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Petrography and olivine and glass chemistry of lavas from the Hawaii Scientific Drilling Project

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Abstract. Many of the lavas from the Hawaii Scientific Drilling Project (HSDP) are olivine-rich (>10 vol %) and weakly altered. The Mauna Loa lavas from the upper part of the HSDP hole are more olivine-rich and generally have olivines with higher forsterite contents than the underlying Mauna Kea lavas. Olivine-rich lavas from these volcanoes contain both euhedral, undeformed phenocrysts and kink-banded xenocrysts of olivines, unlike what was assumed for typical subaerial Hawaiian tholeiites. The forsterite content of both types of olivine ranges widely (80-90%). Many of the HSDP lavas have olivines with forsterite contents of 89-90%, indicating that they grew in magmas with at least 15 wt % MgO. Most of these lavas contain even higher MgO contents (18 to 28 wt %), which are a result of accumulation of olivine phenocrysts and xenocrysts. The olivine xenocrysts in these lavas are inferred to be derived from disaggregation of deformed dunite cumulates, which are present in many of these lavas. Glasses from pahoehoe crusts on some of the HSDP flows have major element compositions that confirm the subdivision of the core based on whole rock compositions. The moderately evolved compositions of the HSDP glasses indicate quenching temperatures similar to those measured during the current Kilauea eruption.

Introduction

The Hawaii Scientific Drilling Project (HSDP) provides an excellent opportunity for detailed examination of the magmatic history of the upper part of two Hawaiian shield volcanoes. The project drilled a 1056-m hole into two overlapping volcanoes. The upper ~280 m of the hole penetrated 29 distinct Mauna Loa lava flows that are interbedded with sediments. The lower ~776 m of the hole recovered 184 Mauna Kea lava flows. Flows in both portions of the hole are interbedded with ashes, soils, and volcanic sands. Unlike previously cored holes in Hawaiian volcanoes, this hole was located outside of any known hydrothermal area to maximize the potential for recovering unaltered rock. The HSDP lavas offer the potential to provide fundamental insights into the geochemical evolution of Hawaiian volcanoes that are not available from studying the thinner and more weathered subaerial sections from these volcanoes (e.g., ~250 m thick Makapuu section from Koolau volcano [*Frey et al.*, 1994]; ~490 m thick Kalaupapa section on East Molokai volcano [*Beeson*, 1976]; and ~550 m thick section on Kahoolawe volcano [*Leeman et al.*, 1994]).

This paper presents an overview of the petrography of the core, the composition of its most abundant phenocryst (olivine), the composition of the glasses that form crusts on some of the pahoehoe flows, and the implications of these results for the petrogenesis of Hawaiian shield lavas. The petrographic results presented here confirm the core logging descriptions [*Hawaii Scientific Drilling Project*, 1994] that many of the HSDP lavas are strongly porphyritic (>10 vol % olivine) and demonstrate that deformed olivines are common in the HSDP lavas. The extent of olivine deformation in individual crystals varies from only one subgrain boundary to abundant kink bands. Some of the weakly deformed grains may be cognate but the strongly deformed grains must be xenocrysts. These xenocrysts probably were derived from the disaggregation of dunitic xenoliths, which are found in many of the HSDP lavas. The moderate CaO content of the xenocryst and xenolith olivines indicates that they were probably picked up by ascending magmas from the shallow cumulate pile within Mauna Loa and Mauna Kea volcanoes. Many of the olivine-rich lavas contain euhedral olivine phenocrysts with 89-90% forsterite (highest is 90.8%). These forsterite-rich olivines were derived from parental magmas with Mg # ((Mg/Mg + Fe^{2+}) 100) of at least 71 to 75 (MgO contents of at least 15 wt %). Unfortunately, the whole rock compositions for the olivine-rich HSDP lavas (especially those with Mg # > 75 and MgO contents >18 wt %) have been compromised by significant accumulation of phenocrysts and xenocrysts of variable compositions. Thus attempts to determine magma compositions for these olivine-rich HSDP lavas are problematic.

Petrography

The core from the HSDP hole was examined by a team of petrographers immediately following each day of drilling. The protocol used in the core descriptions is similar to that used by the Ocean Drilling Program and is included with hand specimen

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descriptions and core photographs in a core log book [*Hawaii Scientific Drilling Project*, 1994]. Subdivision of the core into flow units was simple where sediments (sand or ash) or soil separated the flows and where the flows are lithologically distinct. Contacts between many of the lithologically similar flows were recognized by the presence of red baked zones at the top of the underlying flow. Glassy flow surfaces or rubble zones between mineralogically similar flows without baked zones were judged, in most cases, to be internal contacts within one compound flow (e.g., unit 2 has three flows; the extreme case is unit 173 with 11 flows). Compound flows may have formed in a manner similar to the flow field being produced during the current Puu Oo eruption of Kilauea volcano (see *Mattox et al.*, [1993] for a description of the Puu Oo flow field).

Hand specimen modes were made during core logging using a transparent plastic grid with a ~4 mm spacing. A hand lens was used to count phenocrysts at grid intersections. At least 100 points were counted per flow unit for each core box. Some of the more porphyritic flows have considerable variation in olivine (e.g., 5 to 15 vol %; unit 174), which usually is concentrated in the lower part of the flow.

Two generalizations can be made about the HSDP lavas from the hand specimen descriptions: they are olivine-rich and are relatively unaltered. The average HSDP lava contains ~9 vol % olivine [*Hawaii Scientific Drilling Project*, 1994]. The Mauna Loa portion of the core has somewhat more olivine than the Mauna Kea portion of the core (10.7 versus 8.6 vol %) but there is considerable variation in both portions of the hole. The basal and upper portions of the Mauna Kea section (~65 and 70 m thick, consisting of 14 and 19 flows) are olivine poor (2.3 and 1.4 vol %). In contrast, a 41-m-thick section averages 26.5 vol % olivine (units 92 to 103). Individual Mauna Kea flows range from aphyric (<1 vol % phenocrysts of any mineral) to 32 vol % olivine (unit 64). The Mauna Loa section has a similar variation in olivine content, although one flow, unit 30, has ~37 vol % olivine.

The hand specimen observations were checked by examining 61 thin sections from 57 flows. The thin section modes used a lower threshold for phenocryst size than was practical for the hand specimen modes (0.5 versus ~1 mm). Thus the modes presented in Table 1 have somewhat higher total olivine contents (phenocryst + xenocryst) than those in the core log book. The thin section study led to the recognition of rare pyroxene phenocrysts in some HSDP lavas and allowed the identification of the microphenocryst assemblage (0.1-0.5 mm; Table 1). About 20% of the HSDP lavas have rare plagioclase and/or augite phenocrysts (<1 vol %). Only a few lavas have common plagioclase or augite phenocrysts (>1 vol %). About 50% of the lavas contain microphenocrysts of one or both of these minerals. Hypersthene microphenocrysts occur in about 40% of the Mauna Loa lavas examined but none were observed in the Mauna Kea lavas (Table 1). These observations are similar to previous descriptions of subaerial lavas from these volcanoes [*Macdonald*, 1949; *Lockwood and Lipman*, 1987; *Frey et al.*, 1991]. The plagioclase and pyroxene crystals are generally euhedral to subhedral with minor oscillatory or hourglass zoning (in augites), but a few are resorbed.

The HSDP lavas were classified using the terminology of *Macdonald* [1949] to allow comparison with his observations of rock type variation for Mauna Loa. Lavas with <3 vol % olivine phenocrysts are classified as basalts. Flows with 3-20 vol % olivine phenocrysts are called olivine basalts and those with >20 vol % olivine are picritic basalts. Two other rocks types are identified in Table 1: Plagioclase basalt, which contains >2 vol. % plagioclase and <1 vol % olivine phenocrysts, and porphyritic basalt, which contains phenocrysts of olivine, plagioclase, and augite. About 40% of the HSDP Mauna Loa flows are picritic in contrast to the lower estimates for olivine-rich historical (7-11%) and prehistoric (15-20%) Mauna Loa subaerial surface flows [*Macdonald*, 1949; *Lockwood and Lipman*, 1987] Only about 20% of the HSDP Mauna Kea flows are picritic. Picritic flows are rare on the subaerial surface of Mauna Kea [*Frey et al.*, 1990, 1991] but are abundant among the few flows that have been dredged from the submarine east rift zone of the volcano [*Garcia et al.*, 1989].

