m) contours from *Bathymetry of the North Pacific Charts* by Chase et al. (1970), Scripps IMR Technical Report Series (TR-13). Triangles indicate dredge locations for samples examined in this study.

three seamounts located near the Midway region of the Hawaiian Ridge, in older chains that intersect the ridge. These data provide constraints on the origin and evolution of lavas from these linear seamount chains and the propagation rate of the chains.

The least altered samples from each dredge haul were selected for thin sectioning. On the basis of thin section examination, samples were selected for chemical analysis. Limited lithologic variation was noted for any one dredge haul and, in general, the rocks recovered from each seamount are representative of only one eruptive stage of a typical Hawaiian volcano (as outlined by Macdonald and Abbott, 1974). Gardner Seamount is an exception. Both tholeiitic and alkalic lavas were recovered, although they were obtained in different dredge hauls (6-7 and 37, respectively). In addition to the petrographic examination, whole-rock, major and trace element, and mineral analyses were made to determine which eruptive stage each sample represented. These analyses are also useful for evaluating chemical variations along the Hawaiian Ridge, which may be indicative of mantle heterogeneity or of temporal changes in processes of magma generation.

Analytical methods

Samples were trimmed with a water-cooled diamond saw to remove altered material. The freshest portions of each sample were ground in a tungsten carbide shatterbox. Splits of these powders were analyzed for major and minor elements at the University of Manitoba. Si, Al, Fe (total), Mg, Ca, K, Ti and Mn contents were determined with a multichannel ARL X-ray spectrometer. Na was determined using a Perkin-Elmer 303 atomic absorption spectrophotometer. Ferrous iron analyses were made by titration using sodium diphenylamine sulfonate as an indicator. P contents were determined by colorimetry. H_2O values were determined by heating a sample in a stream of dry oxygen in an induction furnace at 100°C; the H_2O was collected on anhydrone and weighed. For CO_2 analyses, the samples were decomposed in warm HCl. The evolved CO_2 was passed through a drying train and collected on ascarite.

Rare earth elements (REE), Ba, Sr and Rb abundances were determined by mass spectrometric isotope dilution techniques (Schnetzler et al., 1967a, b). Conventional K-Ar measurements were made

using isotope dilution mass spectrometry methods as described by Dalrymple and Lanphere (1969, 1971), Dalrymple et al. (1971), Gramlich (1970), and Naughton et al. (1980).

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, rhodonite and rutile. Instrument operating conditions were usually 15 kV and 10–20 nA sample current. Each analysis is an average of 6–8 points per grain and 4–6 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 and spectrometer background. Beam current drift was continuously regulated to within 0.1 nA/hr. Mineral analyses were obtained using a *ZAF* correction program. 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.

Results

The results of our work on samples from along and near the Hawaiian Ridge will be discussed together to emphasize the overall similarity of these lavas.

Petrography

Petrographically, all samples examined (except those from the seamount south of the Hawaiian Ridge, 20-8) are typical of lavas from the Hawaiian Islands. These samples can be subdivided into two groups based on phenocryst content and texture: basalts and hawaiites-mugearites. The basalts contain olivine phenocrysts and have subophitic to intergranular texture (Table 1). The hawaiites-mugearites are aphyric or contain sparse plagioclase phenocrysts in a subpilotaxitic to subtrachytic matrix. All of the samples contain at least minor amounts of groundmass olivine or olivine pseudomorphs. The samples are somewhat altered but to varying degrees. The basalts from dredge haul 6-7 are virtually unaltered beneath a 1–2 cm thick weathering rind. In contrast, samples from dredge haul 9-11 are moderately altered and are not suitable for K-Ar age dating. The difference in degree of alteration of these samples is probably a result of the higher percentage of vesicularity in the altered samples. The hawaiites-mugearites which are nearly non-vesicular, are relatively free of alteration except for local areas which were originally glassy.

The lavas recovered from the seamount south of the Hawaiian Ridge (20-8) are distinctive because they contain amphibole phenocrysts which are extremely rare in Hawaiian lavas (exceptions: a rhyodacite from Oahu, a hawaiite near the summit of Haleakala Volcano, two trachytes from W. Maui and a trachyte and a benmoreite from Kohala Volcano; Macdonald and Abbott, 1974).

Mineral chemistry

Groundmass plagioclase is present in all the samples analyzed. The composition of the groundmass plagioclase can normally be used to classify volcanic rocks (Keil et al., 1972). Tholeiites contain lower K_2O contents than alkalic basalts (<0.20 vs. >0.25 wt.% K_2O). For the alkalic suite, basalts should have groundmass and normative plagioclase anorthite contents greater than 50% (Coombs and Wilkinson, 1969). Hawaiites should have anorthite contents between 30 and 50% (andesine); mugearites, between 10 and 30% (oligoclase). However, microprobe analyses of groundmass plagioclase from unaltered volcanic rocks with normative andesine and oligoclase contents have consistently higher anorthite contents. For instance, groundmass plagioclase compositions in New Zealand and Hawaiian hawaiites range from An_{57} to An_{64}, and from mugearites from An_{39} to An_{48} (Price and Chappell, 1975; Dalrymple and Garcia, 1980). Alkalic basalts generally have groundmass plagioclase with anorthite contents $>62\%$.

Groundmass plagioclase was analyzed by microprobe for samples from each dredge haul (except 9-11, which contains very fine-grained, quenched plagioclase grains). Based on groundmass plagioclase compositions, samples from dredge haul 6-7 are tholeiites; the others are all alkalic lavas (Table 2). Among the alkalic lavas, 37-A, 37-C and possibly 41-B are basalts; 34-18-B, 65-24-A and probably 65-24-D are hawaiites; and 51-A, 51-D, 20-8-J, 20-8-O and possibly 41-A are mugearites.

