

# Olivine-hosted melt inclusions in Hawaiian picrites: equilibration, melting, and plume source characteristics

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Received 1 August 2000; received in revised form 1 April 2001

## Abstract

Olivine-hosted melt inclusions in tholeiitic picrites from five Hawaiian volcanoes (Koolau, Mauna Loa, Kilauea, Loihi, and Hualalai) have major and trace element compositions that illustrate the magmatic characteristics of ocean island volcanoes and the nature of mantle plumes. The geochemistry of these melt inclusions reflects the well known geochemical features that distinguish Hawaiian shield volcanoes, but with considerably greater diversity than whole rock compositions, providing a higher resolution of the magmatic processes contributing to Hawaiian plume magmatism. Naturally quenched inclusions from Kilauea, Mauna Loa, and Hualalai have been modified by crystallization of olivine on the walls of the inclusion and diffusive interaction with the host crystal. In contrast, melt inclusions in two Loihi picrites have not been affected by re-equilibration with their host olivines, reflecting a relatively brief interval between crystallization of the olivines and eruption of these lavas. Corrected major element compositions of experimentally melted inclusions from two Koolau picritic tholeiites are similar to those of erupted lavas from this volcano and document the presence of Koolau melts with at least 14% MgO. Trace element characteristics of melt inclusions from Mauna Loa, Kilauea, and Loihi can be produced by melting of a moderately depleted, garnet lherzolite source. The extent of melting generally increases from Loihi < Kilauea < Mauna Loa, although rare inclusions from Mauna Loa also indicate contributions of relatively small degree (2–4%) melts to these lavas. Extent of melting and isotopically defined source components appear to be linked in the melting regime, with the Mauna Loa component being sampled preferentially at larger degrees of melting. Melt inclusions with trace element characteristics indicating a recycled basaltic eclogite source were not found at Mauna Loa or any of the other volcanoes. Compositions of the Koolau inclusions do require a unique source component, however, possibly reflecting contributions from ancient lithosphere, either within the plume or entrained in the upper mantle. © 2002 Elsevier Science B.V. All rights reserved.

*Keywords:* Melt inclusion; Hawaiian picrite; Equilibration; Melting; Plume source characteristic

## 1. Introduction

The geochemical characteristics of melt inclusions are opening new perspectives on the processes that create magmas and the nature of their mantle and crustal source regions. In this study, the major and trace element compositions of melt inclusions trapped

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in primitive olivine phenocrysts from a suite of Hawaiian tholeiitic picrites are used to investigate the nature of mantle plumes and basaltic magmatism at hotspot volcanoes.

The geochemistry of Hawaiian magmas reflects a complex interplay of source heterogeneity, variable extents of melting, and evolution of the magmas prior to eruption. Forsteritic olivines, magnesian glasses, and trends in lava compositions demonstrate the common occurrence of picritic magmas with at least 15–17 wt.% MgO at Hawaiian shield volcanoes (Nicholls and Stout, 1988; Garcia et al., 1995a; Rhodes, 1996; Clague et al., 1995; Norman and Garcia, 1999). Systematic variations of radiogenic isotopic compositions in shield-building tholeiites reveal contributions of different mantle source components to the magmas (see Pietruszka and Garcia, 1999 for a recent summary; also Staudigel et al., 1984; DePaolo, 1996; Hauri et al., 1996; Bennett et al., 1996; Lassiter et al., 1996; Hauri and Kurz, 1997; Brandon et al., 1999). Key major and trace element characteristics of Hawaiian tholeiites such as Ca/Al and Zr/Nb are correlated with radiogenic isotopic compositions, reflecting primary compositions of the mantle source regions or variations in melting and magma transport that are linked with involvement of the different source components (Frey et al., 1994; Rhodes and Hart, 1995; Hauri, 1996; Pietruszka and Garcia, 1999; Norman and Garcia, 1999).

Previous studies of melt inclusions in Hawaiian basalts have revealed an astonishing diversity of compositions compared to those of erupted lavas, providing increased resolution of the processes that create and modify plume magmas. Ultramafic melts with 18.5–21 wt.% MgO have been inferred from olivine-hosted melt inclusions in Hawaiian tholeiites (Sobolev and Nikogosian, 1994). Trace element patterns of melt inclusions from Mauna Loa range from unusually enriched in LREE to strongly depleted in incompatible trace elements such as LREE, Ba, Nb, U, and Th (Nikogosian and Sobolev, 1996; Sobolev et al., 2000). LREE-depleted inclusions from Mauna Loa that are also enriched in Sr may provide evidence for recycled oceanic lower crust in the Hawaiian plume (Sobolev et al., 2000).

In this paper, olivine-hosted melt inclusions in picritic lavas from Mauna Loa, Kilauea, Loihi, Hualalai, and Koolau volcanoes are used to examine the origin of these magmas, source compositions in the Hawaiian plume, and the compositional effects of interactions between the melt inclusions and the host olivine. Melting relations among the volcanoes, the distinctive compositions of Koolau lavas, and possible contributions of mafic lithologies in the source regions of these magmas are discussed.

## 2. Samples and procedures

Major and trace element compositions of naturally quenched glass melt inclusions in olivine phenocrysts from submarine flows at Loihi, Kilauea, Hualalai, and Mauna Loa were measured by electron microprobe and laser ablation ICPMS, respectively, following procedures described by Garcia et al. (1995b), Norman (1998) and Norman et al. (1998). Matrix glass from pillow margins of the Loihi, Kilauea, and Hualalai flows were also analysed. In addition, melting experiments on partially crystallized inclusions from two Koolau picrites were conducted to homogenize these inclusions to a glass for analysis. No corrections were applied to the trace element abundances for olivine gain or loss to the inclusions during quenching or the melting experiments because such corrections would be small relative to the observed range of trace element compositions. The dataset for this study comprises 290 major element analyses and 110 trace element analyses.

Mineralogy and whole rock compositions of the picrites from Loihi (LO-02-02, LO-02-04), Kilauea (KIL-1-10, KIL-2-1), Hualalai (H-5), and Koolau (KOO-17a, KOO-CF) have been described previously (Norman and Garcia, 1999). Fourteen submarine flows from the southwest rift of Mauna Loa were also included in this study; mineral and glass compositions of these lavas are given by Garcia et al. (1995a). Of significance for this study is the predominance of forsteritic (Fo87-91), normally zoned olivines in all of these picrites (Garcia et al., 1995a; Norman and Garcia, 1999). Olivines of this composition crystallize from melts with at least 13–17% MgO, so the inclusions trapped in these olivines provide a record of the relatively primitive magmas from which they grew. The scarcity of reversely zoned