A major focus of the thin section examination was to determine whether the olivine phenocrysts in the HSDP lavas are undeformed euhedral crystals, in which case they may be phenocrysts (i.e., cognate), or deformed, in which case they are xenocrysts. *Helz* [1987] made the only broad search for kink-banded olivines in Hawaiian tholeiites (but only from Kilauea volcano). She found that such olivines are virtually absent from subaerial Kilauea lavas. Detailed studies of some olivine-rich Hawaiian tholeiites found only undeformed, euhedral olivine phenocrysts [e.g., *Nicholls and Stout*, 1988; *Garcia et al.*, 1995], although other studies have found abundant deformed olivine crystals in olivine-rich tholeiites [e.g., *Helz*, 1987; *Wilkinson and Hensel*, 1988].

Most of the porphyritic HSDP lavas contain common (2-10 vol %) to abundant (>10 vol %) deformed olivines with one or more dislocation surfaces (Table 1). Many of these olivines display obvious kink bands (Plate 1) which must have formed by solid state deformation [*Raleigh*, 1968]. These strongly deformed crystals belong to class 1 of *Helz* [1987]; they are irregular in outline, and their planar extinction discontinuities extend across the entire grain. Unlike the rocks studied by *Helz* [1987], the HSDP lavas also contain small olivines (<1 mm) with these features. Deformed olivine was subordinate in the 1959 Kilauea Iki eruption picritic lavas (<20% of total phenocrysts) in contrast to its abundance in the HSDP picritic lavas (>40% of total phenocrysts in most lavas, especially those from Mauna Loa; Table 1). Many of the kink-banded olivines have resorbed margins (Plate 1). Some of the weakly deformed grains (one or two faint dislocations) are euhedral and contain glass inclusions, although most have only spinel inclusions. Euhedral crystals (Plate 1), class 2 of *Helz* [1987], are also abundant in many of the HSDP lavas (Table 1). Undeformed, strongly resorbed crystals (class 3 crystals of *Helz*, [1987]) are very rare in the HSDP flows. A few HSDP lavas contain rare "decorated" crystals similar to those described by *Albarede and Tamagnan* [1988] from Reunion Island. Elongate crystals (rods in Table 1) are common in some of the HSDP Mauna Loa lavas (Plate 1 and Table 1). This type of crystal is thought to form by rapid quenching of mafic magma [*Donaldson*, 1976].

Many of the porphyritic HSDP lavas contain gabbroic and/or peridotitic xenoliths (Table 1). Such xenoliths were thought to be virtually absent in shield-building lavas [*Clague*, 1987] and to be of cumulate origin [*Jackson*, 1968]. Most of the HSDP xenoliths are small (0.5 to 3 cm across). The gabbroic xenoliths are usually equal mixtures of plagioclase and augite, although some contain plagioclase with olivine or, in very rare cases, just plagioclase. The peridotitic xenoliths are mainly dunites, but there are also rare wherlites and very rare clinopyroxenites. Most of the dunites, contain deformed (kinked), anhedral

Table 1. Petrography of Mauna Lavas From the Hawaii Scientific Drilling Project Hole

Unit	Depth, m	Rock Name	Mg #	Olivine				Plag		Augite		Opx	Opaques	Vesicu- larity	Glass	Alter- ation	K_2O/P_2O_5	Xeno- liths
				ph	xeno	Rods	mph	ph	mph	ph	mph	mph	mph					
									Mauna Loa									
11*	74.1	olivine basalt	69.0	8.0	4.6	-	1.8	-	<0.1	-	-	1.0	<0.1	3.8	A	none	1.7	G,P
13	94.5	picritic basalt	84.0	14.6	29.4	-	2.2	8.4	4.4	-	-	-	0.2	15.6	C	weak	1.5	P
14	104.9	picritic basalt	68.8	7.4	21.6	-	2.0	-	<0.1	<0.1	0.4	0.2	<0.1	7.4	C	strong	1.6	G,P
15b	117.7	olivine basalt	76.1	7.8	10.4	<0.1	1.2	-	-	-	1.4	4.0	0.2	1.6	R	mod.	1.5	G,P
15c*	129.3	picritic basalt	77.5	10.4	12.4	2.8	5.6	-	<0.1	-	<0.4	0.2	0.2	5.4	C	weak	1.4	G,P
16	136.9	picritic basalt	76.3	9.8	10.2	3.4	4.8	-	1.2	-	0.2	0.4	0.2	3.8	R	weak	1.4	P
17	147.9	olivine basalt	76.3	5.6	6.6	6.0	8.2	-	0.8	-	0.8	0.2	<0.1	2.2	R	mod.	1.4	P,G
19	156.1	basalt	62.2	0.6	0.4	-	2.8	-	0.2	-	0.2	-	-	13.4	C	mod.	0.9	–
20	161.9	basalt	65.4	1.0	–	-	1.8	-	0.6	-	-	-	<0.1	26.0	C	weak	1.6	–
21	165.2	basalt	61.0	0.2	–	-	1.6	-	<0.1	-	-	-	-	42.2	A	weak	0.8	–
23*	176.2	olivine basalt	67.7	2.4	1.6	-	4.8	-	<0.1	-	-	-	-	20.0	R	weak	1.6	–
27	184.5	basalt	57.9	0.4	0.4	-	2.2	0.6	9.2	0.4	0.4	-	-	19.2	A	weak	0.9	G
29	199.8	olivine basalt	73.1	3.8	5.0	4.8	3.8	-	-	-	-	5.4	0.4	7.0	R	weak	1.5	P
30	205.8	picritic basalt	82.4	16.0	18.6	-	7.2	-	-	-	-	-	0.4	21.0	A	strong	1.0	P
32	210.8	picritic basalt	79.6	10.8	13.8	0.4	4.4	-	-	-	-	-	<0.1	6.4	A	weak	0.6	P
34*	233.5	picritic basalt	75.1	6.2	15.6	1.2	5.4	-	-	-	-	3.6	<0.1	4.2	C	weak	1.3	P
35	229.3	picritic basalt	75.5	12.2	8.4	-	3.4	-	-	-	<0.1	-	<0.1	35.4	A	weak	0.9	P
37	241.5	olivine basalt	69.5	4.2	6.0	-	2.6	-	-	-	-	-	<0.1	16.2	C	weak	0.9	–
37*	243.3	olivine basalt	69.5	4.0	5.2	-	2.4	-	-	-	-	-	<0.1	14.4	C	weak	0.9	P
40	260.4	olivine basalt	73.1	6.8	6.8	1.8	4.2	-	0.6	<0.1	0.2	-	0.2	8.2	C	weak	1.4	G,P
43	268.3	olivine basalt	72.8	7.6	4.2	1.8	4.6	-	1.0	-	0.4	0.8	<0.1	9.8	R	weak	1.3	G
									Mauna Kea									
45*	282.0	olivine basalt	63.9	4.2	5.0	-	2.6	-	0.2	-	<0.1	-	0.2	10.2	R	mod.	1.6	P
47a	285.7	olivine basalt	57.0	2.6	2.4	-	4.4	<0.1	0.2	-	0.2	-	<0.1	20.6	R	mod.	0.9	P
47c	289.0	olivine basalt	63.5	4.4	3.4	-	5.0	-	0.8	-	0.4	-	<0.1	7.2	R	mod.	1.3	G
49*	299.3	plag basalt	48.9	-	-	-	1.4	3.4	2.8	-	-	-	-	2.4	R	weak	2.1	G
51	306.2	basalt	47.1	-	-	-	-	-	0.2	-	-	-	-	30.4	R	mod.	2.0	-
52*	308.2	basalt	48.5	-	-	-	<0.1	-	0.2	-	-	-	-	5.4	R	weak	2.0	-
53	313.1	basalt	57.4	0.6	0.6	-	1.0	-	0.4	0.4	1.0	-	0.2	15.4	R	mod.	0.5	-
54	315.1	basalt	54.7	<0.1	-	-	<0.1	-	0.4	-	0.2	-	0.2	20.0	C	mod.	0.7	-
55*	320.6	porphyr. basalt	71.0	6.8	6.0	-	3.2	0.6	0.4	2.4	1.4	-	0.4	16.4	R	weak	0.7	P,G
57	325.0	basalt	43.9	<0.1	-	-	0.8	-	0.8	-	0.6	-	<0.1	35.4	C	mod.	1.6	-
57	327.5	basalt	44.8	-	-	-	0.5	1.0	0.6	-	0.4	-	<0.1	3.0	R	mod.	1.7	-
58	331.7	basalt	54.1	-	-	-	-	-	-	-	-	-	-	0.8	C	weak	1.8	P
59*	342.1	olivine basalt	60.8	1.4	6.2	-	0.8	-	-	-	-	-	0.2	2.0	R	weak	1.9	-
62	354.8	basalt	55.9	1.0	0.4	-	1.2	<0.1	0.4	0.4	0.4	-	<0.1	3.0	R	fresh	1.8	P,G
64*	367.9	picritic basalt	82.5	23.0	19.2	-	4.2	-	-	0.4	-	-	0.2	10.8	R	weak	0.7	P,G
69*	378.6	picritic basalt	77.6	17.8	4.8	-	3.8	-	-	0.2	0.4	-	0.4	21.6	R	mod.	0.4	P,G
70	389.5	picritic basalt	79.9	18.0	11.8	-	1.8	-	-	-	-	-	<0.1	14.0	R	fresh	1.6	G,P
72*	400.6	basalt	55.9	1.8	0.8	-	1.2	0.6	0.8	0.6	-	-	0.4	0.6	R	fresh	1.7	G
75	416.0	basalt	64.1	2.0	1.4	-	1.4	-	-	1.8	0.6	-	-	0.8	R	weak	1.7	G, P
76*	424.5	picritic basalt	78.6	19.4	18.6	1.2	2.6	0.2	-	<0.1	0.2	-	0.2	9.8	R	weak	0.5	G