Clinopyroxene (cpx) groundmass grains occur in

TABLE 1

Modes in volume % for selected samples from along and near the Hawaiian Ridge based on 1000 counts/samples

	Along ridge									Near ridge				
	9-11	51-A	51-D	41-A	41-B	37-A	37-C	6-7A	6-7F	20-8-J	20-8-O	34-18B	65-24-A	65-24-D
Phenocrysts:														
Plagioclase	—	—	—	tr.	1	2	1	1	4	9	5	—	tr.	tr.
Olivine	30	—	—	tr.*[1]	10	9	13	20	20	—	—	—	—	—
Clinopyroxene	—	—	—	—	tr.	1	1	tr.	1	1	tr.	—	—	—
Magnetite	—	—	—	—	tr.	—	—	—	—	1	1	tr.	—	tr.
Hornblende	—	—	—	—	—	—	—	—	—	12	5	—	—	—
Groundmass:														
Plagioclase	7*[2]	43	42	54	38	36	38	35	33	49	51	46	43	58
Olivine	—	16	10	2	12	6	5	tr.	4	—	—	—	—	—
Clinopyroxene	18*[2]	11	7	14	17	16	17	32	22	9	8	4	10	24
Opaques	11*[2]	26	28	19	17	20	16	5	10	8	10	38	27	15
Hornblende	—	—	—	—	—	—	—	—	—	2	2	—	—	—
Matrix	34	4	13	11	5	10	9	7	6	9	18	12	20	3
Vesicularity	16	tr.	1	tr.	3	tr.	tr.	tr.	tr.	9	3	6	19	10

tr. = trace.
*[1] Altered.
*[2] Quench phases.

TABLE 2

Plagioclase and anorthoclase compositions of groundmass grains from lavas along and near the Hawaiian Ridge

(A) Along ridge

	51-A	51-D	41-A	41-B	37-A	37-C	6-7A	6-7F
SiO_2	55.3	54.9	55.3	51.8	51.5	51.5	52.1	52.2
Al_2O_3	27.9	27.9	27.4	30.2	29.8	29.7	29.9	29.6
FeO	0.8	0.8	0.8	0.8	0.9	0.8	0.9	1.0
CaO	10.0	9.9	9.3	13.0	13.2	13.2	13.2	13.5
Na_2O	5.7	6.0	6.5	4.0	3.8	3.9	3.9	3.8
K_2O	0.4	0.4	0.5	0.25	0.25	0.3	0.15	0.15
Total	100.1	99.9	99.8	100.0	99.4	100.4	100.2	100.3
An% range	45–50	40–47	38–58	60–64	63–66	62–66	70–76	64–70

(B) Near ridge

	20-8-J	20-8-O		34-18-B		65-24-A	65-24-D	
SiO_2	57.6	57.0	64.5	53.1	55.9	52.3	52.4	64.6
Al_2O_3	26.5	26.5	20.6	29.1	27.3	29.4	29.9	19.7
FeO	0.7	0.7	0.4	0.8	0.4	0.9	0.8	0.5
CaO	8.2	8.2	1.8	11.7	9.4	12.0	12.6	0.9
Na_2O	6.2	6.6	6.5	4.6	6.1	4.8	4.2	6.9
K_2O	0.8	0.7	0.4	0.8	0.4	0.4	0.4	7.2
Total	100.0	99.7	100.0	99.8	99.5	99.8	100.3	99.8
An% range	26–40	34–40	4–15	50–63	26–40	52–60	36–61	2–5

Analyst: M. Garcia.

TABLE 3

Representative analyses of clinopyroxene and amphibole in lavas from along and near the Hawaiian Ridge

	Along			Near			
Sample No.	6-7A	6-7F	37-C	65-24-D	20-8-O	20-8-J	20-8-O
Mode*	gm	gm	gm	gm	ph	ph	amph-ph
SiO_2	51.4	49.7	46.4	44.8	47.3	49.2	39.0
TiO_2	0.9	1.3	2.5	4.3	1.7	1.1	4.7
Al_2O_3	3.0	4.9	6.5	6.9	6.0	4.3	13.3
Cr_2O_3	0.5	0.7	0.4	0.0	0.0	0.0	0.0
FeO	7.6	7.6	8.3	9.8	9.4	8.9	14.3
MnO	0.2	0.2	0.1	0.2	0.4	0.4	0.4
MgO	17.2	16.3	12.6	11.6	11.9	12.6	11.2
CaO	18.7	19.4	21.6	21.6	21.8	22.1	11.5
Na_2O	0.2	0.3	0.6	0.7	0.9	0.9	2.9
K_2O	0.0	0.0	0.0	0.0	0.0	0.0	1.3
Total	99.7	100.3	99.0	99.9	99.4	99.5	98.6
Wo	38.3	40.4	47.3	47.4	47.4	47.0	
En	49.2	47.0	38.4	35.4	36.0	37.5	
Fs	12.5	12.5	14.4	17.1	16.6	15.5	

Analyst: M. Garcia.
*Mode: ph = phenocryst; gm = groundmass; amph = amphibole.

all of the samples studied, but many samples have grains too small to yield reliable microprobe analyses. Microprobe analyses were made on groundmass cpx grains to further document the magmatic affinities of the lavas studied (Table 3). Kushiro (1960), Le Bas (1962) and Nisbet and Pearce (1977) have shown that the composition of cpx in mafic lavas can be used to distinguish magma types. Fodor et al. (1975) and Clague et al. (1980a) demonstrated that Hawaiian tholeiites have a lower wollastonite (Wo) component and lower TiO_2 and Na_2O than Hawaiian alkalic lavas.