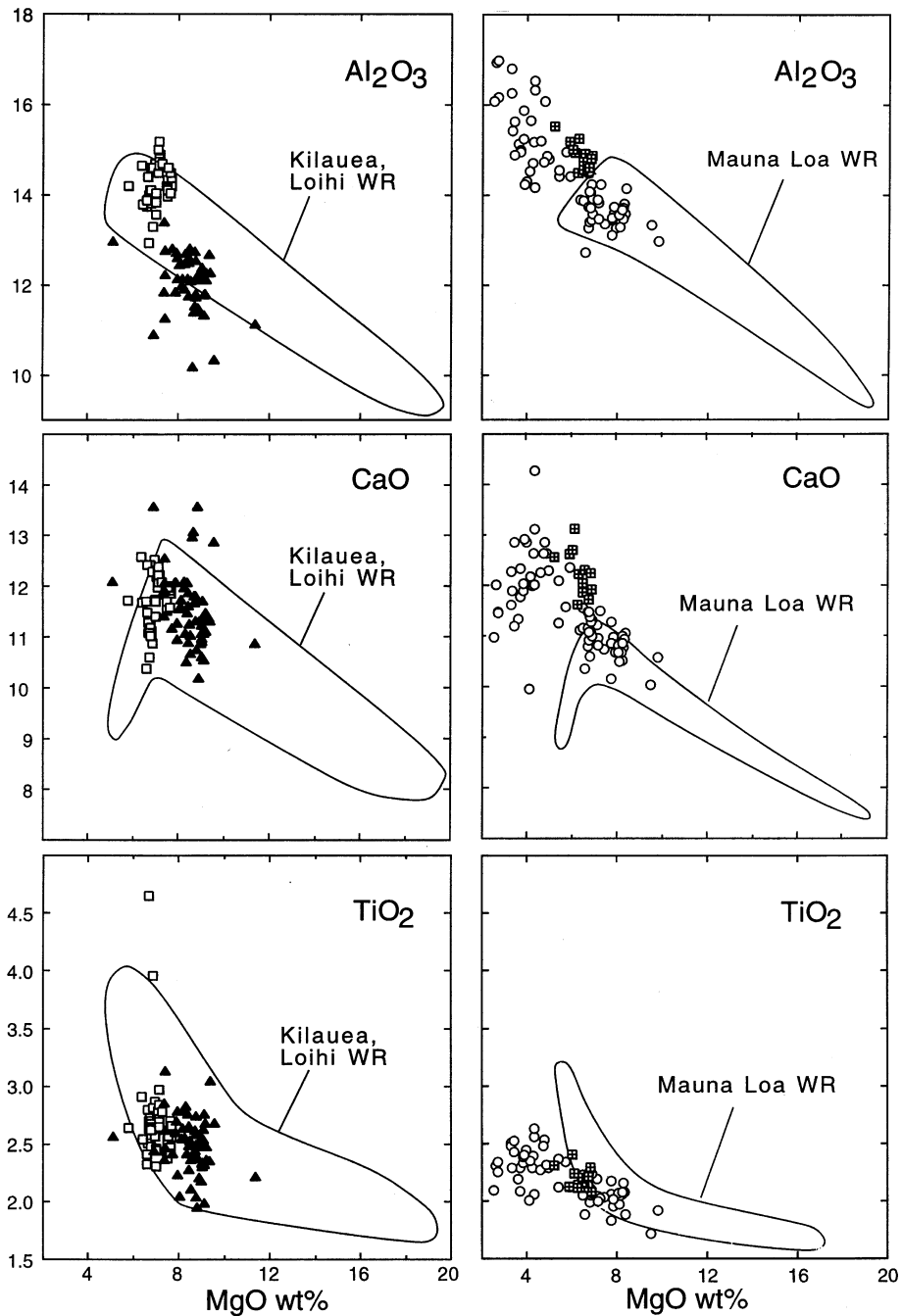


Fig. 1. MgO vs. Al<sub>2</sub>O<sub>3</sub>, CaO, and TiO<sub>2</sub> contents of naturally quenched melt inclusions from Kilauea (open squares), Loihi (filled triangles), Hualalai (crossed square), and Mauna Loa (open circles) compared to compositions of erupted lavas and matrix glasses. Extreme compositions observed in the Mauna Loa inclusions are well outside the range observed for whole rock (WR) samples from that volcano, and reflect compositional modification of the inclusions by quenching and diffusive reaction with the host olivine.

olivines, the lack of plagioclase and pyroxene microphenocrysts or xenocrysts, and the relatively simple populations of olivine compositions in these lavas suggest that they largely avoided the complex processes of mixing and fractionation associated with the evolution of Hawaiian magmas in shallow magma chambers such as those inferred for Kilauea's Puna Ridge (Clague et al., 1995).

The Loihi picrites are unusually water-rich, with up to 1.5% H<sub>2</sub>O dissolved in the melt (Kent et al., 1999a). Major element composition and H<sub>2</sub>O, Cl, B, S, and Be abundances in a suite of melt inclusions from these picrites show that a modified seawater-derived hydrothermal brine was incorporated into these melts during crystallization of the olivine and

trapping of the melt inclusions (Kent et al., 1999a). Assimilation of seawater-derived fluids appears to be widespread at Loihi (Kent et al., 1999b), so these unusually water-rich picrites may represent endmembers of a common process at submarine volcanoes. Melt inclusions in these picrites are enriched in B and Cl, but other incompatible lithophile elements such as P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O were not affected by assimilation of the fluids (Kent et al., 1999a), so we assume that the lithophile trace elements determined here also reflect primary magmatic compositions.

All of the melt inclusions in this study are naturally quenched except for those from the two Koolau picrites (KOO-17a and KOO-CF) which are

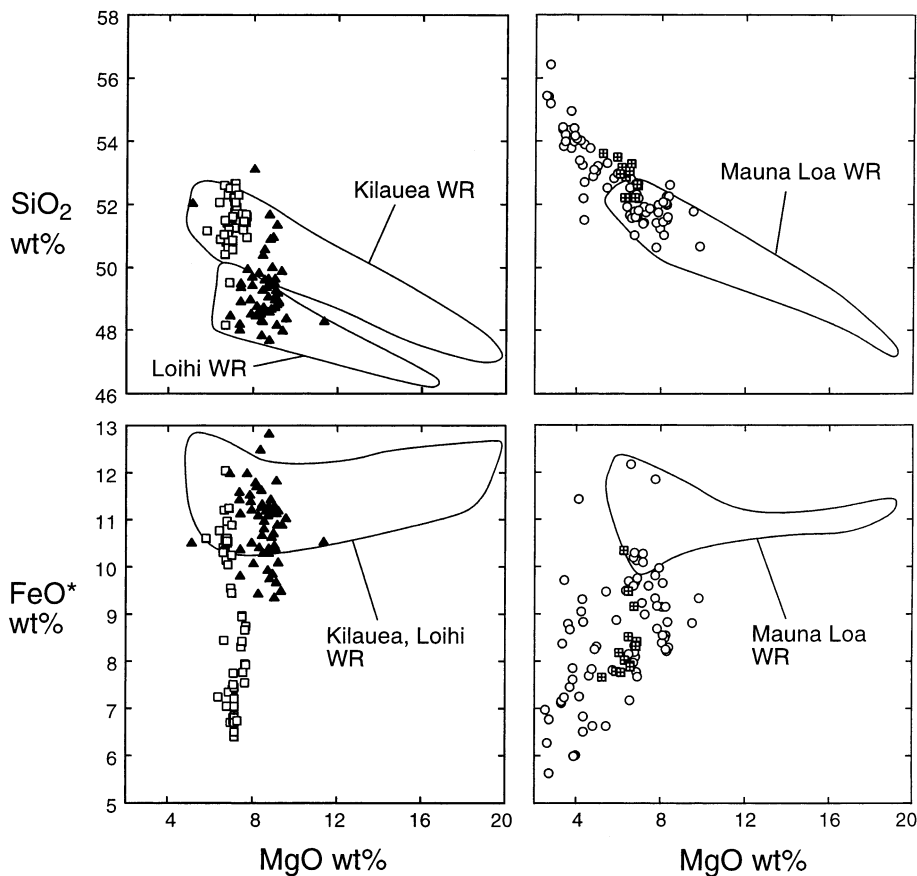


Fig. 2. SiO<sub>2</sub> and FeO\* (total Fe as FeO) vs. MgO contents of naturally quenched inclusions from Kilauea, Loihi, Hualalai, and Mauna Loa compared to whole rock (WR) compositions of erupted lavas and matrix glasses. Symbols same as Fig. 1. The low FeO\* and MgO and high SiO<sub>2</sub> in many of these inclusions reflect post-entrapment loss of FeO and MgO to the host olivine rather than primary magmatic compositions. Loihi inclusions show little evidence for compositional modification.

fine-grained subaerial flows. Olivine-hosted melt inclusions from these samples were re-melted experimentally and quenched to a glass. For these experiments, olivines with observable inclusions were selected and mounted in clear epoxy, then polished to expose the crystal but not the inclusion. The crystals were examined optically and those containing suitable melt inclusions were extracted. Two sets of melting experiments were performed on the Koolau inclusions. One set of experiments involved melting individual inclusions from sample KOO-CF at 1250 °C for approximately 1 min on an optical heating stage, followed by quenching to a glass. In the second set of experiments, batch melting experiments were performed on both samples by placing approximately 60–70 grains of olivine from each sample in Pt boats and suspending them in a gas-mixing muffle furnace at 600 °C. The temperature was ramped to 1250 °C over 2 h and held at this temperature for 20 min before quenching in water. Oxygen fugacity in the furnace was controlled by a 1:1 mixture of CO–CO<sub>2</sub>, corresponding to an  $f_{\text{O}_2} = -10.3$  or Iron–Wustite +1 at 1250 °C. Olivine compositions were measured 50–100 μm from the inclusion. The measured compositions of melted Koolau inclusions and corresponding host olivine show a broad range of  $K_d$  values (Fig. 3), indicating disequilibrium between the melt and the host olivine. The measured major element compositions of these inclusions were corrected to be in equilibrium with the host olivine according to the procedure of Danyushevsky et al. (2000), assuming an FeO<sub>total</sub> content of 10.8 wt.%, corresponding to the bulk rock value of these lavas, and an  $\text{Fe}^{2+}/\text{Fe}^{3+} = 9.0$ . This correction produces compositions with a narrow range of  $K_d$  values that average ~0.32 (Fig. 3).