Table 1. (continued)

Unit	Depth, m	Rock Name	Mg #	Olivine				Plag		Augite		Opx	Opaques	Vesicularity	Glass	Alteration	K_2O/P_2O_5	Xenoliths
				ph	xeno	Rods	mph	ph	mph	ph	mph	mph	mph					
78	429.8	basalt	59.2	2.8	0.8	-	1.0	-	-	<0.1	-	-	-	2.6	R	weak	1.6	-
80	433.9	picritic basalt	80.4	16.8	12.4	-	2.4	-	-	-	-	-	-	13.4	R	weak	1.2	-
88	452.4	basalt	55.3	0.8	0.2	-	0.2	-	-	-	0.2	-	0.2	1.6	C	weak	0.9	-
89	459.8	basalt	61.2	2.6	0.6	-	1.4	-	-	-	0.8	-	0.4	1.6	R	weak	1.6	G
91	472.8	olivine basalt	70.1	8.4	9.4	-	1.4	-	0.2	-	0.2	-	0.4	15.6	C	mod.	1.5	P
96	485.9	olivine basalt	71.3	4.4	3.4	0.2	3.0	-	-	-	1.2	-	0.2	12.8	R	weak	1.8	P
97*	489.8	picritic basalt	69.0	6.8	8.8	-	1.0	-	-	-	0.4	-	0.8	8.6	R	weak	1.4	G
103	513.5	olivine basalt	78.0	11.8	5.6	0.2	2.4	-	-	-	2.2	-	0.4	12.6	R	weak	1.4	P
105	520.4	olivine basalt	73.3	8.2	7.0	0.4	1.8	0.2	0.2	-	-	-	0.6	8.0	R	weak	1.9	G,P
109	542.4	picritic basalt	78.1	10.6	14.2	-	3.0	-	-	-	0.2	-	0.2	14.2	R	weak	1.4	P
118*	590.6	picritic basalt	76.1	16.2	5.2	-	3.4	-	0.6	-	0.2	-	1.2	18.8	R	weak	1.6	P
137*	669.8	plivine basalt	73.8	10.4	8.8	0.8	4.4	-	-	-	0.2	-	0.8	20.2	C	weak	1.4	P
147	721.1	olivine basalt	73.0	10.0	7.8	-	2.4	-	-	-	0.4	-	0.6	0.6	R	weak	1.3	P
153*	748.2	basalt	57.4	1.0	1.4	-	1.0	0.6	0.2	1.4	1.0	-	<0.1	1.8	R	weak	1.8	G
167*	821.3	olivine basalt	63.1	2.2	1.2	0.2	1.6	0.4	0.2	0.2	0.6	-	<0.1	5.0	R	mod.	1.6	G
176*	869.5	basalt	61.0	2.2	0.8	0.6	2.0	-	0.2	-	<1.0	-	0.2	18.6	A	none	1.6	-
190*	923.1	olivine basalt	65.9	4.2	3.0	-	1.0	-	0.2	-	0.4	-	<0.1	2.4	R	mod.	1.6	P
203*	966.7	olivine basalt	72.2	9.2	3.4	3.0	1.4	-	1.2	-	<1.0	-	0.6	18.2	C	mod.	1.6	-
218*	1009.5	basalt	59.5	1.2	1.0	-	1.6	-	1.1	1.0	0.6	-	1.0	2.4	R	none	1.7	P
224*	1043.9	olivine basalt	67.1	3.6	2.6	0.8	3.2	-	1.0	0.2	0.4		0.2	15.8	C	weak	1.7	-

Mineralogy and vesicularity values are in volume percent and are based on a minimum of 500 points counted per sample. Phenocrysts (ph) are >0.5 mm; microphenocrysts (mph) are 0.1-0.5 mm; xenocrysts (xeno) have one or more dislocation planes. Alteration level is based on petrographic observations only. Chemical ratios (Mg# and K2O/P2O5) from *Rhodes* [this issue]. Glass: abundance of interstitial glass or cryptocrystalline material; A, abundant (10-20%); C, common (2-10%); R, rare (0.1-2.0%). Xenoliths: G, gabbro and related plagioclase-rich plutonic rocks; P, olivine-and/or pyroxene-rich plutonic rocks.

*Microprobed lavas.

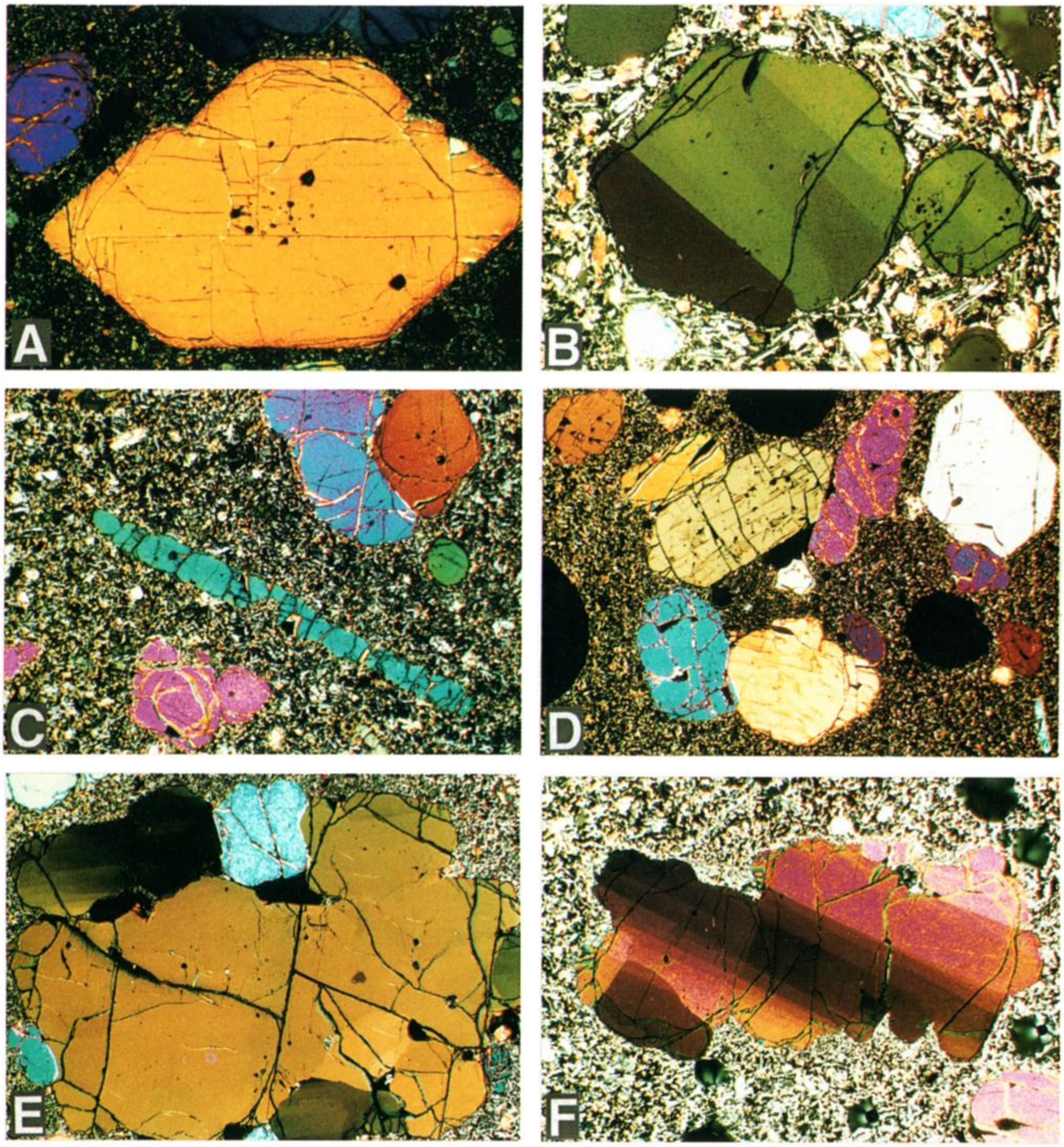

Plate 1. Photomicrographs illustrating the different types of olivine in the HSDP lavas. The field of view for Plates 1a and 1b is 2.5 mm across; the field of view for the other photomicrographs is ~5 mm wide. (a) Euhedral, undeformed phenocryst with inclusions of brown glass and Cr-spinel from unit 64. (b) Weakly kinked (5° variation in extinction angle) pair of olivine crystals with Cr-spinel inclusions from unit 40. (c) Elongate crystal (rod) of olivine with phenocrysts and an aggregate of phenocrysts from unit 34. (d) Aggregates of euhedral olivine phenocrysts from unit 35; dark areas are vesicles. (e) Deformed dunitic xenolith with one large grain and many smaller grains from unit 143. (f) Strongly deformed olivine xenocryst from unit 11 (extinction angle ~14°).

olivines (Plate 1), but some consist of undeformed euhedral olivines.

