Submarine Picritic Basalts from Ko`olau Volcano, Hawai`i: Implications for Parental Magma Compositions and Mantle Source

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Previous studies of Ko‘olau Volcano subaerial basalts have invoked melting of recycled oceanic crust (garnet pyroxenite) as a mantle source to explain the unusually high SiO_2 (53-55 wt.%), moderate MgO (6-8 wt.%) and low olivine contents (<5 vol.%) of these lavas. To evaluate whether such usual lavas form the bulk of Ko‘olau Volcano, we sampled for the first time the dissected flanks of this volcano and the landslide blocks derived from Ko‘olau and the volcanoes on the neighboring island of Molokai using the SHINKAI 6500 submersible, the remotely operated vehicle (ROV) KAIKO and dredging. Olivine-rich basalts (>10 vol.%) with high MgO contents (14 to 31.5 wt.%) are abundant among submarine Ko‘olau lavas. Many of these picritic lavas have accumulated olivine, including xenocrysts with one or more subgrain boundaries. However, euhedral, undeformed olivine with forsterite contents of 88-90% and normal zoning is the dominant crystal type in these Ko‘olau submarine basalts. Olivine CaO contents are moderate (0.16-0.27 wt%) and NiO contents are generally high (up to 0.60 wt%) compared to olivines from other Hawaiian volcanoes. These results indicate that subaerial Ko‘olau exposures give a biased sampling of the volcano and that the olivines in these submarine lavas grew at crustal depths in parental magmas with MgO contents of at least 14-15 wt.%. Thus, they were primarily derived from melting peridotite, like other Hawaiian tholeiitic magmas. The wide range in olivine CaO contents indicates that there is a much greater range in Ko‘olau parental magma compositions than observed for subaerial lavas.

1. INTRODUCTION

Subaerial lavas from Ko‘olau volcano are compositionally distinct among Hawaiian lavas in all aspects of their geochemistry [major element, trace elements and isotopes; e.g., Roden et al., 1984; 1994; Frey et al., 1994; Hauri, 1996; Takeguchi and Takahashi, in review]. They typically have lower olivine abundances (<5 vol.%) and MgO concentrations (6-8 wt%) and higher silica (53-55 wt%) than tholeiitic lavas from other Hawaiian shield volcanoes [e.g., Jackson et al., 1999]. The high silica concentration in Ko‘olau basalts has been difficult to explain by crustal processes such as higher degrees of fractionation because Ko‘olau lavas typically have lower concentrations of incompatible elements [Norman and Garcia, 1999]. Alternatively, it has been proposed that the mantle plume source for Ko‘olau magmas contains a mafic component derived from recycled oceanic crust [eclogite; Hauri, 1996]. Estimates for the proportion of this component in the source for Ko‘olau lavas have been as high as 100% [Takeguchi and Takahashi, in review].

Our understanding of Ko‘olau volcano has been based entirely on collections of subaerial exposures. At many

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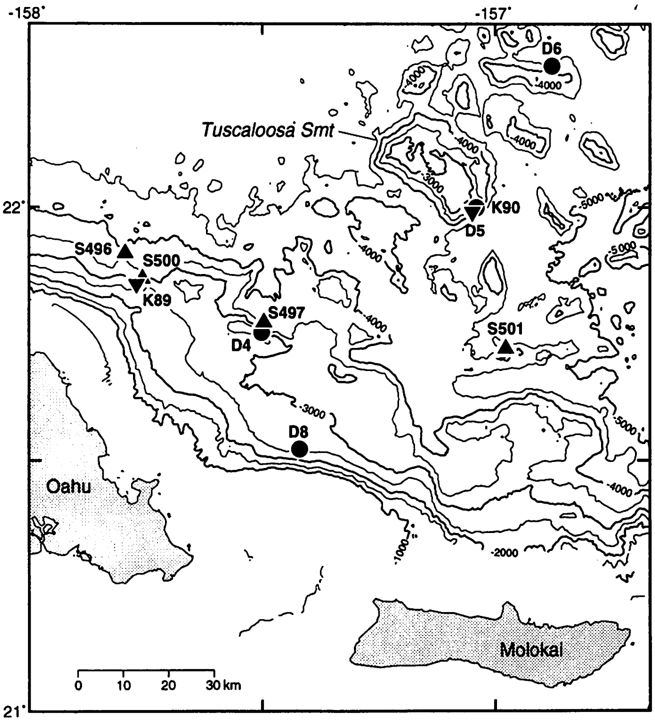

Figure 1. Bathymetric map of the area northward of the islands of Oahu and Molokai showing Nuuanu and Wailua landslide blocks and the locations where samples for this study were collected. Solid triangles show Shinkai 6500 submersible dive locations, and solid stars indicate ROV Kaiko dives and dredgehaul locations. Bathymetry for this map was obtained during the JAMSTEC 1998 and 1999 cruises in Hawai'i [Smith and Satake, this volume]. Contour interval is 500 m.

other Hawaiian volcanoes it has been shown that the subaerial lavas are less MgO-rich than those on the submarine flanks of these volcanoes [e.g, Garcia et al., 1989]. It has been proposed that these volcanoes have an internal density filter that allows lower density, differentiated magmas to erupted subaerially from a shallow, summit magma chamber and higher density, olivine-rich magmas to be intruded into the rift zones and erupted primarily offshore [Ryan, 1987]. One of the objectives of this study was to determine whether a density filter has operated within Ko'olau volcano. If so, previous studies presented a biased perspective of this volcano. In addition, it was anticipated that cold water temperature (~0°C) would allow the submarine rocks to avoid the intense tropical weathering that characterizes Ko'olau subaerial outcrops [e.g., Frey et al. 1994]. Marine expeditions were undertaken in 1998 and 1999 to sample for the first time the submarine flanks of Ko'olau and the landslide blocks derived from this volcano and those from the neighboring island of Molokai using the JAMSTEC deep submergence vehicles KAIKO and SHINKAI 6500, and dredging methods (Fig. 1). Whole-rock geochemical analyses (major and trace elements, and Sr, Nd and Pb isotope analyses) are given for many of these sample in the papers in this volume by Shinozaki et al. [2001] and Tanaka et al. [2001].

