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Petrology and K-Ar Ages of Dredged Samples from Laysan Island and Northampton Bank Volcanoes, Hawaiian Ridge, and Evolution of the Hawaiian-Emperor Chain

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Notes

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INTRODUCTION

The Hawaiian-Emperor volcanic chain is made up of at least 107 indentifiable shield volcanoes (Chase and others, 1970; Bargar and Jackson, 1974; Clague and others, 1980) and is the longest linear island and seamount chain in the Pacific (Fig. 1). Beginning at the active volcanoes Kilauea and Mauna Loa on the island of Hawaii, this chain of volcanoes extends west-northwestward along the Hawaiian Ridge for a distance of 3,500 km, where it turns northward and continues another 2,300 km as the Emperor Seamounts, ending near the intersection of the Aleutian and Kurile Trenches.

It is now thought that the Hawaiian-Emperor chain was formed as the Pacific lithospheric plate moved first northward and then northwestward relative to the Hawaiian hot spot, a more or less stable melting anomaly in the asthenosphere, and that the bend in the chain reflects a major change in Pacific plate motion. Several mechanisms have been proposed to explain the Hawaiian (and other) hot spots, including a propagating fracture (Betz and Hess, 1942; Jackson and Wright, 1970); diapiric upwelling along a line of structural weakness (Green, 1971; McDougall, 1971); thermal (Morgan, 1972a, 1972b) or chemical (Anderson, 1975) plumes of gravitationally unstable material rising from the deep mantle; shear

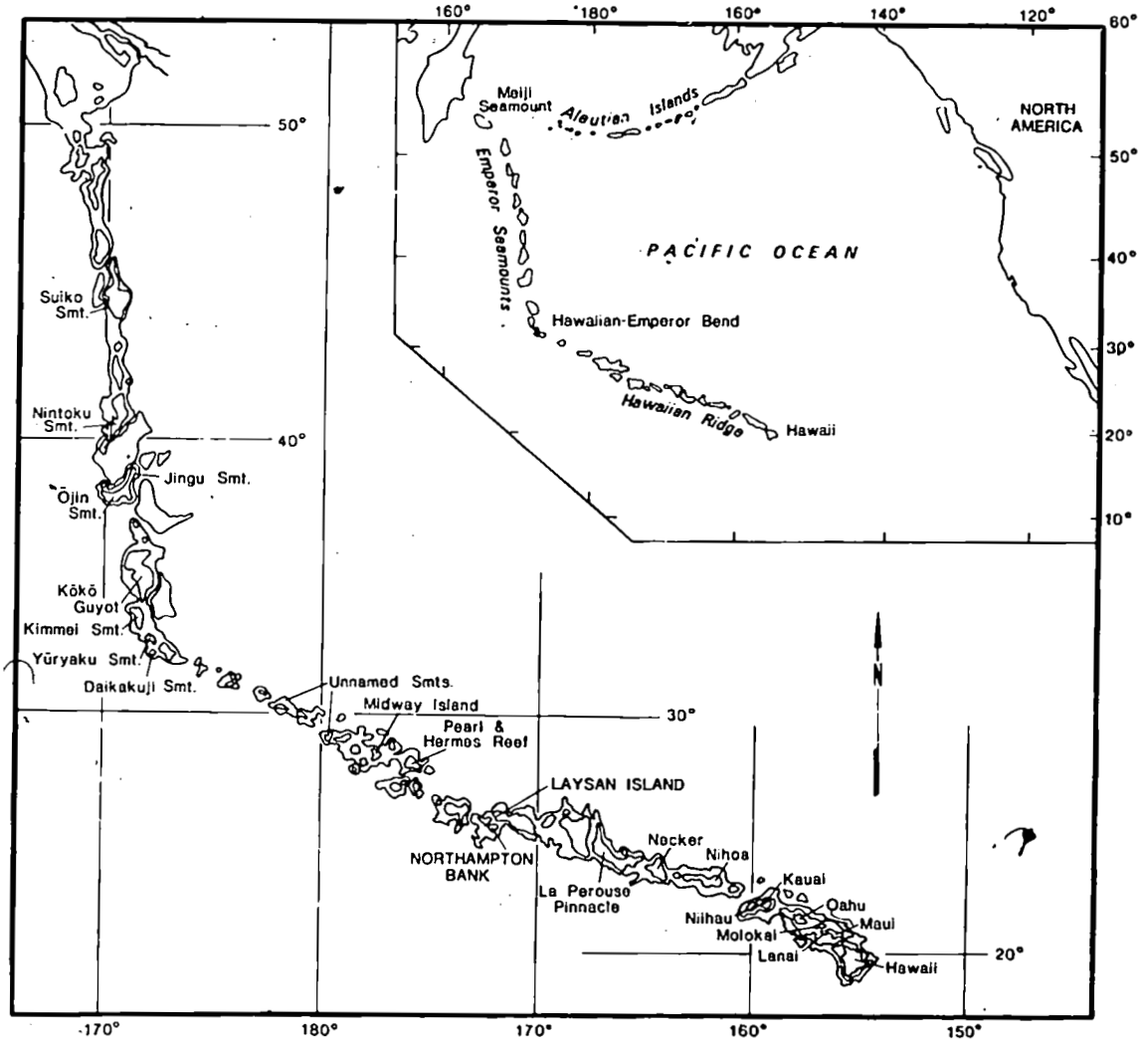

Figure 1. Bathymetric map of the Hawaiian Ridge showing the locations of Laysan Island and Northampton Bank. Other radiometrically dated volcanoes are identified by name. Contour interval is 1 km and based on bathymetry by Chase and others (1970). Inset shows the location of the Hawaiian-Emperor volcanic chain in the North Pacific.

melting coupled with thermal feedback (Shaw, 1973) and geographically stabilized by gravitational sinking of refractory residua (Shaw and Jackson, 1973); and extrusion induced by lateral motion along plate boundaries (Handschumacher, 1973). Despite the variety of dynamic models proposed, there has yet to be devised a definitive experiment to test any of them. All these mechanisms are, however, encompassed by the general (or kinematic) hot spot hypothesis, which, when used in the broadest sense, implies neither mechanism nor excess heat.

The general hot spot hypothesis has two important kinematic corollaries that are independent of hot-spot fixity and can be tested directly, using age and petrologic data. One is that the ages of the volcanoes in a linear chain should increase as a function of distance from the hot spot. The second is that the lavas of the volcanoes should be chemically similar or should have evolved chemically in some systematic way if the volcanoes were fed from a single melting anomaly. These corollaries have been the subject of considerable research on the Hawaiian-Emperor chain over the past decade or so, culminating in Deep Sea Drilling Project (DSDP) Leg 55 drilling in the Emperor Seamounts, during which volcanic rocks were cored on three of the volcanoes (Jackson, Koizumi, and others, 1980). The validity of these two corollaries has been verified by extensive K-Ar radiometric and petrologic studies in both the islands and the dominantly submarine sections of the chain. In the most recent K-Ar study and synthesis, Dalrymple and others (1980b) showed that the ages of 27 dated volcanoes increase systematically at a rate of about 0.0125 m.y./km (8 cm/yr) from the active volcanoes Kilauea and Mauna Loa (0 m.y.) to Suiko Seamount (64.7 ± 1.1 m.y.), more than 1,300 km north of the Hawaiian-Emperor bend (Fig. 1). Petrologic and chemical

studies have shown that the volcanoes of the chain closely resemble Hawaiian volcanoes in both the major- and trace-element chemistry of the lavas and in the sequence and volumes in which the principal rock suites occur (Kirkpatrick and others, 1980; Jackson and others, 1980). In addition to the age and chemical data, the Leg 55 results showed that Suiko Seamount formed at a latitude of $26.9^{\circ} \pm 3.5^{\circ}$, that the Hawaiian hot spot has been at relatively low latitudes for the past 65 m.y. (Kono, 1980), and that the Emperor volcanoes were once islands that have since subsided 2,000 m or more beneath the sea (see summary *in* Jackson and others, 1980). Thus, not only is the (approximately) fixed hot spot hypothesis a reasonable explanation for the origin of the entire Hawaiian-Emperor volcanic chain, but also the Emperor volcanoes apparently have constructional, erosional, and subsidence histories very similar to those of the well-studied Hawaiian Islands (Stearns, 1966; Macdonald and Abbott, 1970).

In their synthesis of the chronology of volcanic propagation in the Hawaiian-Emperor chain, Dalrymple and others (1980b) noted that there were three major sections of the chain for which age data did not yet exist. The gap between Suiko and Meiji Seamounts (Fig. 1) will be difficult to fill without drilling because the seamounts north of Nintoku are covered by a blanket of ice-rafted debris. The gap immediately east of the bend will never be completely filled because there are only two volcanoes in this section of the chain. The third gap is a 1,070-km-long section between La Perouse Pinnacle and Pearl and Hermes Reef. The purpose of this paper is to report new K-Ar and chemical data on samples from Laysan Island and Northampton Bank volcanoes, which lie near the center of the La Persouse-Pearl and Hermes gap.

SAMPLE LOCATIONS AND DESCRIPTIONS

Northampton Bank is ~600 km southeast of Midway Islands. The volcano rises to within 33 m of mean sea level, is roughly conical,

and has a volume of 6.8 x 10^3 km^3 (Bargar and Jackson, 1974), about the same size as West Maui. Samples were recovered by the University of Hawaii R/V Kana Keoki in one dredge in 1,160 m of water on the south side of the volcano at lat. 25° 17.8'N, long. 172° 01.3'W. The dredge recovered approximately equal volumes of volcanic rock and biogenic carbonate weighing a total of 168 kg.

The volcanic rock samples recovered from Northampton Bank are angular and massive, and they range from 7 to 35 cm in length. Most samples have no manganese coating, although some have manganese crusts as thick as 1-2 mm. Larger samples have a 1- to 2-cm-thick weathered rim characterized by altered olivine. The interior of most samples is fresh, with little or no olivine alteration. All of the volcanic rocks appear identical in hand sample and could be from a single flow or dike.

Laysan Island is adjacent to and about 60 km northeast of Northampton Bank (Fig. 1). With a volume of 11.3 x 10^3 km^3 (Bargar and Jackson, 1974), Laysan volcano is nearly twice as large as Northampton Bank and comparable in size to Lanai. It is slightly elongate east-west and is topped by a large, flat platform from which rises a small coral island. The samples studied were recovered in a single dredge during cruise LEE8-76-NP (Dalrymple and others, 1980a) on the north side of the volcano at lat. 25° 54.8'N, long. 171° 46.3'W from a water depth of 690 to 350 m. The dredge recovered 16 volcanic rocks and 8 small fragments of coralline material. The volcanic rocks are well rounded and range from 3 to 28 cm in length; most are massive with a platy cleavage. All samples have manganese coating that range in thickness from a patina to about 0.5 mm. Two of the samples are conglomerates of volcanic cobbles and pebbles in a matrix of carbonate silt. Most samples are weathered to brown near the outer surface, but are fresh inside the 0- to 0.5-cm-thick alteration rind; some of the smaller pebbles are weathered throughout.

PETROGRAPHY, MINERALOGY, AND GEOCHEMISTRY

Petrographically, the samples from Northampton Bank are similar, except in the content of olivine phenocrysts, which ranges from 5% to 25% by volume. All of the samples are nearly holocrystalline (<5% glass), and all contain olivine as the sole phenocryst phase. The groundmass consists of very pale brown augite (~40%), plagioclase (~30%), iron-titanium oxides (20%-25%), glass (~5%), and olivine (<1%). The three dated samples are fairly fresh and contain unaltered olivine crystals, although nearly all of the olivine is partly replaced along fractures by a fibrous greenish-brown smectite. The individual analyzed and dated samples are described in detail in the Appendix.