The groundmass cpx samples from dredge 6-7 have distinct tholeiitic affinities: they have low Wo contents (i.e. 38–40%; see Fig. 2) and low TiO_2 and Na_2O contents (i.e. 0.9–1.3 and 0.2–0.3). In contrast, analyses of groundmass cpx in the other samples plot in the alkalic field in Fig. 2 (47% Wo) and have higher TiO_2 and Na_2O contents (i.e. 2.5–4.3 and 0.6–0.7). The cpx phenocrysts in samples from dredge haul 20-8 also have alkalic affinities with high Wo, TiO_2 and Na_2O contents.

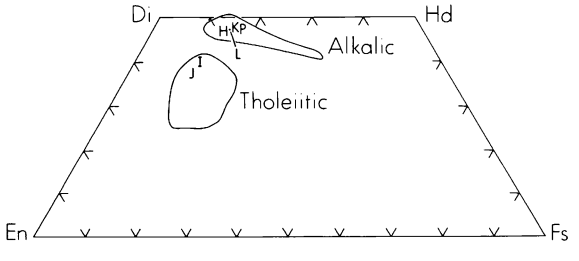

Fig. 2. Quadrilateral components of clinopyroxene. Fields for tholeiitic and alkalic basalts from Clague et al. (1980a). Refer to Table 4 for symbol identification.

Amphibole phenocrysts and microphenocrysts are present in samples from dredge haul 20-8. They are Ti-rich, Si-poor and have a Mg number of 59 (Table 3). They are classified as kaersutites based on the nomenclature of Leake (1978). As mentioned previously, amphiboles are very rare in Hawaiian volcanic rocks. There are only two analyses of Hawaiian amphiboles, both from trachytes. The trachyte from Kohala Volcano contains amphibole with moderate to high Si and low Ti (Basaltic Volcanism Study Project, 1981), an edenite according to Leake's (1978) classification. The other trachyte is from West Maui Volcano and it also contains high Si and low Ti but it is alkali-rich (richterite phenocrysts, arfvedsonite microphenocrysts; Velde, 1978).

Olivines are abundant and fresh in samples from dredge haul 6-7. Cores of these olivines are very forsteritic (Fo_{87-89}), which are among the highest values reported for Hawaiian olivines (see Maaloe and Hansen, 1982).

Geochemistry

The whole-rock chemistry data substantiate the petrographic and mineral chemistry interpretations and can be used to further diagnose the magma type of the samples (Table 4).

The Macdonald and Katsura (1964) total alkalis vs. SiO_2 plot is useful in determining magma type for these samples, if the nature of alteration of each sample is considered. Samples from dredge haul 6-7 are virtually unaltered. Their compositions plot well within the tholeiite field (Fig. 3; points *I*, *J*). The compositions of four slightly altered samples (9-11, 41-B, 37-A, 37-C; points *A*, *E*, *G*, *H*) plot near the tholeiitic-alkalic boundary. The remaining samples, which were classified as hawaiites-mugearites on petrographic evidence, all plot well within the alkalic field between Macdonald's (1968) average basalt and trachyte. To characterize these samples within the alkalic series, their normalized compositions were plotted on a Coombs and Wilkinson

TABLE 4

Whole-rock, major element analyses and C.I.P.W. norms (dry, Fe_2O_3/FeO adjusted to 0.20, normalized to 100%) of volcanic rocks from along and near the Hawaiian Ridge

		Along ridge									Near ridge					
Sample		9-11	51-A	51-D	41-A	41-B	37-A	37-C	6-7A	6-7F	20-8-J	20-8-O	34-18-B	34-18-C	65-24-A	65-24-D
Symbol		*A*	*B*	*C*	*D*	*E*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*	*O*	*P*
SiO_2		44.40	42.60	43.30	45.95	45.10	44.90	45.20	46.40	46.30	57.65	57.35	45.65	46.90	49.70	50.10
TiO_2		2.40	3.84	3.78	3.92	2.32	2.32	2.28	1.68	1.66	1.09	1.10	3.44	2.96	2.56	3.19
Al_2O_3		10.56	13.32	13.14	15.26	14.48	14.72	14.53	10.61	10.54	18.67	18.28	17.90	17.26	17.57	16.80
Fe_2O_3		3.86	4.40	5.42	6.79	4.46	4.28	4.42	2.67	2.22	2.72	3.35	10.60	8.30	7.21	5.74
FeO		9.14	10.38	9.36	6.34	7.58	7.64	7.82	8.74	9.42	1.20	1.24	2.22	2.62	1.68	2.76
MnO		0.19	0.20	0.21	0.21	0.18	0.17	0.17	0.17	0.17	0.13	0.13	0.17	0.19	0.12	0.16
MgO		16.63	5.72	5.43	4.70	9.55	9.60	9.44	16.05	16.95	1.41	1.28	2.37	3.15	1.72	2.58
CaO		7.13	8.91	9.24	8.58	9.76	9.76	9.51	8.70	8.77	5.08	5.07	6.93	8.36	7.06	8.45
Na_2O		2.09	3.29	3.27	3.41	2.56	2.53	2.42	1.74	1.73	5.36	5.34	3.82	4.02	4.56	3.86
K_2O		0.68	0.86	1.08	1.27	0.65	0.64	0.58	0.16	0.10	4.63	4.49	1.89	1.39	2.94	3.70
P_2O_5		0.41	2.97	2.91	0.63	0.36	0.36	0.35	0.26	0.19	1.13	0.96	0.80	1.30	1.34	1.16
H_2O^+		1.18	0.90	1.02	1.37	1.53	1.50	1.50	0.96	0.76	0.14	0.15	1.26	0.84	0.65	0.17
H_2O^-		1.49	2.27	1.50	1.45	1.17	1.46	1.37	1.77	0.94	0.41	0.72	2.62	2.22	2.62	0.80
CO_2		0.02	0.07	0.12	0.05	0.08	0.04	0.15	0.01	0.04	0.16	0.21	0.05	0.16	0.10	0.22
Total		100.18	99.73	99.78	99.93	99.78	99.94	99.74	99.92	99.79	99.78	99.67	99.72	99.67	99.83	99.69
Norms:																
	Or	4.1	5.3	6.6	7.7	4.0	3.9	3.5	0.9	0.6	27.7	27.0	11.8	8.6	18.1	22.3
	Ab	18.2	28.9	28.6	29.9	22.1	21.7	21.2	15.1	14.9	45.2	45.2	33.1	35.5	36.5	26.9
	An	17.9	19.8	18.5	23.4	27.0	27.8	28.1	21.3	21.1	13.4	12.9	27.5	26.0	19.6	17.9
	Ne	—	—	—	—	0.2	0.3	—	—	—	0.4	0.4	0.5	—	2.0	3.5
Di	Wo	6.6	2.5	3.8	6.9	8.6	8.3	7.7	8.9	9.2	1.9	2.6	1.3	3.5	3.3	7.2
	En	4.5	1.2	1.8	3.4	5.3	5.1	4.7	6.1	6.4	0.9	1.1	0.5	1.5	1.2	3.5
	Fs	1.6	1.2	1.9	3.3	2.9	2.7	2.7	2.1	2.1	1.0	1.6	0.9	1.9	2.1	3.5
						2.7										
Hy	En	4.0	5.0	4.1	0.5	—	—	3.3	13.8	11.4	—	—	—	0.4	—	—
	Fs	1.4	5.0	4.4	0.5	—	—	1.9	4.6	3.7	—	—	—	0.5	—	—
Ol	Fo	23.9	6.0	5.7	5.8	13.5	13.8	11.5	14.9	17.7	1.8	1.5	4.0	4.4	2.3	2.1
	Fa	9.1	6.7	6.6	6.4	8.2	8.2	7.2	5.5	6.4	2.1	2.3	8.6	6.1	4.5	2.3
	Mt	3.1	3.6	3.6	3.1	2.9	2.9	3.0	2.8	2.8	0.9	1.0	3.0	2.5	2.1	2.0
	Il	4.7	7.6	7.4	7.7	4.6	4.6	4.5	3.3	3.2	2.1	2.1	6.9	5.9	5.1	6.2
	Ap	1.0	7.3	7.1	1.5	0.9	0.9	0.9	0.6	0.5	2.7	2.3	2.0	3.2	3.3	2.8
	D.I.	22.3	34.2	35.2	37.6	26.3	25.8	24.8	16.1	15.5	73.2	72.6	45.4	44.1	56.7	52.7

