An Evaluation of Temporal Geochemical Evolution of Loihi Summit Lavas: Results From *Alvin* Submersible Dives

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Stratigraphically controlled sequences of in situ lavas were collected from Loihi Seamount using the *Alvin* submersible to evaluate the volcano's temporal geochemical evolution. Three sections with up to 370 m of relief were sampled from the two pit craters at the summit of Loihi. All of the analyses were done on glass separates. Our results indicate that tholeiitic and alkalic volcanism at the summit of Loihi has been coeval. The tholeiitic and alkalic lavas have similar incompatible element patterns and O, Pb, Sr, and Nd isotope ratios but are distinct in some incompatible element ratios. These results are consistent with the different Loihi rock types being derived by variable degrees of melting from a common source. The crossing and light-rare-earth-enriched rare earth element patterns and variable Sc/Yb ratios of the tholeiites indicate that their source was a garnet lherzolite. The relatively low $\delta^{18}O$ values (~4.9 ‰) for Loihi lavas are interpreted to be characteristic of the Hawaiian plume.

INTRODUCTION

Loihi Seamount is the southernmost volcano in the Hawaiian chain. It is located 35 km south of the island of Hawaii on the flanks of Mauna Loa and Kilauea, two active tholeiitic shield volcanoes. Loihi was discovered by *Emery* [1955], who gave it the Hawaiian name meaning "the long one" in recognition of its elongate shape (Figure 1). It was assumed to be an old seamount unrelated to the Hawaiian hotspot [*Moore and Fiske*, 1969] until it had two major earthquake swarms in 1971-1972 and 1975 [*Klein*, 1982]. A dredge haul on Loihi in 1978 recovered glassy lavas, confirming that it is an active volcano. The rocks obtained in the initial dredge haul are tholeiitic [*Moore et al.*, 1979], but subsequent dredging in 1981 recovered a wide diversity of rock types ranging from tholeiite to basanitoid [*Moore et al.*, 1982].

The discovery of alkalic lavas on Loihi fundamentally changed models for hotspot volcanism [*Clague*, 1987]. Previous models for Hawaiian hotspot volcanism assumed that each volcano was composed almost entirely of tholeiitic lavas (95-99%) with a thin veneer of alkalic lavas produced during the waning stages of shield development and posterosional volcanism [*Macdonald*, 1968]. The age of the dredged Loihi alkalic and tholeiitic lavas was estimated using palagonite rim thicknesses. The alkalic lavas were found to have systematically thicker rims than the tholeiitic lavas but with broad overlap (1-12 µm versus 0.5-4 µm) [*Moore et al.*, 1982]. Using palagonite growth rates for mid-ocean ridge basalts (MORB), average ages of 1.6 ka and 0.5 ka were inferred for the Loihi alkalic and tholeiitic lavas, respectively [*Moore et al.*, 1982]. Unfortunately,

palagonite rim growth rates are affected by many factors, including vesicularity and composition of the glass, which vary strongly among the Loihi lavas (e.g., vesicularity varies from <1 to >50 vol %) [*Moore et al.*, 1982].

This study was initiated to further evaluate the temporal evolution of Loihi's lavas. Determining the relative age of its alkalic and tholeiitic lavas is essential to deciphering the melting history [e.g., *Ribe*, 1988] and geochemical evolution of Loihi, which may exemplify the early stage of growth of all Hawaiian volcanoes [*Clague*, 1987]. The temporal evolution in the geochemistry of lavas from a volcano is best determined using stratigraphically controlled sequences of lava. Loihi has two summit pit craters with over 300 m of relief (Figure 2). Three sequences of in situ samples were collected from the walls of these pit craters using the *Alvin* submersible. This paper presents the results from a petrologic study of these samples. Our results indicate that alkalic and tholeiitic volcanism have been coeval at the summit of Loihi and that these lavas are probably derived from a common mantle source by variable degrees of partial melting. The source is relatively undepleted (compared to MORB) and has moderate $^{87}Sr/^{86}Sr$ (0.70355) and $^{206}Pb/^{204}Pb$ (18.2-18.5) and low $\delta^{18}O$ (4.9) isotopic values, which may be representative of the plume component for Hawaiian magmas. The chemical composition of lavas in the stratigraphic sequences is quite variable even among the tholeiites, which indicates that magma bodies in Loihi have been short-lived.

REGIONAL GEOLOGY

The morphology and structure of Loihi have been delineated in several recent studies [*Moore et al.*, 1982; *Malahoff et al.*, 1982; *Fornari et al.*, 1988]. Loihi has two prominent rift zones extending north and south from the summit; both curve to the east (Figure 1). The south rift is 19 km long. The north rift is
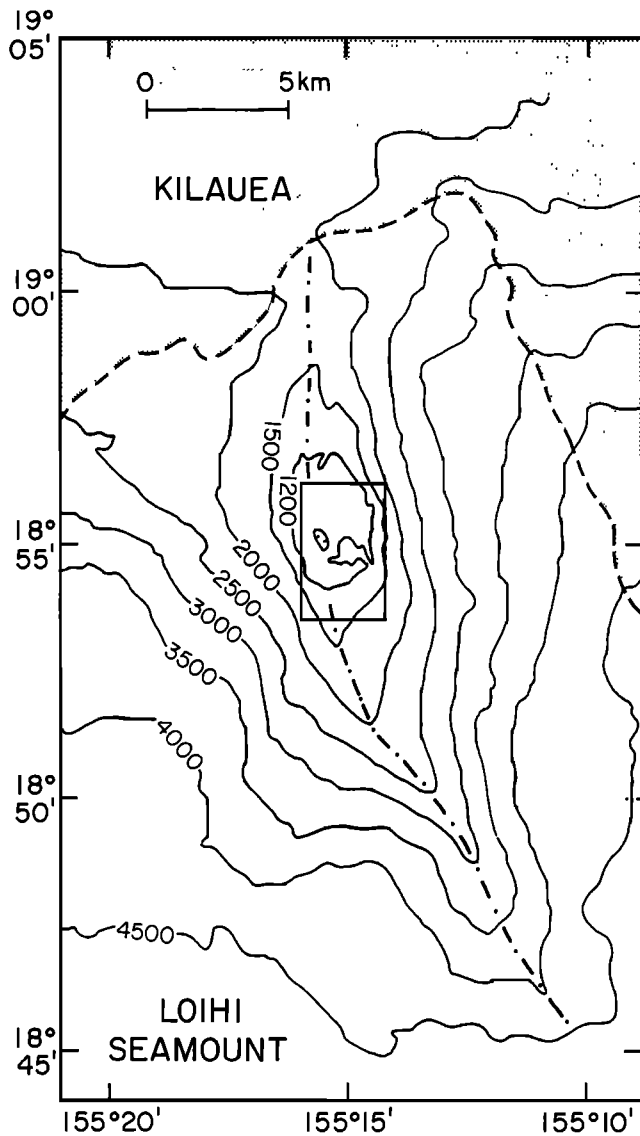
Fig. 1. Bathymetric map of Loihi Seamount; simplified from the Sea Beam map of *Fornari et al.* [1988]. Contours are in meters. Dashed line is an estimate of the location of the contact between Loihi and Kilauea (stippled) lavas. The dashed-dotted line indicates the axis of the main north and south rift zones. Box indicates the location of Figure 2.

shorter (~8 km) but consists of two parallel prongs that extend out from the summit platform. The western prong is the most prominent. Loihi's summit consists of a broad platform with some prominent cones along its margin and two deep pit craters (Figure 2). The pit craters are steep-walled (slopes of 25°-42°), and both are elongate to the NW. They may be composite features formed by several collapse events (especially the eastern pit). The western pit crater has about 300 m of relief and is surrounded by a ridge with cones, except on the southeast side where it is truncated by the eastern pit crater. This truncation indicates that the western pit crater is probably older [*Fornari et al.*, 1988]. The eastern pit crater has about 370 m of relief on its NW side but only about 170 m of relief on its east side. The walls of these pit craters are excellent sites for collecting stratigraphically controlled sequences of lava.

STRATIGRAPHIC SECTIONS

Three sections were sampled in traverses up the walls of Loihi's pit craters: two sections in the east pit and one in the

west pit (Figure 2). Only in situ samples were collected using the submersible's mechanical arm. The suite from the north side of the east pit includes 22 glassy lavas collected from a water depth range of 987 to 1316 m (dive 1801; Figures 2 and 3). The base of the southeast portion of the east pit is mantled with talus. Fifteen samples were collected from depths between 977 and 1277 m, including a traverse to a cone on the northeast edge of the summit platform (dive 1803). The west side of the west pit is mantled with talus at its base. Five- to ten-meter-long rock columns lie at the base of the crater wall. Four samples were collected near the base (1275-1291 m), but a 190-m section of the crater is covered with talus. Ten samples were collected between depths of 986 and 1084 m, and 13 other samples were collected along the northern rim of the pit crater (dive 1802; see Figure 2). Some of the samples from the upper portion of the west pit lack glassy rims. A traverse was also made along the axis of the upper portion of the south rift, and 20 samples were collected between water depths of 966 and 1330 m (dive 1804; Figure 2). Hydrothermal vents were found on the flanks of two cones along this traverse [*Karl et al.*, 1988].