Chemical analyses of olivine phenocrysts and of groundmass plagioclase and clinopyroxene grains were made by electron microprobe (Table 1). Variations in mineral compositions are small and, except for olivine, greater within one sample than between the averages of the three samples analyzed. Compositions of groundmass plagioclase grains in the three Northampton Bank samples fall within the range of compositions of plagioclase in tholeiitic volcanic rocks from Maui, although the Northampton Bank samples contain somewhat more K_2O (0.38 ± 0.01 versus 0.23 ± 0.02 wt % K_2O; Keil and others, 1972). Clinopyroxene compositions of the Northampton Bank rocks are typical of those of Hawaiian tholeiitic clinopyroxene (Fodor and others, 1975) but are somewhat enriched in TiO_2. At present, olivine in tholeiitic basalt cannot be distinguished from that in alkalic basalt (Fodor and others, 1977). Phenocrysts of olivine in the Northampton Bank basalt are essentially homogeneous, although some grains have optical discontinuities near their margins. The forsterite content of sample 5-4c is greater than any value reported by Fodor and others (1977) for volcanic rocks from Maui (Fo_{89} versus Fo_{85}).

TABLE 1. MICROPROBE MINERAL COMPOSITIONS OF BASALT SAMPLES DREDGED FROM NORTHAMPTON BANK SEAMOUNT, HAWAIIAN CHAIN.

	Groundmass clinopyroxene			Groundmass plagioclase*			Olivine phenocrysts*			
	5-4a	5-4b	5-4c	5-4a	5-4b	5-4c	5-4a	5-4b (core)	5-4b (rim)	5-4c
SiO_2	50.43	50.27	49.81	50.83	52.19	52.07	40.21	39.70	39.52	40.71
TiO_2	1.54	1.48	1.85							
Al_2O_3	4.38	3.97	3.66	29.60	28.38	29.24				
Cr_2O_3	0.45	0.25	0.19							
FeO	7.82	8.28	8.52	0.86	0.84	0.84	16.13	16.27	16.14	10.71
MnO	0.21	0.18	0.19				0.23	0.22	0.18	0.16
MgO	16.01	15.31	14.96				43.05	43.07	43.07	47.43
CaO	19.19	20.05	20.38	14.32	13.38	13.30	0.35	0.34	0.35	0.25
Na_2O	0.25	0.25	0.24	3.76	4.17	4.05				
K_2O	0.13	0.12	0.14	0.38	0.39	0.37				
Total	100.41	100.16	99.94	99.75	99.35	99.87	99.97	99.60	99.26	99.26

Note: Analyses in weight percent.

* Average of two or more grains.

The results of whole-rock analyses of the three Northampton Bank samples (Table 2) are very similar. The samples are clearly of tholeiitic basalt similar to the shield-building tholeiitic basalt that forms the bulk of the exposed Hawaiian Islands. Compositionally, the Northampton Bank tholeiite most closely resembles Kilauea tholeiite (Wright, 1971), although the Northampton Bank samples contain less Al_2O_3 than do Kilauea samples with the same MgO content.

Trace-element data for two of the Northampton Bank samples (Table 2) confirm the oceanic-island tholeiitic composition of the basalt. These samples clearly contain more Sr, Ba, and Rb than mid-ocean-ridge basalt and closely resemble tholeiitic basalt of the exposed Hawaiian shields (Leeman and others, 1980; D. A. Clague, unpub. data). The K/Ba ratios in these samples average 31, identical to those in tholeiitic basalt from the Hawaiian Islands and in other dredged samples of tholeiitic basalt from along the chain (Clague and Frey, 1979; Leeman and others, 1980). These results suggest that the Northampton Bank tholeiite was generated from a mantle source broadly similar to that which generated the basalt making up the shields of the Hawaiian Islands.

The samples from Laysan Island petrographically are similar to one another; all are hawaiite and mugearite with textures ranging from intergranular to subtrachytic. On the basis of the dominant groundmass ferromagnesian mineral, and samples fall into two main groups. About one-half of the samples contain abundant groundmass clinopyroxene and little to no groundmass; the other half contain less clinopyroxene and more olivine (see Appendix). Most of the rocks are moderately altered and contian from 2% to 23% smectite, mostly replacing glass. All of the olivine is replaced by "iddingsite." No secondary calcite was was observed. All but two of the samples are massive (<2.5% vesicles). Most samples contain sparse phenocrysts and microphenocrysts of plagioclase and opaque Fe-Ti oxides ± olvine. Four samples contain a few grains of reddish biotite in the groundmass. Apatite

TABLE 2. WHOLE-ROCK CHEMICAL ANALYSES AND TRACE-ELEMENT DATA OF NORTHAMPTON BANK DREDGE SAMPLES.

	5-4a	5-4b	5-4c
SiO_2	48.10	47.75	47.80
Al_2O_3	12.12	11.71	11.82
Fe_2O_3	3.50	3.98	2.67
FeO	7.98	7.82	8.94
MgO	10.53	10.85	10.94
CaO	10.60	9.92	10.53
Na_2O	2.09	2.06	2.05
K_2O	0.40	0.32	0.28
H_2O	1.83	2.51	1.87
TiO_2	2.32	2.28	2.36
P_2O_5	0.23	0.24	0.23
MnO	0.16	0.16	0.17
CO_2	0.11	0.12	0.04
Total	99.97	99,72	99.70
Nb	16		18
Zr	133		131
Y	25		27
Sr	313		293
Rb	6.7		5.0
Zn	109		109
Cu	120		115
Ni	501		478
Cr	974		960
V	255		249
Co	75		72
Ba	78		102

K. Ramlal, analyst for whole-rock analyses.

R. Brackett, analyst for trace-element data.

Note: Oxide analyses in weight percent, trace element analyses in ppm.

is present as tiny needles in nearly every sample.

The major-element analyses of 14 samples from Laysan Island volcano (Table 3) closely resemble those of Hawaiian hawaiite and mugearite from the alkalic eruptive stage (Macdonald, 1968). None of these lavas represents unmodified mantle melts because they are not in equilibrium with olivine of mantle composition. All of the Laysan Island samples are of differentiated lavas derived by crystal fractionation from a more magnesian alkali basalt parental magma or magmas. Most of the rocks are sufficiently altered that quantitative evaluation of the shallow crystal fractionation that led to their formation is difficult. Two discrete fractionation trends, however, are evident on a plot of Al_2O_3 versus CaO (Fig. 2), showing that samples containing less than 8 wt % CaO and those containing more than 8 wt % CaO cannot be related by continuous crystal fractionation. Both groups of differentiated lavas possibly could be derived from the same or similar parent magmas, but, if so, the fractionated bulk mineral assemblage must have been different for each group. The physical conditions under which the parent magma crystallized and fractionated could be responsible for the two fractionation trends, although it is equally feasible that the two groups had compositionally distinct parental magmas. These two groups correspond to the two groups identified petrographically and described above.

Trace-element data (Table 3) confirm the alkalic nature of the Laysan lavas. Compared to tholeiitic basalt, these lavas are strongly enriched in the incompatible elements K_2O, P_2O_5, Sr, and Ba. The low Ni, Cr, and Co (sample D1-2) contents indicate that the lavas underwent fairly extensive olivine (containing a trace of Cr-spinel) fractionation before eruption. Likewise, the low Sc content indicates fractionation of clinopyroxene, and the nearly constant Sr content suggests that plagioclase was a significant component of the fractionated mineral assemblage. The

TABLE 3. WHOLE-ROCK CHEMICAL ANALYSES AND TRACE ELEMENT DATA FOR SAMPLES DREDGED FROM LAYSAN ISLAND.

Sample No.	D1-1	D1-2	D1-3	D1-4	D1-5	D1-6	D1-7
SiO_2	44.19	46.76	45.69	49.38	49.27	46.82	45.65
Al_2O_3	16.73	14.81	18.80	16.51	18.4	17.03	17.66
FeO*	12.48	11.81	13.25	9.63	10.45	9.85	12.64
MgO	4.98	5.27	2.38	3.56	2.30	4.21	2.62
CaO	8.70	9.86	5.11	7.55	5.01	8.33	5.06
Na_2O	3.07	3.68	4.08	5.23	4.42	3.38	4.26
K_2O	1.35	1.29	1.72	1.90	2.81	1.75	2.21
TiO_2	4.10	3.88	3.50	2.86	2.56	3.40	2.95
P_2O_5	.77	.62	1.02	.78	.93	.84	.87
MnO	.12	.15	.16	.18	.17	.12	.14
Total	96.49	98.14	95.71	97.58	96.32	95.73	94.06
Sc	17	17	20	13	10	13	13
V	280	330(329)	137	104	101	186	90
Cr	48	67(32)	49	53	50	37	51
ni	31	20(22)	28	14	19	21	17
Zn	162	127(111)	139	126	153	164	136
Rb	21	23(27)	20	40	63	39	54
Sr	980	820(831)	800	1250	940	1100	1100
Zr	240	235(240)	325	315	380	315	360
Ba	445	405(509)	600	590	700	550	720

(cont.)

TABLE 3. (CONTINUED)

Sample No.	D1-8	D1-9	D1-10	D1-11	D1-12	D1-14	D1-16
SiO_2	43.92	46.22	47.96	50.38	47.02	46.09	44.90
Al_2O_3	15.31	17.10	17.53	17.16	17.27	15.70	15.46
FeO*	11.95	12.80	11.47	8.47	12.92	10.82	11.12
MgO	5.39	2.90	2.49	2.97	2.27	4.12	4.56
CaO	9.37	6.24	5.79	6.13	5.76	8.97	9.16
Na_2O	2.98	3.99	4.57	4.37	4.49	3.44	4.34
K_2O	1.53	2.19	2.41	2.61	2.10	1.64	1.67
TiO_2	4.27	3.07	2.58	2.11	3.03	3.86	3.61
P_2O_5	.78	.77	.87	.70	1.03	.74	.74
MnO	.14	.20	.17	.13	.12	.16	.19
Total	95.64	95.48	95.84	95.03	96.01	95.54	95.75
Sc	14	15	10	7	19	16	14
V	285	131	97	61	138	235	240
Cr	51	59	49	42	48	34	47
ni	27	20	18	20	9	19	13
Zn	150	144	152	135	139	140	103
Rb	34	52	52	70	55	38	41
Sr	1000	920	1000	1000	900	960	920
Zr	255	350	375	425	315	280	280
Ba	455	560	560	740	570	440	500

Note: Oxide analyses in weight percent, trace element analyses in ppm. SiO_2, Al_2O_3, FeO*, CaO, K_2O, TiO_2, P_2O_5, and MnO by X-ray fluorescence (XRF); analysts, S. Bright, and D. A. Clague. MgO, Na_2O, and all trace elements by XRF; analyst J. Carr, project leader V. G. Mossotti, U.S. Geological Survey. Sample D1-2 was also analyzed for trace elements at Woods Hole Oceanographic Institution by R. Brackett. The data are shown in parentheses. In addition to the element contents listed, this sample has Nb = 55 ppm, Y = 33 ppm, Cu = 19 ppm, and Co = 36 ppm.