### 3. Results

#### 3.1. Major elements

Naturally quenched inclusions from Loihi, Kilauea, Hualalai, and Mauna Loa have some of the most extreme compositions observed in Hawaiian magmas (Figs. 1 and 2). Inclusions from Kilauea, Loihi, and Hualalai have MgO values that cluster

Table 1

Major and trace element composition of matrix glass from Hawaiian picrites

	H-5 Hualalai	Kil-1-10 Kilauea	Kil-2-1 Kilauea	LO-O2-O2 Loihi	LO-O2-O4 Loihi
<i>wt.%</i>					
SiO <sub>2</sub>	51.75	50.80	50.85	48.82	49.00
TiO <sub>2</sub>	2.16	2.43	2.64	2.35	2.37
Al <sub>2</sub> O <sub>3</sub>	14.18	13.55	14.05	12.25	12.25
FeO	10.77	10.78	10.53	11.05	11.10
MnO	0.20	0.18	0.18	0.15	0.20
MgO	6.82	7.47	6.77	9.11	9.00
CaO	11.13	11.10	11.03	10.92	10.98
Na <sub>2</sub> O	2.19	2.20	2.25	2.33	2.35
K <sub>2</sub> O	0.33	0.40	0.46	0.53	0.54
P <sub>2</sub> O <sub>5</sub>	0.23	0.25	0.28	0.26	0.28
Total	99.76	99.16	99.04	97.77	98.07
<i>ppm</i>					
Sc	31	31	28	28	27
V	295	312	306	331	340
Cr	296	322	215	538	560
Co	40	48	38	57	55
Ni	92	124	95	215	209
Cu	144	162	141	278	272
Zn	95	131	103	149	152
Ga	20.4	23.2	21.7	22.6	23.1
Rb	5.2	7.8	8.4	12.9	12.9
Sr	291	348	353	368	377
Y	23.4	25.7	24.5	20.9	20.5
Zr	120	156	155	136	134
Nb	9.7	14.9	15.7	18.9	19.4
Mo	0.53	0.82	0.64	0.84	0.98
Cs	0.04	0.10	0.07	0.13	0.14
Ba	67	105	108	147	156
La	8.4	12.1	12.2	14.4	15.0
Ce	21.3	29.6	30.5	34.5	36.3
Pr	3.15	4.26	4.35	4.59	4.92
Nd	15.9	21.4	21.1	21.4	22.5
Sm	4.49	5.63	5.6	5.03	5.43
Eu	1.54	1.99	1.96	1.70	1.82
Gd	4.80	5.96	5.68	5.02	4.94
Dy	4.59	5.41	5.02	4.27	4.46
Ho	0.91	1.03	0.97	0.78	0.81
Er	2.35	2.55	2.53	2.03	2.12
Yb	2.01	2.19	2.03	1.76	1.78
Lu	0.28	0.30	0.28	0.24	0.24
Hf	3.19	4.08	3.99	3.5	3.46
Ta	0.63	0.91	0.93	1.08	1.16
Pb	0.94	1.30	1.08	1.95	1.99
Th	0.57	0.95	0.92	1.11	1.11
U	0.19	0.33	0.33	0.36	0.37

Data by EMP (majors) and LA-ICPMS (traces).

Table 2

Major element compositions of naturally quenched melt inclusions from Loihi picrites LO-02-02 and LO-02-04

	LO-02-02							LO-02-04	
	5/1	5/2	4/1	6/6	6/7	6/8	6/9	1/1	1/2
SiO <sub>2</sub>	48.95	48.77	48.31	49.55	48.00	50.60	48.55	49.95	49.00
TiO <sub>2</sub>	2.48	2.48	2.22	2.18	3.05	2.11	2.42	2.42	2.60
Al <sub>2</sub> O <sub>3</sub>	12.28	12.40	11.13	12.25	12.28	12.56	12.53	12.82	11.87
FeO	10.10	10.47	10.55	10.73	10.90	10.98	12.50	12.00	11.55
MgO	9.21	9.02	11.38	8.98	9.38	8.54	8.34	7.71	7.86
CaO	11.51	10.65	10.90	10.90	11.34	10.70	10.54	11.20	12.10
Na <sub>2</sub> O	2.24	2.25	2.05	2.43	1.97	2.37	2.01	2.06	2.22
K <sub>2</sub> O	0.52	0.55	0.52	0.57	0.48	0.38	0.88	0.31	0.52
P <sub>2</sub> O <sub>5</sub>	0.36	0.29	0.29	0.18	0.27	0.18	0.39	0.31	0.33
Sum	97.65	96.88	97.35	97.77	97.67	98.42	98.16	98.78	98.05
	1/3	1/4	1/5	2/1	2/2	2/3	2/4	2/5	3/1
SiO <sub>2</sub>	49.30	49.65	48.70	47.85	48.30	48.50	48.50	48.95	48.90
TiO <sub>2</sub>	2.49	2.45	2.38	2.76	2.66	2.80	2.45	2.47	2.37
Al <sub>2</sub> O <sub>3</sub>	11.78	11.55	11.50	12.53	12.52	12.50	10.91	11.28	12.12
FeO	11.30	11.10	11.45	11.65	11.35	11.10	12.00	11.15	11.20
MgO	8.44	8.70	8.83	8.41	8.42	8.27	6.90	7.40	9.20
CaO	11.65	11.70	13.60	12.10	11.90	12.00	13.60	12.10	11.15
Na <sub>2</sub> O	2.11	2.15	1.76	2.11	2.08	2.05	2.00	2.02	2.36
K <sub>2</sub> O	0.57	0.39	0.42	0.41	0.49	0.52	0.49	1.26	0.51
P <sub>2</sub> O <sub>5</sub>	0.30	0.29	0.29	0.30	0.41	0.36	0.19	1.16	0.29
Sum	97.94	97.98	98.93	98.12	98.13	98.10	97.04	97.79	98.10
	3/2	3/3	3/4	3/5	3/6	3/7	4/1	6/1	6/2
SiO <sub>2</sub>	49.10	49.00	48.85	48.60	48.60	49.40	49.45	48.40	48.20
TiO <sub>2</sub>	2.34	2.33	2.32	2.50	2.38	2.40	2.59	2.68	2.76
Al <sub>2</sub> O <sub>3</sub>	12.20	12.20	12.20	12.55	11.40	10.20	12.15	10.35	11.35
FeO	11.30	11.30	11.15	10.40	11.20	11.20	11.30	11.05	11.85
MgO	9.00	9.01	9.12	8.75	8.68	8.60	8.73	9.55	9.13
CaO	11.00	11.10	11.10	11.75	13.10	13.00	11.85	12.90	11.45
Na <sub>2</sub> O	2.29	2.27	2.28	2.28	2.06	2.20	2.26	2.04	2.26
K <sub>2</sub> O	0.50	0.50	0.50	0.71	0.55	0.50	0.52	0.70	0.61
P <sub>2</sub> O <sub>5</sub>	0.30	0.29	0.31	0.43	0.33	0.40	0.33	0.30	0.35
Sum	98.03	98.00	97.83	97.97	98.30	97.90	99.18	97.97	97.96
	6/3	6/4	8/1	9/1	9/2	9/3	10/1	10/2	10/3
SiO <sub>2</sub>	49.20	49.00	49.30	51.70	47.70	48.55	49.10	49.10	49.90
TiO <sub>2</sub>	2.68	2.54	2.63	2.04	2.74	2.70	2.62	2.31	2.36
Al <sub>2</sub> O <sub>3</sub>	11.82	12.27	12.17	11.81	11.75	12.73	12.75	12.27	12.70
FeO	10.90	10.40	10.40	10.30	12.85	11.40	9.95	11.20	9.50
MgO	9.16	9.06	9.06	8.77	8.74	7.88	8.72	9.00	9.35
CaO	11.40	11.75	11.75	11.35	11.35	12.10	11.85	10.95	11.40
Na <sub>2</sub> O	2.05	2.31	2.32	1.90	2.13	2.16	2.35	2.35	1.96
K <sub>2</sub> O	0.83	0.65	0.65	0.27	0.61	0.58	0.50	0.52	0.53
P <sub>2</sub> O <sub>5</sub>	0.52	0.34	0.33	0.22	0.34	0.44	0.31	0.28	0.38
Sum	98.56	98.32	98.61	98.36	98.21	98.54	98.15	97.98	98.08

Low totals indicate high water contents in these glasses (Kent et al., 1999a).