The thicknesses of the stratigraphic sections recovered from Loihi's pit craters are greater than those exposed in the walls of Kilauea caldera (Figure 3). The age of the Kilauea section is about 2.8 ka [*Casadevall and Dzurisin*, 1987]. The Loihi sequence is probably older than the Kilauea caldera sequence given its greater thickness (up to 370 m versus 135 m) and less
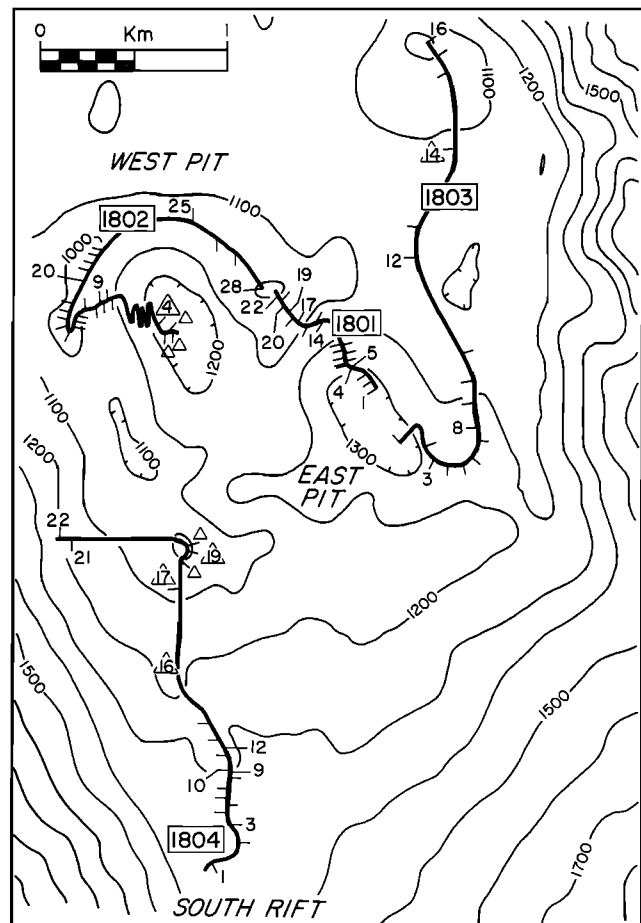

Fig. 2. Bathymetric map of the southern summit area and upper portion of the south rift of Loihi Seamount based on Sea Beam data [after *Fornari et al.*, 1988]. Heavy lines show the dive tracks for the four *Alvin* submersible dives (1801-1804). Tick marks along the dive tracks show sample locations. Numbers next to ticks refer to specific samples. Triangles indicate alkalic samples. Contour interval is 100 m.
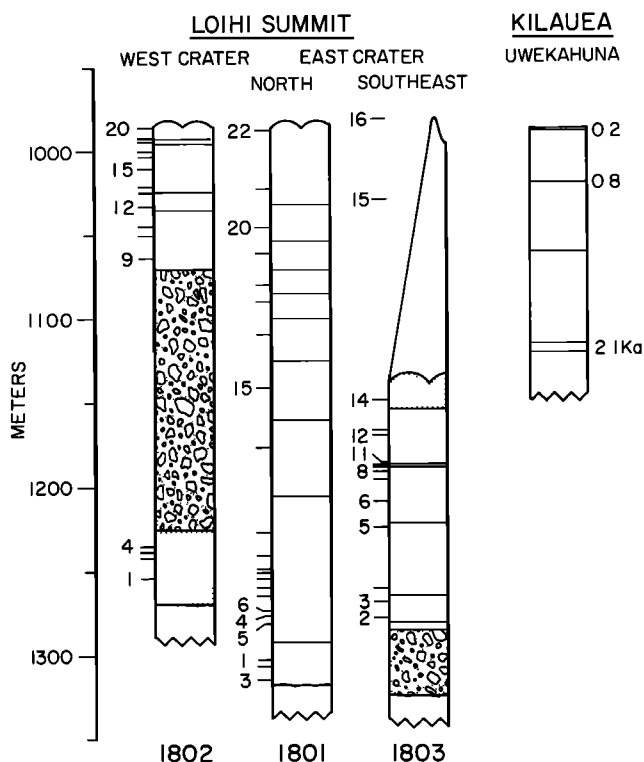
Fig. 3. Schematic sections for the three traverses up the walls of Loihi's west and east pit craters (dives 1801-1803). Sample locations are noted by the tick marks on the columns. Lines in the sections separate chemically distinct rock types. The alkalic rocks are shown by the stippled pattern. Portions of the sections covered by talus are indicated by the rocky pattern. The top of the southeast section from the east crater (dive 1803) is just above sample 11. The other samples were collected along the eastern rim of the summit platform (see Figure 2). All sections are shown in meters below sea level. For comparison, the Kilauea caldera section at Uwekahuna Bluff is shown at the same scale (summarized from *Casadevall and Dzurisin* [1987]). The ages of the Kilauea tephra units (in thousands of years) are shown [from *Casadevall and Dzurisin*, 1987].

frequent eruptive activity (based on earthquake activity) [*Klein*, 1982].

PETROGRAPHY

Dredged lavas from Loihi have been described petrographically in several studies [e.g., *Moore et al.*, 1982; *Frey and Clague*, 1983; *Hawkins and Melchior*, 1983]. We observed and collected both pillow lavas and sheet flows. Sheet flows were found only near vents along the south rift zone traverse. Their lateral extent is unknown. There are no chemical differences between the different flow morphologies, but the vesicularity of the sheet flow samples is higher.

Vesicularity of our samples varies greatly (0.1-43 vol %). The alkalic lavas have consistently high vesicularity, which is probably related to the high volatile content of Loihi alkalic lavas [*Byers et al.*, 1985]. The tholeiites are extremely variable in vesicularity (0.1-41 vol %). The picritic tholeiitic basalts collected near (<10 m) their vents along the south rift are strongly vesicular (~40 vol %). Some subaerial lavas are highly vesicular near their vent and decrease in vesicularity away from the vent (e.g., 1947-1948 Hekla eruption [*Einarsson*, 1949]; 1984 Mauna Loa eruption). Thus proximity to the vent may play an important role in controlling the vesicularity of Loihi's lavas and, perhaps, of all submarine basalts.

All the samples in this study contain olivine phenocrysts (>0.5 mm diameter) or microphenocrysts (0.1-0.5 mm), although they are rare (<0.1-0.2 vol %) in the evolved alkalic lavas (glass MgO contents of 4.6-5.5 wt %; Table 1). Olivine is abundant (~32 vol %) in two tholeiitic samples (1804-10 and 1804-11). Most olivine grains are euhedral, but many show resorption features. Clinopyroxene is present in all of the samples with glass MgO contents <7.0 wt % but is absent or rare (<0.1-0.2 vol %) in samples with MgO contents >7.0 wt % (as is typical of Hawaiian tholeiites) [e.g., *Wright*, 1971]. Clinopyroxene microphenocrysts and phenocrysts are commonly euhedral and strongly zoned; some grains have sector zoning or overgrowths on resorbed cores. Plagioclase is rare in all glasses with MgO contents above 5.5 wt % and absent in glasses with MgO contents above 7.0 wt %. Where present, plagioclase is euhedral, weakly zoned and small (<0.5 mm).

ANALYTICAL METHODS

Glass was used exclusively for all chemical and isotopic analyses to avoid the effects of seawater contamination and accumulation of minerals so that a representative magmatic liquid composition could be determined. Glass was carefully handpicked using a binocular microscope. Grains with adhering minerals or any sign of alteration were rejected. Major elements were determined using a wavelength-dispersive electron microprobe at the University of Hawaii. The reported values (Table 1) are averages of seven to 10 spot analyses per sample using a 25-μm beam size, 10- to 12-nA sample current, and 20-s counting time for each element (except P and Mn with 50-s counting times). Relative analytical precision is 1-2% for major elements and 5-10% for minor elements (i.e., <1.0 wt %).

Abundances of rare earth elements (REE; La, Nd, Sm, Eu, Gd, Dy, Ho, Yb, and Lu), K, Co, Cr, Mn, Cu, Ni, Sc, Sr, V, Y, Zn, and Zr abundances (Table 2) were determined on 23 samples by inductively coupled plasma, emission spectrometry (ICP-ES) at the University of Washington using methods similar to those described by *Xue et al.* [1990]. Approximately 750 mg of handpicked glass chips from each sample were rinsed in deionized water, then digested in a mixture of concentrated HF-HClO$_4$-HNO$_3$. After evaporation, dissolution of the resulting salts in dilute HCl produced a complete solution for most of the samples. Residual Cr-spinel in several samples was filtered out, fused with NaOH, dissolved in dilute HCl, and combined with the filtrate. All analyses were done on a Baird PS-1, 47-channel spectrometer using both synthetic high-purity solutions and concurrently prepared natural rock solutions as standards. Reported REE abundances were corrected using isotope dilution data for Columbia River basalt ARHCO-1; other trace element abundances were corrected against Kilauea basalt BHVO-1. Analytical precision is 2-5% relative for all elements except Ho (10%).