The cores of most HSDP lavas appear unaltered to slightly altered in hand specimen, except along fractures where they are commonly stained and coated with clay [*Hawaii Scientific Drilling Project*, 1994]. The Mauna Kea flows are, in general, somewhat more altered in appearance than the Mauna Loa lavas, although some of the basal Mauna Kea flows are among the least altered lavas from the hole. Brecciated and rubbly flow tops and bottoms are often moderately altered and tops of many of the massive flows are baked red. The vesicles in the HSDP lavas are free of secondary minerals except in the basal unit, which has a very thin coating of clay lining vesicles and rare needles of zeolite. The low level of alteration among the HSDP lavas is probably related to the low temperature of water in the well (5-18°C between 300 m and the base of the hole [*Thomas et al.*, this issue]). In contrast, many of the lavas from >500 m in the SOH-4 drill hole from Kilauea's east rift zone are hydrothermally altered [*West et al.*, 1994] because temperatures in the hole were 50-150°C at depths of 500 to 1000 m. The maximum temperature measured in the SOH-4 hole was ~300°C [*Trusdell et al.*, 1992].

Many of the olivines in the HSDP lavas have thin, discontinuous iddingsite rims (<0.01 mm). The lavas containing this type of olivine are listed in Table 1 as having weak levels of alteration. Some rocks have thicker and more continuous iddingsite rims (0.01-0.05 mm) and locally, stains in the matrix; they are characterized as having moderate to strong levels of alteration in Table 1. A few of the lavas from the top and bottom of the hole have no visible signs of alteration. To evaluate whether olivine alteration is a good indicator of geochemical alteration, it was compared with the K_2O/P_2O_5 of the lavas. Previous studies have shown that K is lost during weathering of Hawaiian basalts but that P is relatively immobile [e.g., *Lipman et al.*, 1990; *Frey et al.*, 1991] and that the K_2O/P_2O_5 is generally between 1.5 to 2.0 in Hawaiian tholeiites [*Wright*, 1971]. Thus, K_2O/P_2O_5 ratios below 1.5, especially those below 1.0, are a good indication of geochemical alteration. Some, but not all of, the lavas with thicker iddingsite rims have low K_2O/P_2O_5 ratios (Table 1). Some of the lavas with low K_2O/P_2O_5 ratios have thin and discontinuous iddingsite rims and appear only weakly altered in thin section. Thus, the level of olivine alteration is not a good indication of rock alteration for the HSDP cores. What other petrographic features are important for indicating level of geochemical alteration in these cores?

All of the lavas with low K_2O/P_2O_5 (>1) ratios are strongly vesicular (10 vol % or more), except unit 32. Thus the vesicularity of a lava plays a key role in its alteration history probably because it increases the surface area of the rock. Another potentially important factor that may influence the extent of geochemical alteration is the crystallinity of the lavas (more crystalline rocks tend to be less altered [e.g.,*Dalrymple and Lanphere*, 1969]). All of the HSDP lavas contain some interstitial glass or cryptocrystalline material (Table 1). It is more abundant in the Mauna Loa lavas than the Mauna Kea lavas. Some of the lavas with abundant glass (>10 vol %) have low K_2O/P_2O_5 (e.g., units 21 and 32) but others do not (units 11 and 176). Thus, for rocks that appear weakly altered in thin section, high vesicularity (>10 vol %) is the best indicator that they are probably geochemically altered.

Geochemistry

Analytical Methods

Mineral and glass compositions were measured at the University of Hawaii using a five- spectrometer, Cameca SX-50 electron microprobe. Natural mineral and glass standards were used for calibration, an accelerating voltage of 15 kV was used, and a PAP-ZAF matrix correction procedure was applied to all analyses. For olivine, a focused 20 nA beam and peak counting times of 60 s were used. For glasses, a defocused (20 μm) beam and peak counting times of 60 s for all elements except for Na (40 s), K and P (100 s) were used. Backgrounds were measured for half the peak counting times. The reported glass analyses are an average of five spot analyses; mineral analyses are an average of three spot analyses. Relative analytical error, based on repeated analysis of the Smithsonian standards A99 glass (from a Kilauea lava) and San Carlos olivine, is <1% for major elements, <5% for minor elements.

Olivine

The core composition of olivine crystals was determined to evaluate whether it was in equilibrium with the whole rock composition of its host. Olivine was the only mineral analyzed during this study. At least ten crystals were analyzed in each section from the 24 flow units that were microprobed (see Table 1), except for the nearly aphyric evolved lavas. For the more porphyritic lavas, 15 or more crystals were usually analyzed. Over 500 olivine crystals were analyzed for this study making it the most extensive study of olivine composition in Hawaiian lavas. The cores of HSDP olivine range from 90.8 to 74.7% forsterite, except for two evolved lavas (units 49 and 52 with MgO contents of 6.1 and 6.3), which contain only olivine microphenocrysts and have forsterite contents of 63 to 51% (Table 2). Some lavas have a restricted core composition range (e.g., unit 45) but most have a wide range (e.g., unit 15, Figure 1). There is no systematic difference in composition between undeformed and deformed olivines (Figure 1 and Table 2), which was also noted by *Wilkinson and Hensel* [1988] for some Mauna Loa and Kilauea picritic basalts. The CaO content of all of these olivines is moderate and increases with decreasing forsterite content from 0.18 to 0.37 wt % (Table 2). These CaO contents are consistent with low pressure crystallization [*Stormer*, 1973; *Jurewicz and Watson*, 1988]. The NiO content ranges widely (0.55 to 0.03 wt %) and decreases with forsterite content.

Zoning profiles across olivines from HSDP lavas indicate overall moderate to strongly normal zoning (up to 17% forsterite) or no zoning even for the lower forsterite content crystals (Figure 2). Previous studies of Mauna Kea and Kilauea submarine lavas found common reversely zoned rims (1-2% forsterite) on lower forsterite olivines (<86% [*Yang et al.*, 1994; *Clague et al.*, 1995]. An extensive study of the picritic lavas from the 1959 eruption of Kilauea found about equal abundance of reversely and normally zoned olivines among the lower forsterite crystals [*Helz*, 1987]. Some of the HSDP lower forsterite crystals do have a mild zoning reversal (<1% forsterite) 50-100 μm from their rims (Figure 2), which indicates that these lower forsterite olivines partially reequilibrated with their host magma prior to eruption.