Table 3

Major element data for naturally quenched melt inclusions from Kilauea picrites KIL-2-1 and KIL-1-10

KIL-2-1											
	1/1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	1/10	1/11
SiO <sub>2</sub>	51.40	50.80	52.55	52.60	52.30	50.85	50.40	50.65	48.15	49.50	51.30
TiO <sub>2</sub>	2.73	2.70	2.87	2.32	2.70	2.67	2.51	2.48	4.65	3.96	2.57
Al <sub>2</sub> O <sub>3</sub>	14.05	13.90	14.70	13.75	14.60	14.00	13.90	13.81	12.95	13.30	13.90
FeO	10.15	10.57	6.70	10.40	7.05	10.50	11.20	10.97	12.05	11.25	9.55
MnO	0.15	0.16	0.11	0.15	0.11	0.16	0.17	0.17	0.19	0.16	0.15
MgO	6.73	6.66	6.94	6.61	6.79	6.76	6.64	6.79	6.69	6.86	6.93
CaO	10.62	11.32	12.55	10.40	12.45	11.05	11.50	11.20	11.10	10.90	11.75
Na <sub>2</sub> O	2.41	2.25	2.13	2.17	2.22	2.23	2.05	2.10	2.06	2.09	2.19
K <sub>2</sub> O	0.46	0.35	0.43	0.44	0.47	0.45	0.41	0.42	0.50	0.57	0.46
P <sub>2</sub> O <sub>5</sub>	0.27	0.39	0.27	0.31	0.27	0.27	0.23	0.26	0.35	0.42	0.31
Total	98.97	99.10	99.25	99.15	98.96	98.94	99.01	98.85	98.69	99.01	99.11
	1/12	1/13	2/1	2/2	2/3	2/4	2/5	2/6	2/7	2/8	2/9
SiO <sub>2</sub>	52.15	52.65	50.95	51.50	52.05	52.20	52.05	52.50	51.15	51.70	50.95
TiO <sub>2</sub>	2.81	2.80	2.64	2.80	2.80	2.75	2.91	2.81	2.64	2.75	2.63
Al <sub>2</sub> O <sub>3</sub>	14.65	14.60	14.00	14.40	14.55	14.60	14.65	14.60	14.21	14.65	14.00
FeO	6.85	6.80	10.60	8.45	7.35	7.40	7.25	7.35	10.60	7.45	10.35
MnO	0.08	0.07	0.18	0.15	0.13	0.15	0.16	0.14	0.19	0.15	0.19
MgO	7.15	7.08	6.75	6.65	7.10	7.05	6.35	6.87	5.76	7.15	6.67
CaO	12.40	12.25	11.25	12.45	12.20	12.20	12.60	12.30	11.75	12.20	11.30
Na <sub>2</sub> O	2.26	2.28	2.20	2.17	2.28	2.27	2.28	2.21	2.21	2.28	2.29
K <sub>2</sub> O	0.47	0.45	0.46	0.42	0.49	0.48	0.48	0.46	0.46	0.47	0.46
P <sub>2</sub> O <sub>5</sub>	0.27	0.35	0.27	0.27	0.32	0.27	0.34	0.29	0.24	0.27	0.25
Total	99.09	99.33	99.30	99.26	99.27	99.37	99.07	99.53	99.21	99.07	99.09
	2/10	3/1	3/2	3/3	3/4	3/5	3/6	3/7	3/8	3/9	3/10
SiO <sub>2</sub>	50.85	51.25	51.20	51.75	52.65	51.90	51.90	52.50	50.90	50.85	52.20
TiO <sub>2</sub>	2.63	2.74	2.65	2.64	2.72	2.80	2.80	2.69	2.64	2.64	2.79
Al <sub>2</sub> O <sub>3</sub>	14.05	14.50	14.05	14.50	14.90	14.80	14.90	14.80	14.05	14.10	15.00
FeO	10.55	7.50	10.05	7.75	6.40	7.05	6.75	6.50	10.60	10.50	6.75
MnO	0.20	0.15	0.17	0.16	0.13	0.13	0.12	0.11	0.18	0.18	0.12
MgO	6.83	7.07	6.81	7.10	7.15	7.13	7.17	7.11	6.75	6.74	7.10
CaO	11.15	12.00	11.05	12.30	12.10	12.35	12.25	12.30	11.20	11.10	12.35
Na <sub>2</sub> O	2.25	2.33	2.35	2.37	2.32	2.34	2.35	2.30	2.34	2.32	2.37
K <sub>2</sub> O	0.46	0.48	0.48	0.32	0.49	0.50	0.50	0.49	0.49	0.47	0.48
P <sub>2</sub> O <sub>5</sub>	0.28	0.24	0.24	0.27	0.37	0.35	0.39	0.37	0.25	0.28	0.27
Total	99.25	98.26	99.05	99.16	99.23	99.35	99.19	99.17	99.40	99.08	99.43
KIL-1-10											
	3/11	3/12	3/13	3/14	3/15	1/1	2/1	2/2	2/3	4/1	4/2
SiO <sub>2</sub>	52.50	52.05	51.70	52.30	51.05	50.90	51.45	50.95	50.57	51.35	51.70
TiO <sub>2</sub>	2.65	2.84	2.97	2.78	2.62	2.54	2.70	2.66	2.46	2.53	2.44
Al <sub>2</sub> O <sub>3</sub>	14.75	14.65	15.20	14.70	14.10	13.80	14.50	14.20	13.57	14.33	14.21
FeO	6.80	7.20	6.70	6.75	10.55	10.76	7.95	8.75	10.88	8.40	8.30
MnO	0.13	0.13	0.13	0.11	0.17	0.17	0.13	0.18	0.18	0.17	0.15
MgO	7.15	7.13	7.13	7.26	6.76	6.41	7.63	7.69	6.99	7.51	7.45
CaO	12.10	12.25	12.40	12.10	11.05	11.70	12.02	11.93	11.43	11.80	11.87
Na <sub>2</sub> O	2.37	2.35	2.34	2.28	2.34	2.18	2.18	2.12	2.16	2.23	2.23
K <sub>2</sub> O	0.51	0.45	0.44	0.46	0.48	0.39	0.41	0.42	0.39	0.41	0.39

(continued on next page)

Table 3 (continued)

	KIL-2-1					KIL-1-10					
	3/11	3/12	3/13	3/14	3/15	1/1	2/1	2/2	2/3	4/1	4/2
P <sub>2</sub> O <sub>5</sub>	0.40	0.27	0.31	0.49	0.27	0.26	0.23	0.30	0.22	0.28	0.25
Total	99.36	99.32	99.32	99.23	99.39	99.11	99.20	99.20	98.85	99.01	98.99
	4/3	4/4	5/1	5/2	5/3	5/4	6/1	6/2	8/1	8/2	
SiO <sub>2</sub>	51.45	51.25	51.60	50.87	51.05	51.60	51.68	51.20	51.43	51.45	
TiO <sub>2</sub>	2.45	2.46	2.56	2.45	2.41	2.31	2.47	2.38	2.42	2.57	
Al <sub>2</sub> O <sub>3</sub>	14.15	13.97	14.37	13.83	13.88	14.05	14.50	14.10	14.05	14.60	
FeO	8.42	8.97	7.93	10.25	10.30	9.44	7.55	8.95	8.67	7.77	
MnO	0.14	0.15	0.16	0.17	0.17	0.19	0.14	0.16	0.18	0.13	
MgO	7.51	7.50	7.69	6.99	6.60	7.00	7.61	7.47	7.62	7.52	
CaO	11.54	11.59	11.88	11.77	11.72	11.73	11.95	11.73	11.60	12.00	
Na <sub>2</sub> O	2.23	2.23	2.20	2.10	2.18	2.16	2.20	2.19	2.17	2.22	
K <sub>2</sub> O	0.40	0.41	0.42	0.36	0.40	0.37	0.45	0.36	0.40	0.38	
P <sub>2</sub> O <sub>5</sub>	0.24	0.25	0.28	0.22	0.23	0.25	0.28	0.24	0.25	0.21	
Total	98.53	98.78	99.09	99.01	98.94	99.10	98.83	98.78	98.79	98.85	

around 6–8 wt.%, similar to those of the matrix glasses from these samples (Figs. 1 and 2; Tables 1–4). The Mauna Loa inclusions have MgO contents that extend from values similar to those of the matrix glasses (5.8–8.4 wt.%; Garcia et al., 1995a) to as low as 2.5 wt.% MgO (Figs. 1 and 2; Table 5). FeO\* (total Fe calculated as FeO) in the naturally quenched inclusions from Kilauea and Mauna Loa also extends to more extreme values than those observed in whole rocks and matrix glasses (Fig. 2). Loihi inclusions are exceptional in having FeO\* contents similar to those of erupted tholeiites from this volcano. All of the other suites show trends to

very low FeO\* (Fig. 2). Kilauea and Loihi inclusions show a relatively wide range of FeO\* at constant MgO, whereas the inclusions from Mauna Loa and Hualalai show a general trend of decreasing FeO\* with decreasing MgO (Fig. 2).