Our results show that olivine-rich basalts (>10 vol.%) are abundant among the submarine lavas recovered from Ko'olau Volcano in contrast to their rarity in subaerial exposures. The olivine crystals in these submarine rocks vary from euhedral, undeformed phenocrysts to strongly deformed xenocrysts. The forsterite content of both types of olivines range from 78-90% forsterite but most are 88-90%. There is no correlation of olivine composition with crystal morphology. CaO contents of all olivines are moderate (~0.16-0.27 wt%) indicating they grew at crustal depths. NiO contents of these olivines range widely (0.20-0.60 wt%) and they correlate with forsterite content. These results suggest there is a wide range in composition for Ko'olau parental magmas and that many of these magmas had MgO contents >14 wt.%, as have been found for other Hawaiian shield volcanoes. Thus, Ko'olau magmas were probably derived at least in large part from melting peridotite.

2. SAMPLES AND PETROGRAPHY

The olivine-rich lavas (>10 vol.% olivine) used in this study were obtained from the submarine flanks of Ko'olau volcano during SHINKAI 6500 submersible dives 496, 497 and 500 (SHINKAI samples are labeled with a 'S' prefix), KAIKO ROV dive 89 (KAIKO samples are labeled with a 'K' prefix), and dredgehaul 4 (dredged samples are labeled with a 'D' prefix). Olivine-rich lavas were obtained from landslide blocks adjacent to Molokai volcanoes during SHINKAI dive 501 and dredgehaul 8. The giant landslide block Tuscaloosa (~40 km long; Fig. 1) yielded olivine-rich lavas during KAIKO dive 90 and dredgehaul 5. An unnamed distal landslide block yielded olivine-rich lavas in dredgehaul 6 (Fig. 1). This block and Tuscaloosa Seamount were probably derived from Ko`olau volcano [Yokose, this volume].

All of the submarine rocks have a coating of Mn oxide on at least one surface. The Ko`olau samples typically have a thicker Mn-coating than those from Molokai volcanoes (1-5 mm vs. <1 mm). Beneath this coating, many of the submarine lavas appear to be remarkably unaltered. They contain fresh olivine and glass (Table 1). Others have variable degrees of olivine iddingization. Samples labeled as weakly altered in Table 1 have only thin rims (<0.005 mm thick) of iddingsite on olivines; those labeled as moderately altered have thicker rims (0.005-0.025 mm) and iddingsite

Table 1. Petrography of picritic lavas from Koolau and Molokai volcanoes

Sample	Rock MgO wt%	Max. pheno Fo%	Olivine			Cpx	Opx	Plag	Opaque	Gmass	Vesicles	Alteration
			pheno	xeno	mph	mph	mph	mph	mph			
Koolau												
S496-3	-	89.2	9.2	10.4	7.2	-	-	-	-	73.2	0.8	weak
S497-2	21.2	89.7	12.6	15.2	4.2	<0.1	<0.1	-	-	68.0	9.6	moderate
S497-6	23.5	89.7	26.8	5.2	6.0	-	-	-	-	62.0	13.6	moderate
S497-9	-	85.4	25.0	4.4	2.6	-	0.6	-	1.2	66.2	1.6	moderate
S500-1	14.8	90.1	17.2	3.4	0.6	0.4^{X}	-	-	<0.1	78.8	<0.1	weak
S500-2B	30.6	89.3	35.8	7.8	5.8	3.2	<0.1	1.8	0.4	45.0	<0.1	moderate
S500-5B	22.5	90.3	22.8	6.2	2.6	-	-	-	<0.1	68.4	2.0	weak
S500-6	23.2	90.0	20.4	8.8	1.6	$<0.1^{X}$	-	-	<0.1	69.2	2.0	weak
K89-2	14.9	90.3	13.0	4.2	1.8	-	0.6	-	0.2	80.2	5.6	none
K89-4	18.6	89.5	13.4	21.0	3.0	-	-	-	<0.1	62.6	2.6	none
K89-5	18.6	90.1	13.6	11.2	4.0	0.4^{X}	-	-	<0.1	70.8	5.0	none
K89-6	15.9	90.3	14.0	11.6	1.4	$<0.1^{X}$	$<0.1^{X}$	$<0.1^{X}$	<0.1	72.8	3.2	none
D4-7	25.4	89.1	17.8	23.0	6.6	-	-	-	<0.1	52.6	6.0	none
D4-8	10.4	88.6	9.0	<0.1	3.0	<0.1	-	<0.1	-	88.0	22.8	none
Tuscaloosa												
K90-1	17.4	84.4	10.6	3.4	6.8	-	-	-	-	79.2	12.6	weak
D5-13	-	89.2	13.6	6.8	8.4	-	-	-	<0.1	71.2	33.6	weak
D5-16	14.7	90.0	14.2	5.0	9.8	-	-	<0.1	<0.1	71.0	2.4	none
Molokai												
S501-2	28.0	89.5	26.6	19.2	2.2	-	-	-	0.4	51.6	5.0	weak
S501-7	22.6	89.5	9.4	20.6	5.2	-	-	-	<0.1	64.8	0.4	weak
D8-1^{P}	15.5	88.5	6.8	11.2	0.6	8.8	-	5.6	<0.1	67.0	0.8	weak
D8-4	-	89.0	17.6	15.4	6.4	-	-	-	<0.1	60.6	1.6	none
Other block												
D6-1	16.6	88.8	8.6	12.0	2.2	0.2	-	<0.1	-	77.0	1.4	weak

Mineralogy and vesicularity (vesicles) values are in volume percent based on 500 point counts per sample with the mineralogy adjusted to be vesicle-free. Phenocrysts (pheno) are >1.0 mm; microphenocrysts (mph) <1.0 mm; xenocrysts (xeno) have one or more dislocation planes or are strongly resorbed. Cpx- clinopyroxene, Opx-orthopyroxene; Plag- plagioclase; Gmass- groundmass. Alteration level is based on petrographic observations; none - no signs of a alteration; weak - thin iddingsite rims on olivine; moderate - thicker iddingsite rims, alteration along fractures and matrix may be stained. ^{P} Mode includes 3.4 vol.% cpx phenocrysts and 1.4 vol.% plagioclase phenocrysts. ^{X} xenocrysts of pyroxene or plagioclase. Whole-rock MgO data from Shinozaki et al. (this volume).

along fractures. The vast bulk of the olivine in all samples is unaltered.