The composition of olivine in 20 small (1-10 mm diameter) dunitic xenoliths in HSDP tholeiitic lavas was determined for comparison with the compositions of phenocrysts and xenocrysts in the HSDP lavas. All but two of these xenoliths contain weakly to strongly deformed olivine grains. The forsterite content of the dunitic olivines is evenly spread between 83.3 and 90.4% forsterite. This range is only slightly smaller than the overall range for phenocrysts and xenocrysts in HSDP tholeiitic lavas (the xenolithic olivines do not extend to as low values; see Figure 3 for phenocryst and xenocryst

Table 2. Representative Olivine Core Compositions From HSDP Lavas

	Mauna Loa																
	Unit 11				Unit 15				Unit 23			Unit 34			Unit 37		
	P	R	K	P	P	R	K	P	P	K	R	K	P	P	K	P	P
SiO_2	40.55	40.40	39.81	39.78	40.62	40.17	40.10	39.28	39.94	39.30	38.25	40.63	40.75	39.73	40.67	40.70	39.73
FeO	9.24	10.80	13.84	14.57	8.91	11.17	12.19	16.53	14.67	17.50	23.15	9.06	9.19	14.71	9.23	9.41	14.95
NiO	0.48	0.32	0.38	0.30	0.55	0.36	0.39	0.30	0.27	0.25	0.23	0.57	0.59	0.25	0.44	0.43	0.29
MgO	49.54	48.62	45.61	45.36	49.40	47.95	47.08	43.47	44.88	42.60	37.82	49.32	49.22	44.96	48.90	48.86	44.48
CaO	0.19	0.22	0.23	0.21	0.19	0.20	0.22	0.26	0.23	0.23	0.23	0.18	0.18	0.24	0.18	0.19	0.22
Total	100.00	100.36	99.87	100.22	99.67	99.85	99.98	99.84	99.99	99.88	99.68	99.76	99.93	99.89	99.42	99.59	99.67
Fo%	90.5	88.9	85.4	84.7	90.8	88.4	87.3	82.4	84.50	81.3	74.4	90.6	90.5	84.49	90.4	90.2	84.1

	Mauna Kea															
	Unit 45			Unit 49		Unit 52		Unit 55			Unit 64			Unit 76		
	K	P	P	mph	mph	mph	mph	P	K	P	P	K	R	R	K	P
SiO_2	40.00	40.20	39.50	35.50	34.85	36.40	35.65	40.35	40.30	39.55	40.55	40.40	40.60	40.65	40.55	40.53
FeO	12.80	13.20	15.80	37.50	40.75	31.95	36.05	10.60	12.00	15.75	10.80	10.75	10.89	10.55	10.70	10.80
NiO	0.25	0.24	0.21	0.05	0.06	0.07	0.05	0.34	0.21	0.18	0.30	0.26	0.21	0.43	0.42	0.42
MgO	45.75	45.80	43.85	26.55	23.85	30.90	27.80	48.30	47.10	44.15	47.90	47.78	48.10	48.40	48.25	48.15
CaO	0.28	0.32	0.30	0.34	0.27	0.34	0.37	0.22	0.27	0.24	0.34	0.35	0.36	0.23	0.23	0.22
Total	99.08	99.76	99.66	99.94	99.78	99.66	99.92	99.81	99.88	99.87	99.89	99.54	100.16	100.25	100.15	100.12
Fo%	86.4	86.1	83.2	55.8	51.0	63.3	57.9	89.0	87.5	83.3	88.8	88.8	88.7	89.1	88.9	88.8

	Mauna Kea														
	Unit 97			Unit 118			Unit 167		Unit 176			Unit 218		Unit 224	
	K	P	R	P	K	R	P	R	P	R	P	P	R	P	R
SiO_2	40.65	40.55	40.75	40.60	40.55	39.30	39.55	38.30	40.24	39.91	39.45	40.40	38.30	39.93	39.00
FeO	10.60	11.25	11.45	10.05	11.05	17.83	15.57	21.80	10.60	13.46	15.43	10.47	22.50	12.95	18.10
NiO	0.36	0.34	0.37	0.45	0.40	0.24	0.24	0.22	0.39	0.37	0.30	0.44	0.25	0.36	0.27
MgO	47.88	47.45	47.40	48.25	47.63	42.30	44.17	38.80	48.14	45.71	44.35	48.46	38.65	46.20	42.40
CaO	0.23	0.25	0.24	0.24	0.22	0.24	0.27	0.24	0.24	0.22	0.26	0.22	0.25	0.21	0.23
Total	99.72	99.84	100.21	99.59	99.85	99.95	99.80	99.36	99.61	99.67	99.79	99.93	99.95	99.65	100.00
Fo%	89.0	88.3	88.1	89.5	88.5	80.9	83.5	76.0	89.0	85.8	83.7	89.2	75.4	86.4	80.7

Olivine grain types: P, phenocryst; R, resorbed; K, kink-banded; mph, microphenocryst.

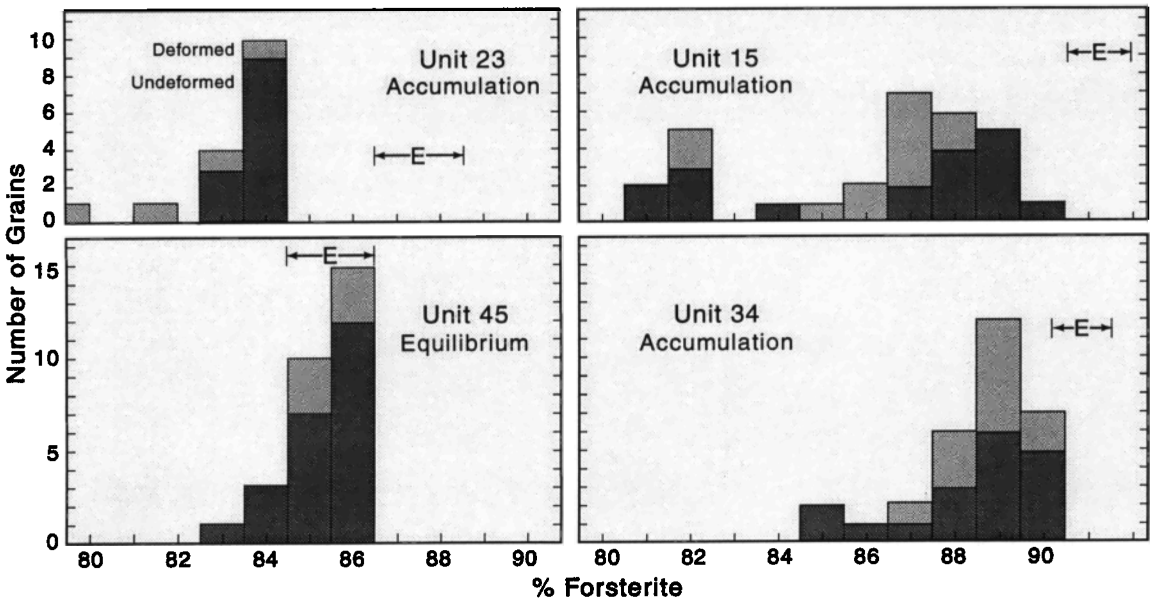

Figure 1. Histograms of the percent forsterite in deformed and undeformed olivines from four selected HSDP lavas. The brackets with arrows and an E show the range of forsterite contents that would be in equilibrium with the host rock composition assuming a Fe/Mg olivine/whole rock K_D = 0.3 ± .03 [*Roeder and Emslie*, 1970; *Ulmer*, 1989]. Unit 45 olivine is in equilibrium with its host lava composition despite the presence of some xenocrysts. Both phenocrysts and xenocrysts are clearly out of equilibrium with the whole rock composition of the other flow units. The wide compositional ranges for phenocrysts and xenocrysts in flow units 15 and 34 indicate that these flows probably accumulated and picked up olivine.

ranges). The dunitic olivines generally have the same compositional range as the xenocrysts in the host lavas. The CaO content of the dunitic olivines is moderate (0.18-0.31 wt %) indicating shallow level crystallization.

Glass

Twenty of the pahoehoe HSDP lavas have well-defined glassy crusts. Most of these lavas are from the upper and lower portions of the hole. The glasses are mostly from flow tops but a few are from the base and others are from tops of internal flow contacts (Table 3). Fragments of the glass were chipped off the crusts for microprobe analyses. Most of the glasses are brown and translucent but contain abundant microlites of plagioclase, olivine, and augite. Some of the glasses have a dull black appearance. During microscopic examination three of the glasses appeared obviously altered and were not analyzed. Two other, less-altered glasses were analyzed and gave low Na_2O contents (1.7 and 1.4 wt %) and slightly low totals (98.9-99.0 wt %). Three other glasses yielded low K_2O/P_2O_5 (0.8-1.1), although one of these glasses from flow unit 220 has an unaltered section with much higher K_2O, somewhat higher MgO and CaO, but lower SiO_2 and FeO contents (Table 3).

Two of the Mauna Loa flows have variable glass compositions (7.5 to 5.6 wt % MgO; units 1 and 3). This is probably a result of the abundant but variable microlite content in the glasses. The high microlite content and resulting low MgO content of the glasses (average 6.3 wt %) probably are both related to low "quenching" temperatures. The Mauna Loa empirical glass geothermometer [*Montierth et al.*, 1995] gives magma temperatures of 1140° to 1185°C for these glasses; the Kilauea geothermometer [*Helz and Thornber*, 1987] gives temperatures of 1125° to 1165°C (average 1140°C), which are similar to those obtained for lavas from the ongoing Puu Oo eruption [*Neal et al.*, 1988; *M. O. Garcia*, unpublished data, 1994].