In addition, all of the lanthanide REE, Rb, Cs, Ba, Th, Nb, Y, Hf, Ta, and U were determined by inductively coupled plasma, mass spectrometry (ICP-MS) on 13 of the same samples (Table 3) at Washington State University. For each sample, 100-200 mg of glass were dissolved on a hotplate at 110°C using HF, HNO$_3$, and HClO$_4$ in an open teflon vial. After the sample was evaporated to incipient dryness, an additional evaporation with HClO$_4$ at 165°C converted insoluble fluorides to soluble perchlorates. An In-Re internal standard was used to monitor drift. The samples were analyzed using a Sciex Elan 250 ICP-MS, with cross-flow nebulizer, water-cooled torch, and Brooks mass flow controllers. Oxide

TABLE 1. Representative Microprobe Analyses of Major Elements in Pillow Rim Glasses Collected From Loihi Volcano With the *Alvin* Submersible

Sample	Class	SiO$_2$	TiO$_2$	Al$_2$O$_3$	FeO*	MgO	CaO	Na$_2$O	K$_2$O	P$_2$O$_5$	MnO	Total
1801-01	Thol	48.77	2.64	13.63	11.73	6.82	11.90	2.36	0.44	0.21	0.20	98.70
1801-04	Thol	48.67	2.75	14.04	11.98	6.18	11.39	2.58	0.52	0.23	0.19	98.53
1801-05	Thol	49.48	2.43	13.55	11.89	6.93	11.46	2.42	0.41	0.18	0.16	98.91
1801-09	Thol	49.52	2.47	13.56	12.06	7.00	11.45	2.37	0.40	0.19	0.16	99.18
1801-13	Thol	49.55	2.42	13.52	11.84	7.07	11.35	2.38	0.41	0.19	0.18	98.91
1801-14	Thol	49.05	2.68	13.56	11.70	6.79	12.01	2.52	0.50	0.18	0.17	99.16
1801-16	Thol	49.13	2.82	13.86	11.67	6.49	11.53	2.56	0.60	0.25	0.16	99.07
1801-17	Thol	49.31	2.82	13.70	11.46	6.83	11.94	2.50	0.51	0.22	0.18	99.47
1801-19	Thol	48.67	2.87	13.75	11.74	6.71	11.69	2.58	0.57	0.24	0.21	99.03
1801-20	Thol	48.62	2.82	13.71	11.78	6.62	12.02	2.52	0.49	0.24	0.20	99.02
1801-21	Thol	49.22	2.79	13.84	11.87	6.48	11.74	2.42	0.46	0.22	0.19	99.23
1801-22	Thol	49.31	2.61	13.84	11.84	6.80	11.65	2.41	0.42	0.20	0.18	99.26
1802-04B	Alk	47.17	3.59	14.75	12.84	5.01	10.76	3.55	1.02	0.38	0.22	99.29
1802-09A	Thol	49.46	2.71	13.83	11.97	6.57	11.74	2.39	0.42	0.20	0.18	99.47
1802-20	Thol	49.39	2.68	13.81	11.60	6.94	11.72	2.41	0.44	0.24	0.17	99.40
1803-14	Alk	47.12	3.88	14.17	13.10	5.49	11.10	3.31	0.84	0.38	0.18	99.57
1803-16	Thol	49.69	2.48	13.26	11.52	7.50	11.72	2.33	0.36	0.18	0.18	99.22
1804-01	Thol	49.19	2.46	13.35	11.40	7.29	12.21	2.40	0.49	0.21	0.19	99.19
1804-10	Thol	49.20	2.56	12.93	11.46	8.01	12.02	2.35	0.44	0.21	0.16	99.34
1804-12	Thol	49.20	2.63	13.40	11.27	7.22	12.04	2.48	0.50	0.19	0.18	99.11
1804-16	Alk	48.38	4.14	13.48	13.57	4.56	9.49	3.53	0.99	0.45	0.22	98.81
1804-19	Alk	48.73	3.76	13.82	12.75	5.17	10.21	3.33	0.89	0.34	0.19	99.19
1804-21	Trans	48.23	2.54	13.54	11.88	7.19	12.30	2.67	0.56	0.21	0.19	99.31
1804-22	Trans	47.97	2.57	13.58	11.80	7.02	12.41	2.71	0.58	0.23	0.18	99.05

Total iron reported as FeO*. The class (rock type) for each sample was determined from Figure 4; Alk, alkalic, Thol, tholeiitic; Trans, transitional. In weight percent. Analyst: M. Garcia

interference corrections were determined for each run using two solutions prepared from single-element standards. Sample intensities were first corrected for isobaric oxide interferences and then for instrumental drift using a mass-weighted average of the drift of In and Re [after *Doherty*, 1989]. The elemental intensities were calibrated against a curve constructed from three "in-house" standards, which were dissolved with each batch of unknowns. The Hawaiian basalt standard, BHVO-1, was run as an unknown. Analytical precision is 1-2% for the ICP-MS analyses.

For Sr, Nd, and Pb isotopic measurements, 30-50 mg of fresh, glass were leached successively in acetone, ultrapure 6N HCl, and ultrapure water in an ultrasonic bath. Following digestion with HF-HNO$_3$, spiking, chemical separation, and mass spectrometric analyses for Pb, Sr, and Nd ratios were performed as described by *Mahoney et al.* [1991]. Isotopic fractionation corrections, standard values, total procedural blank levels, and experimental uncertainties are listed in Table 4.

For oxygen isotope measurements, coarsely ground (>80 mesh) glass, which had been heated under vacuum for 2 hours at 350°C to remove any adsorbed moisture, was hand-ground in acetone using an agate mortar and pestle to about 400 mesh and dried to 110°C in air for 30 min. Seven to 15 mg of powdered glass were used for each analysis. Oxygen was

extracted using ClF$_3$ [*Borthwick and Harmon*, 1982] in a manner similar to the BrF$_5$ method developed by *Clayton and Mayeda* [1963]. The resulting CO$_2$ gas was analyzed with a Finnigan MAT Delta E triple collector, 90° sector mass spectrometer at the University of Minnesota. Oxygen isotope ratios are normalized to SLAP (δ^{18}O V.SMOW = -55.0°/oo) and are reported relative to V.SMOW. The δ^{18}O value for NBS-28 quartz on this scale is +9.5 ± 0.15°/oo. Each sample was run at least twice; the duplicates are within ±0.15°/oo of the average value (most are <0.06°/oo; see Table 5).

Major Elements

The lavas collected from the summit region of Loihi have a substantial range in glass composition (e.g., 4.5-8.0 wt % MgO). Three rock types were recovered: tholeiitic, alkalic, and transitional basalts (Figure 4). The vast majority (>85%) of the new samples are tholeiitic. Alkalic lavas were recovered from the base of the western pit crater, from surface flows along the upper portion of the south rift zone, and along the eastern margin of the summit platform (Figure 2). Two transitional lavas were taken on the southwest side of the summit platform at about 1400 m water depth. The range in lava composition among the *Alvin*-collected suite of samples is smaller than the range for the dredge suite of *Moore et al.*

TABLE 2. ICP-ES Analyses of Trace Elements and Minor Elements in Pillow Rim Glasses From Loihi Volcano

Sample	Sc	V	Cr	Co	Ni	Cu	Zn	Sr	Y	Zr	Ba	La	Nd	Sm	Eu	Gd	Dy	Ho	Yb	Lu	K2O	MnO
1801-1	31	339	431	45	118	107	108	354	26	141	118	12.10	19.00	4.99	1.76	5.63	4.90	0.96	2.12	0.30	0.45	0.186
1801-4	29	359	223	39	82	139	108	361	26	155	121	12.80	20.30	5.39	1.81	5.73	5.10	1.01	2.16	0.31	0.49	0.179
1801-5	31	326	331	51	78	120	147	337	23	148	106	11.60	17.50	4.73	1.64	5.12	4.48	0.86	1.84	0.25	0.44	0.183
1801-9	32	344	425	72	129	160	116	341	24	151	112	11.90	20.10	4.99	1.70	5.24	4.72	0.93	1.88	0.27	0.50	0.186
1801-13	30	322	343	51	79	118	112	336	22	135	105	11.40	16.30	4.36	1.59	5.03	4.22	0.77	1.72	0.23	0.43	0.181
1801-14	34	392	398	62	157	159	117	382	25	153	135	13.40	19.60	5.08	1.77	5.61	4.82	0.92	2.02	0.28	0.56	0.191
1801-16	27	351	341	36	96	122	112	398	24	159	141	14.50	20.10	5.19	1.83	5.72	4.70	0.88	1.94	0.26	0.59	0.180
1801-17	30	360	418	42	138	136	116	380	24	153	133	13.60	19.90	5.13	1.78	5.61	4.74	0.91	1.97	0.27	0.53	0.185
1801-19	32	391	296	55	117	162	122	413	25	167	150	14.70	21.00	5.45	1.86	5.85	4.86	0.94	2.02	0.28	0.64	0.190
1801-20	30	381	211	40	88	149	108	404	26	159	138	13.90	20.10	5.40	1.84	5.67	4.93	0.94	2.10	0.29	0.57	0.187
1801-21	29	350	322	48	112	132	105	329	26	139	106	12.10	18.90	5.09	1.77	5.65	4.95	0.97	2.12	0.30	0.44	0.175
1801-22	32	371	397	50	122	128	112	341	25	147	108	11.60	17.20	4.77	1.71	5.49	4.74	0.90	2.07	0.28	0.46	0.185
1802-4B	25	428	27	44	80	130	130	580	29	219	256	23.60	29.90	7.06	2.33	6.99	5.68	1.08	2.30	0.31	1.04	0.194
1802-9A	31	357	378	50	117	126	106	331	26	145	106	11.70	17.90	5.10	1.73	5.50	4.88	0.97	2.13	0.30	0.46	0.179
1802-20	33	380	409	53	136	145	114	348	26	146	110	11.50	18.40	4.84	1.74	5.63	4.89	0.92	2.14	0.29	0.46	0.193
1803-14	24	416	21	42	54	72	128	554	27	220	229	21.70	29.60	6.99	2.31	6.77	5.50	1.05	2.09	0.29	0.88	0.187
1803-16	32	341	430	47	121	110	108	329	23	135	98	11.10	16.60	4.54	1.57	4.92	4.38	0.84	1.84	0.26	0.40	0.183
1804-1	31	331	710	57	222	162	109	346	21	137	128	11.40	16.40	4.39	1.50	4.61	3.98	0.77	1.63	0.23	0.50	0.178
1804-10	31	328	1220	51	204	167	107	347	21	132	115	12.20	17.60	4.44	1.55	4.87	4.07	0.77	1.63	0.22	0.48	0.178
1804-12	34	357	1115	67	226	204	111	361	22	140	122	12.50	17.70	4.65	1.62	5.09	4.24	0.81	1.74	0.24	0.51	0.182
1804-19	25	435	46	41	50	100	139	509	33	213	227	22.90	30.00	7.43	2.45	7.60	6.42	1.25	2.74	0.38	0.88	0.200
1804-21	31	354	375	54	125	138	111	389	21	147	147	13.20	18.70	4.60	1.57	4.73	4.06	0.77	1.63	0.22	0.57	0.183
1804-22	34	380	394	70	154	153	115	400	22	155	164	14.90	21.90	5.28	1.74	5.25	4.56	0.90	1.76	0.25	0.66	0.186
BHVO-1	30	321	ND	41	117	153	104	392	25	ND	134	15.10	23.70	6.08	2.00	6.09	5.03	0.99	1.96	0.27	ND	0.179
BHVO-1*	32	317	289	45	121	136	105	396	28	179	139	15.80	25.20	6.20	2.06	6.40	5.20	0.99	2.02	0.29	0.54	0.179

In ppm; K O and MnO in wt%. The Hawaiian basalt standard BHVO-1 was analyzed as an unknown with the Loihi samples.