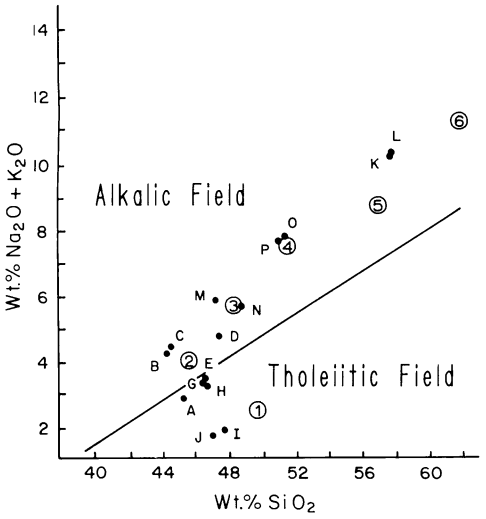

Fig. 3. Alkali-silica diagram with Macdonald-Katsura (1964) dividing line for alkalic and tholeiitic fields. Refer to Table 4 for symbol identification. Average composition of Hawaiian lavas: *1* = tholeiite; *2* = alkalic olivine basalt; *3* = hawaiite; *4* = mugearite; *5* = benmoreite; *6* = soda trachyte (from Macdonald, 1968).

(1969) diagram (Fig. 4). Although the lavas are somewhat altered, they all plot within the hawaiite field except for the two samples from the seamount south of the ridge which plot in the benmoreite field.

Major elements are not always a reliable indicator of magma type, especially for altered volcanic rocks (Cann, 1970). A variety of nonmobile minor and trace elements have been used to discriminate

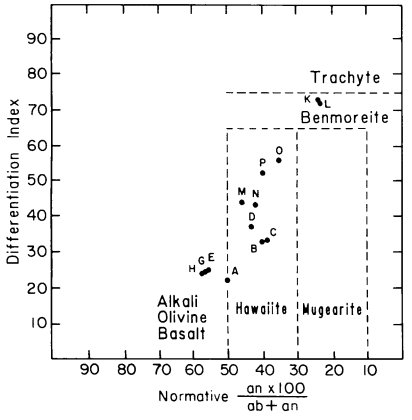

Fig. 4. Differentiation index (normative Q, Ab, Or and Ne) vs. normative anorthite diagram with fields for classifying differentiated alkalic lavas (from Coombs and Wilkinson, 1969). Symbols as in Table 4.