Few major element glass data are available for Mauna Kea shield lavas because they are not exposed subaerially; all previous samples were dredged from its east rift [*Garcia et al.*,

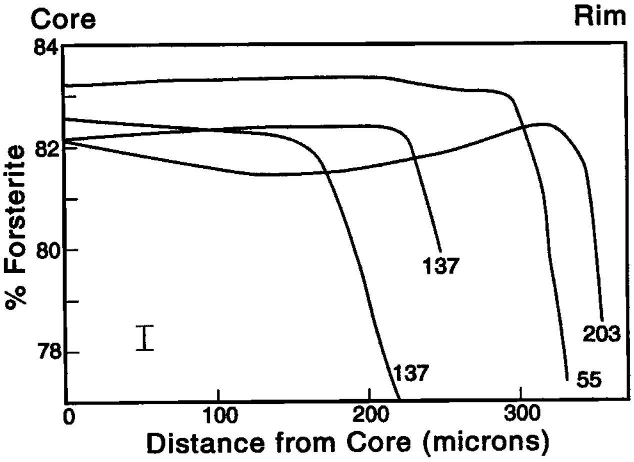

Figure 2. Forsterite zoning profiles across four lower forsterite content (82-84%) HSDP olivine phenocrysts. Most of these profiles and all of those for higher forsterite content olivines have normal zoning. One profile (unit 203) has a reversed section about 100 μm wide adjacent to a normally zoned rim. All of the profiles are based on 6-7 μm wide steps. The error bar in the lower left corner is 2 sigma for these 10 s count/steps.

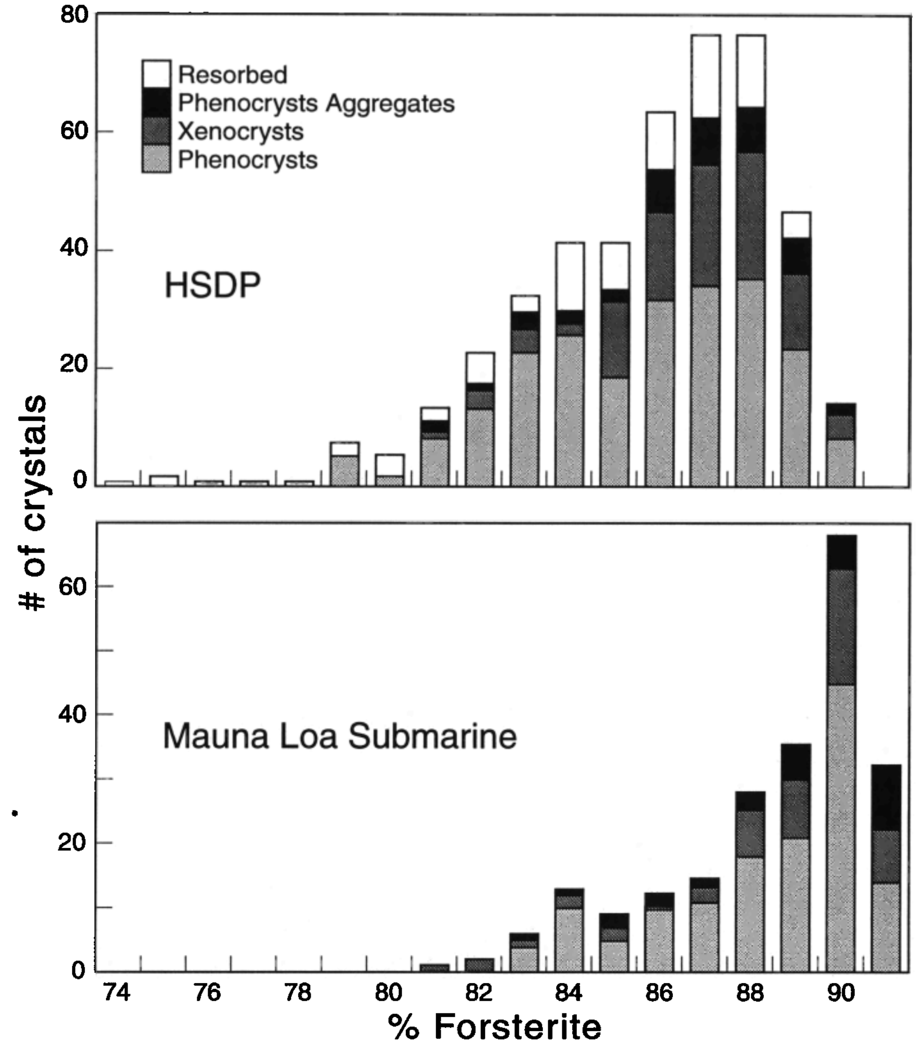

Figure 3. Histograms of percent forsterite in the cores of ~ 450 HSDP olivine phenocrysts and ~275 olivine phenocrysts from Mauna Loa submarine lavas [*Garcia et al.*, 1995]. Most of the HSDP olivines have forsterite contents of 86-88%. Xenocrysts have nearly the same distribution as phenocrysts and aggregates of phenocrysts (three or more undeformed grains). The resorbed crystals extend to much lower forsterite contents and were clearly out of equilibrium with their host magmas. The submarine Mauna Loa lavas contain a higher percentage of phenocrysts, and they have a higher average forsterite contents with a strong peak at 90% forsterite.

1989; *Moore and Clague*, 1992]. The six new unaltered Mauna Kea glass analyses presented here expand the total number of glass analyses to 24. The MgO contents of these HSDP glasses are low (5.6-6.5, Table 3), as was found for the submarine glasses. Almost all of the published glass data for Mauna Loa are also from submarine lavas [*Garcia et al.*, 1989;*Moore and Clague*, 1992; *Garcia et al.*, 1995]. For the major elements that are useful for distinguishing lavas from different Hawaiian volcanoes [*Garcia et al.*, 1989], the new HSDP glass data expand the TiO_2 and K_2O fields for Mauna Loa and Mauna Kea glasses but not the SiO_2 fields (Figure 4).

Glass Chemistry as an Indicator of Parentage

Volcanic glasses offer an opportunity to document magma compositions and their liquid line of descent. In many cases, especially for strongly porphyritic rocks like those from the HSDP, whole rock compositions include the effects of accumulation of phenocrysts and/or xenocrysts. Olivine phenocryst accumulation has been well documented by recent studies of subaerial and submarine Mauna Loa lavas [*Wilkinson and Hensel*, 1988; *Garcia et al.*, 1995; *Rhodes*, 1995]. Olivine xenocryst accumulation has been shown for some Kilauea lavas [*Helz*, 1987; *Clague et al.*, 1995].

Wright [1971] demonstrated that the younger prehistoric and historical subaerial lavas from Kilauea are geochemically distinct from those of its neighbor, Mauna Loa. Attempts to extend this analysis to the oldest exposed subaerial Mauna Loa lavas, the Ninole Basalt, were unsuccessful for major elements because those lavas are somewhat altered [*Lipman et al.*, 1990]. Fresh glasses were obtained from Mauna Loa's oldest exposed lavas along its submarine southwest rift zone. These glasses confirm and extend the geochemical distinction between these

Table 3. Microprobe Analyses of Glasses From Hawaii Scientific Drilling Hole Lavas

Unit	Depth, m	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
						Mauna Loa						
1I	13.4	52.37	2.64	13.04	12.64	0.20	5.63	10.00	2.48	0.52	0.33	99.85
1I	13.4	52.42	2.37	11.72	12.13	0.19	7.49	10.80	2.12	0.45	0.29	99.98
2I	21.0	52.37	2.64	12.94	12.60	0.18	5.56	10.01	2.46	0.52	0.33	99.61
3T	30.9	52.45	2.61	12.85	12.42	0.19	5.60	9.82	2.44	0.53	0.33	99.24
3T	30.9	52.46	2.47	11.70	12.25	0.23	7.52	9.97	2.17	0.45	0.29	99.51
22T	167.5	52.67	2.25	13.47	11.05	0.17	6.63	10.77	2.27	0.36	0.23	99.87
23T	173.0	52.86	2.22	13.55	11.35	0.18	6.55	10.97	2.34	(0.23)	0.21	100.46†
36T	230.5	52.10	2.49	13.30	11.55	0.19	6.31	10.62	2.32	0.37	0.24	99.49
37I	240.2	52.35	2.44	13.25	11.43	0.17	6.34	10.62	2.27	0.36	0.23	99.46
37I	246.6	52.15	2.69	12.98	12.08	0.17	6.14	10.28	2.31	0.40	0.27	99.47
						Mauna Kea						
131B	309.7	52.05	2.54	13.58	10.94	0.18	6.60	11.20	2.21	0.39	0.25	99.94
149I	731.7	52.07	2.66	13.72	11.66	0.17	6.32	11.09	2.05	(0.22)	0.25	100.21†
154B	753.3	51.53	2.92	13.61	11.05	0.17	6.30	10.92	(1.71)	0.52	0.31	99.04†
177B	877.6	51.61	2.80	13.33	11.49	0.18	6.23	10.78	2.06	0.44	0.26	99.18
203T	963.9	52.20	2.62	13.72	10.50	0.18	6.53	11.04	(1.41)	0.42	0.27	98.91†
205T	973.6	52.18	3.33	12.98	12.35	0.20	5.63	10.41	2.43	0.44	0.36	100.31
213T	998.4	52.15	3.23	13.30	11.85	0.22	5.95	10.60	2.36	(0.31)	0.33	100.30†
220T	1023.4	51.65	3.60	13.15	12.45	0.19	5.75	10.35	2.13	(0.32)	0.38	99.97†
220T	1023.4	51.26	3.59	13.16	11.50	0.18	6.17	10.58	2.00	0.68	0.36	99.48
223T	1037.3	51.78	3.30	13.45	11.65	0.17	6.15	10.55	2.03	0.57	0.35	100.00