*Used as the standard for Cr, Zr and K O, so no values are given for these elements. The expected values for the standard are an average of values from *Gladney and Roelandts* [1988] and *Govindaraju* [1989].

TABLE 3. ICP-MS Analyses of Trace Element Abundances in Pillow Rim Glasses From Loihi Volcano

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Ba	Th	Nb	Y	Hf	Ta	U	Rb	Cs
1801-1	11.91	27.0	3.70	17.7	5.26	1.86	5.37	0.90	5.31	1.02	2.67	0.35	2.03	0.30	107	0.73	14.00	27.24	3.14	0.70	0.21	8.71	0.09
1801-4	13.58	31.3	4.25	20.5	5.86	2.07	5.81	1.02	5.98	1.13	3.02	0.38	2.27	0.34	127	0.80	15.67	29.19	3.58	0.82	0.23	9.78	0.10
1801-5	13.20	28.3	3.87	18.4	5.46	1.92	5.45	0.95	5.57	1.05	2.71	0.33	1.96	0.29	105	0.77	11.17	26.10	3.35	0.76	0.20	7.29	0.08
1801-14	13.77	31.2	4.23	20.0	5.70	2.02	5.70	0.96	5.66	1.05	2.78	0.36	2.09	0.31	127	0.81	15.72	27.45	3.54	0.83	0.22	10.44	0.10
1801-19	15.11	34.7	4.61	22.0	6.20	2.21	6.14	1.01	5.89	1.10	2.88	0.37	2.12	0.31	146	0.96	18.24	28.30	3.79	1.01	0.27	11.12	0.12
1801-22	13.56	28.8	4.04	19.0	5.71	1.95	5.89	1.04	5.92	1.15	2.99	0.39	2.30	0.34	133	0.85	12.25	30.34	3.48	0.78	0.22	8.56	0.10
1802-4B	29.05	60.0	7.60	33.7	8.90	2.97	8.28	1.38	7.69	1.42	3.69	0.46	2.71	0.40	280	1.86	27.58	35.69	5.29	1.85	0.45	22.39	0.25
1803-14	25.08	53.3	6.92	31.2	8.33	2.77	7.43	1.24	6.94	1.27	3.26	0.39	2.28	0.34	238	1.50	24.02	31.76	4.92	1.60	0.38	17.25	0.17
1803-16	12.94	27.0	3.70	17.3	5.00	1.79	5.26	0.91	5.22	1.01	2.62	0.33	1.90	0.27	97	0.79	11.88	26.60	3.04	0.77	0.20	7.58	0.08
1804-1	13.11	27.2	3.75	17.1	4.98	1.75	5.12	0.90	5.06	0.97	2.43	0.31	1.82	0.26	126	0.77	10.97	23.30	3.08	0.78	0.20	8.59	0.10
1804-10	13.76	29.5	4.06	18.8	5.35	1.86	5.43	0.94	5.39	1.01	2.58	0.33	1.89	0.28	114	0.78	11.82	24.78	3.28	0.82	0.21	9.59	0.09
1804-19	26.13	54.8	7.08	32.1	8.81	2.90	8.38	1.44	8.07	1.53	4.01	0.50	3.02	0.45	231	1.61	23.44	37.04	5.32	1.64	0.46	16.82	0.19
1804-21	16.72	34.0	4.54	20.7	5.87	2.00	5.76	0.97	5.54	1.06	2.67	0.33	1.95	0.29	161	0.99	13.77	25.33	3.65	0.98	0.23	10.82	0.11
BHVO-1	16.10	36.0	4.90	23.2	6.53	2.26	6.27	1.04	5.95	1.10	2.81	0.35	2.00	0.30	131	1.10	17.30	27.90	3.96	1.06	0.30	9.70	0.10
BHVO-1*	15.80	39.0	5.70	25.2	6.20	2.06	6.40	0.96	5.20	0.99	2.40	0.33	2.02	0.29	139	1.08	19.00	27.60	4.40	1.23	0.40	11.00	0.13

In ppm. The Hawaiian basalt standard BHVO-1 was analyzed as an unknown with the Loihi samples.

*The expected values for the standard are an average of values from Gladney and Roelandts [1988] and Govindaraju [1989].

[1982] (see Figure 4) which covers a much larger portion of the volcano and includes basanitoids.

The *Alvin* suite of Loihi lavas forms a relatively coherent group on MgO variation diagrams (Figure 5). Values for TiO_2, FeO, Na_2O, K_2O, P_2O_5, and Al_2O_3 (except for the younger alkalic samples) increase with decreasing MgO; CaO, and to a lesser degree SiO_2, decrease with decreasing MgO. The Al_2O_3/CaO ratio also increases with decreasing MgO, even for the samples with MgO contents >7 wt % (Figure 5), which contain virtually no clinopyroxene or plagioclase phenocrysts (<0.1 vol %). Compared to other Hawaiian tholeiitic shield lavas, Loihi tholeiites have the lowest SiO_2 (average about 49.2) and highest CaO (up to 12.4 wt %). The K_2O and FeO contents also are somewhat higher.

The alkalic lavas are the most evolved among our suite of samples. They range from about 4.6 to 5.5 wt % MgO but their total alkali contents are less than 5 wt %; thus, none are hawaiites (based on the classification scheme of *Le Bas et al.* [1986]). We found two distinct types of alkalic lavas. The south rift lavas have higher SiO_2, and lower Al_2O_3 and CaO than the other alkalic lavas (Figure 5). However, at the same MgO value, both have the same Al_2O_3/CaO ratios. No plagioclase phenocrysts are present in any of these lavas but plagioclase microphenocrysts (0.1-0.5 mm) are more abundant in the south rift lavas (3.8-7.3 vol %) than in the other alkalic lavas (1.0-2.4 vol %).

TRACE ELEMENTS

A wide range of both compatible and incompatible trace element abundances was determined for the *Alvin* suite of Loihi lavas (Tables 2 and 3). Among the most incompatible elements, Cs and Rb have the largest enrichment factors (~3.1), followed in order by Ba, Th, Nb, Ta, U, La, and Ce (with factors of 2.9 to 2.2). Cr, Ni, and Sc are compatible elements in the Loihi lavas and vary widely at a given MgO content. The high Cr contents for the picritic glasses (1270 and 1186 ppm; samples 1804-10 and 1804-12) are partly due to the presence of Cr-spinel microphenocrysts in the analyzed glass. Sr and V, which can be compatible elements, especially in evolved Hawaiian lavas, are incompatible in all of the Loihi lavas. Well-defined linear variations that project through the origin are present for the strongly incompatible elements (Figure 6). Ratios of these elements also yield good linear correlations with the evolved alkalic lavas having the highest ratios (Figure 7).

Both ICP-ES and ICP-MS analyses were made of selected Loihi glasses to obtain a thorough characterization of these samples. This resulted in duplicate REE, Y, and Ba measurements for some samples. The ICP-ES Ce data are not reliable because of instrument problems and were not included in Table 2. For the other elements, most are within 10% (except for Dy). To evaluate which values are more accurate, we compared the results for a standard (BHVO-1) that is similar in composition to the Loihi glasses and was analyzed as an unknown with both sets of ICP analyses. A comparison of these results shows that both techniques produced results similar (within 10%) to the consensus values for BHVO-1, although the ICP-MS value for Dy and Er are about 10% high and the values for Pr and Ta are similarly low (Tables 2 and 3). The REE patterns shown in Figure 8 combine the ICP-ES data with the Ce and Pr obtained by ICP-MS. The ICP-MS Tb, Er, and Tm were not included in the patterns because they caused small positive anomalies that are analytical in origin (i.e., patterns constructed using only the ICP-MS data do not have anomalies for these elements).