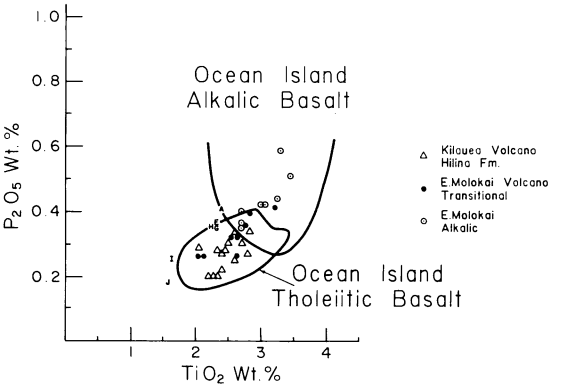

Fig. 5. P_2O_5-TiO_2 diagram with ocean island tholeiitic and alkalic basalt fields from Bass et al. (1973). Data for E. Molokai volcano from Clague and Beeson (1980) and for Kilauea volcano from Easton and Garcia (1980). For key to letter symbols, see Table 4.

magma types for altered volcanic rocks. However, only a few of these immobile elements have been used to discriminate ocean island tholeiites from ocean island alkalic basalts. Bass et al. (1973) and others have used a TiO_2-P_2O_5 plot to delineate these two magma types for basaltic lavas. Only the basalts from this study are plotted in Fig. 5. The tholeiitic lavas from dredge haul 6-7 plot just below the oceanic island tholeiitic field (probably due to the high MgO contents of the samples). The samples which plot near the tholeiitic-alkalic boundary on the total alkalis vs. SiO_2 diagram also plot near the same boundary on the TiO_2 vs. P_2O_5 diagram. Petrographically similar rocks were reported from East Molokai Volcano, Hawaii, and were termed transitional basalts in recognition of the gradational transition in some Hawaiian volcanoes from tholeiitic to alkalic compositions (Beeson, 1976). The term, transitional basalt, is adopted here for samples from dredge hauls 37, 9-11 and sample B from dredge haul 41.

Four samples representative of the suite of rocks recovered in the 8 dredge hauls from along and near the Hawaiian Ridge were analyzed for REE, Rb and Ba abundances by isotope dilution mass spectrometry (Table 5). REE analyses are useful in further deciphering the magmatic affinities of these rocks and in comparing them with typical Hawaiian lavas. In addition, REE analyses are useful for evaluating variations in the source for Hawaiian lavas along the chain (Clague and Frey, 1980; Leeman et al., 1980).

TABLE 5

Abundance of REE, Rb, Sr and Ba in dredged volcanic rocks from along and near the Hawaiian Ridge (in ppm) determined by isotope dilution

	6-7F	41-A	51-A	20-8-J
Sr	217	736	828	965
Rb	0.92	24.7	10.5	95.6
Ba	74.6	340	230	940
Ce	18.4	70	104	157
Nd	12.8	41.6	81.4	60.3
Sm	3.54	9.5	22.3	9.52
Eu	1.24	3.21	7.17	2.84
Gd	3.99	—	—	7.5
Dy	4.16	8.9	22.0	5.7
Er	—	4.4	—	2.53
Yb	1.67	3.02	4.0	2.12
Lu	0.230	0.38	0.56	0.273

Analyst: C. Noble.

Sample 6-7 was classified using the above criteria as a tholeiite. On a chondrite normalized plot, this sample has a gently sloping, light REE (LREE) enriched pattern and is similar in shape to Kilauea tholeiitic lavas (Fig. 6A). It does not have flat to slight positive slope for LREE as is typical of Mauna Loa tholeiitic lavas. Clague and Frey (1980) noted that although in detail there are differences in the abundances of trace elements between lavas from different Hawaiian volcanoes, there is a strong general similarity in REE distributions. This general similarity of the REE distributions indicates an overall consistency in the source composition and petrogenesis of tholeiites erupted along the Hawaiian chain (Clague and Frey, 1980). The REE data for 6-7 from the middle section of the Hawaiian chain where no REE data were previously available (between Kauai and Midway, a 2000-km-long section of the ridge) support the hypothesis of overall consistency in the source composition and petrogenesis of tholeiites along the Hawaiian chain.

The other three samples analyzed for REE include two hawaiites (41-A and 51-A) and a benmoreite (20-8-J). The hawaiites are identical petrographically (essentially aphyric) and in major element composition to typical alkalic cap lavas from the Hawaiian Islands. Sample 41-A has a REE pattern identical to typical evolved alkalic lavas from Hawaii (see Fig. 6B). In contrast, sample 51-A has a much different REE pattern with a convex-upward shape. The origin of this pattern is unclear.

The REE pattern for 20-8-J cross-cuts the patterns for the other samples and for typical Hawaiian,

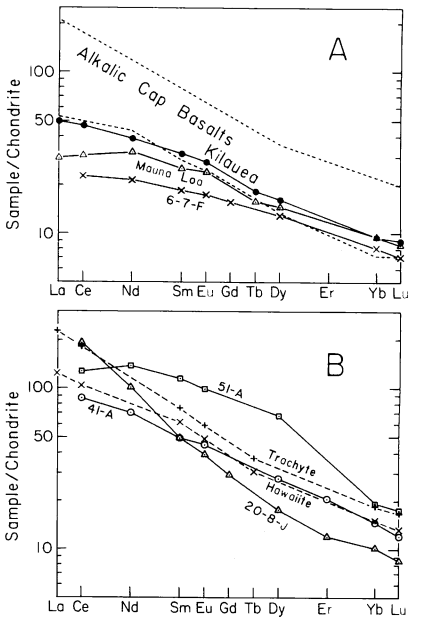

Fig. 6. Chondrite normalized rare earth element patterns.
A. Tholeiitic and alkalic Hawaiian basalts. Kilauea (●) and Mauna Loa (△) tholeiitic basalt patterns are averages (Leeman et al., 1980). Alkalic cap basalt field (between dashed lines) from Schilling and Winchester (1969), Clague et al. (1980b), and Basalt Volcanism Study Project (1981).
B. Evolved alkalic lavas. Hawaiian hawaiite and trachyte patterns are from Basalt Volcanism Study Project (1981). Chondrite values from Taylor and Gorton (1977).

evolved alkalic lavas. It has less heavy REE (HREE) and greater LREE than the other samples. This type of pattern could be derived from a typical Hawaiian hawaiite pattern by amphibole or perhaps more extensive augite fractionation based on crystal/liquid REE partition coefficients of Irving and Price (1981). This sample contains 12 vol.% amphibole and only 1 vol.% augite; therefore, it seems likely that amphibole fractionation might be responsible for the unusual REE pattern of this sample.