Olivine is the dominant mineral in the samples examined ranging in abundance from 12 to 49 vol.% (Table 1). The population of olivine crystals was subdivided into phenocrysts (>1 mm wide with euhedral to subhedral shape), xenocrysts (>1 mm wide with at least one subgrain boundary or resorbed margins), and euhedral microphenocrysts (0.1-1.0 mm wide). Many of the phenocrysts and microphenocrysts contain glass inclusions indicating that they grew in a magma. Most of the olivine xenocrysts are only weakly deformed (1-3 subgrain boundaries with only slight shifts in their extinction angles; 1-5°). However, some olivine crystals are strongly deformed with multiple kink bands with extinction offsets >10°, iron-oxide decorated dislocations forming cellular textures, abundant minute gas inclusions and anhedral shape. Olivine xenocrysts are generally more abundant in the Molokai lavas than those from Ko'olau and Tuscaloosa.

Microphenocrysts or xenocrysts (large crystals with resorbed margins) of plagioclase, clinopyroxene and/or orthopyroxene are present in some of the submarine Ko'olau and Molokai rocks but these minerals are usually rare (<1 vol.%; Table 1). Rare xenoliths of dunite and gabbro were observed in some of the lavas. Vesicularity is generally quite low in all of the samples. Only 4 of 22 samples have >10 vol.% and most have <5 vol.% vesicles (Table 1). None of the Molokai samples examined have >5 vol.%

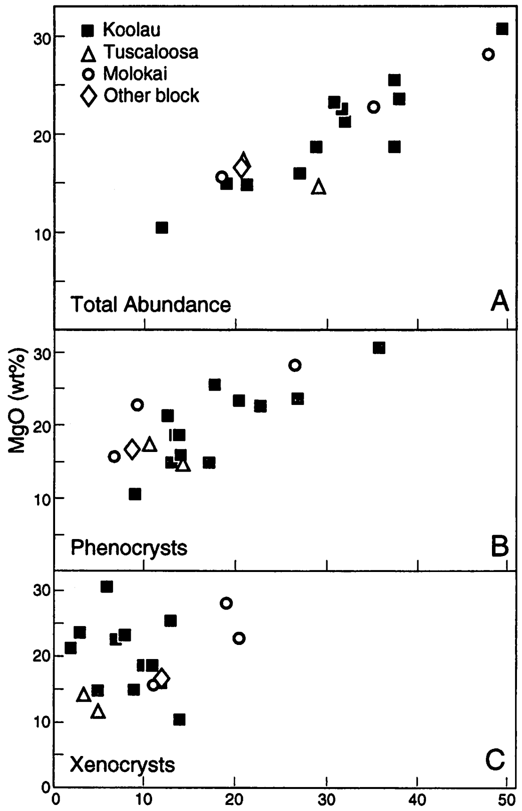

Figure 2. Plots of olivine abundance in basalts from Ko'olau, Molokai, Tuscaloosa and an unnamed landslide block (data from Table 1) versus whole-rock MgO content (in weight percent; data from Shinozaki et al., this volume). A. Total olivine abundance (phenocrysts, microphenocrysts, and xenocrysts); B. phenocryst abundance; and C. xenocryst abundance. Note the good correlation of whole-rock MgO content with total olivine abundance. The two sigma errors for MgO are smaller than the size of the symbols; for the modes, the errors are about twice the size of the symbols for abundances <10 vol. % and 3-4 times the symbol sized for mineral abundances of 20-40 vol.% based on counting statistics.

vesicles. Subaerial Hawaiian lavas typically have higher vesicularity [>10 vol.%; Hawai'i Scientific Drilling Project, 2000] and submarine lavas generally have lower vesicularity (<10 vol.% for lavas erupted in 1 km or more of water; Moore, 1965]. Two of the three lavas from Tuscaloosa Seamount have vesicularities >10 vol.% (Table 1) indicating a possible subaerial or shallow submarine origin for these rocks.

The MgO contents of the Ko'olau and Molokai submarine olivine-rich rocks used in this study range from 14.7 to 30.6 wt% (except sample D4-8 with 10.4 wt%, which also has the lowest olivine content; Table 1). All of the other lavas qualify as picritic basalts [Le Bas, 2000]. There is a good positive correlation for whole-rock MgO content and total olivine content (phenocrysts, xenocrysts and microphenocrysts) for these lavas, and with olivine phenocryst abundance but not with xenocryst abundance (Fig. 2).

3. MICROPROBE METHODS

Olivine and spinel compositions were determined using the University of Hawai'i, five-spectrometer, Cameca SX-50 electron microprobe with SAMx automation. Operating conditions were a minimum spot size (~1 micron), 15 kV and 20 nA beam current. Counting time on the peak for each element was 60 s; background counting time was 30 s. Mineral standards from the Smithsonian collection (San Carlos olivine for Si and Mg, Natural Bridge Diopside for Ca, Minas Gerais Magnetite for Fe [Jareosewich et al., 1979]) and a synthetic NiO were used for the calibration and San Carlos olivine was used as an internal control to check instrument drift and reproducibility for olivine. For spinel, Smithsonian standards (chromite for Cr, San Carlos Olivine for Mg, ilmenite for Fe and Ti) and synthetic jadeite for Al were used; the chromite standard was used as an internal control. Two-sigma precision based on counting statistics is <1% for the major elements and 5-10% for minor elements (CaO and NiO in olivine and TiO_2 in spinel). A PAP-ZAF matrix correction was applied to all analyses. The analyses reported here are all an average of at least 3 spots in the core of each crystal. Detailed zoning profiles (5-micron steps near the margin, 20-40 micron steps in the core) were made for selected euhedral olivine phenocrysts.

4. MINERAL COMPOSITIONS

4.1 Olivine

Compositions were determined for 715 olivine crystals from 22 submarine Ko'olau and Molokai picritic basalts to evaluate their magmatic history. About 470 of these analyses are for Ko'olau lavas making this the most comprehensive study of olivine from any Hawaiian volcano. For each rock at least 30 crystals were analyzed including representatives of each crystal type. Representative olivine core analyses are given in Table 2. A complete data set is provided on the CD with this volume. The weight percent totals for these analyses vary from 99.1 to 100.5 wt%, with the vast majority between 99.3-100.1 wt%. The cation totals range from 2.989 to 3.013 based on 4 oxygens; most of the totals are between 2.994-3.004. These parameters are good indicators of the overall high quality of these data.