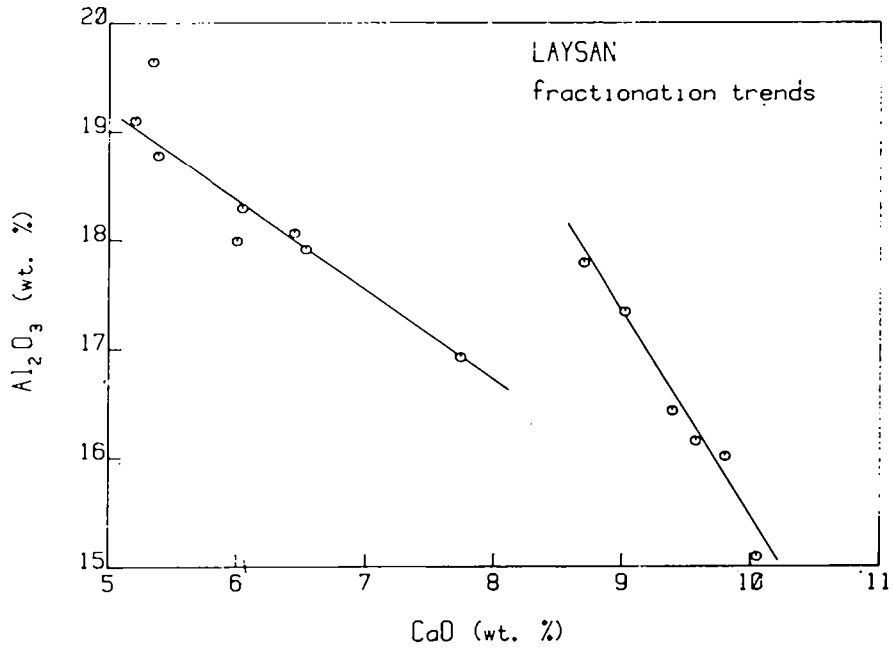

Figure 2. Plot of Al_2O_3 versus CaO for the Laysan Island hawaiites and mugearites. The two discrete fractionation trends cannot be related by continuous crystal fractionation of any reasonable mineral assemblage. The two fractionation sequences may be derived from a single parent alkali basalt magma under different physical conditions or from discrete parent magma. Data plotted are dry reduced, normalized.

decrease in V with increasing Zr and decreasing MgO reflects the crystallization and fractionation of titanomagnetite. This conclusion is consistent with the presence of abundant microphenocrysts of titanomagnetite in many of these lavas. The most differentiated lavas, those with the highest Zr and the lowest MgO contents, have lower P_2O_5 than some of the less fractionated lavas, indicating that apatite is also a fractionating mineral.

In summary, we speculate that the least fractionated Laysan Island lavas were derived from an alkalic basalt by crystallization of mainly olivine and clinopyroxene, and that the group of lavas analyzed represents successive liquids derived by continued fractionation of clinopyroxene, plagioclase, titanomagnetite, and some apatite in at least two parent magmas. Table 4 lists some key trace-element ratios in Laysan Island and Northampton Bank lavas, and in basalts from the three principal eruptive stages of the Hawaiian Islands. The average K/Ba ratio of the Laysan Island lavas (28) is similar to that of alkalic basalt of the alkalic eruptive stage from East Molokai (Clague and Beeson, 1980) and Hualalai (Clague and others, 1981), but differs from that (15) of Hawaiian post-erosional alkalic lavas (Clague and Frey, 1979). These data all indicate that the samples dredged from Laysan Island were erupted during the alkalic eruptive stage.

K/Ar RESULTS

Samples for conventional Ar analyses weighing from 5 to 10 g were cut from hand specimens with a water-cooled diamond saw. An adjacent portion of each sample was finely pulverized (less than 74 μm) and used for the K_2O measurements. Samples for $^{40}Ar/^{39}Ar$ total fusion and incremental heating analyses were each small cores 6 mm in diameter by 10 cm long, weighing from 0.5 to 0.8 g.

Four K_2O measurements were made on each sample by flame photometry after lithium metaborate fusion and dissolution (Ingamells, 1970). Conventional

TABLE 4. KEY TRACE-ELEMENT RATIOS

	Tholeiitic lava			Alkalic stage lava			Post-erosional nephelinic stage lava
	Northampton Bank	Kilauea	Mauna Loa	Laysan Island	Hualalai	East Molokai	Honolulu Volc. Ser.
K/Zr	21	23	24	50.3 ± 4.5	50	31	80
K/Rb	470	390	530	375	200(?)	450	405
K/Ba	30	32	39	28.5 ± 3.1	24	25	16.6
Zr/Y	5.1	7.3	5.2	7.2	7.2	6.5	7.75
Rb/Sr	0.019	0.031	0.019	---	0.08	---	0.024
Ba/Sr	0.30	0.38	0.26	---	0.69	0.50	0.63
P_2O_5/Sr	7.6	8.0	8.0	---	6.5	9.0	7.8

Data from Tables 2 and 3 for Northampton Bank and Laysan Island, from Leeman and others (1980) and Bence and others (1981) for Kilauea and Mauna Loa, from Clague and Beeson (1980) for East Molokai, from Clague and others (1981) for Hualalai, and from Clague and Frey (1979; unpub. data, 1980) for the Honolulu Volcanic series of Stearns and Vaksvik (1935).

Ar analyses were by isotope dilution mass spectrometry using a high-purity (>99.9%) ^{38}Ar tracer and techniques and equipment described by Dalrymple and Lanphere (1969). All samples for Ar extraction, including those for $^{40}Ar/^{39}Ar$ analyses, were baked overnight in the vacuum extraction system at 280 °C. Isotope dilution Ar mass analyses were done with the computerized multiple collector mass spectrometer described by Stacey and others (1978) and Sherrill and Dalrymple (1980).

Samples for $^{40}Ar/^{39}Ar$ dating were sealed in air in flat-bottomed, fused silica vials and irradiated at 1 MW in the core of the U.S. Geological Survey TRIGA reactor (GSTR) for from 25 to 40 hr; they received a neutron dose of approximately 2.5×10^{18} to 4×10^{18} nvt. The effective neutron flux was measured with our standard monitor biotite SB-2. Further details of the GSTR flux characteristics, the monitor mineral, and the corrections for interfering K- and Ca-derived Ar isotopes are given by Dalrymple and Lanphere (1971) and Dalrymple and others (1981).

Temperatures for the $^{40}Ar/^{39}Ar$ incremental heating experiments, measured with a platinum/platinum-rhodium thermocouple inserted into a small hole in the bottom of a machined molybdenum crucible, are accurate to within about ±20 °C. The samples were held for 30 min at each temperature. Ar mass analyses for the $^{40}Ar/^{39}Ar$ experiments were done with a Nier-type, single-collector mass spectrometer utilizing analogue data acquisition.

We have used the new ^{40}K decay and abundance constants recommended by the International Union of Geological Sciences Subcommission of Geochronology (Steiger and Jäger, 1977), and all previously published age data discussed or cited herein have been converted to these new constants. Where appropriate, weighted means were used, where weighting was by the inverse of the estimated variance. This weighting allows data of different quality to be combined without the poorer data disproportionately affecting

the result. $^{40}Ar/^{39}Ar$ isochrons were calculated using the York 2 least-squares cubic fit with correlated errors (York, 1969), and the formula recommended by D. York (Ozima and others, 1977, p. 479) for the correlation coefficient r.

The calculated conventional K-Ar and the $^{40}Ar/^{39}Ar$ total fusion ages for the Laysan Island samples (Table 5), which fall within the range 18.8 to 21.4 m.y., do not show the severe discordance between these two techniques that is common in samples of highly altered submarine basalt (Clague and others, 1975). The $^{40}Ar/^{39}Ar$ incremental heating results (Table 6, Figs. 3-6) are also indicative of samples with relatively undisturbed K-Ar systems. These data show age-spectrum plateaus for more than 50% of the ^{39}Ar released, concordant plateau and isochron ages, isochron intercepts not significantly different from the atmospheric $^{40}Ar/^{36}Ar$ value of 295.5, and low values for the index of fit [SUMS/(n-2)], all characteristic of reliable incremental heating ages (Lanphere and Dalrymple, 1978).

The three Laysan Island samples on which incremental heating experiments were done all give virtually identical plateau and isochron ages. In general, we have been conservative in choosing which increments to include in the calculation of the weighted mean plateau and isochron ages. The results, however, are not changed significantly by including additional increments in the calculations (Table 7).

The consistency between the $^{40}Ar/^{39}Ar$ incremental heating, the conventional K-Ar, and the $^{40}Ar/^{39}Ar$ total fusion results provides strong evidence that the calculated ages of the Laysan Island samples are reliable and reflect crystallization ages. We consider the weighted mean of 19.9 ± 0.3 m.y. of the four isochron ages to represent the age of the alkalic stage of volcanism on Laysan Island volcano. The weighted mean of the plateau ages (20.4 ± 0.3 m.y.) does not differ significantly from the isochron ages at the 95% confidence level.

TABLE 5. CONVENTIONAL K-Ar AND $^{40}Ar/^{39}Ar$ TOTAL FUSION AGE DATA ON SAMPLES FROM LAYSAN AND NORTHAMPTON VOLCANOES, HAWAIIAN VOLCANIC CHAIN

		CONVENTIONAL ANALYSES				
			Argon[b]			
Sample no.	Material	K_2O[a] (wt.%)	Weight (gms)	$^{40}Ar_R$ (10^{-11} mol/gm)	$^{40}Ar_R$ (%)	Calculated age[c] (10^6 yrs)
LAYSAN						
D1-2	hawaiite	1.241 ± 0.014	10.344	3.626	68.0	20.2 ± 0.4
D1-4	hawaiite	1.868 ± 0.011	6.367	5.594	46.2	20.7 ± 0.4
D1-5	mugearite	2.639 ± 0.030	7.097	7.173	86.5	18.8 ± 0.4
D1-16	hawaiite	1.648 ± 0.026	8.519	4.655	48.4	19.5 ± 0.4
NORTHAMPTON						
5-4a	tholeiite	0.217 ± 0.004	8.080 7.128	0.6392 0.6570	13.2 11.7	20.7 ± 0.6
5-4b	tholeiite	0.222 ± 0.005	5.959 5.024	0.4333 0.4633	10.9 5.1	13.7 ± 0.7
5-4c	tholeiite	0.182 ± 0.001	8.412 7.235	0.5436 0.4709	11.4 9.5	19.2 ± 1.5

(cont.)

TABLE 5. (CONTINUED)

$^{40}Ar/^{39}Ar$ ANALYSES[b]

Sample no.	Material	J	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$[d]	$^{36}Ar/^{39}Ar$	$^{36}Ar_{Ca}$ (%)	$^{40}Ar_{K}$ (%)	$^{40}Ar_{R}$ (%)	Calculated Age[c] (10^6 yrs)
LAYSAN									
D1-1	hawaiite	0.005891	3.727	3.286	0.00719	12.4	0.2	49.9	19.7 ± 0.4
D1-2	hawaiite	0.005891	5.542	3.333	0.01280	7.1	0.1	36.5	21.4 ± 0.6
D1-4	hawaiite	0.005678	5.484	1.665	0.01198	3.8	0.1	37.8	21.1 ± 0.6
D1-5	mugearite	0.005678	2.913	0.766	0.00332	6.3	0.2	68.2	20.3 ± 0.3
D1-16	hawaiite	0.005678	3.035	2.413	0.00408	16.1	0.2	66.5	20.6 ± 0.3
NORTHAMPTON									
5-4a	tholeiite	0.009174	14.92	19.91	0.0511	10.6	<.1	9.4	23.4 ± 2.8
5-4b	tholeiite	0.009174	61.60	36.42	0.2159	4.6	<.1	1.2	12.3 ±10.3
5-4c	tholeiite	0.009174	25.69	23.30	0.0898	7.1	<.1	3.9	16.8 ± 4.3

[a] Calculated mean and standard deviation of four analyses.