Note the lack of any significant Eu anomaly for these samples (Fig. 6B) and the high Sr content of these lavas (Table 5). Therefore, plagioclase (and probably apatite) fractionation may not have been important in the formation of these evolved alkalic lavas or the magma may have been relatively oxidized.

Further speculation on the origin of these lavas is unwarranted without additional samples representing the range of lavas erupted at each seamount. Nevertheless, these lavas from the leeward portion

of the Hawaiian Ridge (and the off-ridge samples) are remarkably similar to lavas from the Hawaiian Islands. Therefore, it is likely that the source composition and petrogenesis of lavas from along the Hawaiian chain are very consistent.

K-Ar geochronology

Sample preparation

Acid treatments. In the selection and preparation of dredged lavas for age determination by potassium and radiogenic argon analyses, the criteria of suitability are: (a) to obtain specimens with a low degree of contamination by air argon; and (b) to minimize or remove the alteration products present. Thin section examination allows the elimination of unsuitable samples and this can be supported by electron microprobe analysis (Mankinen and Dalrymple, 1971).

We have found that air argon contamination can be reduced by crushing specimens to 50–100 mesh size, followed by overnight treatment with 1–2% nitric acid, followed by a thorough ultrasonic-assisted washing (Keeling and Naughton, 1974). This has been established as the normal procedure in our work.

The removal of alteration products by some protocol of selection or by a chemical procedure would be desirable. This is especially important for dredged sample suites, because obtaining fresh samples may be impossible. The nature of the alteration products depends on the mineralogy of the rock, the environments in which it has been exposed, and the length of exposure in these environments. All such products, save those with little or no potassium, will have a detrimental effect on K-Ar dating (Mankinen and Dalrymple, 1972). In submarine lavas, weathering causes: (1) the addition of potassium to the rocks by the formation of clay and zeolite; and (2) the loss of argon (Seidemann, 1977).

The success of the ^{40}Ar-^{39}Ar method when applied to submarine volcanics probably results from the ability to differentiate argon retained in the primary minerals from that loosely held and partially lost from altered sections of the rock (Clague et al., 1975). A technique to reduce or remove alteration products should enhance the ability of the conventional K-Ar method to yield ages that more closely approach those found by ^{40}Ar-^{39}Ar techniques (Dalrymple et al., 1980). A chemical treatment technique would have the attractive features of ready availability and ease of application, in contrast to the ^{40}Ar-^{39}Ar method which requires irradiation of the sample in a nuclear reactor [K determination by fast neutrons, $^{39}K\ (n,p) \rightarrow {}^{39}Ar$].

Chemical treatment. We have conducted some preliminary experiments using an Edisonian approach to selecting reagents which might attack or disperse the alteration products. The dilute nitric acid treatment mentioned above causes effervescence of carbonates that even in minor amounts would swamp the ultrahigh vacuum gas purification system used in K-Ar age dating. Also in some cases, it has been found that zeolite is separated from the sample by the treatment. Some rocks that appeared otherwise suitable were completely disintegrated in the acid treatment and ultrasonic wash. Treatment with concentrated HNO_3, dilute HF, H_3PO_4, combinations of HF and H_3PO_4 and ethylene glycol yielded no significant change compared to the dilute HNO_3 treated samples.

The most effective of the reagents tried was 6 normal sulfuric acid (6 N H_2SO_4). In heavily palagonitized samples, overnight treatment caused solution and dispersion of the sample with a loss of up to 22% of the sample weight. To determine the value of this acid treatment, two comparisons were made using dredged samples from the Hawaiian-Emperor chain that were previously analyzed by conventional K-Ar and ^{40}Ar-^{39}Ar techniques. In both cases, the conventional K-Ar ages were significantly younger than the ^{40}Ar-^{39}Ar ages. A tholeiite (5-4A) from Northampton Seamount in the Hawaiian Ridge yielded a conventional K-Ar age of 20.7 ± 0.6 Ma and ^{40}Ar-^{39}Ar ages of 27.1 ± 3.0 Ma for incremental heating (500–975°C plateau, 91% of total ^{39}Ar) and 29.4 ± 1.5 Ma for total fusion (Dalrymple et al., 1981). An age of 29.0 ± 1.7 Ma was obtained on the same sample using conventional K-Ar methods after the 6 N H_2SO_4 treatment. Similarly, a mugearite from Jingu Seamount in the Emperor chain gave an age of 49.2 ± 0.7 Ma by conventional K-Ar methods, 54.3 ± 1.6 Ma by ^{40}Ar-^{39}Ar total fusion, 55.2 ± 0.6 Ma by ^{40}Ar-^{39}Ar incremental heating for 500–700°C plateau (64.5% of total ^{39}Ar) (Dalrymple and Garcia, 1980) and 55.4 ± 2.0 Ma by conventional K-Ar after the 6 N H_2SO_4 treatment. Thus, the acid treatment substantially improved the results of the conventional K-Ar anal-

yses for these samples, yielding results more consistent with ^{40}Ar-^{39}Ar analyses. These results were encouraging, but similar experiments on dredged lavas from the Line Island were inconsistent and inconclusive (Schlanger et al., 1984). Most of the Line Island samples are pillow fragments and, therefore, were probably erupted subaqueously. In contrast, the Jingu and Northampton samples show no evidence of eruption in a subaqueous environment. Thus, the acid treatment technique may not be suitable for subaqueously erupted lavas.