TABLE 4. Sr, Nd, and Pb Isotopic Data for Loihi Glasses

Sample	$^{143}Nd/^{144}Nd$	ϵ_{Nd}	$^{87}Sr/^{86}Sr$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
1801-5 Thol	0.512934	+5.7	0.70356	18.252	15.433	38.001
				18.264	15.440	38.026
1801-19 Thol	0.512966	+6.4	0.70353	18.367	15.479	38.127
1801-22 Thol	0.512984	+6.7	0.70353	18.359	15.480	38.133
	0.512988	+6.8				
1804-1 Thol	0.512950	+6.1	0.70355	18.338	15.458	38.079
1804-10 Thol	0.512955	+6.1	0.70361	18.416	15.469	38.154
	0.512953	+6.1		18.413	15.466	38.122
1804-21 Trans	0.512947	+6.0	0.70356	18.245	15.437	37.986
1802-4B Alk	0.512961	+6.3	0.70358	18.474	15.492	38.205
	0.512961	+6.3				
1804-19 Alk	0.512948	+6.0	0.70358	18.378	15.468	38.116
	0.512947	+6.0				

Isotopic fractionation correction for Nd is $^{148}NdO/^{144}NdO$ = 0.242436 ($^{148}Nd/^{144}Nd$ = 0.241572); for Sr it is $^{86}Sr/^{88}Sr$ = 0.1194. Pb values are adjusted relative to the NBS 981 values of Todt et al. [1983], corrected for fractionation using a 0.84°/oo per amu factor. Nd and Sr isotopic data are reported relative to our measured values for La Jolla Nd ($^{143}Nd/^{144}Nd$ = 0.511855 ± 0.000012 total range; or ± 0.2 ϵ_{Nd} units), and for NBS 987 ($^{87}Sr/^{86}Sr$ = 0.71025 ± 0.00002 total range). Within-run uncertainties on sample Nd and Sr isotopic ratios are less than total ranges measured on La Jolla Nd and NBS 987 standards. Estimated uncertainties on Pb isotopes are $^{206}Pb/^{204}Pb$ = ± 0.010, $^{207}Pb/^{204}Pb$ = ±0.009, $^{208}Pb/^{204}Pb$ = ± 0.032, based on total ranges measured for NBS 987. Total blanks are Pb = 2-40 picograms, Nd < 20 picograms, and Sr < 120 picograms. All are negligible for the purpose of this study. Duplicate Pb analyses for 1801-5 and 1804-10 were run on separate splits of glass.

TABLE 5. Oxygen Isotope Data for Loihi Glasses

| Sample	Rock Type	MgO, wt %	$\delta^{18}O$ Values	$\delta^{18}O$ Average
1804-10	Thol	8.0	4.78, 4.86	4.82 ± .04
1804-1	Thol	7.3	4.63, 4.71	4.67 ± .04
1801-09	Thol	7.0	4.71, 4.91	4.81 ± .10
1801-5	Thol	6.9	4.95, 4.97	4.96 ± .01
1801-1	Thol	6.8	4.92, 5.14, 5.14	5.07 ± .10
1801-22	Thol	6.8	5.03, 5.13	5.08 ± .05
1801-14	Thol	6.8	5.14, 5.17, 5.22	5.18 ± .03
1801-19	Thol	6.7	5.09, 5.09	5.09 ± .06
1801-4	Thol	6.2	4.85, 4.93, 4.98, 5.01, 5.08	4.97 ± .06
1804-21	Trans	7.0	4.58, 4.65, 4.69, 4.69, 4.81	4.68 ± .06
1803-14	Alk	5.5	5.21, 5.27	5.24 ± .03
1804-19	Alk	5.2	5.10, 5.16	5.13 ± .03
1802-4B	Alk	5.0	5.13, 5.22	5.18 ± .04

Analyst E. Ito.
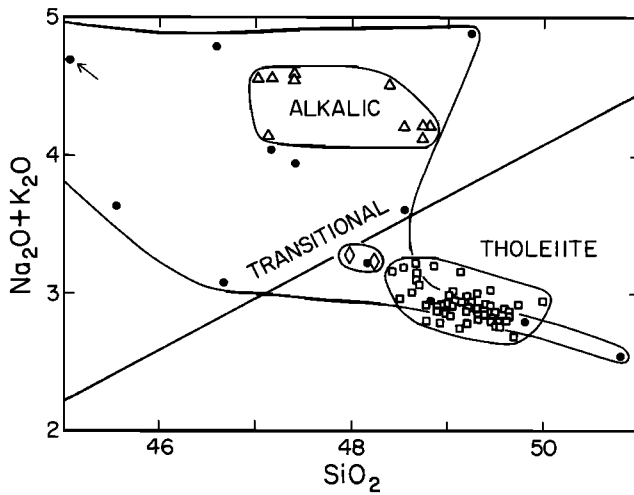
Fig. 4. SiO$_2$ versus total alkalis (all in weight percent) for Loihi glasses. Previous glass data from Loihi [*Moore et al.*, 1982] are shown by the solid dots. The *Alvin*-collected suite of samples is subdivided into three rock types based on the classification scheme of *Moore et al.* [1982]: tholeiitic (squares); transitional (diamonds); and alkalic basalts (triangles). The heavy diagonal line separates the tholeiitic and alkalic fields [from *Macdonald*, 1968].

The REE patterns for Loihi glasses are generally smooth and parallel (Figure 8). They are similar to those of typical Hawaiian lavas (e.g., the U.S. Geological Survey Hawaiian basalt standard, BHVO-1) and those previously published for Loihi whole rock samples [*Frey and Clague*, 1983]. REE patterns for the Loihi tholeiite glasses form a tight group with crossing patterns, especially in the middle to heavy REE range (Figure 8). The glasses with the lowest middle REE abundances have slightly positive Eu anomalies. This has also been noted for some lavas with low REE abundances from Kilauea [*Hofmann et al.*, 1984] and Lanai [*West et al.*, 1992] volcanoes. The anomalies are greatest for Lanai lavas, which are an isotopic end-member for Hawaiian tholeiites [*West et al.*, 1987]. Thus this feature may be characteristic of one of the source components for Hawaiian magmas.

The Loihi alkalic glasses have similar patterns to the tholeiites, but they have higher REE concentrations (Figure 8) and somewhat steeper patterns (La/Yb ratios of about 9 to 11 versus 6 to 8 for the tholeiites; Figure 7). Sample 1804-19, from a young hydrothermally active cone, has a flatter pattern than the other alkalic lavas (Figure 8). Although these lavas are fractionated (i.e., MgO contents of 5.0-5.5 wt %), none have negative Eu anomalies, which is consistent with the absence of plagioclase phenocrysts in these lavas. However, the young alkalic lavas from the Pele's Vents area (a prominent topographic high at the southern end of the summit area; samples 1804-16 to 1804-19) define a nearly perpendicular branch to the overall negative trend on the MgO versus Al$_2$O$_3$ plot (Figure 5), so some plagioclase fractionation must have occurred. This interpretation is supported by (1) their lower Sr/Ce ratio relative to the other alkalic lavas (7 versus 10); and (2) least squares crystal, fractionation calculations which indicate that the fractionation assemblage for these lavas is dominated by plagioclase (48%, with 40% cpx and 12% olivine; $\Sigma R^2 = 0.04$).

Sr, Nd, AND Pb ISOTOPE RATIOS

Eight summit area glasses (five tholeiitic, two alkalic, one transitional) were analyzed for Pb, Sr, and Nd isotopic ratios

(Table 3). The overall ranges of Nd and Sr isotopic values for these samples are restricted; $^{87}Sr/^{86}Sr$ varies between 0.70353 and 0.70361, and the total spread in ϵ_{Nd} is only 1.0 (+6.7 to +5.7; Figure 9a). Both the lowest and highest ratios are for tholeiites. These values define a small field within the much larger array for dredge haul samples from Loihi, although the four dredge haul samples from the summit area analyzed by *Staudigel et al.* [1984] have the same limited Sr isotope range but a somewhat larger range in Nd isotopes. For a different group of dredged samples, *Tatsumoto et al.* [1987] reported a larger spread in $^{87}Sr/^{86}Sr$ ratios (0.70344 to 0.70376) but a relatively narrow range for Nd isotope data (+5.1 to +6.6).

In contrast to our Sr and Nd isotopic data, our Pb isotopic results span as wide a range in $^{206}Pb/^{204}Pb$ ratio (18.25-18.47) as that previously reported for the entire volcano (Figures 9b and 9c). Our Pb isotope data exhibit linear trends with positive slopes, unlike previous results which have a larger analytical uncertainty. There is no correlation of Pb isotopes with Sr or Nd isotopic ratios nor of rock type with any isotopic ratio, as was noted in earlier studies [*Staudigel et al.*, 1984; *Tatsumoto et*
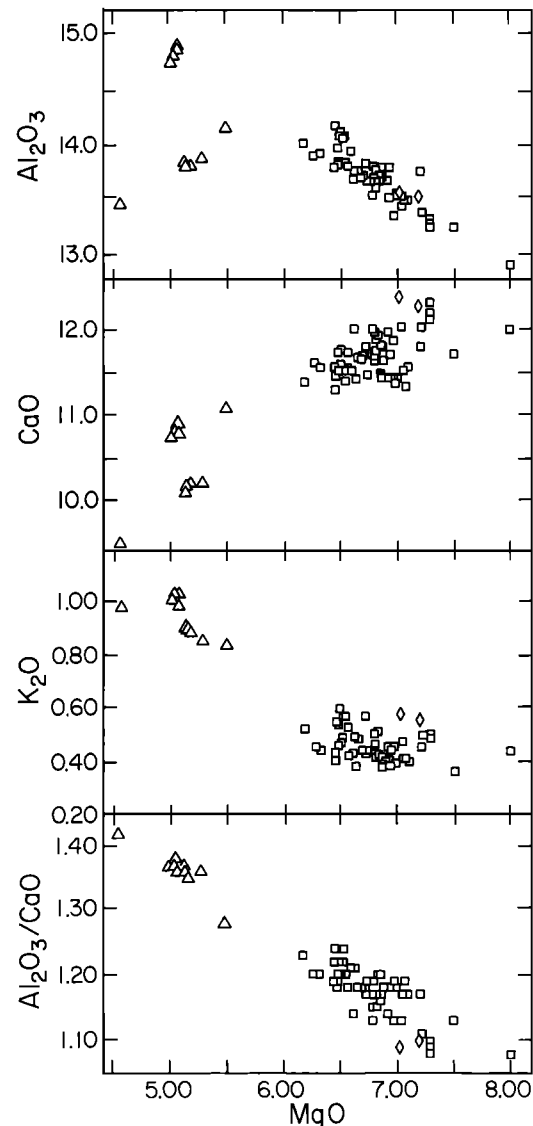