[b] Subscripts indicate radiogenic (R), calcium-derived (Ca), and potassium-derived (K) argon.

[c] $\lambda_\epsilon + \lambda_{\epsilon'} = 0.581 \times 10^{-10}\ yr^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10}\ yr^{-1}$, $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol. Errors are estimates of the standard deviation of analytical precision (Cox and Dalrymple, 1967; Dalrymple and Lanphere, 1971).

[d] Corrected for ^{37}Ar decay, half-life = 35.1 days.

TABLE 6. ANALYTICAL DATA FROM $^{40}Ar/^{39}Ar$ INCREMENTAL HEATING EXPERIMENTS ON DREDGED SAMPLES FROM LAYSAN AND NORTHAMPTON VOLCANOES, HAWAIIAN VOLCANIC CHAIN

Sample	Temp. (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$[a]	$^{36}Ar/^{39}Ar$	^{39}Ar (% of total)	$^{40}Ar_R$	$^{36}Ar_{Ca}$	Apparent age[b] (10^6 yr)
				-- LAYSAN --				
D1-1	500	1.713	1.213	0.0532	6.3	8.8	0.6	16.5 ± 2.3
(J=0.006059)	600	5.81	0.855	0.01288	9.4	35.6	1.8	22.5 ± 1.4
	700	2.896	0.771	0.00367	23.3	64.5	5.7	20.3 ± 0.7
	800	2.768	1.469	0.00340	32.2	67.7	11.7	20.4 ± 0.6
	900	2.299	2.410	0.00217	14.4	80.2	30.2	20.1 ± 0.6
	975	3.793	6.391	0.00762	1.9	54.0	22.8	22.3 ± 1.3
	1050	3.555	15.38	0.00914	8.1	58.1	45.8	22.8 ± 1.0
	fuse	5.294	14.89	0.01458	4.2	41.1	27.8	23.8 ± 1.5
					99.8			
					Recalculated total fusion age = 20.7 ± 1.0			
					Recalculated $^{40}Ar_R/^{39}Ar_K$ = 1.901			
					Total $^{40}Ar_R$ = 3.85 x 10^{-11} mol/gm			
D1-4	450	25.27	0.802	0.0765	0.8	10.7	0.3	28.6 ± 7.7
(J=0.005891)	525	14.68	0.683	0.0419	0.4	16.0	0.4	24.8 ± 6.7
	600	4.249	0.745	0.00788	5.4	46.4	2.6	20.9 ± 0.8
	700	3.031	0.772	0.00375	9.6	65.3	5.6	20.9 ± 0.5
	800	3.434	0.720	0.00518	8.2	56.9	3.8	20.7 ± 0.6
	900	2.472	0.731	0.1865	10.6	79.8	10.7	20.9 ± 0.4
	fuse	2.301	2.249	0.00198	65.0	82.1	30.8	20.0 ± 0.4
					100.0			
					Recalculated total fusion age = 20.4 ± 1.0			
					Recalculated $^{40}Ar_R/^{39}Ar_K$ = 1.928			
					Total $^{40}Ar_R$ = 5.79 x 10^{-11} mol/gm			

[a] Corrected for ^{37}Ar decay, half-life = 35.1 days.

[b] $\lambda_\epsilon + \lambda_{\epsilon'}$ = 0.581 x 10^{-10} yr^{-1}, λ_β = 4.692 x 10^{-10} yr^{-1}, $^{40}K/K$ = 1.167 x 10^{-4} mol/mol. Errors are estimates of the standard deviation of analytical precision (Dalrymple and Lanphere, 1971).

TABLE 6. (CONTINUED)

Sample	Temp. (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$[a]	$^{36}Ar/^{39}Ar$	^{39}Ar (% of total)	$^{40}Ar_R$	$^{36}Ar_{Ca}$	Apparent age[b] (10^6 yr)
D1-16	450	20.70	1.724	0.0635	2.1	10.0	0.7	22.0 ± 3.2
(run 1)	525	15.31	0.867	0.0455	0.5	12.6	0.5	20.4 ± 4.5
(J=0.005891)	600	7.79	0.842	0.0197	2.3	26.2	1.2	21.6 ± 2.0
	700	5.36	0.923	0.0115	8.5	37.9	2.2	21.4 ± 0.9
	800	3.705	0.851	0.00605	10.7	53.5	3.8	20.9 ± 0.7
	900	3.221	0.971	0.00447	8.5	61.2	5.9	20.8 ± 0.5
	fuse	2.250	2.911	0.00198	67.4	84.2	40.1	20.1 ± 0.4
					100.0			
					Recalculated total fusion age = 20.4 ± 1.0			
					Recalculated $^{40}Ar_R/^{39}Ar_K$ = 1.932			
					Total $^{40}Ar_R$ = 5.12 x 10^{-11} mol/gm			
D1-16	500	57.0	0.819	0.1833	0.8	5.1	0.1	27.7 ± 12.8
(run 2)	600	136.6	0.889	0.4557	6.3	1.4	<0.1	18.8 ± 12.8
(J=0.005281)	700	39.12	0.864	0.1251	5.1	5.7	0.2	21.2 ± 5.5
	800	25.05	0.877	0.0762	10.0	10.3	0.3	24.5 ± 2.5
	900	14.61	0.882	0.0415	8.4	16.6	0.6	23.0 ± 1.6
	975	8.49	1.099	0.0226	3.7	22.3	1.3	17.9 ± 2.0
	1050	5.33	1.170	0.0102	2.8	45.2	3.1	22.8 ± 1.5
	fuse	7.55	3.271	0.0195	63.1	27.3	4.6	19.5 ± 0.8
					100.2			
					Recalculated total fusion age = 20.4 ± 1.0			
					Recalculated $^{40}Ar_R/^{39}Ar_K$ = 2.157			
					Total $^{40}Ar_R$ = 5.11 x 10^{-11} mol/gm			

TABLE 6. (CONTINUED)

Sample	Temp. (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$[a]	$^{36}Ar/^{39}Ar$	^{39}Ar (% of total)	$^{40}Ar_R$	$^{36}Ar_{Ca}$	Apparent age[b] (10^6 yr)
				-- NORTHAMPTON --				
5-4a	500	50.3	4.566	0.1613	22.5	5.9	0.8	28.0 ± 6.0
(J=0.005281)	600	11.77	5.50	0.0316	31.4	24.5	4.7	27.4 ± 2.8
	700	9.93	13.40	0.0280	17.3	27.6	13.0	26.1 ± 4.0
	800	16.98	11.97	0.0514	6.5	16.3	6.3	26.3 ± 7.4
	900	29.55	24.36	0.0929	4.8	13.7	7.1	38.8 ± 13.5
	975	9.41	58.5	0.0388	8.8	28.2	41.1	26.0 ± 5.5
	1050	11.45	107.4	0.0560	5.3	30.8	52.2	35.7 ± 7.9
	fuse	30.65	125.6	0.1171	3.6	20.0	29.2	62.5 ± 16.6
					100.2			
					Recalculated total fusion age = 29.4 ± 1.5			
					Recalculated $^{40}Ar_R/^{39}Ar_K$ = 3.107			
					Total $^{40}Ar_R$ = 1.11 x 10^{-11} mol/gm			
5-4c	500	94.7	1.616	0.3122	7.1	2.7	0.1	22.7 ± 20.2
(J=0.005281)	600	48.11	3.461	0.1458	6.8	11.0	0.6	50.0 ± 13.0
	700	39.98	5.755	0.1245	8.4	9.2	1.3	34.6 ± 11.1
	800	15.43	6.302	0.0456	35.6	15.9	3.8	23.3 ± 4.0
	900	12.75	15.63	0.0414	15.0	13.7	10.3	16.7 ± 6.0
	975	30.34	12.47	0.0944	3.6	11.4	3.6	32.9 ± 13.7
	1050	21.67	18.09	0.0768	5.2	2.0	6.4	40.9 ± 11.2
	fuse	9.58	81.09	0.0469	18.3	23.2	47.0	22.2 ± 4.0
					100.0			
					Recalculated total fusion age = 26.2 ± 1.3			
					Recacuated $^{40}Ar_R/^{39}Ar_K$ = 2.769			
					Total $^{40}Ar_R$ = 7.32 x 10^{-12} mol/gm.			

TABLE 7. SUMMARY OF AGE-SPECTRUM AND ISOCHRON ANALYSES OF DATA FROM $^{40}AR/^{39}AR$ INCREMENTAL HEATING EXPERIMENTS ON SAMPLES DREDGED FROM LAYSAN AND NORTHAMPTON VOLCANOES, HAWAIIAN VOLCANIC CHAIN

		Age spectrum		Isochron		
Sample	Increments used	Wt. mean age (10^6 yr)	^{39}Ar (%)	Age (10^6 yr)	intercept	SUMS/ (N-2)
LAYSAN						
D1-1	all	20.8 ± 0.5	100	20.7 ± 0.6	295.3 ± 7.5	5.3
	600° - 900°	20.4 ± 0.4	79.4	19.8 ± 0.4	313.7 ± 11.8	0.05
	*700° - 900°	20.2 ± 0.4	63.6	19.8 ± 0.4	305.6 ± 30.8	0.06
D1-4	all	20.6 ± 1.5	100	20.0 ± 0.2	309.0 ± 6.6	1.2
	*600° - fuse	20.6 ± 0.3	98.8	19.9 ± 0.3	312.5 ± 12.2	1.9
D1-16 (run 1)	all	20.4 ± 0.9	100	20.1 ± 0.2	300.9 ± 2.8	0.80
	*700° - fuse	20.4 ± 0.3	95.1	19.9 ± 0.2	310.9 ± 6.3	0.25
D1-16 (run 2)	all	20.7 ± 2.4	100	20.0 ± 1.0	297.5 ± 2.3	2.0
	*600° - fuse	20.7 ± 2.1	99.2	20.1 ± 1.1	297.4 ± 2.6	2.4
NORTHAMPTON						
5-4a	all	28.0 ± 3.2	100	27.2 ± 2.9	298.0 ± 4.1	1.7
	500° - 975°	27.1 ± 3.0	91.2	26.3 ± 2.3	297.1 ± 4.2	0.23
	*500° - 800°	27.0 ± 2.7	77.6	26.6 ± 2.7	296.4 ± 4.4	0.04
5-4c	*all	24.3 ± 4.1	100	19.4 ± 3.5	302.2 ± 6.7	1.7

* Shown in figures A - F.