Olivine core compositions of Ko'olau picritic basalts range from 78.4-90.4% forsterite (Fo); olivines from the

Table 2. Representative analyses of olivine cores from Koolau submarine olivine-rich basalts

xtal	SiO_2	FeO	NiO	MgO	CaO	Sum	Fo%	xtal	SiO_2	FeO	NiO	MgO	CaO	Sum	Fo%
	S496-3								S500-1						
p	41.00	10.43	0.44	48.26	0.22	100.35	89.2	p	40.65	9.62	0.58	49.05	0.16	100.06	90.1
p	40.36	10.66	0.44	48.31	0.23	100.00	89.0	p	39.93	12.61	0.42	46.74	0.20	99.89	86.9
p	40.27	13.12	0.38	46.06	0.22	100.05	86.2	p	39.78	14.91	0.26	44.79	0.19	99.93	84.3
d	40.84	11.00	0.44	47.96	0.24	100.47	88.6	d	40.63	9.91	0.52	48.89	0.18	100.13	89.8
r	40.60	10.86	0.40	48.02	0.22	100.09	88.7	d	40.05	12.48	0.42	46.72	0.19	99.86	87.0
m	40.67	10.64	0.43	48.22	0.22	100.19	89.0	m	40.09	12.34	0.36	47.10	0.17	100.06	87.2
	S497-2								S500-2B						
p	40.79	10.00	0.49	48.65	0.23	100.17	89.7	p	40.61	10.33	0.40	48.41	0.27	100.03	89.3
p	39.65	15.12	0.35	44.39	0.22	99.72	83.9	p	40.56	10.63	0.42	48.13	0.26	100.00	89.0
d	40.45	9.91	0.44	48.76	0.23	99.78	89.8	p	40.03	12.28	0.41	47.09	0.26	100.06	87.2
d	39.87	13.75	0.41	45.60	0.24	99.87	85.5	p	39.55	14.62	0.30	44.77	0.26	99.49	84.5
r	40.65	10.98	0.45	47.94	0.22	100.23	88.6	d	40.39	10.42	0.41	48.32	0.23	99.77	89.2
m	40.23	12.56	0.36	46.57	0.22	99.96	86.9	d	39.68	14.92	0.35	44.50	0.23	99.67	84.2
	S497-6								S500-5B						
p	40.40	9.94	0.50	48.46	0.18	99.48	89.7	p-1	40.65	9.36	0.58	49.00	0.18	99.76	90.3
p	40.54	10.26	0.47	48.18	0.19	99.64	89.3	p-2	40.51	9.73	0.53	48.78	0.18	99.73	89.9
p	40.54	10.51	0.47	47.99	0.21	99.72	89.1	p-3	40.55	10.13	0.52	48.65	0.18	100.02	89.5
p	39.76	14.26	0.35	45.04	0.26	99.68	84.9	p	40.29	11.87	0.32	47.19	0.19	99.86	87.6
p	39.64	15.21	0.41	44.24	0.18	99.69	83.8	d	40.48	9.92	0.51	48.62	0.19	99.71	89.7
d	40.12	13.71	0.36	45.53	0.20	99.91	85.5	m	40.41	10.80	0.49	47.94	0.16	99.81	88.8
	S497-9								S500-6						
p	39.74	13.83	0.43	45.50	0.20	99.70	85.4	p-1	40.74	9.72	0.56	48.90	0.17	100.10	90.0
p	39.61	15.18	0.41	44.44	0.21	99.85	83.9	p-2	40.72	9.94	0.48	48.74	0.19	100.08	89.7
p	39.08	17.66	0.37	42.25	0.19	99.55	81.0	p-3	40.63	10.58	0.44	48.34	0.19	100.19	89.1
p	38.67	19.70	0.38	40.61	0.21	99.57	78.6	d	40.56	9.69	0.54	48.85	0.20	99.84	90.0
d	39.26	16.14	0.45	43.49	0.19	99.54	82.8	d	38.90	19.04	0.34	41.18	0.19	99.65	79.4
d	39.31	17.71	0.40	41.99	0.20	99.61	80.9	m	40.37	10.93	0.51	47.44	0.20	99.44	88.6
	D4-7								K89-02						
p-1	40.37	10.61	0.40	48.43	0.20	100.01	89.1	p	41.01	9.34	0.60	48.72	0.17	99.84	90.3
p-2	40.25	11.34	0.37	48.04	0.22	100.22	88.3	p	41.03	9.42	0.56	48.64	0.19	99.84	90.2
p-3	40.05	12.01	0.34	47.55	0.23	100.18	87.6	p	40.43	11.82	0.50	46.82	0.17	99.74	87.6
d	40.29	10.57	0.37	48.41	0.21	99.85	89.1	d	40.54	10.77	0.40	47.94	0.17	99.83	88.8
m	40.39	10.70	0.37	48.59	0.23	100.28	89.0	r	39.46	16.16	0.33	43.40	0.22	99.57	82.7
	D4-8								K89-04						
p	40.75	10.95	0.46	47.60	0.22	99.99	88.6	p-1	40.40	10.60	0.43	48.53	0.21	100.17	89.1
p	40.64	11.20	0.47	47.16	0.18	99.65	88.2	p-2	40.31	11.31	0.44	48.08	0.20	100.34	88.3
p	40.25	11.90	0.42	47.16	0.20	99.94	87.6	p-3	39.86	13.31	0.31	46.22	0.22	99.93	86.1
p	39.69	15.27	0.33	44.21	0.22	99.73	83.8	d	39.16	17.63	0.21	42.90	0.24	100.14	81.3
m	39.95	15.17	0.31	43.21	0.22	98.86	83.5	r	39.27	16.39	0.30	43.90	0.24	100.10	82.7
	K89-5								K89-06						
p	40.72	9.55	0.51	48.72	0.19	99.70	90.1	p	40.96	9.42	0.58	49.04	0.19	100.20	90.3
p	40.56	9.86	0.53	48.68	0.18	99.81	89.8	p	40.96	9.54	0.53	49.08	0.18	100.29	90.2
p	39.72	15.31	0.33	44.12	0.20	99.68	83.7	p	40.17	11.92	0.48	47.12	0.19	99.88	87.6
d	40.81	10.07	0.47	48.44	0.19	99.97	89.6	p	39.81	14.48	0.29	44.81	0.20	99.59	84.6
d	40.34	10.32	0.47	48.29	0.18	99.59	89.3	d	40.70	10.43	0.41	48.18	0.18	99.90	89.2
d	40.02	15.00	0.29	44.61	0.22	100.13	84.1	r	40.12	11.67	0.36	47.17	0.19	99.51	87.8

xtal-crystal; p-phenocrysts; d-deformed xenocryst; r-resorbed xenocryst; m-microphenocryst; Fo%-forsterite percent