All samples reported in this work were exposed to our conventional 2% HNO_3 treatment. Any sample which showed excessive reaction or evidence of carbonate was rejected. Because of ambiguous results from submarine specimens subjected to additional acid treatment as mentioned above, only two samples (51A and 41B, both from along the Hawaiian Ridge) were selected for further study. Microprobe examination (scanning electron microscopy and potassium X-ray mapping) of untreated and treated (6 N H_2SO_4) splits of sample 51A showed that potassium was concentrated in interstitial areas in the untreated samples. In the treated samples, these interstitial areas are etched out and the potassium that remains is more randomly distributed. Thus, 6 N H_2SO_4 treatment seems to attack the cryptocrystalline minerals which are prime targets for weathering.

New ages

Conventional K-Ar analyses were made on samples from three seamounts on and three seamounts off the Hawaiian Ridge (Table 6). At least two samples were analyzed from each dredge haul (except 34-18 which had only one suitable sample for K-Ar analysis) and two samples were repeated using the 6 N H_2SO_4 acid treatment. The weighted mean age (WMA) was compiled for each dredge haul (Table 6, footnote *[1]). In general, the results are consistent for each dredge haul. The WMA age of the on-ridge seamounts increases toward the northwest, which is consistent with previous data showing an age progression (Dalrymple et al., 1981). These data yield an approximate propagation rate for the Hawaiian Ridge between Gardner Pinnacles and Kauai of 9.6 ± 0.4 cm/yr (Fig. 7). This is a substantial modification of the average propagation rate for the Hawaiian-Emperor chain recently proposed by Dalrymple et al. (1981) of 8.2 ± 0.2 cm/yr. Our new rate provides a more rigorous estimate for the average rate of movement of the Pacific plate for the last 13 m.y. and is identical to the value of Minister and Jordan (1980) for present-day plate motion of Hawaii.

Beyond Gardner Pinnacles there is no obvious age progression along the Hawaiian Ridge. The ^{40}Ar-^{39}Ar age for Northampton seamount and the K-Ar ages for Midway and the two unnamed seamounts northwest of Midway are all 27 ± 1 Ma (Dalrymple et al., 1981). Did simultaneous volcanism occur along a 1000 km section of the Hawaiian Ridge? More work is needed before we should abandon the simple hotspot model and adopt a "hot line" (Bonatti et al., 1977) or similar hypothesis for the origin of the Midway portion of the Hawaiian Ridge.

Late Cretaceous K-Ar ages (74–77 Ma) were determined for the three near-ridge seamounts (Table 6). These ages are older than any reported radiometric age date for lavas produced by the Emperor-Hawaiian "hotspot" (see Dalrymple et al., 1981). The age of the crust on which these seamounts were built can be determined for seamounts 20-8 and 65-24 using magnetic anomalies. Seamount 20-8 is on anomaly M-1 and Seamount 65-24 sits on M-0. Using the magnetic reversal scale of Harland et al. (1982), seamount 20-8 is on 122–123 Ma oceanic crust and seamount 65-24 is on 118–119 Ma crust. Seamount 34-18 is on oceanic crust produced during the Cretaceous magnetically quiet period. The ages of these three dated seamounts are probably at least 40 Ma younger than the underlying oceanic crust.

Samples from dredge hauls 65-24 and 34-18 are from seamounts that are part of NE-trending seamount chains that trend at nearly 45° to the Emperor Seamounts and Hawaiian Ridge (see Fig. 1). They are unrelated to the Hawaiian hotspot. Seamount 65-24 and Wentworth seamount are both part of the same NNW-trending chain (see Fig. 1). A sample from Wentworth yielded a K-Ar age of 71.0 ± 4.8 Ma (Clague et al., 1975). This is younger than the samples dated from Seamount 65-24 and is therefore consistent with a hotspot origin for this chain of seamounts. However, caution must be used in rigorously interpreting K-Ar ages on somewhat altered dredged lavas of Cretaceous age. For instance, the two seamounts are 311 km apart and their age difference is 5 Ma. This yields a relatively slow propagation rate for this chain of 5.4 cm/yr.

TABLE 6

Potassium-argon data and calculated ages for volcanic rocks dredged from along and near the Hawaiian Ridge

Sample No.	K (wt.%)	Weight (g)	^{40}Ar (radiogenic)		Calculated K/Ar age*[1] (Ma)
			(10^{7} cm^{3} g^{-1})	% of total Ar	
Ridge samples:					
51A	0.658, 0.656	3.012	1.957	19.8	7.4 ± 1.6
51A	0.742, 0.742	3.007	2.376	26.2	8.0 ± 2.1*[2]
51A	0.719, 0.705	3.019	2.882	26.6	10.1 ± 0.6*[3]
				Weighted mean	9.6 ± 0.8
51B	0.861, 0.900, 0.900	4.786	3.230	60.5	9.4 ± 0.7
				Weighted mean all 72-51	9.6 ± 0.8
41A	0.885, 0.906	4.007	4.834	38.0	13.9 ± 0.5
41B	0.396, 0.412	2.075	1.737	16.1	11.1 ± 0.8*[3]
41B	0.442, 0.446, 0.452	4.974	1.836	12.0	10.6 ± 1.7
				Weighted mean all 72-41	13.0 ± 0.6
37A	0.394, 0,400, 0.387	4.002	2.066	20.9	13.5 ± 1.3
37C	0.452, 0.453	4.006	1.992	18.9	11.4 ± 0.8
6 – 7A	0.0794, 0.0792	4.003	0.0393	8.0	12.8 ± 1.0
				Weighted mean	12.3 ± 1.0
Off-ridge samples:					
20-8-O	4.17, 3.99	3.808	122.5	95.8	75.6 ± 4.9
20-8-O	4.64, 4.46, 4.32	1.014	146.4	98.0	78.2 ± 4.6
20-8-J	4.12, 4.10, 4.03	1.019	146.0	95.4	71.7 ± 3.3
				Weighted mean all 20-8	74.3 ± 4.0
34-18C	1.247, 1.247, 1.260	5.330	38.93	87.3	78.4 ± 3.7
34-18C	1.247, 1.247, 1.260	1.582	35.58	81.0	71.7 ± 3.3
				Weighted mean	74.5 ± 3.5
65-24A	2.74, 2.79, 2.81	1.205	87.3	80.8	79.3 ± 3.6
65-24D	3.17, 3.24, 3.09	1.715	93.4	93.3	74.3 ± 3.8
65-24D	3.56, 3.61, 3.69	1.723	10.9	91.9	76.5 ± 3.8
				Weighted mean all 65-24	76.8 ± 3.7