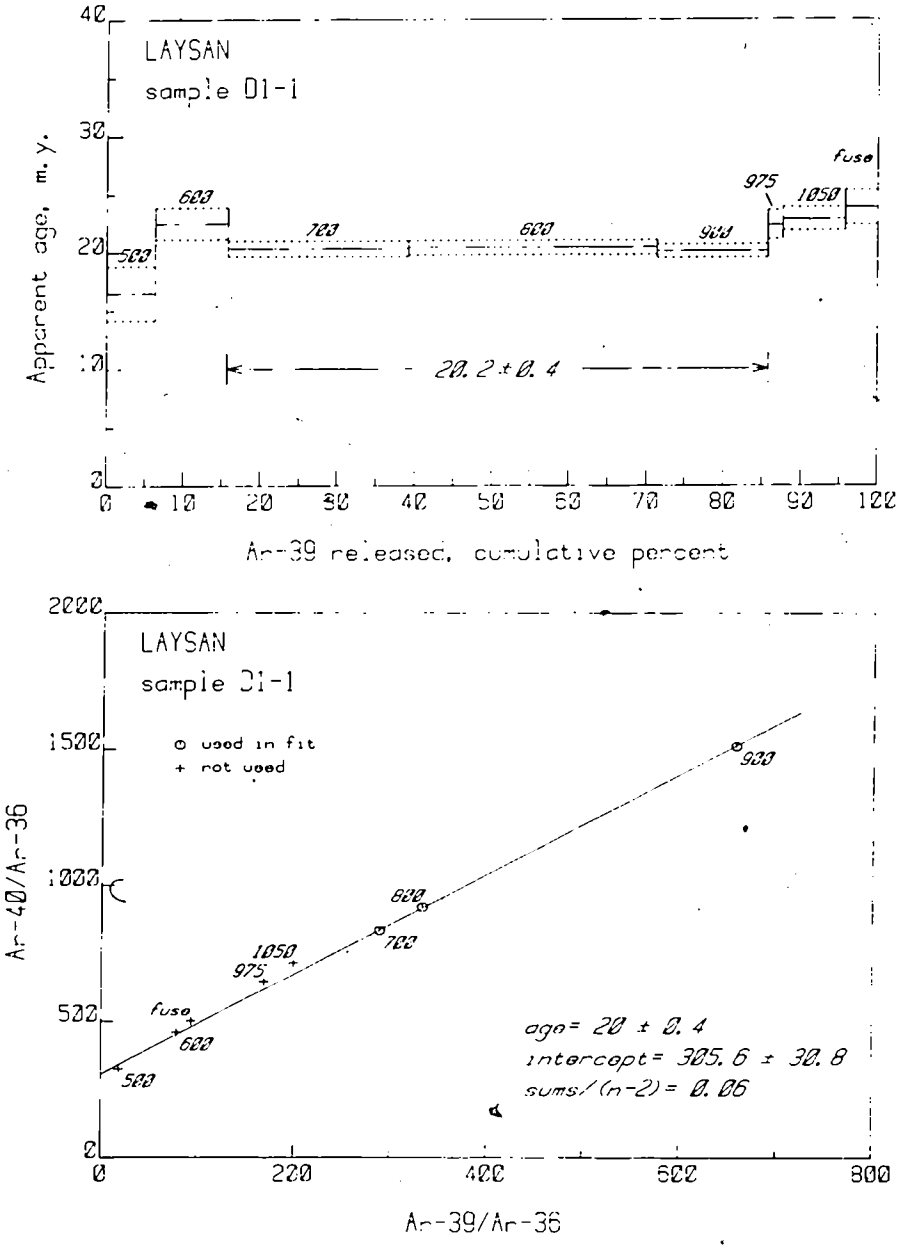

Figure 3. Age spectrum and isochron diagrams for $^{40}Ar/^{39}Ar$ incremental heating experiment on sample D1-1 from Laysan volcano. Dashed lines on age spectrum indicate the estimated standard deviation of analytical precision about the calculated age (solid lines) of each gas increment. Temperatures are in degrees Celsius. Argon isotope ratios are corrected for ^{40}Ar, ^{39}Ar, and ^{36}Ar derived from undesirable reactions with K and Ca.

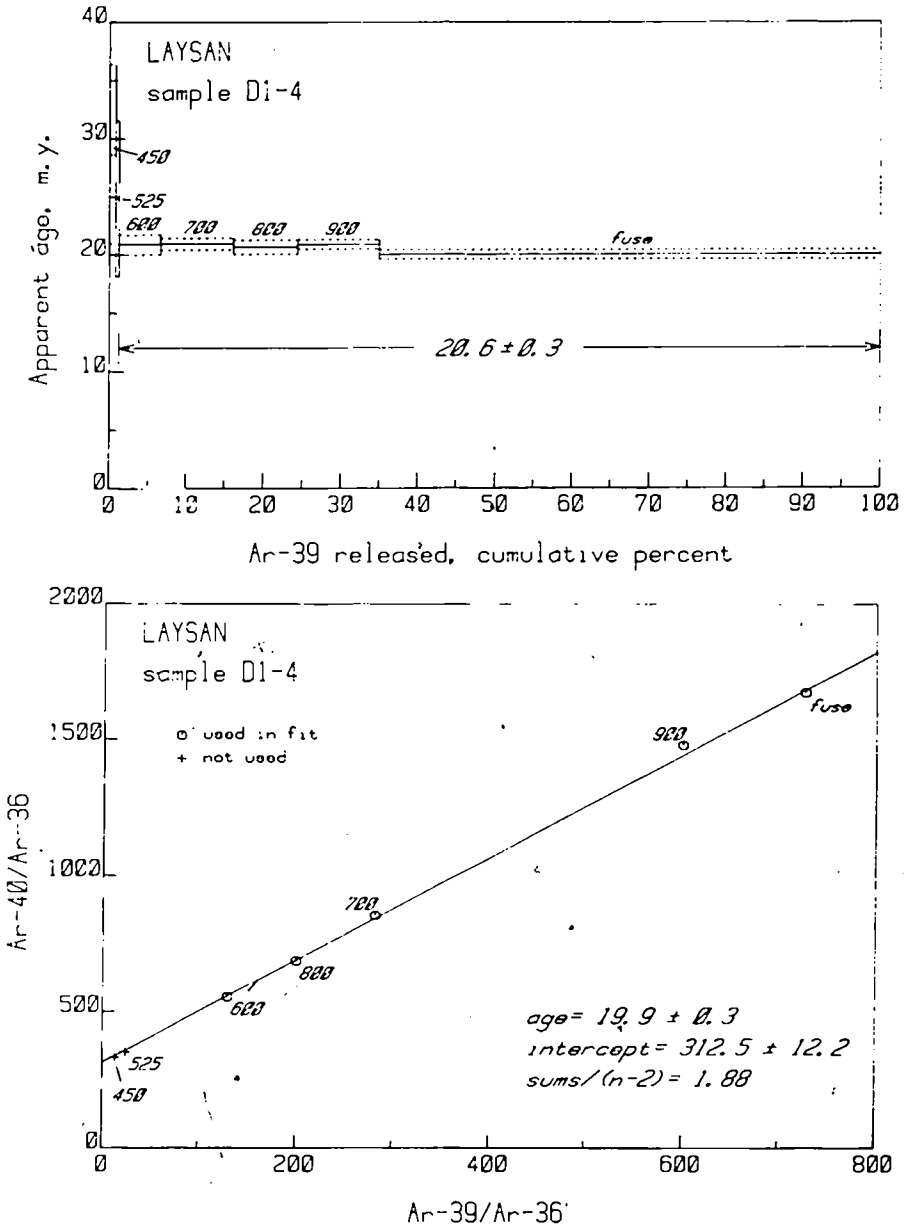

Figure 4. Age spectrum and isochron diagrams for $^{40}Ar/^{39}Ar$ incremental heating experiment on sample D1-4 from Laysan volcano. Symbols as in Figure 2.

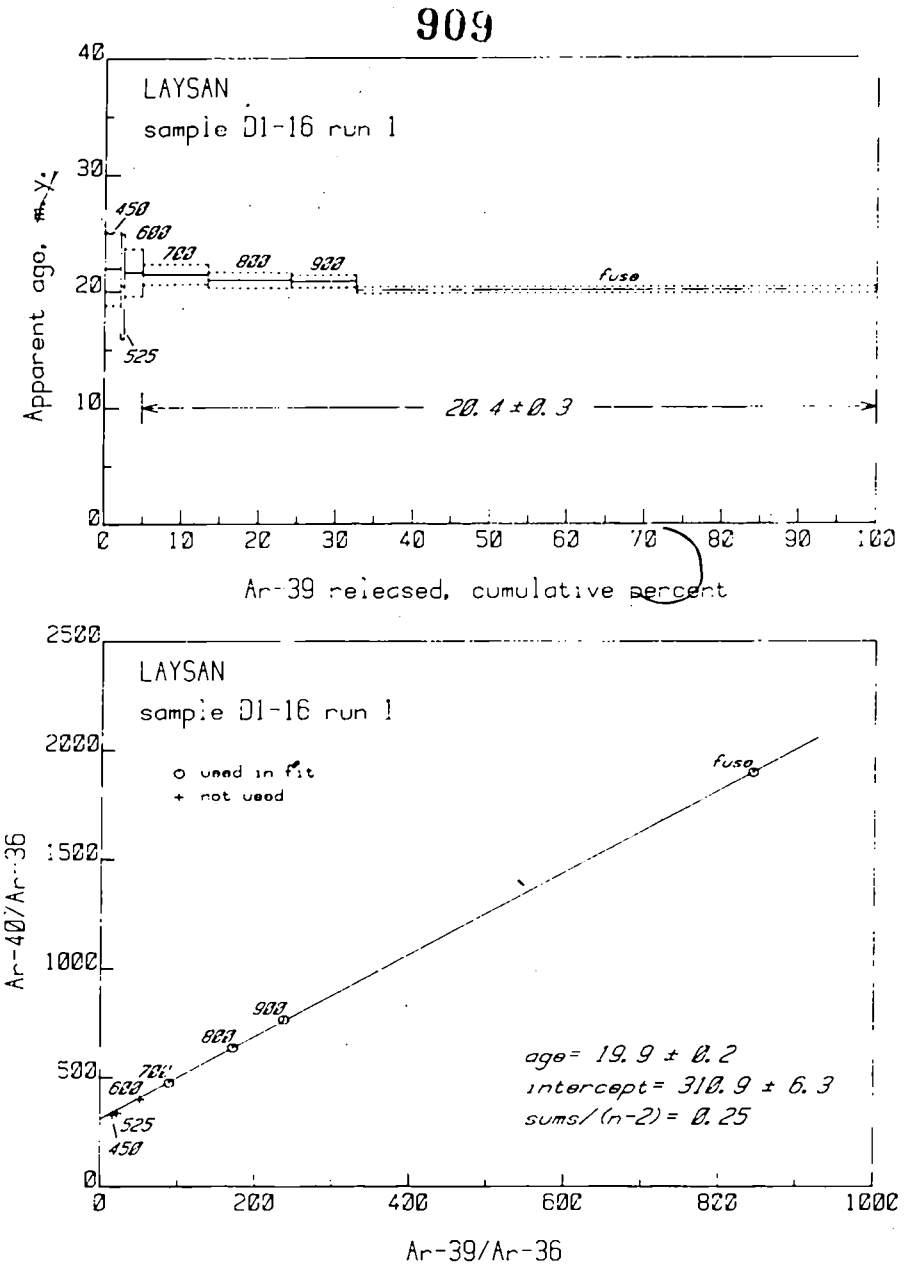

Figure 5. Age spectrum and isochron diagrams for $^{40}Ar/^{39}Ar$ incremental heating experiments on sample D1-16, run 1, from Laysan volcano. Symbols as in Figure 2.