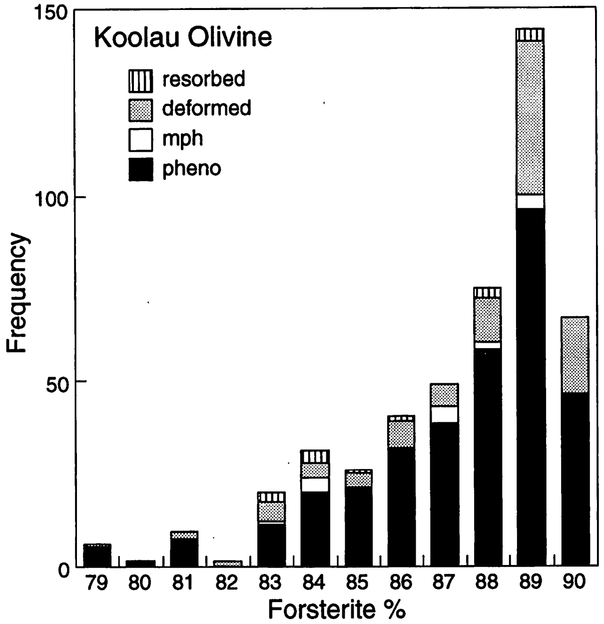

Figure 3. Histogram of forsterite percent in the cores of ~470 olivine phenocrysts, microphenocrysts, deformed xenocrysts, and resorbed but undeformed xenocrysts from a suite of 14 Ko'olau submarine olivine-rich basalts. Most of these olivines have forsterite contents of 88-90%. Xenocrysts have nearly the same distribution as phenocrysts. Resorbed crystals and microphenocrysts have bimodal distributions, which may be a function of too few analyzed crystals. Some of the microphenocrysts have relatively high forsterite contents (87-89%) indicating that they grew in moderately high MgO content magmas (12-14 wt%).

Molokai lavas range from 79.9 to 89.9% Fo. For Tuscaloosa Seamount, olivine varies in composition from 82.7-90.0% Fo and those from the other landslide block range from 82.4 to 89.2% Fo. These ranges for Ko'olau and Molokai olivine composition are typical of tholeiitic lavas from Hawaiian volcanoes [e.g., Clague et al., 1995; Garcia et al., 1995; Garcia, 1996]. Most of the Ko'olau olivines are Fo 88-90% (Fig. 3), which is similar to but slightly less forsteritic than some of the olivines from Mauna Loa submarine basalts (up to 91.3%, the highest reported for Hawaiian basalts; Garcia et al., 1995) but somewhat more forsteritic than most olivines from the Mauna Loa and Mauna Kea picritic lavas obtained by the Hawai'i Scientific Drilling Project [HSDP, 86-88%; Garcia 1996] and those from the east rift zone of Kilauea [Clague and Denlinger, 1994]. Some of the low Fo values may be an artifact of not cutting the probe sections through the core of the analyzed crystals [Pearce, 1984], which is also indicated by the skewed forsterite distribution (Fig. 3).

There is no systematic difference in forsterite content with crystal type in the submarine Ko'olau lavas (Fig. 3). The abundance of phenocrysts and deformed xenocrysts are greatest at 88-90% Fo and decrease markedly at lower forsterite contents, especially for phenocrysts. Similar results were reported for submarine picritic lavas from Kilauea and Mauna Loa [Clague and Denlinger, 1994; Garcia et al., 1995] and for subaerial HSDP picritic lavas [Garcia, 1996]. A bimodal distribution was observed for resorbed

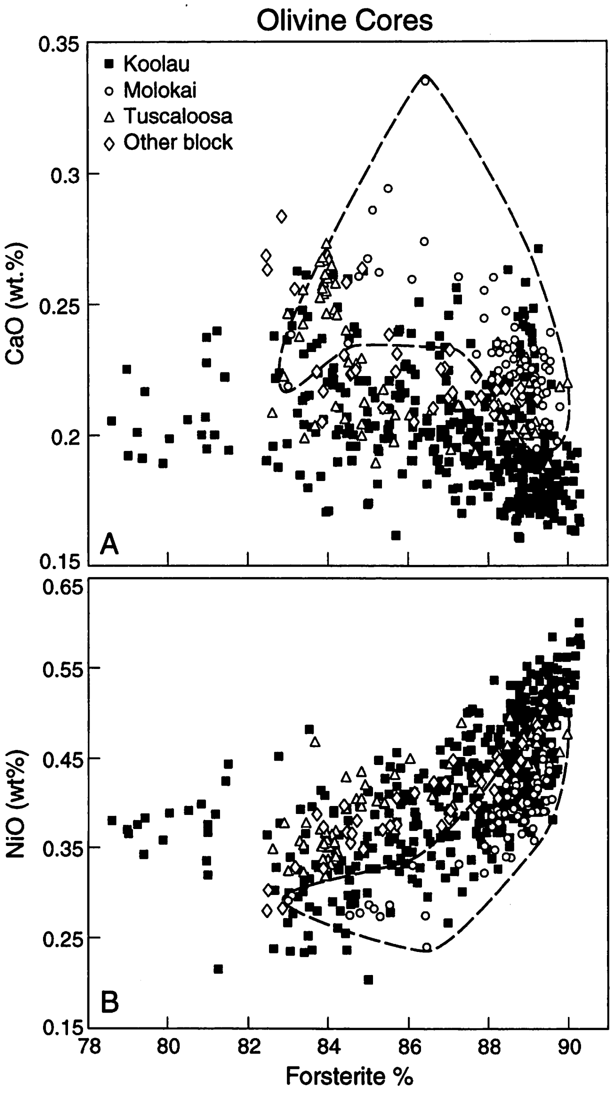

Figure 4. CaO and NiO concentrations versus forsterite percent in the core of olivines from Ko'olau, Molokai, Tuscaloosa and an unnamed landslide block basalts. The olivines from Molokai basalts (enclosed in field) tend to have higher CaO and lower Ni concentrations at a given forsterite value than olivines from Ko'olau basalts. Two sigma errors are about the size of the symbol for forsterite and 0.02 to 0.03 wt% for NiO and CaO.