Fig. 5. MgO variation diagrams for major elements in the *Alvin* suite of glasses from Loihi. Note the two distinct groups of alkalic lavas on the Al$_2$O$_3$ and CaO panels. Symbols as in Figure 4. All values in weight percent.
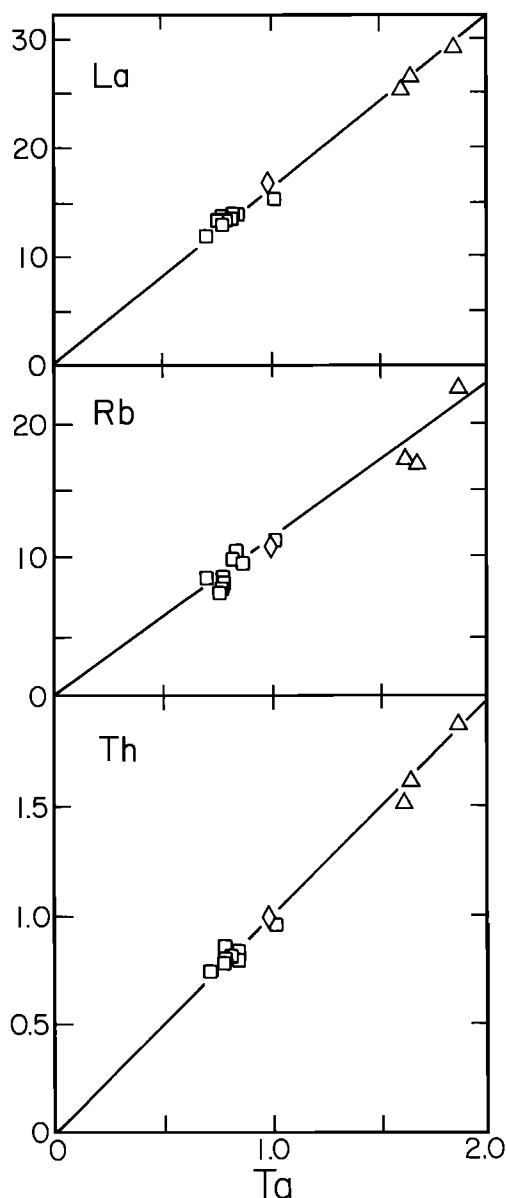
inverse correlation with MgO (Table 5). However, the three evolved alkalic glasses are the controlling factor in this trend. There is no correlation of MgO with $\delta^{18}O$ for the tholeiites despite the large range in MgO (1.8 wt %). The glasses with MgO contents >6.5 wt % (i.e., those with little or no clinopyroxene or plagioclase fractionation) can be subdivided into two groups based on their oxygen isotope and FeO/CaO ratios (Figure 10). There is no apparent correlation of oxygen isotope with the other isotopic ratios, except perhaps with $^{206}Pb/^{204}Pb$ for the high FeO/CaO samples (i.e., >0.96, Figure 10). Uncontaminated basalts from the Cameroon Line also have some low $\delta^{18}O$ values (4.5 to 5.5°/oo) and exhibit poor correlations of O with Pb, Sr, and Nd isotope ratios [*Halliday et al.*, 1988].

TEMPORAL EVOLUTION OF LOIHI LAVAS

There is no systematic compositional variation in Loihi's summit lavas; alkalic and tholeiitic lavas are coeval. For example, the most hydrothermally active area on Loihi, Pele's Vents [*Karl et al.*, 1988], is composed of evolved alkalic lavas that overlie adjacent tholeiites. Another young alkalic lava was found on the eastern flank of the summit (1803-14). The oldest lava sampled (1802-1, which is identical to 1802-4B) is from near the base of the western pit crater and is also alkalic. Tholeiites dominate most of the summit platform and the pit crater sections of Loihi. Thus, although alkalic lavas are not common in the summit area, their eruptions clearly are closely related in time and space to those of the tholeiitic lavas. If the summit area is the region of most recent volcanism on Loihi [*Fornari et al.*, 1988] and its earliest volcanism was alkalic [*Moore et al.*, 1982], then Loihi may be in a transitional growth period between early alkalic volcanism and later tholeiitic volcanism [*Moore et al.*, 1982]. The rarity of tholeiites on the flanks of Loihi [*Jorgenson et al.*, 1988] is strong circumstantial evidence that only the summit area has experienced this transitional stage of volcanism. However, it must be emphasized that the evidence for an early phase of alkalic volcanism is equivocal. Although some alkalic lavas have thicker palagonite rims, this may be a result of their higher vesicularity and alkali content. The results of our stratigraphically controlled study do not support the early alkalic volcanism hypothesis, but we have examined only about 10-15% of Loihi's summit section.

Fig. 6. Variation diagrams for highly incompatible trace elements: Ta versus Rb, Th, and La in Loihi glasses. Note the good linear correlations that project through the origin. Symbols as in Figure 4. All data are in ppm and are from Table 3 (ICP-MS).

al., 1987]. Compared to tholeiitic lavas from other Hawaiian shield volcanoes, Loihi's tholeiites have some of the lowest Sr and highest Nd and Pb isotope ratios (Figure 9). Only Kilauea lavas have higher $^{206}Pb/^{204}Pb$ ratios, although new Pb isotope data for older Kilauea lavas [*Chen et al.*, 1991] overlap with the Loihi field. The trend of our $^{207}Pb/^{204}Pb$ data is at a 35° angle to the overall field for Hawaiian tholeiites (Figure 9b). This feature has also been noted for shield and postshield lavas from other Hawaiian volcanoes [e.g., *Kennedy et al.*, 1991]. *Kennedy et al.* [1991] suggested that this component could not be from oceanic lithosphere and must be a minor plume component.

OXYGEN ISOTOPE RATIOS

Thirteen samples were analyzed for oxygen isotopes, including the eight samples analyzed for Pb, Sr, and Nd isotopes and the most fractionated tholeiitic sample (1801-4). The $\delta^{18}O$ values range from +4.7 to 5.2°/oo and exhibit a rough
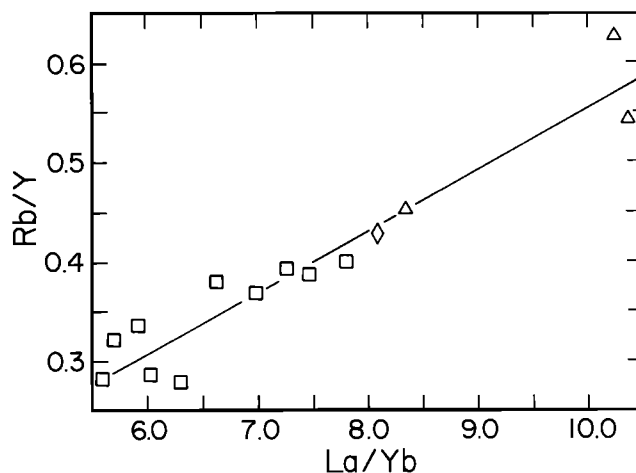

Fig. 7. La/Yb ratio versus Rb/Y ratios for Loihi glasses. Note good linear correlation. Symbols as in Figure 4. All data in ppm.
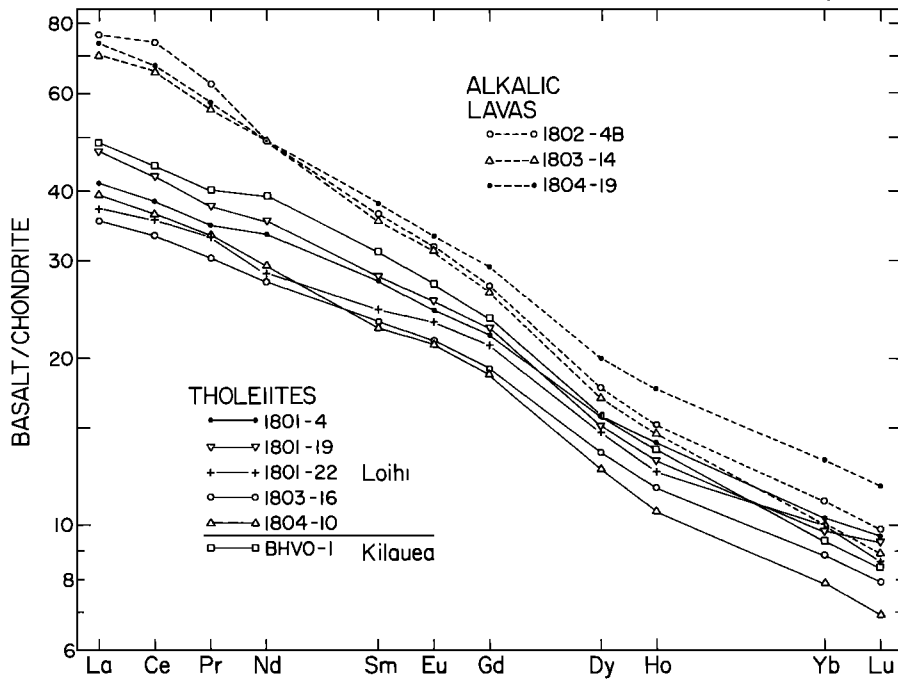
Fig. 8. Chondrite-normalized (C1 chondrite values of *Boynton* [1984]), rare earth element plot of Loihi glasses and U.S. Geological Survey Hawaiian basalt standard from Kilauea Volcano, BHVO-1. Data are from Table 2 for all elements except Ce and Pr (Table 3). The pattern for BHVO-1 is based on our analyses. The patterns for the alkalic glasses are dashed; the patterns for the tholeiitic samples are solid lines. Note the crossing patterns for these isotopically similar tholeiitic samples, including BHVO-1.