Loihi and Kilauea inclusions have Al<sub>2</sub>O<sub>3</sub>, CaO, and TiO<sub>2</sub> contents falling within the range observed in erupted tholeiites and matrix glasses from these volcanoes, with the exception of higher CaO and lower Al<sub>2</sub>O<sub>3</sub> in some of the Loihi inclusions (Fig. 1). SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and CaO contents of the Mauna Loa and Hualalai inclusions range to values considerably higher than those of erupted lavas, and show negative

Table 4

Major element data for naturally quenched melt inclusions from Hualalai picrite H-5

H-5	1/1	2/2	2/3	3/1	3/2	3/3	3/4	3/5	4/1	4/2	4/3	4/4	5/1
SiO <sub>2</sub>	52.61	53.50	52.88	53.28	53.18	53.30	53.05	52.20	52.62	52.97	52.21	52.22	53.63
TiO <sub>2</sub>	2.08	2.12	2.14	2.11	2.24	2.17	2.16	2.11	2.29	2.40	2.20	2.21	2.31
Al <sub>2</sub> O <sub>3</sub>	14.88	15.20	15.25	14.78	14.95	14.91	14.73	14.50	14.80	15.02	14.55	14.60	15.52
FeO	8.42	7.78	8.02	7.92	7.76	7.88	8.53	10.35	8.33	8.18	9.48	9.16	7.67
MnO	0.19	0.15	0.16	0.17	0.17	0.16	0.17	0.19	0.14	0.16	0.18	0.18	0.17
MgO	6.85	5.88	6.26	6.55	6.08	6.56	6.45	6.21	6.80	6.00	6.45	6.73	5.20
CaO	11.92	12.63	12.22	12.31	13.12	12.30	12.05	11.62	12.25	12.70	11.87	11.72	12.57
Na <sub>2</sub> O	2.21	2.16	2.21	2.06	2.04	2.09	2.15	2.15	2.06	2.10	2.16	2.16	2.26
K <sub>2</sub> O	0.37	0.30	0.33	0.26	0.07	0.34	0.32	0.32	0.29	0.31	0.34	0.34	0.33
P <sub>2</sub> O <sub>5</sub>	0.25	0.21	0.24	0.30	0.50	0.28	0.25	0.21	0.34	0.20	0.23	0.20	0.20
Total	99.78	99.93	99.71	99.74	100.11	99.99	99.86	99.86	99.92	100.04	99.67	99.52	99.86



Table 5  
Major element data for naturally quenched melt inclusions from Mauna Loa

	182-3-2	182-3-10	182-6-2	182-6-6	182-6-9	182-6-20	182-7-2	182-7-3	182-7-4	182-7-5
SiO <sub>2</sub>	55.42	56.44	52.27	52.63	51.42	52.00	54.39	53.27	53.79	55.22
TiO <sub>2</sub>	2.31	2.34	2.08	1.88	2.18	2.06	2.20	2.29	2.29	2.25
Al <sub>2</sub> O <sub>3</sub>	16.95	16.98	13.60	14.15	13.50	13.73	15.15	14.72	14.96	16.17
FeO	6.28	5.63	8.85	8.30	9.83	8.56	8.80	9.06	8.68	6.79
MnO	0.11	0.11	0.16	0.14	0.16	0.13	0.16	0.15	0.14	0.13
MgO	2.57	2.67	8.30	8.34	7.71	8.21	3.56	4.20	3.67	2.66
CaO	12.02	11.48	10.95	11.07	11.29	11.00	11.35	12.01	11.79	11.47
Na <sub>2</sub> O	2.72	2.86	2.07	2.06	2.06	2.13	2.36	2.23	2.56	2.79
K <sub>2</sub> O	0.43	0.45	0.32	0.28	0.28	0.35	0.40	0.35	0.36	0.40
P <sub>2</sub> O <sub>5</sub>	0.28	0.27	0.21	0.25	0.20	0.29	0.24	0.22	0.23	0.27
Sum	99.10	99.24	98.79	99.08	98.63	98.46	98.60	98.50	98.48	98.14
	182-7-6	182-7-8	182-8-1	182-8-3	182-8-5	182-8-7	182-8-10	183-3-1	183-3-3	183-3-5
SiO <sub>2</sub>	55.46	53.88	52.72	53.93	52.21	53.12	54.41	51.30	50.96	51.46
TiO <sub>2</sub>	2.10	2.28	2.63	2.06	2.39	2.53	2.51	2.00	1.83	2.05
Al <sub>2</sub> O <sub>3</sub>	16.09	15.43	16.34	16.53	15.19	16.10	16.80	12.95	12.57	13.57
FeO	6.99	8.38	6.52	6.84	9.33	6.64	7.12	8.79	10.11	9.16
MnO	0.14	0.15	0.12	0.13	0.16	0.11	0.11	0.16	0.16	0.14
MgO	2.49	3.32	4.28	4.32	4.25	4.76	3.27	10.23	10.03	8.03
CaO	10.99	11.90	13.11	12.01	12.64	12.87	11.63	10.26	9.85	10.68
Na <sub>2</sub> O	2.81	2.45	2.33	2.84	2.11	2.31	2.58	2.18	2.09	2.19
K <sub>2</sub> O	0.44	0.43	0.39	0.38	0.33	0.42	0.45	0.29	0.27	0.30
P <sub>2</sub> O <sub>5</sub>	0.26	0.26	0.25	0.24	0.22	0.30	0.29	0.22	0.20	0.21
Sum	97.75	98.48	98.69	99.27	98.83	99.15	99.17	98.38	98.11	97.80
	183-3-6	183-3-12	183-3-13	183-3-14	183-3-15	183-3-16	183-3-17	183-3-18	183-3-19	183-3-21
SiO <sub>2</sub>	52.05	51.96	51.39	51.42	51.62	51.52	51.26	51.06	52.08	52.27
TiO <sub>2</sub>	2.07	2.15	2.20	2.06	2.16	2.08	2.01	2.05	2.07	2.08
Al <sub>2</sub> O <sub>3</sub>	13.68	13.90	13.91	13.46	13.81	13.47	13.29	13.31	13.57	13.73
FeO	8.51	9.50	9.25	9.34	8.23	9.17	9.99	9.66	8.39	8.26
MnO	0.17	0.15	0.16	0.16	0.15	0.15	0.16	0.15	0.15	0.15
MgO	8.18	6.34	7.08	7.73	8.25	8.23	7.87	8.06	8.04	8.19
CaO	10.68	11.12	11.22	10.85	10.79	10.51	10.69	10.51	10.83	10.86
Na <sub>2</sub> O	2.21	2.28	2.19	2.16	2.20	2.21	2.17	2.20	2.18	2.24
K <sub>2</sub> O	0.29	0.29	0.30	0.31	0.33	0.32	0.29	0.33	0.31	0.30
P <sub>2</sub> O <sub>5</sub>	0.22	0.21	0.28	0.24	0.24	0.20	0.20	0.23	0.21	0.28
Sum	98.04	97.90	97.97	97.72	97.77	97.86	97.93	97.54	97.84	98.36
	183-3-27	183-3-28l	183-3-30	183-7-li	183-7-2	183-7-5	183-7-6	183-7-8	183-7-11	183-11-a
SiO <sub>2</sub>	51.88	52.01	52.10	51.04	52.81	51.80	52.21	52.62	51.57	52.58
TiO <sub>2</sub>	2.03	1.96	1.97	2.12	2.21	2.14	1.99	2.10	1.88	2.08
Al <sub>2</sub> O <sub>3</sub>	13.36	13.62	13.68	13.29	14.54	13.76	13.72	14.25	12.73	14.08
FeO	9.60	8.71	8.57	10.20	7.18	9.61	9.68	7.79	12.18	8.35
MnO	0.17	0.15	0.13	0.15	0.14	0.16	0.16	0.15	0.21	0.13
MgO	7.41	7.79	8.08	6.69	6.49	6.69	6.75	6.80	6.53	6.73
CaO	10.74	10.99	10.80	10.81	11.89	11.16	10.61	11.27	10.36	11.48
Na <sub>2</sub> O	2.19	2.22	2.23	1.43	2.38	2.22	2.30	2.38	2.02	2.37
K <sub>2</sub> O	0.29	0.28	0.30	1.17	0.30	0.29	0.29	0.29	0.28	0.31
P <sub>2</sub> O <sub>5</sub>	0.20	0.19	0.19	0.18	0.22	0.21	0.19	0.21	0.19	0.23
Sum	97.88	97.91	98.04	97.09	98.17	98.02	97.90	97.86	97.97	98.34