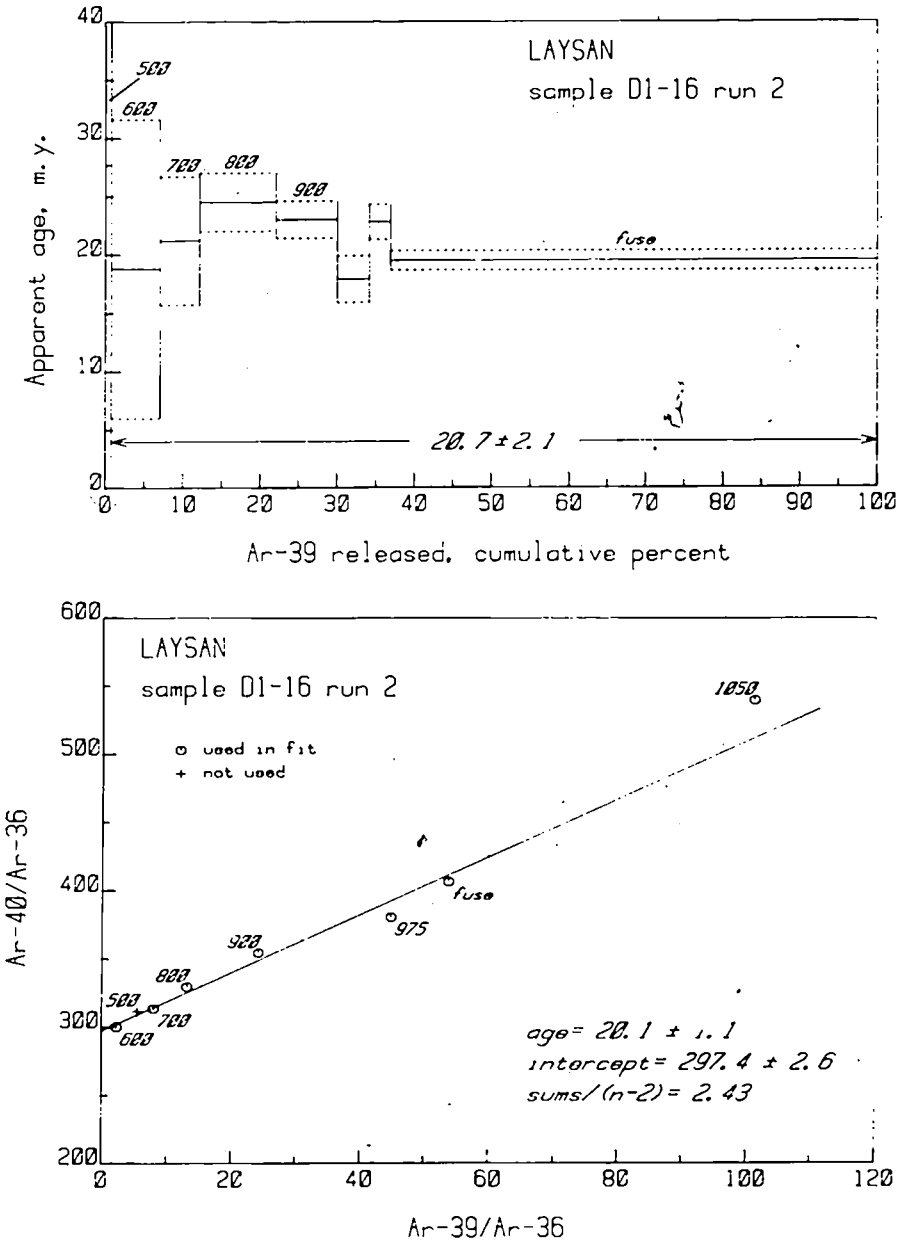

Figure 6. Age spectrum and isochron diagrams for $^{40}Ar/^{39}Ar$ incremental heating experiment on sample DI-16, run 2, from Laysan volcano. Symbols as in Figure 2.

Interpretation of the results for the three tholeiitic samples from Northampton Bank volcano is less straightforward than for the Laysan Island samples. The conventional K-Ar and $^{40}Ar/^{39}Ar$ total fusion ages range from 13.7 to 23.4 m.y. (Table 5). Although the ages obtained by the two total fusion techniques on individual samples are not statistically discordant, owing to the large analytical uncertainties in the $^{40}Ar/^{39}Ar$ total fusion data, the relatively large apparent age differences between samples suggest that the K-Ar systems in these rocks have been disturbed. This result is not surprising in view of previous findings that the K-Ar system in Hawaiian tholeiite is easily disturbed by even moderate alteration in the submarine environment (Dalrymple and others, 1977).

Sample 5-4a has a $^{40}Ar/^{39}Ar$ age spectrum plateau that includes more than 75% of the ^{39}Ar released, an isochron age concordant with the plateau age, and an intercept not significantly different from the atmospheric value (Fig. 7). We interpret these data to represent an age of crystallization and use the isochron age of 26.6 ± 2.7 m.y. to represent the age of the Northampton Bank tholeiitic shield because the calculation of the isochron age requires no assumption about the initial Ar composition. Although we have used only the first four of the eight gas increments in calculating the weighted mean plateau and isochron ages, the results do not change significantly if we use additional increments in the calculations (Table 7).

The age spectrum of sample 5-4c (Fig. 8) indicates a disturbed system and has no plateau. We conclude from the data that this sample yields no useful age information.

It is not unusual for Hawaiian lavas altered in the submarine environment to give discordant $^{40}Ar/^{39}Ar$ total fusion and conventional K-Ar ages and yet yield crystallization ages from $^{40}Ar/^{39}Ar$ incremental heating experiments (Clague and others, 1975; Dalrymple

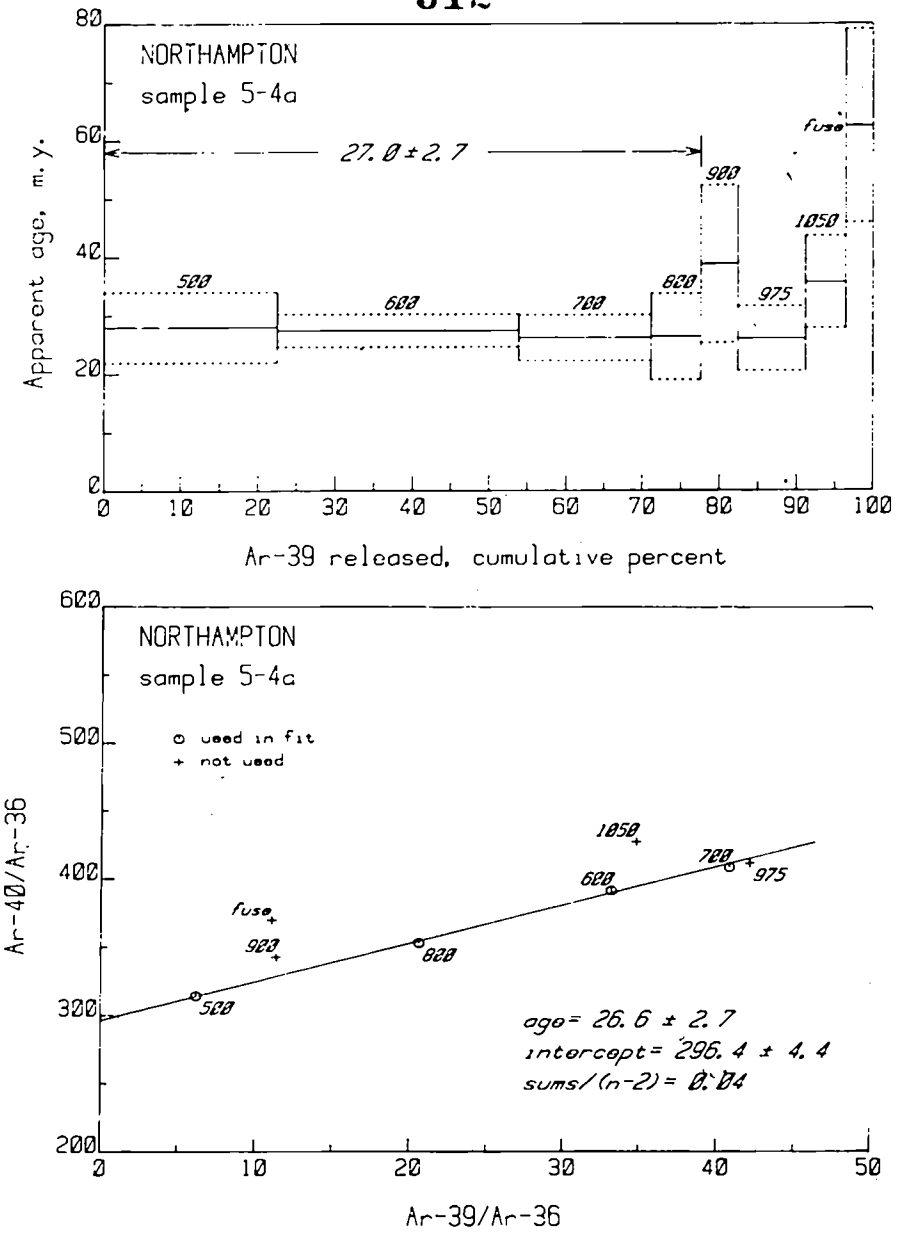

Figure 7. Age spectrum and isochron diagram for $^{40}Ar/^{39}Ar$ incremental heating experiments on sample 5-4a from Northampton volcano. Symbols as in Figure 2.