The presence of large pit craters at the summit of Loihi indicates that magma bodies have underlain the summit area. However, the intercalated nature of its tholeiitic and alkalic lavas are strong circumstantial evidence that Loihi's magma chamber(s) are ephemeral. Perhaps this is a result of the relatively low magma supply rate for Loihi (compared to other Hawaiian shield volcanoes) [*Frey et al.*, 1990]. Similar features are observed among the lavas from the postshield stage of Hawaiian volcanism, which is characterized by relatively low magma supply rates [*Frey et al.*, 1990]. In contrast, mature Hawaiian volcanoes produce relatively homogeneous lava
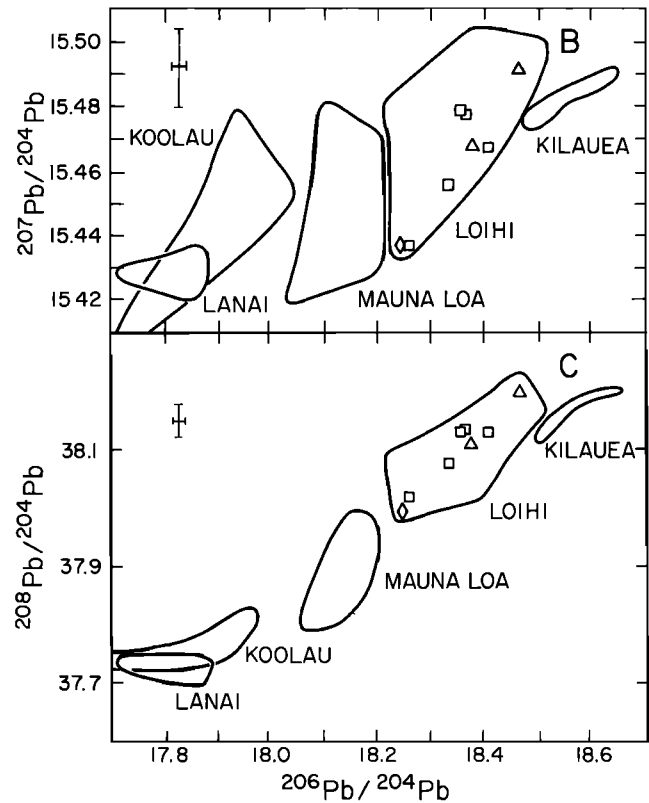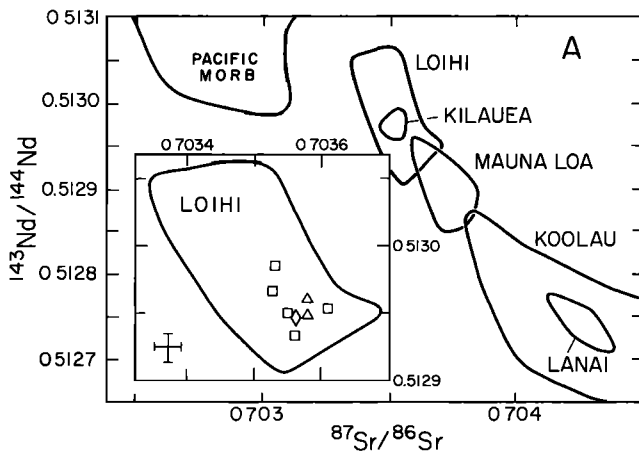
Fig. 9. Sr, Nd, and Pb isotopic ratios in Loihi glasses. Symbols as in Figure 4. The Loihi field is for dredge haul samples [*Staudigel et al.*, 1984]. The inset in Figure 9a shows the range of Sr and Nd isotope ratios in the Alvin suite of samples. The cross represents the total range obtained in the University of Hawaii isotope lab for the La Jolla Nd, NBS 987 Sr, and NBS 981 Pb standards, which is greater than the two-sigma analytical error for our analyses. Fields for some other Hawaiian shield volcanoes are also shown [from *West et al.*, 1987; *Kurz and Kammer*, 1991].

Fig. 9. (continued)

compositions over time. For example, Mauna Loa has erupted tholeiitic lavas with remarkably similar compositions at a given MgO content over the last 30,000 years [*Rhodes*, 1987]. This feature and the generally homogeneous composition of lavas from a single eruption (i.e., they lie on an olivine control line)
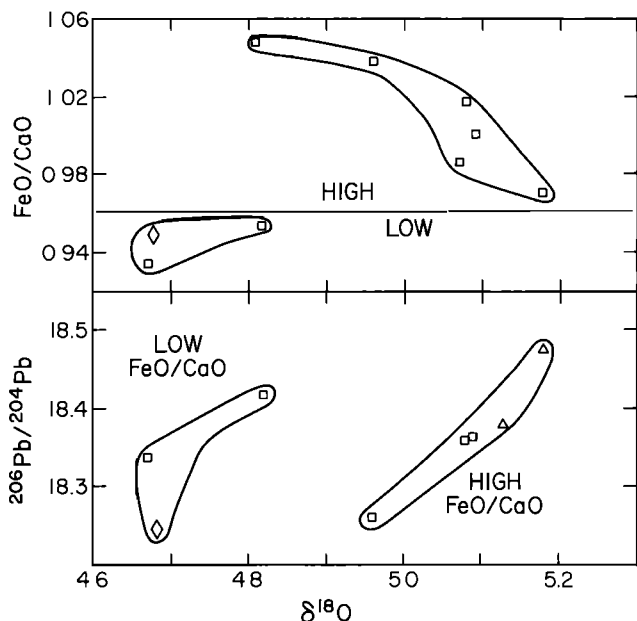
Fig. 10. Oxygen isotope ratio variation (°/oo) versus FeO/CaO ratio and $^{206}Pb/^{204}Pb$ ratio in Loihi glasses. The FeO/CaO ratios are subdivided into high (>0.96) and low fields. Symbols as in Figure 4.

ORIGIN OF LOIHI'S ALKALIC AND THOLEIITIC MAGMAS

The coeval relationship of alkalic and tholeiitic lavas on Loihi is analogous to the postshield stage on some Hawaiian volcanoes (e.g., Mauna Kea Volcano) [see Frey et al., 1990]. In both cases, the tholeiitic and alkalic lavas are isotopically indistinguishable and they have nearly identical primitive-mantle-normalized patterns (Figure 12) [Frey et al., 1991]. Thus the alkalic and tholeiitic lavas from each volcano were probably derived from the same source. Two possible explanations for coeval tholeiitic and alkalic magmas are (1) formation of evolved alkalic magmas by high-pressure fractionation of clinopyroxene from the tholeiitic magma and (2) different degrees of partial melting. Although all of the alkalic glasses that we collected in this study are evolved (<6 wt % MgO), more mafic (8-10 wt % MgO) alkalic glasses have been recovered from Loihi [Moore et al., 1982; D. Foss, unpublished data, 1992]. Thus distinct alkalic parental magmas are produced at Loihi. Furthermore, Loihi's tholeiitic and alkalic lavas have different incompatible trace element ratios (Figure 7) [see also Frey and Clague, 1983] that are not affected by moderate amounts of fractionation but are affected by varying degrees of partial melting. The alkalic lavas consistently have higher ratios of highly incompatible over moderately incompatible elements than the tholeiites (see Figure 7). This

have led to the hypothesis that Mauna Loa has a long-lived shallow summit reservoir [Rhodes, 1987].

Among Loihi tholeiites, there is substantial compositional variation (Figures 4-8). These variations cannot be related to magma mixing or crystal fractionation because these glasses have wide ranges of ratios that are insensitive to these processes in olivine-only magmas (e.g., La/Yb, Nb/Zr, K_2O/TiO_2). Within the well-sampled east pit crater section, there are large but systematic variations in ratios of highly to moderately incompatible major and trace elements (Figure 11) but not of highly incompatible trace elements (e.g., La/Ce - 0.435 to 0.441). Thus the compositional variation among Loihi tholeiites may reflect changes in the degree of partial melting rather than changes in the source components.

EAST PIT CRATER

Fig. 11. Variation in ratios of La/Yb and K_2O/TiO_2 versus stratigraphic height (in meters below sea level) for glasses from Loihi dive 1801. Only the more mafic glasses are plotted (>6.7 wt % MgO) to minimize the effects of fractionation of phases other than olivine.
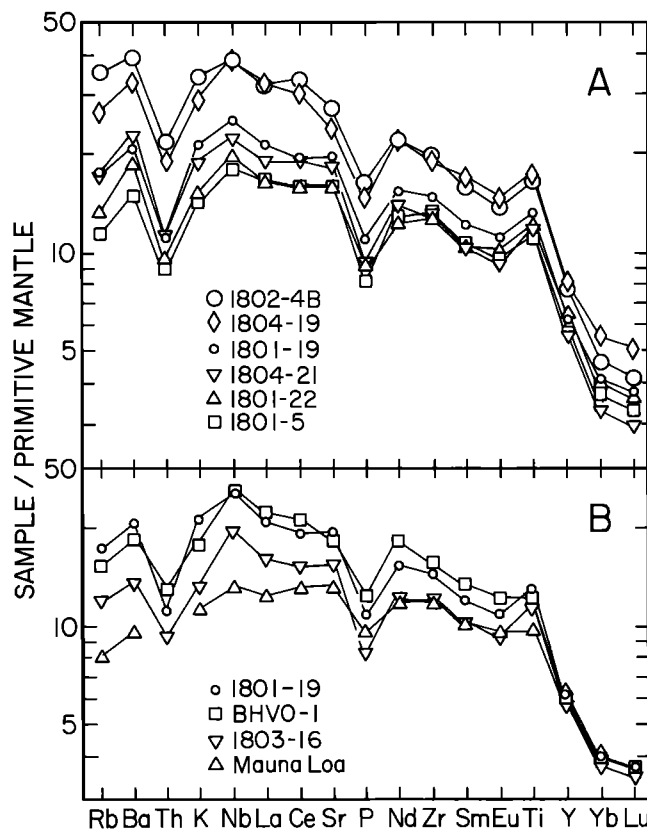