but undeformed xenocrysts and microphenocrysts in the Ko'olau submarine lavas (83-84, 87-89%; Fig. 3) but this may be an artifact of too few data. It is important to note that four Ko'olau submarine lavas have euhedral microphenocrysts with high Fo contents (89%), indicating that these crystallized in relatively MgO-rich magmas (>13 wt%). For individual lavas, phenocrysts and deformed xenocrysts have similar large ranges in Fo content. The Fo content of undeformed xenocrysts is clearly lower than most phenocrysts in some lavas but not in others. Thus, the source of the resorbed xenocrysts and the composition of the magmas they entered were varied.

CaO contents of all of the olivines are moderate (0.16-27 wt%) and show a broad negative correlation with forsterite content (Fig. 4). The olivines from Ko'olau lavas generally have lower CaO contents than those from Molokai lavas. The olivines from the slide blocks overlap with both fields in CaO content. Previous studies of olivine in Hawaiian picritic basalts found a good correlation between CaO content in whole rock and olivine [Norman and Garcia, 1999], which agrees with experimental work [Libourel, 1999]. Thus, the wide range in Ko'olau olivine CaO content at a given forsterite value (Fig. 4) probably indicates a wide spectrum of Ko'olau parental magma CaO contents in contrast to observations for subaerial Ko'olau lavas [e.g., Frey et al., 1994]. The moderate level of CaO in the Ko'olau olivines indicates that they grew at crustal depths [e.g., Stormer, 1973; Larsen and Pedersen, 2000]. The broad negative trend of CaO with forsterite content in Ko'olau, Molokai and Tuscaloosa olivines agrees with experimental crystallization results [Jurewicz and Watson, 1988] suggesting that these olivines are magmatic and not mantle derived.

NiO contents in Ko'olau olivines range widely (0.20-0.60 wt%) compared to those from Molokai lavas (0.24-0.53 wt%; Fig. 4) and are higher than those reported for olivines from other Hawaiian shield volcanoes. Also, Ko'olau olivines tend to have higher NiO contents at a given forsterite content then those from Molokai (Fig. 4). The broad curved trend of Ni vs. forsterite content for Ko'olau olivine is thought to be indicative of crystal fractionation [e.g., Nakamura, 1995].

Detailed zoning profiles were made of selected euhedral, undeformed high forsterite (88-90%) phenocrysts from Ko'olau submarine picrites. All of these crystals are normally zoned. Some have classic crystal fractionation-produced profiles [c.f., Pearce, 1984]; other crystals have flat profiles from the core to within 50 to 200 microns from the rim. The crystals with flat core profiles re-equilibrated with the host magma prior to eruption. Thus, they probably had even higher forsterite contents prior to re-equilibration.

Table 3. Representative spinel analyses in Koolau submarine olivine-rich basalts

sample	TiO_2	Al_2O_3	Cr_2O_3	FeO*	MgO*	sum
K89-04						
p-1	0.96	13.00	48.51	24.30	11.32	98.09
p-2	1.15	13.61	46.31	25.76	10.97	97.80
p-3	1.71	15.46	41.21	28.12	11.13	97.63
matrix	1.15	13.14	47.43	26.06	10.52	98.30
S500-5B						
p-1	0.86	16.15	47.51	19.45	14.21	98.18
p-3	0.77	13.99	50.15	19.08	14.15	98.15
p-4	1.02	14.65	47.60	21.90	13.08	98.25
matrix	0.82	14.10	50.41	18.96	14.46	98.75
S500-6						
p-2	0.95	15.56	48.70	19.18	14.20	98.59
p-3	0.92	14.24	48.41	21.17	13.21	97.96
p-4	3.49	13.18	29.86	37.94	11.08	95.54
matrix	1.03	12.82	47.86	25.27	10.70	97.67
D4-7						
p-1	1.61	15.73	44.60	22.00	13.72	97.66
p-2	1.08	14.45	46.93	22.41	13.14	98.01
p-3	1.32	16.45	43.85	22.91	13.32	97.85
matrix	1.19	14.83	45.15	24.19	12.54	97.90

Spinels p-1 to p-4 are inclusions in olivines; see Table 2 for host mineral compositions.

4.2 Spinel Compositions

Core compositions were determined for 96 spinel crystals that occurred as either inclusions in olivine phenocrysts or in the matrix of four submarine Ko'olau picritic basalts to evaluate their magmatic history. Representative analyses are given in Table 3 and a complete data set is provided on the CD with this volume. The recalculated weight percent totals (adjusted for ferric iron) for these analyses vary from 97.4 to 99.5 wt%, with the vast majority between 98.0-99.2 wt%. These totals indicate that there are minor amounts of other elements that were not analyzed.

The compositions of matrix spinels are remarkably similar to those for inclusions in olivine phenocrysts for the Ko'olau submarine basalts (Table 3). Both have relatively have Cr numbers [100(Cr/Cr + Al)], ranging from 72.0-83.6 for matrix crystals and 71.3-85.3 for inclusions. These are among the highest reported for Hawaiian tholeiites [e.g., Maaløe, S., and B. Hansen, 1982; Wilkinson and Hensel, 1988; Clague et al., 1995], which indicate that these spinels grew in relatively primitive melts. The TiO_2

contents of most of the Ko'olau spinels are rather low (<2 wt%, with many <1 wt%). Mg#s [(Mg/Mg + Fe^{2+})100] of the spinels range from 33.9 to 57.9 but most range from 41 to 53. The systematic compositional trends observed for the spinel data indicate rapid crystallization avoiding the effects of post-eruption re-equilibration.