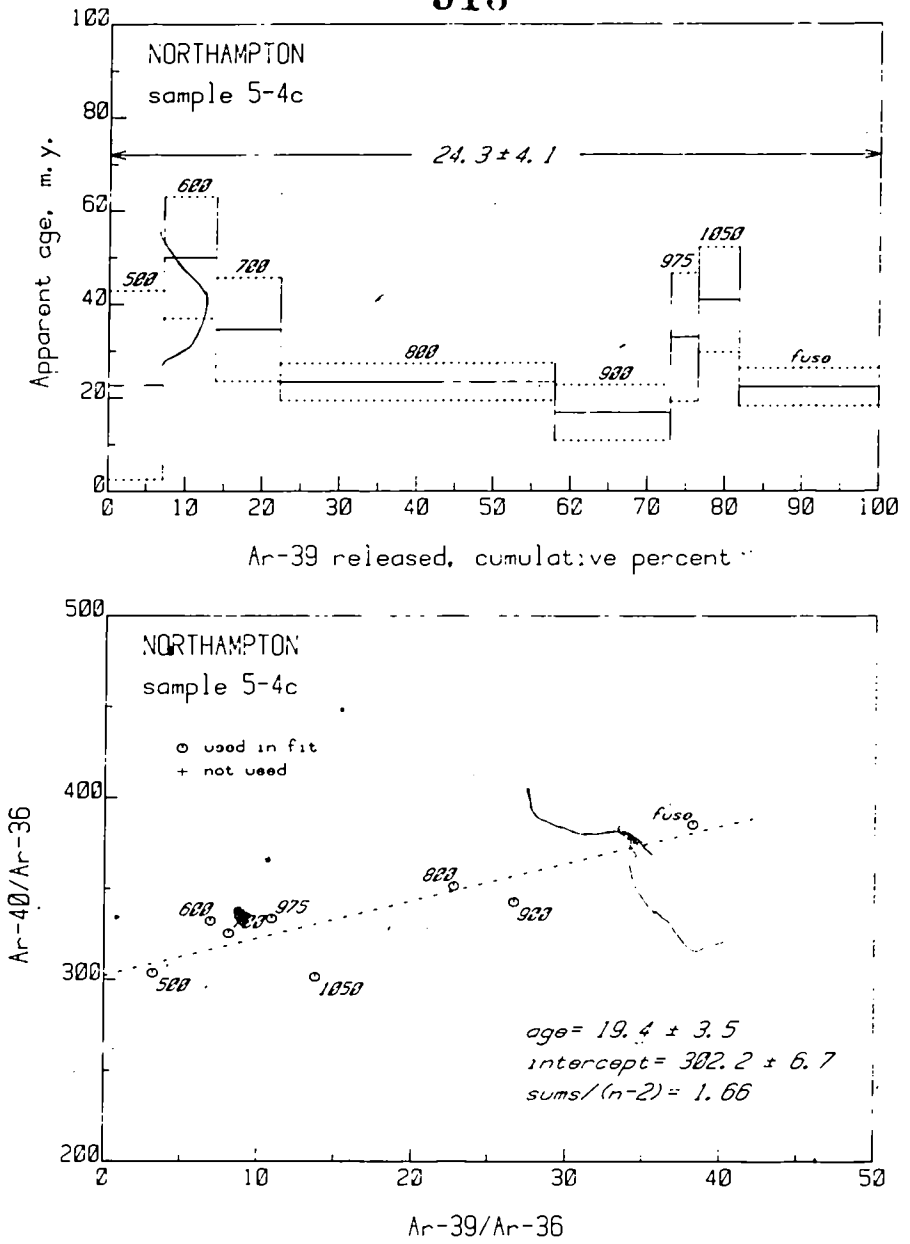

Figure 8. Age spectrum and isochron diagrams for $^{40}Ar/^{39}Ar$ incremental heating experiment on samples 5-4c from Northampton volcano. The calculated plateau and isochron ages are not considered reliable and are shown for reference only (see text). Symbols as in Figure 2.

and Clague, 1976; Dalrymple and others, 1980b). As discussed in the papers cited, this is probably due to the total or near total loss of both radiogenic ^{40}Ar and K-derived ^{39}Ar, the latter by diffusion, recoil, or both, from the altered parts of the rock. A significant advantage of the $^{40}Ar/^{39}Ar$ incremental heating technique is that it provides sufficient internal criteria, discussed above, to evaluate the reliability of the result (Lanphere and Dalrymple, 1978), and it is on this basis that we interpret the data for sample 5-4a as a crystallization age. Although we have no reason to doubt the reliability of the age of 26.6 ± 2.7 m.y. for Northampton Bank, it is based on results from a single sample and should be interpreted with some caution until it is verified by additional dredging and dating.

DISCUSSION AND CONCLUSIONS

The new data from Laysan Island and Northampton Bank show that the lavas dredged from these volcanoes geochemically resemble those of the principal Hawaiian Islands. The tholeiitic basalt from Northampton Bank, which may well derive from a single flow or eruption, demonstrates that tholeiitic basalt similar to modern Hawaiian tholeiite is present along the Hawaiian Ridge. In contrast to the Northampton Bank samples, most previously dredged or drilled samples of tholeiitic basalt from the Hawaiian Ridge are so badly altered that they are difficult to identify unequivocally as oceanic-island tholeiite.

The volcanic cobbles recovered from Laysan Island are all of hawaiite and mugearite chemically similar to rocks erupted on the Hawaiian Islands during the alkalic eruptive stage. These rocks represent at least two discrete fractionation trends and were derived by crystal fractionation of olivine, clinopyroxene, plagioclase, apatite, and titanomagnetite from two parent alkalic basalt magmas in shallow magma chambers. Clague (1974) described alkalic differentiates dredged from

several other localities along the Hawaiian Ridge and southern Emperor Seamounts, and Dalrymple and Garcia (1980) described samples from Jingū Seamount in the central Emperor Seamounts. The abundance of differentiated alkalic lavas along the chain suggests that many of these volcanoes evolved to the alkalic eruptive stage and commonly had shallow magma reservoirs in which alkalic basalt parent magmas crystallized and evolved.

Because the alkalic stage of Hawaiian volcanoes typically follows the tholeiitic shield-building stage by only a few hundred thousand years (McDougall, 1964; Porter and others, 1977), the K-Ar age of 19.9 ±0.3 m.y. for the Laysan Island samples is probably only slightly younger than the age of shield construction. The olivine tholeiite recovered from Northampton Bank is typical of the tholeiitic basalt that forms the bulk of all of the Hawaiian shields, and its calculated age of 26.6 ± 2.7 m.y. is thought to represent the age of the main volcanic edifice beneath Northampton Bank.

The new data bring to 29 the number of Hawaiian-Emperor volcanoes for which K-Ar ages are available. The data for the entire chain are summarized in Table 8. We have followed the practice of Jackson and others (1972) and used the oldest reliable age on shield-building (tholeiitic) lavas from each volcano for which a significant range in ages has been reported, rather than the youngest (McDougall, 1971) or the average (McDougall, 1979) age. Because the construction times of Hawaiian shields are believed to be only 1 m.y. or less (McDougall, 1964; Jackson and others, 1972), the choice of which ages to use is probably not critical when treating the chain as a whole, and this uncertainty becomes smaller than the analytical errors at about 20 m.y. For many of the dated volcanoes, particularly those west and north of Northampton Bank, tholeiitic shield-building lavas have not been

TABLE 8. SUMMARY OF K-Ar GEOCHRONOLOGY ALONG THE HAWAIIAN-EMPEROR VOLCANIC CHAIN

Volcano Name	Volcano No[a]	Distance From Kilauea Along H-E Trend[a] (Kilometers)	Best K-Ar Age[b] (10^6 yr)	Ref.	Remarks
Kilauea	1	0	>0 $^{+0.4}_{-0.0}$	--	Historic tholeiitic eruptions
Mauna Kea	3	54	0.375 ± 0.05	1	Samples from tholeiitic shield (Hamakua Group)
Kohala Mtn.	5	100	0.40 ± 0.02	2	Samples from tholoeiitic shield (Pololu Volcanic Series)
Haleakala	6	182	0.86 ± 0.03	3	Age on alkalic basalt (Kula Volcanic Series)
W. Maui	8	221	1.32 ± 0.04	3	Samples from tholeiitic shield (Wailuku Volcanic Series)
Lanai	9	226	1.28 ± 0.04	4	Samples from tholeiitic shield
E. Molokai	10	256	1.52 ± 0.05	3	Samples from tholeiitic shield (lower member of East Molokai Volcanic Series)
W. Molokai	11	280	1.89 ± 0.06	3	Sample from tholeiitic shield (West Molokai Volcanic Series)
Koolau	12	339	2.6 ± 0.1	3,5	Samples from tholeiitic shield (Koolau Volcanic Series)
Waianae	13	374	3.7 ± 0.1	5	Samples from tholeiitic shield (lower member of Waianae Volcanic Series)
Kauai	14	519	5.14 ± 0.20	3,6	Sample from tholeiitic shield (Napali Formation)
Niihau	15	565	5.5 ± 0.2	7	Samples from tholeiitic shield (unplublished data)
Nihoa	17	780	7.2 ± 0.3	8	Samples from tholeiitic shield
Necker	25	1058	10.3 ± 0.4	8	Samples from tholeiitic shield

(cont.)

TABLE 8. (CONTINUED)

Volcano Name	Volcano No[a]	Distance From Kilauea Along H-E Trend[a] (Kilometers)	Best K-Ar Age[b] (10^6 yr)	Ref.	Remarks
La Perouse Pinnacle (French Frigates Shoal)	26	1209	12.0 ± 0.4	8	Samples from tholeiitic shield.
Laysan	36	1818	19.9 ± 0.3	9	Dredged Samples of hawaiite and mugearite
Northampton Bank	37	1841	26.6 ± 2.7	9	Dredged samples of tholeiitic basalt
Pearl & Hermes Reef	50	2281	20.6 ± 0.5	10	Dredged samples of phonolite, hawaiite & alkalic basalt
Midway Islands	52	2432	27.7 ± 0.6	11	Samples of mugearite & hawaiite from conglomerate overlying tholeiitic basalt in drill hole
Unnamed	57	2600	28.0 ± 0.4	10	Dredged samples of alkalic basalt
Unnamed	63	2825	27.4 ± 0.5	10	Dredged samples of alkalic basalt, probably frompost-erosional suite
Daikakuji	67	3493	42.4 ± 2.3	12	Dredged samples of alkalic basalt
Yūryaku	69	3520	43.4 ± 1.6	10,12	Dredged samples of alkalic basalt
Kimmei	72	3668	39.9 ± 1.2	12	Dredged samples of alkalic basalt
Koko	74	3758	48.1 ± 0.8	13	Dredged samples of alkalic basalt, trachyte, and ?
Ōjin	81	4102	55.2 ± 0.7	14	Samples of hawaiite and tholeiite from DSDP Site 430

(cont.)

TABLE 8. (CONTINUED)

Volcano Name	Volcano No[a]	Distance From Kilauea Along H-E Trend[a] (Kilometers)	Best K-Ar Age[b] (10^6 yr)	Ref.	Remarks
Jingū	83	4175	55.4 ± 0.9	15	Dredged samples of hawaiite and mugearite
Nintoku	86	4452	56.2 ± 0,6	14	Samples of alkalic basalt from DSDP Site 403, probably from post-erosional stage.
Suiko	90	4794	59.6 ± 0.6	16,17	Single dredged sample of mugearite
	91	4860	64.7 ± 1.1	14	Samples of alkalic basalt and tholeiite from DSDP Site 433

[a] - From Jackson and others (1975) and K. E. Bargar (written communication, 1978).

[b] - All data have been converted to the new constants $\lambda_\epsilon + \lambda_{\epsilon'} = 0.581 \times 10^{-10}$ yr^{-1}, $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}, $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol.

References:

1. Porter and others (1977)
2. McDougall and Swanson (1972)
3. McDougall (1964)
4. Bonhommet and Others (1977)
5. Doell and Dalrymple (1973)
6. McDougall (1979)
7. G. B. Dalrymple (unpublished data)
8. Dalrymple and others (1974)
9. This paper
10. Clague and others (1975)
11. Dalrymple and others (1977)
12. Dalrymple and Clague (1976)
13. Clague and Dalrymple (1973)
14. Dalrymple and others (1980b)
15. Dalrymple and Garcia (1980)
16. Saito and Ozima (1975)
17. Saito and Ozima (1977)

recovered, and the ages of these volcanoes are based on the ages of post-shield-building lavas. For all of the volcanoes except the unnamed volcano 63 (Table 8), the samples are from the alkalic eruptive stage, and the K-Ar ages should be close to but younger than shield building ages. The samples from volcano 63 probably are from lava erupted during the post-erosional stage and, by analogy with volcanoes of the principal Hawaiian Islands, may be younger than the main shield by as much as several million years.

The Hawaiian-Emperor age data are plotted as a function of distance from Kilauea in Figure 9. In addition to the K-Ar data, we have plotted three fossil minimum ages for volcanoes for which no radiometric data exist. These include an age of 28 to 31 m.y. for nannofossils in volcanogenic deposits at DSDP Site 311 on the archipelagic apron of a volcano 240 km west of Midway Islands (Bukry, 1975), an age of 39 to 41 m.y. for dredged large benthic foraminifers from Kammu Seamount near the bend (H. M. Sachs, quoted *in* Clague and Jarrard, 1973, p. 1138-1139), and an early Maestrichtian age for nannoflora in deposits above basalt at DSDP Site 192 on Meiji Seamount (Worsley, 1973) at the northern end of the Emperor chain. It is evident from Figure 9 that the age data substantiate the age-distance corollary and provide strong support for the general (kinematic) hot spot hypothesis for the origin of the entire Hawaiian-Emperor chain. An unweighted least-squares line through the radiometric data, forced through the origin, yields an average volcanic propagation rate of 8.2 ± 0.2 cm/yr (Fig. 9).