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Table 5 (continued)

	183-11-b	183-11-1m	183-11-2i	183-11-4	183-11-13	183-12-7b	183-12-9	183-12-14	183-12-16	183-13-6
SiO <sub>2</sub>	51.62	51.60	51.84	52.32	51.67	51.43	53.00	51.77	52.62	51.94
TiO <sub>2</sub>	2.06	2.05	2.07	2.11	2.05	2.04	2.12	2.02	2.16	2.00
Al <sub>2</sub> O <sub>3</sub>	13.42	13.46	13.60	14.07	13.88	13.49	14.43	14.24	14.50	13.83
FeO	10.29	10.14	9.77	8.10	9.70	10.10	8.89	9.01	7.98	10.27
MnO	0.15	0.16	0.16	0.14	0.15	0.16	0.15	0.15	0.14	0.16
MgO	6.71	6.82	6.85	6.79	6.47	7.11	5.87	7.22	6.69	7.12
CaO	11.09	11.06	11.00	11.38	11.16	10.96	12.36	11.50	11.49	10.83
Na <sub>2</sub> O	2.29	2.32	2.32	2.25	2.26	2.31	1.69	2.07	1.94	2.15
K <sub>2</sub> O	0.31	0.32	0.32	0.30	0.30	0.30	0.34	0.28	0.33	0.30
P <sub>2</sub> O <sub>5</sub>	0.19	0.19	0.18	0.29	0.20	0.17	0.20	0.21	0.27	0.18
Sum	98.13	98.11	98.10	97.75	97.84	98.07	99.03	98.48	98.12	98.79
	183-15-1	183-15-3	183-15-4	183-15-8	183-15-9	183-15-x	183-15-x1	184-2-1	184-2-2	184-2-5
SiO <sub>2</sub>	50.68	54.47	54.03	54.04	54.44	54.22	53.42	50.66	51.76	52.61
TiO <sub>2</sub>	1.92	2.48	2.33	2.35	2.38	2.53	2.01	1.84	2.02	1.93
Al <sub>2</sub> O <sub>3</sub>	12.98	16.27	15.89	15.65	15.27	15.64	14.53	13.11	13.75	12.92
FeO	9.34	7.17	7.86	7.26	7.63	7.25	11.45	11.86	9.19	7.87
MnO	0.14	0.13	0.14	0.14	0.14	0.14	0.17	0.18	0.15	0.16
MgO	9.77	3.25	3.79	4.10	3.80	3.39	4.06	7.71	7.79	10.34
CaO	10.58	12.27	11.90	12.19	12.05	12.85	9.96	10.17	10.85	10.22
Na <sub>2</sub> O	2.30	2.25	2.46	2.34	2.17	1.84	2.17	2.05	2.15	1.95
K <sub>2</sub> O	0.31	0.41	0.37	0.37	0.38	0.40	0.36	0.27	0.30	0.30
P <sub>2</sub> O <sub>5</sub>	0.21	0.24	0.23	0.25	0.21	0.24	0.21	0.24	0.21	0.18
Sum	98.24	98.94	99.00	98.69	98.46	98.51	98.34	98.09	98.16	98.47
	184-2-9	184-5-2i	184-5-2	184-5-3	184-6-1	184-6-2	184-6-3	184-6-12	184-7-1	184-7-1m
SiO <sub>2</sub>	51.04	52.22	52.22	52.67	52.83	52.54	53.32	52.54	53.23	54.11
TiO <sub>2</sub>	1.97	2.24	2.24	2.24	2.34	2.22	2.37	2.12	2.29	2.44
Al <sub>2</sub> O <sub>3</sub>	12.70	13.94	13.94	14.53	14.96	14.60	14.42	14.55	14.80	14.30
FeO	8.78	7.69	7.69	8.20	7.82	8.17	6.65	9.47	8.31	6.02
MnO	0.15	0.14	0.14	0.13	0.13	0.13	0.12	0.16	0.14	0.13
MgO	10.62	6.87	6.87	6.71	5.70	6.45	5.36	5.38	4.93	3.94
CaO	10.15	11.35	11.32	10.93	11.58	11.57	12.11	11.26	12.29	12.86
Na <sub>2</sub> O	2.10	2.42	2.42	2.32	2.35	2.24	2.42	2.19	2.19	2.51
K <sub>2</sub> O	0.28	0.30	0.30	0.34	0.35	0.32	0.42	0.34	0.29	0.29
P <sub>2</sub> O <sub>5</sub>	0.19	0.21	0.21	0.23	0.25	0.25	0.24	0.22	0.22	0.24
Sum	97.98	97.34	97.34	98.31	98.31	98.50	97.43	98.25	98.71	96.84
	184-7-1r	184-7-3	184-7-8	184-7-9	184-7-10	183-7-5				
SiO <sub>2</sub>	54.20	53.79	53.06	54.01	52.89	51.80				
TiO <sub>2</sub>	2.40	2.27	2.31	2.43	2.48	2.14				
Al <sub>2</sub> O <sub>3</sub>	14.24	15.21	14.88	14.89	14.74	13.76				
FeO	6.00	7.70	8.26	9.71	7.84	9.61				
MnO	0.12	0.13	0.15	0.16	0.13	0.16				
MgO	3.86	4.56	4.81	3.40	4.69	6.69				
CaO	12.92	12.26	12.65	11.21	12.63	11.16				
Na <sub>2</sub> O	2.46	2.29	2.22	2.35	1.98	2.22				
K <sub>2</sub> O	0.29	0.33	0.33	0.45	0.46	0.29				
P <sub>2</sub> O <sub>5</sub>	0.21	0.23	0.24	0.23	0.26	0.21				
Sum	96.70	98.76	98.92	98.84	98.09	98.02				

correlations with MgO (Figs. 1 and 2). SiO<sub>2</sub> in the Loihi inclusions also extends to higher values compared to the erupted lavas, but no correlation with MgO is apparent (Fig. 2).

Corrected major element compositions of the Koolau melt inclusions (Fig. 3; Table 6) correspond well to magmatic trends observed in whole rock compositions of erupted Koolau tholeiites, with MgO contents of 8–14% (Fig. 4). The Koolau inclusions have low TiO<sub>2</sub> and low CaO at a given SiO<sub>2</sub> content compared to inclusions from the other volcanoes, producing higher Na<sub>2</sub>O/TiO<sub>2</sub> and lower CaO/Al<sub>2</sub>O<sub>3</sub> ratios (Figs. 5 and 6). The high MgO contents of corrected Koolau inclusion compositions (up to 14 wt.%), and the close correspondence between the major element compositions of the inclusions and erupted Koolau lavas show that the melt inclusions and their host olivines are genetically related to Koolau magmatism rather than xenocrysts. This provides additional evidence that

at least some of the magmas feeding Koolau were picritic (Garcia, 2000) and that Koolau was similar to other Hawaiian volcanoes in this respect.

### 3.2. Trace elements

In both the matrix glasses and the melt inclusions, concentrations of incompatible trace elements (e.g., La, Zr, Nb, Ba, Sr) generally decrease in the sequence Loihi > Kilauea > Hualalai ≈ Mauna Loa (Figs. 7–9; Table 7). Two inclusions from Mauna Loa are exceptional in having the highest concentrations of highly incompatible elements (e.g., La, Nb, Ba) found in this study (Figs. 8 and 9). The Mauna Loa inclusions with anomalously low MgO (<6 wt.%) also tend to have higher incompatible element abundances (Fig. 10). Koolau melt inclusions have LREE and Zr contents similar to those from the other volcanoes, but they are distinguished by generally higher Sr contents (Figs. 9 and 10). Niobium contents of the Koolau inclusions range from similar to those of Mauna Loa to the lowest values found by this study (Fig. 9).