5. DISCUSSION

5.1 Rock Type Variations: Subaerial vs. Submarine

Olivine-rich lavas are relatively rare among subaerial Ko'olau lavas. For example, only two of the ~100 lavas studied in the Makapuu section of southeast Ko'olau volcano [Frey et al., 1994] have olivine abundances >10 vol.% [Garcia, unpublished data]. In both cases, the high olivine concentrations are due to settling of olivine within moderately olivine-phyric lavas (5-10 vol.% olivine). Another stratigraphic study of Ko'olau lavas and dikes in a tunnel found only 1 of 24 samples with olivine abundances >10 vol.% [11 vol.%; Jackson et al., 1999]. In contrast, about half of the submarine Ko'olau lavas we collected have >10 vol.% olivine [Shinozaki et al., this volume). The high abundance of picritic basalts on the flanks of Hawaiian volcanoes is in striking contrast to their paucity in flood basalts sequences both on land [e.g., Deccan; Krishnamurthy et al., 2000] and at sea [Ontong Java; Neal et al., 1997]. Although the magma from flood basalts and Hawaiian lavas are both thought to be derived from mantle plumes, the magmatic plumbing systems for these volcanic systems must be quite different to explain why picritic basalts are so abundant on Hawaiian volcanoes.

Subaerial Ko'olau lavas typically have relatively low MgO contents (6-8 wt%) and only ~8% have MgO concentrations >10 wt% [Frey et al., 1994; Jackson et al., 1999]. Among these subaerial lavas, only ~2% have MgO >13 wt% and qualify as picrites [Le Bas, 2000]. For the suite of recovered submarine Ko'olau lavas, 19 of 42 lavas have MgO >13 wt% [Shinozaki et al., this volume] and all but one of the olivine-rich sample have MgO contents >13 wt% (Table 1). Thus, subaerial exposures provide a biased sampling of Ko'olau volcano rock types and a density filter must have operated within this volcano, as was noted for other Hawaiian volcanoes [e.g., Garcia et al., 1989]. The density of the olivine-rich Ko'olau magmas would have been high (2.80 to 2.95 g cm^{-3}) compared to magma densities for subaerially erupted, weakly olivine-phyric or aphyric basalts (~2.70 g cm^{-3}). These results support the model of Ryan [1987] that magma is preferentially erupted on Hawaiian volcanoes based on its density. According to this model, lower density magmas rise within the ediface and erupt from the summit to build the subaerial portion of the volcano, while denser, olivine-rich magmas are intruded into rift zones and erupted on the submarine flanks of the volcano.

5.2 Origin of Olivine-rich Ko'olau Lavas and Implications for Parental Magma Composition

Studies of picritic basalts from Hawai'i and elsewhere have successfully utilized olivine compositions to infer the compositions of parental magmas [e.g., Francis, 1985; Wilkinson and Hensel, 1988; Hansteen, 1991; Rhodes, 1995; Garcia, 1996; Fram and Lesher, 1997; Krishnamurthy et al., 2000]. Many of the Ko'olau submarine basalts contain euhedral, undeformed olivines with forsterite contents of 90% and all but one of the lavas in this study (S497-9) contain at least Fo 88% olivines (Table 1). These high forsterite olivines (88-90%), the most prevalent composition within these lavas (Fig. 3), probably grew in magmas with Mg#s of 69-73 (Fig. 5). Five of the 12 Ko'olau samples used in this study fall within this Mg# range. If we assume that 10% of the total iron is ferric (based on the oxidation state of rapidly quenched subaerial and submarine Hawaiian basalts; Moore and Ault, 1965; Byers et al., 1985], a Fe/Mg K_d of 0.30±0.03 (which is consistent with the crustal origin of the olivines; Ulmer, 1989) and equilibrium crystallization, then the high forsterite olivines (88-90.3%) grew in magmas with 14-15 wt.% MgO.

A minimum estimate of 14-15 wt% MgO content for some Ko'olau parental magma is consistent with the range of parental magma compositions that have been proposed for other Hawaiian tholeiitic volcanoes based on studies of picritic lavas (13-17 wt% MgO; e.g., Clague et al., 1995; Rhodes, 1995; Garcia et al., 1995] and with the high MgO glass sands found at the foot of Kilauea Volcano (up to 15 wt%; Clague et al., 1991]. Such high MgO magmas would have been in equilibrium with and were probably derived from a peridotitic mantle source [Maaløe and Hansen, 1982].

The proposed Ko'olau parental magma MgO minimum estimate is substantially lower than observed for many of the submarine Ko'olau lavas (21.2-30.6 wt.%; Table 2). Furthermore, the forsterite contents of the olivines in these lavas are too low to have been in equilibrium with the whole rock composition (Fig. 5). Therefore, these high MgO Ko'olau lavas must have accumulated olivine. This interpretation is supported by the good correlation of whole-rock MgO content for these lavas with total olivine abundance (Fig. 2). The good correlation of MgO with total phenocryst abundance in these lavas (but not with their xenocryst abundance) suggests that accumulation of phenocrystic olivine is the major cause of the high MgO content in some Ko'olau submarine lavas.

What is the origin of the xenocrystic olivines? There is a wide compositional range for xenocrysts in individual lavas (e.g., Fo 82-90% in sample K89-6; Fig. 5). Some of the low Fo values may be an artifact of the thin section not cutting the center of the crystal [e.g., Pearce, 1984] but it is unlikely that all of the low values are related to sectioning problems. The strongly deformed olivines have anhedral margins and rare, small dunitic xenoliths are present in some Ko'olau submarine lavas. Thus, it seems likely that the strongly deformed olivines in these submarine basalts were probably derived by disaggregating dunitic xenoliths. Partially digested dunitic xenoliths are also present in many of the HSDP tholeiitic lavas, which contain abundant strongly deformed olivine xenocrysts [Garcia, 1996]. The moderate CaO contents and forsterite compositions of the Ko'olau deformed olivines indicate that they were probably derived from deformed cumulates. This reasoning has also been applied to explain the presence of deformed olivines in the lavas from the 1959 Kilauea eruption [Helz, 1987]. The survival of dislocations in the deformed olivines gives an indication of how long these features might persist in a magma. Dislocations in olivines are reported to have survived for at least 22 years in the molten Kilauea Iki lava lake [Helz, 1987]. Thus, some of the deformed Ko'olau olivines may have been picked up by ascending magmas decades before they were erupted.