Although there is a striking increase in the age of the volcanoes as a function of distance from Kilauea, the increase is not exactly linear. As Jackson (1976) pointed out, the scatter may be due to errors in the age data, to the fact that different stages of volcanism have been dated on the different volcanoes, to real changes in the volcanic propagation rate, or to a combination of these factors.

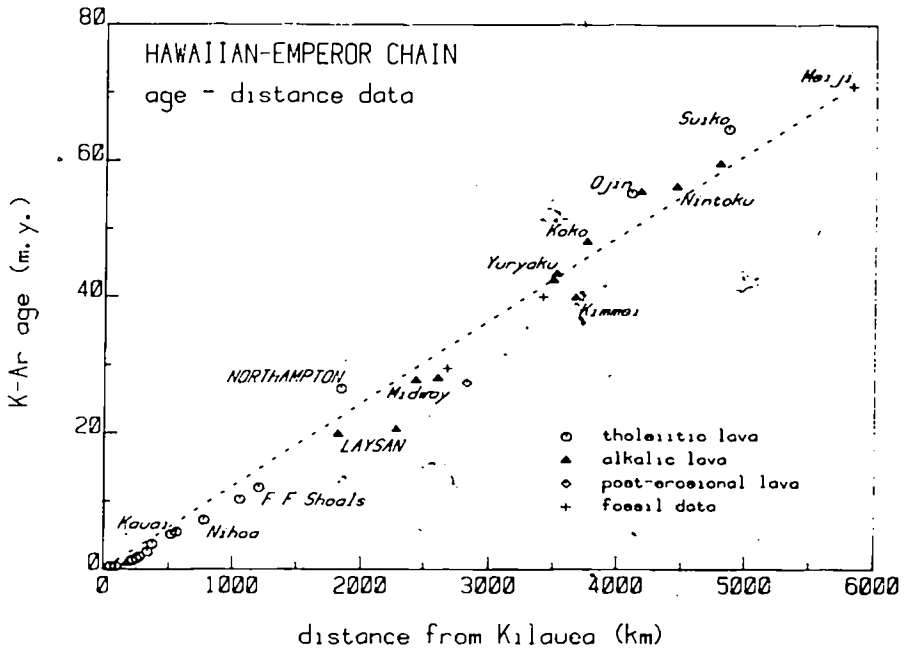

Figure 9. Age of volcanoes in the Hawaiian-Emperor chain as a function of distance from the Kilauea Volcano. Dashed line (8.2 ± 0.2 cm/yr) is a least squares fit to the radiometric data forced through the origin. Data from Table 8.

Certainly, errors in dating contribute some uncertainty to the results. While the deviations from linearity are too great to be accounted for entirely by analytical errors, most of the samples recovered by dredging and drilling (that is, from Laysan Island to Suiko Seamount) are altered to some degree and are datable only by $^{40}Ar/^{39}Ar$ incremental heating techniques that are thought to provide sufficient internal checks to identify unreliable data. There may be, however, factors in $^{40}Ar/^{39}Ar$ dating of lavas altered in the submarine environment that are not adequately understood, and it is possible that the data set contains a few incorrect ages.

Petrographic and chemical data show that the age data are from lavas erupted during different stages, and thus at different times, in the life cycles of the volcanoes. On the basis of the chronology of the well-studied Hawaiian shields, we have assumed that the age difference between the inception of tholeiitic shield-building volcanism and the cessation of the alkalic stage of volcanism is always 1 m.y. or less. If our assuption is correct, then the scatter due to this difference is small. Extensive chemical studies and drilling (Jackson and others, 1980) have shown that the volcanoes in the Hawaiian-Emperor chain follow the same eruptive sequence observed in the principal Hawaiian Islands. We are uncertain, however, that the timing of the successive stages applies with equal validity throughout the entire volcanic chain, although dating of both tholeiitic and alkalic lavas from Ojin and Suiko Seamounts (Dalrymple and others, 1980b) suggests that it probably does. Thus, some of the scatter in the ages may be due to larger than anticipated differences in age between tholeiitic and alkalic volcanism, although it seems unlikely that this factor can explain all of the irregularities in the data.

Real short-term changes in the volcanic propagation rate were first proposed by Jackson and others (1972) to account for the observation that the age-distance data for the volcanoes of

the principal Hawaiian Islands are nonlinear and indicate an acceleration of propagation during the last 5 m.y. or so. Shaw (1973) and Walcott (1976) proposed thermal feedback and mechanisms to account for such short-term variations. Short-term nonlinearity has been disputed by McDougall (1979), who argued that the departures from linearity along the Hawaiian segment of the chain are explainable solely by dating errors and by differences in the volcanic stage sampled. Our new Laysan Island and Northampton Bank data strongly suggest that the volcanic propagation rate may not be exactly linear. The distances of these two volcanoes from Kilauea differ by less than 25 km (Table 8). At a uniform propagation rate of 8 to 9 cm/yr, their ages should differ by only about 0.28 to 0.32 m.y. instead of the 6.7 m.y. indicated by the measured ages. A similar discrepancy occurs in the ages of volcanoes near the bend (Fig. 9). More detailed age data will be needed before we know whether these age-distance irregularitites are due partly to nonlinear volcanic propagation. The present data indicate, however, that nonlinear propagation should be retained as a working hypothesis.

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APPENDIX: SAMPLE DESCRIPTIONS

NORTHAMPTON BANK

5-4a Tholeiitic basalt. Intergranular to interstitial textured olivine porphyritic basalt. Olivine phenocrysts (10%) as large as 3 x 7 mm have greenish-brown saponite alteration on fractures and rims of most grains; and picotite and opaque inclusions in a groundmass of 35%-40% very pale brown augite, 30% plagioclase (An_{60-68}), 20%-25% opaque Fe-Ti oxides, and <5% glass mostly altered to smectite. Average groundmass grain size is 0.1 mm.

5-4b Tholeiitic basalt. Like 5-4a except that some olivine phenocrysts are concentrically zoned and kink-banded. Average groundmass grain size is 0.1 mm.

5-4c Tholeiitic basalt. Like 5-4a except that olivine phenocrysts as long as 6 mm make up 10%-15% of the rock. Average groundmass grain size is 0.1 mm.

LAYSAN ISLAND

D1-1 Hawaiite. Sample has subtrachytic texture and contains rare phenocrysts of augite, Fe-Ti oxides, and olivine; and microphenocrysts of plagioclase in a groundmass of 45% plagioclase (An_{52}), 20% augite, 22% opaque Fe-Ti oxides, 11% smectite after glass, olivine, plagioclase, very rare biotite, and 2% vesicles. Fe-Ti oxides are commonly rimmed by hematite. Average grain size is 0.05 mm.

D1-2 Hawaiite. Sample has hyalopilitic texture and contains rare phenocrysts of plagioclase and olivine in a groundmass of 44% plagioclase, 26% opaque Fe-Ti oxides, 26% clinopyroxene, 4% smectite after glass, and rare biotite. Average grain size is 0.01 mm.

D1-3 Hawaiite. Sample has intergranular texture and contains rare phenocrysts of plagioclase and olivine in a groundmass of 60% plagioclase, 26% opaque Fe-Ti oxides, 2% augite,

4% olivine (iddingsite), 5% vesicles, and 4% clays. Average grain size is 0.05 mm.

D1-4 Hawaiite. Sample has subtrachytic texture and contains rare phenocrysts of plagioclase, Fe-Ti oxides, and olivine in a groundmass of 44% plagioclase, 28% augite, 26% Fe-Ti oxides, and 2% smectite after glass, and rare biotite. Olivine is altered to iddingsite. Average grain size is 0.02 mm.

D1-5 Mugearite. Sample has hyalopilitic to felty texture and contains rare phenocrysts of plagioclase in a groundmass of 41% plagioclase, 22% augite, 17% opaque Fe-Ti oxides, 5% olivine, 5% vesicles, and 10% smectite. Smectite occures both as vesicle fillings and as replacements of glass. Olivine is replaced by iddingsite. Average grain size is 0.02 mm.

D1-6 Hawaiite. Sample has subtrachytic texture and contains phenocrysts of opaque Fe-Ti oxides and rare plagioclase in a groundmass of 45% plagioclase, 15% augite, 17% opaque Fe-Ti oxides, 23% smectite, rare biotite, and apatite. Average grain size is 0.3 mm.

D1-7 Mugearite. Sample has hyalopilitic to felty texture and contains microphenocrysts of plagioclase, opaque Fe-Ti oxides, and olivine in a groundmass of 52% plagioclase, 11% augite, 15% opaque Fe-Ti oxides, 8% olivine (iddingsite), 2% vesicles, and 12% smecite. Average grain size is 0.01 mm.

D1-8 Hawaiite. Sample has subtrachytic texture and contains phenocrysts of plagioclase and opaque Fe-Ti oxides in a groundmass of 36% plagioclase, 20% augite, 25% opaque Fe-Ti oxides, 19% smectite, and rare apatite and olivine (iddingsite). Plagioclase is partially altered to smectite. Average grain size is 0.01 mm.

D1-9 Mugearite. Sample has hyalopilitic texture and contains rare phenocrysts of opaque Fe-Ti oxides and microphenocrysts of plagioclase in

a groundmass of 35% plagioclase, 11% augite, 22% opaque Fe-Ti oxides, 4% olivine (iddingsite), 14% vesicles, and 14% smectite. Average grain size is 0.01 mm.

D1-10 Mugearite. Sample has hyalopilitic texture and contains phenocrysts of plagioclase and opaque Fe-Ti oxides in a groundmass of 55% plagioclase, 19% augite, 15% opaque Fe-Ti oxides, 1% olivine (iddingsite), 1% vesicles, 9% smectite, and rare apatite. Average grain size is less than 0.01 mm.

D1-11 Mugearite. Sample has hyalopilitic texture and contains phenocrysts of plagioclase and microphenocrysts of opaque Fe-Ti oxides in a groundmass of 43% plagioclase, 23% augite, 17% opaque Fe-Ti oxides, 17% smectite, rare olivine (iddingsite), and rare apatite. Average grain size is less than 0.01 mm.

D1-12 Mugearite. Sample has hyalopilitic texture and contains phenocrysts of plagioclase, opaque Fe-Ti oxides, and olivine (iddingsite) in a goundmass of 55% plagioclase, 6% augite, 21% opaque Fe-Ti oxides, 5% olivine (iddingsite), 3% vesicles, 10% smectite, and rare apatite. Average grain size is 0.01 mm.

D1-14 Hawaiite. Sample has hyalopilitic to intergranular texture and contains phenocrysts of plagioclase and olivine (iddingsite), and microphenocrysts of opaque Fe-Ti oxides in a groundmass of 38% plagioclase, 28% augite, 25% opaque Fe-Ti oxides, 2% olivine (iddingsite), 7% smectite, and rare apatite. Average grain size is 0.01 mm.

D1-16 Hawaiite. Sample has subtrachytic texture and contains phenocrysts of plagioclase in a groundmass of 31% plagioclase, 41% augite, 25% opaque Fe-Ti oxides, 2% smectite, and rare apatite. Average grain size is 0.01 mm.

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