Incompatible trace element ratios such La/Yb, Zr/Nb, Sr/Ba, and Ba/Nb are especially useful for understanding the petrogenesis of Hawaiian tholeiites because they provide information about melting and source characteristics in the plume, and should not be affected by olivine fractionation or compositional modification of an inclusion by gain or loss of olivine during eruption or the melting experiments. Zr/Nb ratios of Hawaiian tholeiites typically correlate with Sr, Nd, and Pb isotopic compositions (Roden et al., 1994; Rhodes, 1996; Norman and Garcia, 1999) and therefore are a useful proxy for recognizing contributions from different source components where isotopic data are not available. The Loihi inclusions tend to have high La/Yb and low Zr/Nb, Zr/La, and Sr/Ba ratios, whereas those from Mauna Loa tend to have low La/Yb and high Zr/Nb, Zr/La, and Sr/Ba (Figs. 8 and 11). The two inclusions from Mauna Loa with high incompatible element contents also have unusually low Zr/Nb and high La/Yb ratios for this volcano (Figs. 8 and 11). The Kilauea melt inclusions tend to have trace element compositions intermediate between those from Loihi and Mauna Loa. All of the inclusions from Mauna Loa, Kilauea, and Loihi have similar Ba/Nb ratios (Fig. 9). Koolau inclusions have distinctly higher Ba/Nb (Figs. 9 and 11), and Zr/

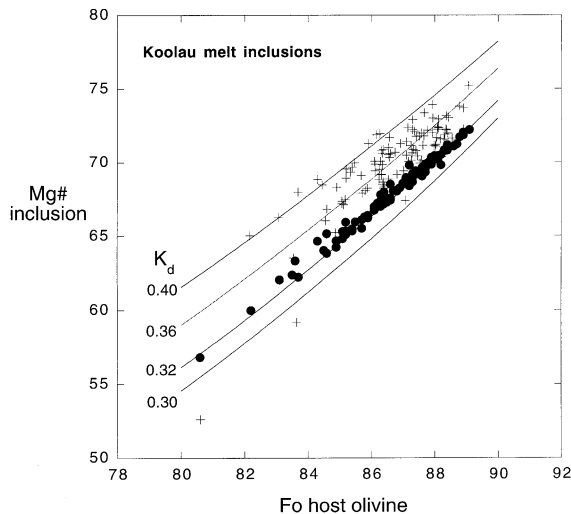


Fig. 3. Mg# (Mg/Mg + Fe atomic) of experimentally melted Koolau inclusions compared to the forsterite content (Fo) of their host olivine. Measured compositions of the inclusions (crosses) span a broad range of  $K_d$  that extend to relatively high values, indicating disequilibrium related primarily to loss of Fe from the inclusion. The corrected compositions of these inclusions (filled circles) show a much more restricted range of  $K_d$  values that average  $\sim 0.32$ . The inclusion compositions were corrected according to the procedures outlined by Danyushevsky et al. (2000) assuming 10.8% FeO in the melt and  $\text{Fe}^{2+}/\text{Fe}^{3+} = 9.0$ .

Table 6

Corrected major element data for experimentally melted inclusions and host olivine from Koolau picrites

KOO-17A														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO <sub>2</sub>	50.91	51.30	50.95	51.51	50.94	51.57	51.55	52.08	51.21	51.31	52.46	51.68	49.24	50.55
TiO <sub>2</sub>	1.77	1.53	1.51	1.54	1.51	1.67	1.72	1.75	1.60	1.60	1.59	1.65	2.41	1.30
Al <sub>2</sub> O <sub>3</sub>	12.35	12.13	12.10	11.93	12.01	12.74	12.95	12.74	12.02	12.44	12.52	12.28	13.09	13.01
FeO total	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80
Fe <sub>2</sub> O <sub>3</sub>	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
FeO	9.74	9.74	9.74	9.75	9.73	9.72	9.75	9.75	9.74	9.74	9.73	9.74	9.74	9.73
MnO	0.13	0.11	0.10	0.10	0.05	0.12	0.16	0.11	0.09	0.09	0.09	0.10	0.12	0.08
MgO	12.28	13.02	13.32	13.50	13.25	11.60	11.16	11.02	13.07	12.48	11.28	12.29	12.20	13.42
CaO	8.19	7.72	7.69	7.03	8.01	8.12	8.08	8.45	7.92	8.03	7.96	7.77	9.64	7.08
Na <sub>2</sub> O	2.37	2.28	2.22	2.25	2.35	2.30	2.44	2.35	2.27	2.40	2.36	2.25	1.53	2.57
K <sub>2</sub> O	0.54	0.51	0.64	0.63	0.45	0.46	0.43	0.30	0.48	0.39	0.39	0.53	0.34	0.59
P <sub>2</sub> O <sub>5</sub>	0.33	0.32	0.34	0.37	0.32	0.30	0.49	0.23	0.18	0.27	0.25	0.34	0.21	0.33
Cr <sub>2</sub> O <sub>3</sub>	0.19	0.14	0.18	0.19	0.17	0.19	0.05	0.03	0.23	0.04	0.17	0.17	0.26	0.14
Mg#	69.2	70.4	70.9	71.2	70.8	68.0	67.1	66.8	70.5	69.5	67.4	69.2	69.1	71.1
Fo olivine	87.6	88.1	88.4	88.4	88.4	86.8	86.3	86.1	88.2	87.7	86.3	87.4	87.6	88.6
	15	16	17	18	19	20	21	22	23	24	25	26	27	28
SiO <sub>2</sub>	52.28	50.91	51.23	52.32	51.09	50.49	49.95	52.50	51.25	51.35	51.57	50.84	50.65	52.38
TiO <sub>2</sub>	1.45	1.65	1.55	1.48	1.68	1.33	1.75	1.17	1.89	1.70	1.58	1.50	1.64	1.61
Al <sub>2</sub> O <sub>3</sub>	11.98	12.21	12.08	12.18	12.28	13.11	13.20	12.82	13.68	13.36	12.23	12.19	12.26	13.50
FeO total	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80
Fe <sub>2</sub> O <sub>3</sub>	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
FeO	9.75	9.73	9.72	9.73	9.73	9.75	9.72	9.75	9.75	9.72	9.74	9.74	9.75	9.70
MnO	0.10	0.10	0.07	0.11	0.10	0.12	0.09	0.15	0.10	0.15	0.13	0.13	0.09	0.15
MgO	12.41	13.21	12.96	12.06	12.66	13.53	12.61	11.32	9.66	10.28	12.73	13.85	12.87	9.01
CaO	7.70	7.88	8.05	7.74	8.02	7.01	7.79	7.22	9.04	9.09	7.68	7.38	8.02	8.82
Na <sub>2</sub> O	2.26	2.17	2.25	2.28	2.24	2.58	2.68	2.75	2.42	2.32	2.27	2.24	2.34	2.44
K <sub>2</sub> O	0.44	0.45	0.45	0.48	0.63	0.53	0.66	0.57	0.55	0.49	0.43	0.53	0.54	0.69
P <sub>2</sub> O <sub>5</sub>	0.24	0.29	0.29	0.23	0.21	0.17	0.27	0.36	0.34	0.28	0.26	0.25	0.38	0.29
Cr <sub>2</sub> O <sub>3</sub>	0.18	0.20	0.15	0.19	0.16	0.16	0.08	0.19	0.12	0.07	0.17	0.16	0.25	0.21
Mg#	69.4	70.8	70.4	68.8	69.9	71.2	69.8	67.4	63.8	65.3	70.0	71.7	70.2	62.3
Fo olivine	87.4	88.3	88.1	87.1	87.9	88.7	88.2	86.4	84.6	85.4	87.8	88.8	88.1	83.5
	29	30	31	32	33	34	35	36	37	38	39	40	41	42
SiO <sub>2</sub>	50.71	51.15	51.36	50.80	50.65	50.96	51.35	52.44	51.68	51.90	52.34	51.05	51.87	52.26
TiO <sub>2</sub>	1.81	1.56	1.83	1.53	1.53	1.70	1.60	1.55	1.57	1.49	1.84	1.75	1.59	1.39
Al <sub>2</sub> O <sub>3</sub>	12.58	12.30	12.28	11.61	11.90	12.24	12.37	12.38	12.19	12.18	12.71	12.54	12.26	11.34
FeO total	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80
Fe <sub>2</sub> O <sub>3</sub>	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
FeO	9.74	9.73	9.73	9.75	9.74	9.72	9.73	9.72	9.73	9.75	9.72	9.73	9.73	9.72
MnO	0.11	0.09	0.10	0.08	0.09	0.10	0.11	0.11	0.09	0.17	0.16	0.05	0.11	0.15
MgO	12.36	12.86	12.30	14.08	13.95	12.89	12.34	11.62	12.20	12.29	10.28	11.96	12.20	12.24
CaO	8.26	7.48	7.91	7.61	7.75	7.92	7.89	7.79	7.97	7.69	8.96	8.19	7.86	8.10
Na <sub>2</sub> O	2.35	2.30	2.29	2.17	2.12	2.31	2.23	2.38	2.20	2.20	2.21	2.44	2.27	2.37
K <sub>2</sub> O	0.46	0.70	0.48	0.48	0.59	0.46	0.61	0.44	0.54	0.55	0.34	0.51	0.46	0.48
P <sub>2</sub> O <sub>5</sub>	0.26	0.44	0.30	0.51	0.32	0.28	0.35	0.24	0.38	0.37	0.17	0.36	0.27	0.33
Cr <sub>2</sub> O <sub>3</sub>	0.16	0.19	0.21	0.18	0.16	0.20	0.23	0.14	0.24	0.20	0.07	0.22	0.18	0.41
Mg#	69.3	70.2	69.3	72.0	71.8	70.3	69.3	68.1	69.1	69.2	65.3	68.7	69.1	69.2
Fo olivine	87.7	88.0	87.5	88.9	88.9	88.1	87.5	86.7	87.3	87.3	85.2	87.3	87.3	87.3