5.3. Origin of Tuscaloosa and the Other Landslide Block Based on Olivine Composition

The debris from the Nuuanu (Ko'olau) and Wailau (Molokai) landslides overlap each other [Moore et al., 1994], which has stymied efforts to reconstruct the size and history of these two landslides. Even the relative age of the two slides has been an open questioned [Moore et al., 1994]. The source volcano for some of the blocks from the two landslides remains ambiguous. For example, although Tuscaloosa Seamount is thought to have been derived from Ko'olau Volcano [e.g., Yokose, this volume], the origin of the block to the north of it (which was sampled by dredge-haul 6) is unknown. The orientation of this unnamed block is parallel to the island of Molokai but there are no other blocks of similar size and orientation near it (Fig. 1).

Olivine composition may be useful in determining the source of the landslide blocks. Norman and Garcia [1999] found that olivines from subaerial Ko'olau lavas have distinctly lower CaO contents than olivines from other Hawaiian shield volcanoes and they related this difference to the distinct composition of Ko'olau lavas. This result was confirmed here but the range of Ko'olau olivine CaO content is much greater than previously reported, which implies a greater range of Ko'olau magma composition than was observed in subaerial lavas. Thus, low CaO content remains a distinctive feature of some but not all Ko'olau olivines (Fig. 5). NiO content may also be of use in determining the source of these blocks. Ko'olau olivines appear to have somewhat higher NiO contents at a given forsterite content than olivines from other Hawaiian shield volcanoes, especially at Fo contents of 84-87% [Norman and Garcia, 1999; Fig. 4]. One problem with this analysis is that we have only a limited amount of data for Molokai volcanoes. Nonetheless, there are no reported analyses of Molokai lavas that are similar to the distinctive chemistry of subaerial Ko'olau lavas [Takeguchi and Takahashi, in review].

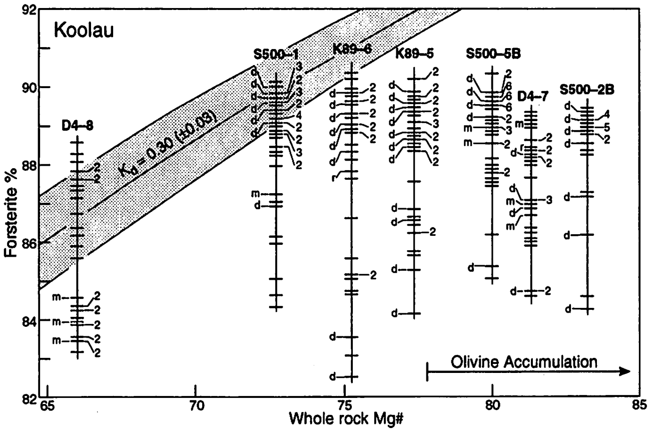

Figure 5. Plot of whole rock Mg# [(Mg/Mg + Fe^{2+}) 100], assuming 10% Fe^{3+}, versus forsterite percent in olivine cores from a suite of representative Ko'olau submarine basalts. The vertical lines represent individual flows and the horizontal lines represent olivine core compositions. Deformed xenocrysts are designated with a "d" at the end of the horizontal line, microphenocrysts by a "m" and resorbed but undeformed crystals by an "r". All other horizontal lines are for euhedral, undeformed phenocrysts. The numbers next to the lines refer to the number of analyzed crystals with that composition, with only one deformed, resorbed or microphenocryst shown for each line. There are wide variations in phenocryst and xenocryst compositions for most lavas but high forsterite content olivine crystals (88-90%) are dominate. Some of the olivines plot within the equilibrium field for their whole rock compositions for lavas with lower Mg# (<75). Olivines in rocks with higher Mg#s plot below the equilibrium field indicating that these rocks have probably accumulated olivine. The equilibrium field is based on a Fe/Mg partition coefficient for olivine/whole rock of 0.30 ±0.03 [Roeder and Emslie, 1970]. The arrow in the lower right corner shows the effect of olivine accumulation. The error bar is in the upper left corner is for 2 sigma.

Olivines in lavas recovered from the two landslide blocks have higher NiO contents for a given forsterite in the range of Fo 83-86 than those from Molokai but overlap the Molokai field at higher Fo values (Fig. 4). CaO contents in olivines from the two landslide blocks show the same relationships with generally lower values than those from Molokai lavas but with considerable overlap at high and low forsterite values (Fig. 4). These results are consistent with a Ko'olau source for these blocks, which has been proposed based on reconstruction of the blocks [Yokose et al., this volume], but the olivine data are not sufficient to prove a Ko'olau origin.

6. SUMMARY

Submarine Ko'olau lavas are petrographically and geochemically diverse. Unlike subaerial Ko'olau lavas, many are remarkably olivine-rich (up to 49 vol.%) and relatively weakly altered. Euhedral, undeformed olivines with forsterite contents of 88-90% are the most common composition within a suite of 14 submarine picritic Ko'olau basalts. These olivines probably grew in magmas with 14-15 wt% MgO. This minimum estimate for Ko'olau parental magma MgO content is consistent with studies of other Hawaiian shield volcanoes and indicates a peridotite source for at least some Ko'olau magmas. The wide range in olivine CaO contents indicates that there is a much greater range in Ko'olau parental magma compositions than has been observed for subaerial lavas from this volcano.

The high MgO content of some Ko'olau lavas (22-30.6 wt%) is a consequence of olivine phenocryst accumulation based on the good correlation of olivine phenocryst abundance with whole-rock MgO content. Thus, the high MgO contents of the Ko'olau submarine lavas are not an indication of primary magma compositions. The deformed olivine xenocrysts in the Ko'olau picritic basalts were probably derived from disaggregated deformed dunitic cumulates from Ko'olau magmas. This interpretation is supported by the presence of dunitic inclusions in a few of the olivine-rich lavas.

Acknowledgments. I would like to thank the captains and crew of the R/V Kairei and Yokosuka, and the dedicated shipboard science team, especially chief scientist Jiro Naka and co-chief E. Takahashi, for the opportunity to participate in the JAMSTEC Hawai'i cruises and for their collaboration during interpretation of cruise results. Sarah Sherman, Kelly Kolysko-Rose and Heidi Comer assisted with sample preparation and in creating the olivine database for this study, and John Smith provided the bathymetric map for Figure 1. This work was supported by National Science Foundation grant OCE-9729894. This is SOEST contribution no. 5576.

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