†Altered glasses; values in parentheses are low for K_2O or Na_2O compared to P_2O_5
Location of glass on flow: T, top; B, base; I, internal contact.

two volcanoes, especially for SiO_2 and TiO_2 at a given MgO content [*Garcia et al., 1995*]. HSDP recovered both Mauna Loa and Mauna Kea lavas. Is there a geochemical distinction between glasses from these volcanoes?

Previous whole rock studies have shown that Mauna Kea shield lavas are geochemically similar to Kilauea, especially for trace element and isotope ratios [e.g., *Yang et al.*, 1994], but the Mauna Kea data set was limited prior to the HSDP because its shield lavas are only exposed offshore. Most of the Mauna Kea glass data ([HSDP from Table 3; and submarine from *Garcia et al.*, [1989] and *Moore and Clague* [1992]) plot within the Kilauea fields or outside of the Mauna Loa fields on the MgO variation diagram for TiO_2, except at low MgO contents (<6 wt % MgO, Figure 4). All but the two mafic HSDP Mauna Loa glasses plot within the Mauna Loa TiO_2 field (Figure 4). On the SiO_2 plot, the Mauna Kea glasses plot in both the Kilauea and the Mauna Loa fields (Figure 4). In contrast, all of the HSDP Mauna Loa glasses have high SiO_2 contents and plot in the Mauna Loa SiO_2 field (Figure 4).

Garcia et al. [1989] showed in a reconnaissance study of submarine Hawaiian tholeiitic glasses that there is considerable overlap between Mauna Loa and Kilauea for other major elements except above 7 wt % MgO, when olivine is usually the only mineral present [*Wright*, 1971]. For these more mafic glasses, Al_2O_3 tends to be higher and K_2O tends to be lower in Mauna Loa glasses. None of the Mauna Kea submarine or HSDP glasses have MgO contents above 7 wt % and they range widely in K_2O (Figure 4) and Al_2O_3 contents. The wide compositional variation among the Mauna Kea submarine glasses has been interpreted, in part, to be related to magma mixing [*Yang et al.*, 1994]. Despite the potential complexities, the HSDP glass data are consistent with the lithologic and trace element subdivision of the core into Mauna Loa and Mauna Kea sections [*Hawaii Scientific Drilling Project*, 1994; *Rhodes*, this issue; *Yang et al.*, this issue].

The Mauna Loa glasses define a relatively tight trend on MgO variation diagrams for K_2O and SiO_2 and a somewhat wider trend on the MgO variation TiO_2 diagram (Figure 4). This limited compositional variation for these six widely spaced glasses from the HSDP core (13 to 247 m) are consistent with whole rock major element data for historical and young prehistoric Mauna Loa lavas [*Wright*, 1971; *Rhodes*, 1983; *Rhodes and Hart*, 1995]. The HSDP glasses could have been derived from similar parental magmas. In contrast, the Mauna Kea glasses range widely in composition (Figure 4) and must be derived from a wide range of parental magmas that were modified by magma mixing and crustal assimilation (see below). More Mauna Kea glass analyses are needed to evaluate the major element distinctions between Hawaiian volcanoes, especially at higher MgO contents (>7 wt %), and should be collected with other petrologic data to establish the magmatic history of the glasses. Such glass data are critical to interpreting the effects of various crustal processes on magma compositions so that we can realistically evaluate mantle processes (high-pressure crystal fractionation and melting) and understand the temporal evolution of Hawaiian volcanoes during their passage over the Hawaiian hotspot.

Origin of the Olivine-Rich HSDP Lavas

The HSDP lavas are remarkably olivine-rich compared to other subaerially erupted Hawaiian shield lavas [e.g.,

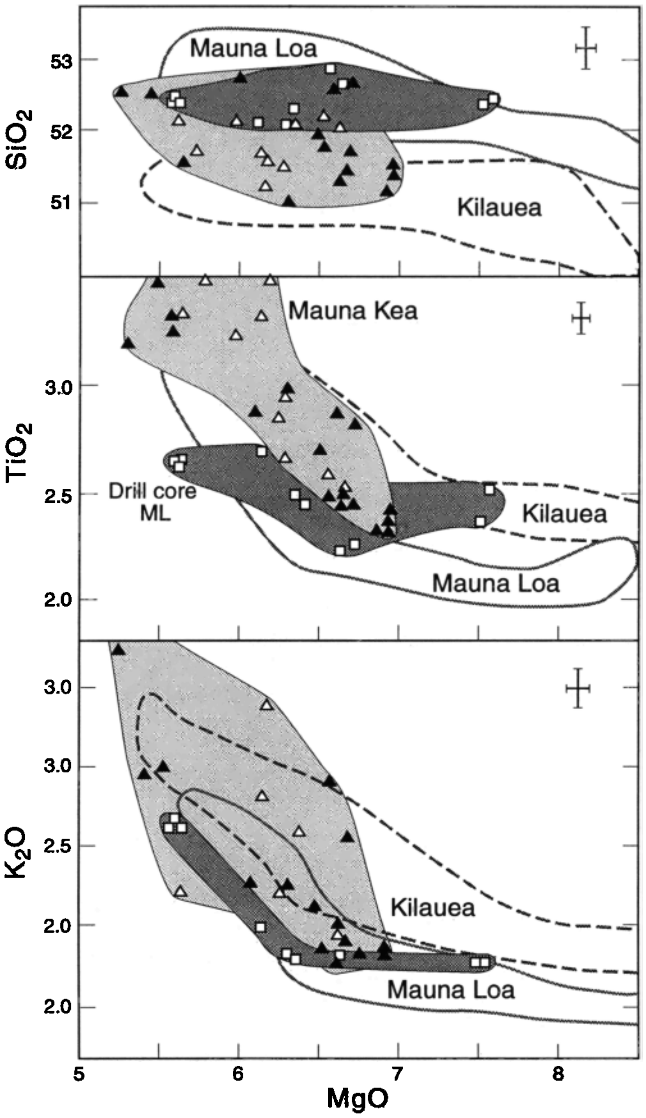

Figure 4. MgO variation diagrams for TiO_2, SiO_2, and K_2O contents in HSDP glasses (open symbols, data from Table 3) and submarine Mauna Kea glasses (solid triangles, data from *Garcia et al.* [1989] and *Moore and Clague* [1992]). Data for the Kilauea and Mauna Loa fields are from *Garcia et al.* [1989], *Moore and Clague* [1992] (Mauna Loa only) and M. O. Garcia (unpublished data, 1996 (Kilauea only). Most of the HSDP Mauna Loa glasses have low K_2O and TiO_2 and high SiO_2 contents and may have been derived from similar parental magmas. The Mauna Kea HSDP and submarine glasses range widely on these plots and must have been derived from distinct parental magmas and/or have complicated magmatic histories.