Fig. 12. Primitive-mantle-normalized diagrams. Primitive mantle values are from Sun and McDonough [1989]. Data for Loihi and BHVO-1 taken from Tables 1-3 (using the values obtained in this study for BHVO-1). REE and Ba values are from Table 2. Data for the Mauna Loa sample is from Gurriet [1988] for sample ML1-7. (a) Loihi tholeiitic and alkalic glasses. (b) Comparison of two Loihi tholeiites that define the range of variation for Loihi tholeiites from the Alvin suite of samples, with tholeiites from adjacent volcanoes (Mauna Loa and Kilauea). All of the samples have similar MgO contents and $^{87}Sr/^{86}Sr$ ratios (0.70360 ± 5). Note the consistently low values for Th and P and high value for Ti; these are common features for all Hawaiian shield lavas.

and the overall similarity of trace element patterns (REE, Figure 8, and primitive-mantle-normalized, Figure 12) and O, Pb, Sr and Nd isotope ratios (Figure 9) of the Loihi tholeiitic and alkalic lavas are best explained by variable degree of partial melting of a common source.

IMPLICATIONS FOR SOURCE PROCESSES AND COMPOSITION

The relative degree of partial melting represented by Loihi lavas, compared to other Hawaiian tholeiites, can be inferred using the experimental results of *Falloon and Green* [1988] and trace element ratios of isotopically similar lavas. Because Hawaiian tholeiites are produced by melting in the garnet stability field [e.g., *Frey and Roden*, 1987], pressure is not an important variable in controlling magma composition. Therefore the low SiO_2 and high FeO contents of Loihi glasses relative to other Hawaiian tholeiites indicate a lower degree of partial melting for Loihi, assuming their sources are similar in composition.

Kilauea's historical lavas are isotopically similar to Loihi lavas (see Figure 9 and *Chen et al.* [1991]). On a primitive-mantle-normalized diagram (Figure 12), a typical Kilauea tholeiite, BHVO-1 (which has essentially the same MgO content as the Loihi glasses, ~7 wt %), has somewhat higher incompatible trace element values than all but one of our Loihi tholeiites (sample 1801-19 and only its Rb, Ba, and K values are greater than those for BHVO-1). However, BHVO-1 has higher SiO_2 and lower FeO contents (at the same MgO content) but similar trace element ratios to Loihi tholeiites. Thus Loihi lavas may have formed by similar to somewhat lower degrees of partial melting than Kilauea lavas. In contrast, an isotopically similar tholeiite from Mauna Loa, ML1-7 [*Gurriet*, 1988], has a distinctly lower FeO content and highly incompatible element abundances (Rb to Sr on Figure 12) and higher SiO_2 content than Loihi tholeiites, indicating that it represents a higher degree of partial melting. These inferences are consistent with simple melting models for Hawaiian volcanoes [e.g., *Frey et al.*, 1990].

The light REE-enriched and crossing REE patterns of Loihi tholeiites (Figure 9) are consistent with variable degrees of melting of a garnet-bearing source [*Frey and Clague*, 1983]. The variable Sc/Yb (13 to 19) ratio of the olivine-only tholeiites is indicative of variable amounts of clinopyroxene or variable garnet/clinopyroxene ratio in the source. Loihi lavas are also characterized by high $^3He/^4He$ ratios [*Kurz et al.*, 1983] and volatile contents [*Garcia et al.*, 1989]. Thus the source for Loihi lavas is probably a relatively undepleted garnet lherzolite.

Isotopic data indicate that lavas from Hawaiian shield volcanoes contain two dominant source components [e.g., *West et al.*, 1987]. Loihi and Kilauea lavas are the best examples of one of the components (Figure 10). Their major and trace element contents and O, He, Pb, Sr and Nd isotope ratios define end-members on plots of data for Hawaiian shields. Within this end-member there is significant compositional variation which cannot be attributed to magmatic processes. Our new Loihi data define linear trends on incompatible trace element ratio-ratio and Pb isotope ratio plots (Figures 7 and 9). This requires at least two components in the source for Loihi's lavas. Does the ratio of these components change during the evolution of Hawaiian volcanoes? Unfortunately, the lavas from this transitional stage are buried by several kilometers of later lavas on older Hawaiian volcanoes. Furthermore, these volcanoes rapidly subside before subaerial erosion can expose the transitional lavas. Thus we do not know whether the older Hawaiian volcanoes have Loihi-like lavas. If they do, then Hawaiian volcanoes would have a temporal variation in

composition reflecting a change in the proportions of source components. The early lavas, such as those from Loihi, would have a high $^3He/^4He$ ratio that would reflect a less depleted source. This source might be the "plume" component for Hawaiian shield lavas that becomes diluted with another source component during the growth of each volcano. Alternatively, both components may be present within the plume, with the Loihi component possibly having a lower melting temperature.

A LOW $\delta^{18}O$ MANTLE RESERVOIR

Our new oxygen isotope data for Loihi are distinctly low (average $\delta^{18}O$ = 4.9 ± 0.2‰ excluding the evolved alkalic glasses) compared to the assumed oxygen isotopic composition of the mantle (5.7 + 0.2‰ [*Javoy et al.*, 1986]). Previous studies of Hawaiian tholeiites also have found low values for submarine glasses [*Kyser et al.*, 1982] (average 5.4 ± 0.3), [*Garcia et al.*, 1989] (5.1 ± 0.3, including an average value of 5.0 for three Loihi basalts). These low values are probably not related to assimilation of altered crust because *Garcia et al.* [1989] found no correlation of $\delta^{18}O$ with δD for Hawaiian pillow rim glasses and the δD values they measured (-88 to -61 for the suite of tholeiitic glasses; -84 to -69 for Loihi) are representative of mantle values (-80 to -50) [*Garcia et al.*, 1989].

There is a growing $\delta^{18}O$ data base for oceanic island volcanoes indicating that the lavas from these volcanoes have lower values than MORB (e.g., Tenerife: 5.1 to 5.7, average 5.27) [*Javoy et al.*, 1986] (Ascension: 5.2 to 5.4) [*Weis et al.*, 1987] (Cameroons: 4.6 to 5.9, average 5.4) [*Halliday et al.*, 1988] (versus 5.7 to 6.2 for MORB) [*Ito et al.*, 1987]. Why do these oceanic island lavas have low $\delta^{18}O$ values? Kyser [1986] proposed that Hawaiian basalts are mixtures of primitive mantle with very low $\delta^{18}O$ values (4.0 to 4.6) and the incompatible-element depleted, MORB source mantle. There is no independent confirmation of such a low $\delta^{18}O$ mantle from mantle xenolith studies. Alternatively, the sublithospheric mantle (i.e., beneath the MORB source) may have more intermediate oxygen isotope values (4.9-5.5). Similar values have been reported for high-temperature, "primary" continental peridotite xenoliths and have been interpreted as representative of the deeper, more primitive mantle [e.g., *Harmon et al.*, 1986]. The high $^3He/^4He$ ratios in Loihi glasses have been used to infer a relatively primitive source for Loihi [*Kurz et al.*, 1983]. Thus the low $\delta^{18}O$ values observed in many oceanic island basalts (4.9-5.4) may be indicative of a deeper, more primitive source than tapped during MORB volcanism.

Among Hawaiian volcanoes, the younger volcanoes have consistently lower $\delta^{18}O$ ratios (Loihi, 4.7 to 5.2 for basalts; Kilauea, 4.9 to 5.1), whereas the older volcanoes have higher values (up to 5.5 for Mauna Loa, 5.3 for Mauna Kea and 5.5 for Hualalai) [*Garcia et al.*, 1989]. A similar but opposite trend is observed for $^3He/^4He$ ratios [*Kurz et al.*, 1983; *Kurz and Kammer*, 1991]. The higher $\delta^{18}O$ values for some tholeiitic glasses from the older volcanoes may represent a progressive variation in the proportion of the source components during the growth of Hawaiian volcanoes [*Garcia et al.*, 1989]. Our new data confirm that Loihi, the youngest Hawaiian volcano, represents an end-member in this variation. Thus low $\delta^{18}O$ values in Hawaiian tholeiites may be inherited from the Hawaiian hotspot source and representative of hotspot sources in general.

CONCLUDING REMARKS

With our eight new Pb, Sr, and Nd isotopic ratios and 13 O isotope values for stratigraphically controlled samples (in

addition to the He, Sr, Nd, and Pb isotope ratios for 15 dredged samples [*Staudigel et al.*, 1984] from widely scattered locations on the volcano), Loihi is arguably the isotopically best characterized Hawaiian shield volcano (even without the unpublished values of *Tatsumoto et al.* [1987]). However, it should be emphasized that this data set is only representative of the outer shell of Loihi and that most of its history (85%) is unknown.

It is ironic that the well-exposed and easily accessible subaerial Hawaiian shield volcanoes are not better characterized isotopically, especially Kilauea, with only four samples with published Pb, Sr, and Nd isotopic ratios. Additional isotopic analyses will probably increase the overlap between fields for tholeiitic lavas from the three active shield volcanoes, Loihi, Kilauea, and Mauna Loa. However, understanding of the isotopic and geochemical variability within the Hawaiian plume is hampered by the limited exposed portion (10% or less) of the erupted sequence of any subaerial Hawaiian volcano.

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