*[1] $\lambda = 0.581 \cdot 10^{-10}$ yr^{-1}, $\lambda\beta = 4.962 \cdot 10^{-10}$ yr^{-1}, ^{40}K/K = $1.67 \cdot 10^{-4}$ mol mol^{-1}. Ages are estimated standard deviation of analytical precision (Cox and Dalrymple, 1967). Weighted mean age (WMA) of each group was calculated by weighting each measured age by the inverse of its estimated variance.

*[2] Treated, conc. HNO_3.

*[3] Treated, 6 N H_2SO_4.

For the same age period, the Line Islands chain (15–20° to the south) had a propagation rate of 9.6 ± 0.4 cm/yr (based on ages from 13 seamounts; Schlanger et al., 1984). Such a large difference in propagation rate between two relatively closely spaced chains is unlikely (see Minister and Jordan, 1980). Thus, the propagation rate for the "Wentworth" chain (based on only two data points) is suspect.

A hotspot origin for this chain is also indicated by the fact that these NNW-trending chains and Line Islands chain are both on small circles about the same plate to hotspot Euler pole. New radiometric ages for the Line Islands chain clearly document that it is a "hotspot" trace active between 93 and 59 Ma (Schlanger et al., 1984). Our preliminary results suggest that these NNW-trending chains north of the Hawaiian Ridge also document the late Cretaceous movement of the Pacific plate.

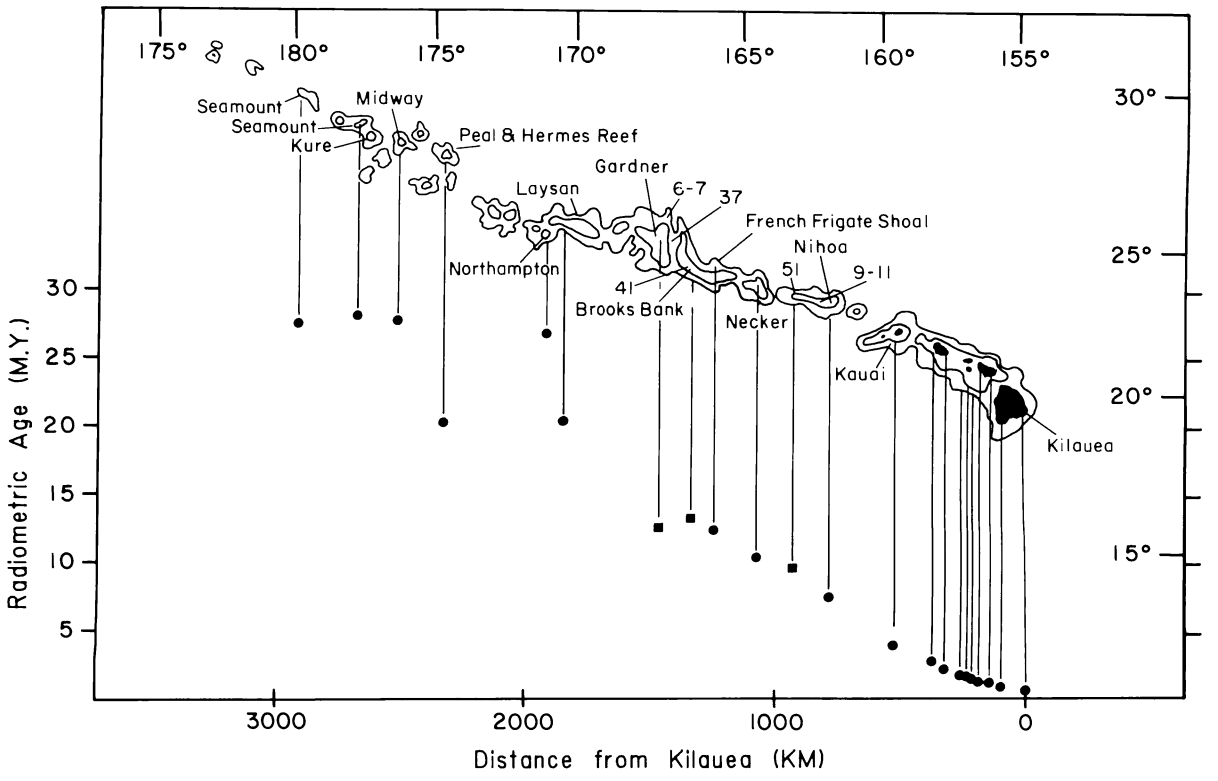

Fig. 7. Radiometric age (m.y.)–distance from Kilauea volcano (km) plot for Hawaiian Ridge volcanoes. Data for dots from Dalrymple et al., 1981; squares from this study.

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Appendix

Location of dredge sites along and near the Hawaiian Ridge sampled by the R/V KANA KEOKI

Dredge	Latitude (°'N)	Longitude (°'W)	Depth (m)
Along ridge:			
9-11	23 06.7	162 28.8	1650–2080
51	23 15.0	163 6.1	730
41	24 2.9	166 33.6	1040–1050
37	25 13.3	167 51.4	665–850
6-7	25 41.0	167 41.8	1290–1390
Near ridge:			
20-8	26 27.2	177 51.6	930
34-18	27 55.2	171 3.8	890
65-24	31 8.5	179 44.8	2950

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