Macdonald, 1949]. Is this an indication that they were derived from high MgO parental magmas or that they have accumulated or picked up olivine? The high forsterite content of some of the olivines in many of the picritic HSDP lavas (89-90.8%, Figure 5 and Table 2) indicates that these lavas had high MgO parents. These high forsterite content olivines probably formed in magmas with Mg # of 71 to 75, assuming a K_D of 0.30 (which is reasonable for the moderate CaO contents of the olivine [*Ulmer*, 1989] and a $Fe^{3+}/Fe^{2+} + Fe^{3+}$ ratio of 0.10 in the magmas (which is consistent with Fe^{3+} analyses on mafic Hawaiian submarine glasses, < 7 wt % MgO [*Byers et al.*, 1985]). Most previous work on the oxidation state of Hawaiian tholeiitic lavas has shown that they oxidized during subaerial eruption and that the least oxidized part of the flow (rapidly quenched glass) has a $Fe^{3+}/Fe^{2+} + Fe^{3+}$ of ~0.10 [e.g., *Moore and Ault*, 1965]. *Carmichael and Ghiorso* [1986] noticed that some submarine Kilauea lavas have higher $Fe^{3+}/Fe^{2+} + Fe^{3+}$ ratios than many subaerial Kilauea lavas. They suggested that the subaerial lavas become reduced during eruption due to the degassing of S. Their interpretation, unfortunately, is based on a small data set of submarine lavas with complex histories (mixed magmas [*Clague et al.*, 1995]). The only other data set for $Fe^{3+}/Fe^{2+} + Fe^{3+}$ ratios for undegassed (for S and H_2O), submarine Hawaiian tholeiites is for Loihi volcano. These glasses have $Fe^{3+}/Fe^{2+} + Fe^{3+}$ ratios of 0.07 to 0.12 [*Byers, et al.*, 1985] and are more reduced than subaerial Kilauea lavas. Until more data are available, it seems that a $Fe^{3+}/Fe^{2+} + Fe^{3+}$ ratio of 0.10 is the most reasonable estimate for Hawaiian tholeiitic magmas.

The MgO content of the HSDP magmas that produced the high forsterite olivines can be estimated from the Mg# range of the HSDP lavas (Figure 5) and the trend of their iron content [*Rhodes*, this issue]. This yields a MgO range of 15 to 16.5 wt %, which would be a minimum for the MgO content of the parental magma of at least some HSDP lavas. This estimate is consistent with the high MgO glass sands found at the foot of Kilauea Volcano (up to 15 wt % [*Clague et al.*, 1991]) and with the results from a petrologic study of olivine-rich submarine Mauna Loa lavas, which found olivines with even higher forsterite contents (Figure 3) indicating parental magmas with 16-17.5 wt % MgO [*Garcia et al.*,1995]. This MgO range, however, is substantially lower than the MgO content of many of the HSDP lavas (i.e., 20-28 wt % [Rhodes, this issue]). Why do these HSDP lavas have such high MgO contents?

Many of the HSDP lavas contain a wide range of olivine compositions that are well beyond equilibrium with the host rock composition (Figure 5). Many of the olivines in these rocks (20-75 %, Table 1) have obvious deformation features and some have resorbed margins (Plate 1). These olivines are xenocrystic and were probably derived from disaggregated dunitic xenoliths, which are present in many of the HSDP lavas (Table 1). The source of these dunites is probably deformed cumulates from earlier magmas from these volcanoes rather than the underlying mantle because of the moderate CaO contents and forsterite compositions of these deformed olivines. The same explanation was used by *Helz* [1987] and *Clague et al.* [1995] for the source of deformed olivines in some Kilauea lavas. The lack of cumulus textures in most Hawaiian dunites is undoubtedly due to the large volume of cumulates that form in Hawaiian shield volcanoes [*Walker*, 1993] and their rapid deformation [*Clague and Denlinger*, 1994]. Thus the very high MgO content of some HSDP lavas is probably the result of both contamination by dunitic xenoliths and accumulation of phenocrysts. The whole rock compositions of these lavas are compromised and should not therefore be used as direct indicators of primary magma compositions.

The undeformed olivines also have wide compositional ranges in many of the olivine-rich flows, which may, in part, reflect "delayed fractionation" [cf. *Maaloe et al.*, 1988]. This interpretation is supported by the similarity of the forsterite and Ni zoning profiles in some HSDP olivines. Ni diffusion in olivine is slower than Fe and Mg, so high forsterite olivines in an evolving melt will commonly have a reequilibrated forsterite profile but the Ni profile may be unchanged [*Nakamura*, 1995]. The residence time of high Ni olivines with these types of

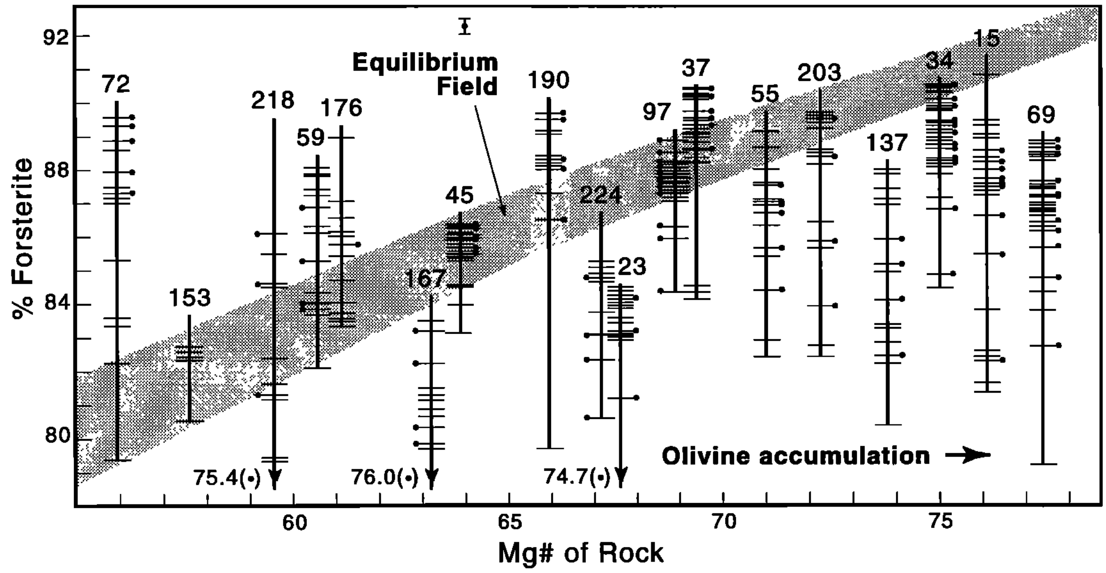

Figure 5. Plot of whole rock Mg # ((Mg/Mg + Fe^{2+}) 100), assuming 10% Fe^{3+} (see text for a discussion of this estimate), versus percent forsterite in olivine crystal cores for selected HSDP flow units. The vertical lines represent individual flows (unit numbers are given above the lines), and the horizontal lines represent olivine core compositions. Xenocrysts are designated with a solid dot at the end of the horizontal line. There are wide variations in phenocryst and xenocryst compositions for most lavas. Flow units 45 and 153 are the rare exceptions to this pattern. Olivines from both these flows plot within the equilibrium field (gray band) for their whole rock compositions (Fe/Mg for olivine/whole rock = 0.30 ± .03 [*Roeder and Emslie*, 1970]. The arrow in the lower right corner shows the effect of olivine accumulation. The error bar in the upper left corner is for 2 sigma.

profiles in a magma at 1150°C would be up to ~3 years based on calculations by *Nakamura* [1995]. Thus some of the euhedral olivines may have been carried for several years in the magmas for some of the HSDP lavas. The reverse zoning of forsterite and Ni content in some of the undeformed olivines indicates that they may have been picked up several years prior to their eruption. The survival of dislocations in the deformed olivines gives an indication of how long these features might last in a magma. Helz [1987] documented deformed olivines surviving for at least 22 years in the molten Kilauea Iki lava lake. Thus, some of these deformed olivines may have been picked up decades before they were erupted.

Summary

The HSDP lavas are petrographically and geochemically diverse. Many are remarkably olivine-rich and most are only weakly altered. The upper part of the hole consists of Mauna Loa lavas, which are more olivine-rich and contain more forsterite-rich olivines (>89%) than the underlying Mauna Kea lavas. Forty percent of the HSDP Mauna Loa lavas contain orthopyroxene microphenocrysts, which are absent in the underlying HSDP Mauna Kea flows. Many of the olivines in the olivine-rich HSDP lavas (20-74%) are deformed and are probably xenocrystic. These xenocrysts were probably derived from deformed dunite cumulates within the same volcano. This interpretation is supported by the presence of small fragments of dunitic inclusions in many of the olivine-rich HSDP flows and the moderate CaO content of the olivines from the xenocrysts and dunites. Thus the high Mg # and MgO content of some the HSDP lavas (>75 and 18-28 wt % [*Rhodes*, this issue] is a result of contamination and not an indication of parental magma compositions.

Many of the olivine-rich Mauna Loa lavas contain undeformed olivines with forsterite contents >89% (highest is 90.8%) indicating that they formed in magmas with >15 wt % MgO (up to 16.5 wt %). This interpretation is consistent with the discovery of high MgO submarine glasses at the foot of Kilauea (15 wt % [*Clague et al.*, 1991]) and the report of even higher forsterite contents (91.3%) in undeformed olivines from the submarine flank of Mauna Loa [*Garcia et al.*, 1995]. Thus Hawaiian lavas may be derived from some of the most mafic and hottest magmas produced during the Cenozoic period.

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