Table 6 (continued)

KOO-17A														
	43	44	45	46	47	48	49	50	51	52	53	54	55	56
SiO <sub>2</sub>	51.18	52.89	51.92	51.35	51.54	51.53	51.55	52.12	50.71	51.23	51.83	51.73	53.07	52.27
TiO <sub>2</sub>	1.42	1.23	1.47	1.49	1.56	1.66	1.51	1.78	1.61	1.66	1.62	1.52	1.26	1.53
Al <sub>2</sub> O <sub>3</sub>	12.46	12.99	12.22	11.95	12.29	12.28	12.28	13.22	12.33	12.35	12.19	11.86	11.40	12.15
FeO total	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80
Fe <sub>2</sub> O <sub>3</sub>	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
FeO	9.74	9.74	9.74	9.74	9.73	9.72	9.75	9.74	9.73	9.72	9.73	9.74	9.72	9.74
MnO	0.08	0.14	0.06	0.13	0.11	0.11	0.11	0.14	0.07	0.11	0.11	0.06	0.10	0.10
MgO	13.34	10.29	12.22	12.96	12.47	12.01	12.54	9.72	12.92	12.26	12.27	12.67	12.12	12.26
CaO	7.35	7.94	7.62	7.58	7.92	7.93	7.78	8.92	7.73	8.20	7.90	7.70	7.68	7.87
Na <sub>2</sub> O	2.34	2.52	2.28	2.21	2.25	2.13	2.27	2.39	2.17	2.26	2.27	2.25	2.45	2.33
K <sub>2</sub> O	0.54	0.56	0.68	0.50	0.48	0.65	0.45	0.39	0.85	0.52	0.49	0.57	0.48	0.27
P <sub>2</sub> O <sub>5</sub>	0.24	0.28	0.40	0.67	0.24	0.53	0.38	0.26	0.56	0.32	0.24	0.46	0.29	0.23
Cr <sub>2</sub> O <sub>3</sub>	0.10	0.20	0.21	0.21	0.21	0.26	0.18	0.12	0.14	0.18	0.15	0.24	0.22	0.05
Mg#	70.9	65.3	69.1	70.3	69.5	68.8	69.6	64.0	70.3	69.2	69.2	69.9	69.0	69.2
Fo olivine	88.4	85.1	87.3	87.9	87.6	87.1	87.6	84.5	88.1	87.5	87.4	87.7	87.1	87.3
KOO-CF														
	57	58	59	60	61	62	63	64	1	2	3	4	5	6
SiO <sub>2</sub>	52.11	52.09	50.56	50.66	51.36	51.49	52.24	51.79	51.71	51.95	52.10	51.94	51.72	51.83
TiO <sub>2</sub>	1.52	1.65	1.56	1.46	1.36	1.73	1.68	1.68	1.72	2.06	1.53	1.61	1.68	1.60
Al <sub>2</sub> O <sub>3</sub>	12.20	12.68	12.11	12.21	12.12	13.08	12.43	12.81	13.10	13.45	12.59	11.96	11.93	12.72
FeO total	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.80	10.81	10.83	10.80	10.81	10.82	10.83
Fe <sub>2</sub> O <sub>3</sub>	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
FeO	9.74	9.73	9.74	9.72	9.73	9.73	9.75	9.73	9.73	9.75	9.72	9.73	9.74	9.75
MnO	0.09	0.10	0.06	0.05	0.11	0.13	0.12	0.10	0.10	0.09	0.09	0.10	0.06	0.11
MgO	12.22	12.62	13.27	14.18	13.01	10.05	11.25	10.95	11.09	9.64	11.72	12.98	12.97	11.16
CaO	8.05	8.03	7.98	7.27	7.27	9.21	8.06	8.13	7.77	8.14	7.59	7.25	7.33	8.10
Na <sub>2</sub> O	2.35	1.17	2.21	2.25	2.23	2.38	2.38	2.40	2.48	2.72	2.45	2.34	2.30	2.45
K <sub>2</sub> O	0.25	0.31	0.41	0.62	0.75	0.51	0.40	0.62	0.61	0.60	0.59	0.47	0.55	0.54
P <sub>2</sub> O <sub>5</sub>	0.24	0.19	0.68	0.34	0.63	0.27	0.27	0.37	0.30	0.32	0.26	0.20	0.33	0.33
Cr <sub>2</sub> O <sub>3</sub>	0.05	0.24	0.22	0.05	0.21	0.22	0.21	0.23	0.19	0.10	0.16	0.20	0.18	0.20
Mg#	69.1	69.8	70.8	72.2	70.4	64.8	67.3	66.7	67.0	63.8	68.2	70.4	70.4	67.1
Fo olivine	87.3	87.2	88.3	89.1	88.0	85.1	86.3	86.1	86.3	84.6	86.9	88.0	88.0	86.3
	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SiO <sub>2</sub>	52.08	52.31	52.90	51.56	51.70	51.87	52.47	51.44	52.20	51.95	51.43	53.36	52.16	51.85
TiO <sub>2</sub>	1.55	1.55	1.40	1.68	1.74	1.77	1.50	1.61	1.62	1.76	2.00	1.56	1.51	1.45
Al <sub>2</sub> O <sub>3</sub>	12.89	13.14	12.63	12.89	12.96	12.99	12.60	12.26	13.00	12.93	14.35	11.84	12.21	12.06
FeO total	10.81	10.80	10.81	10.80	10.81	10.81	10.82	10.83	10.81	10.80	10.79	10.81	10.81	10.82
Fe <sub>2</sub> O <sub>3</sub>	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
FeO	9.73	9.72	9.73	9.72	9.73	9.73	9.74	9.75	9.73	9.72	9.71	9.73	9.73	9.74
MnO	0.08	0.10	0.11	0.08	0.09	0.12	0.15	0.08	0.15	0.07	0.12	0.10	0.08	0.09
MgO	11.16	10.62	10.57	11.28	11.16	11.24	11.09	12.99	10.72	10.78	8.97	11.57	11.91	12.86
CaO	8.04	7.79	7.91	7.91	7.73	7.75	7.63	7.46	8.08	8.20	8.65	7.43	7.68	7.63
Na <sub>2</sub> O	2.48	2.52	2.53	2.53	2.53	2.39	2.47	2.33	2.56	2.42	2.58	2.19	2.44	2.39
K <sub>2</sub> O	0.39	0.60	0.54	0.66	0.60	0.50	0.59	0.53	0.31	0.49	0.65	0.51	0.49	0.31
P <sub>2</sub> O <sub>5</sub>	0.20	0.26	0.27	0.29	0.31	0.26	0.39	0.17	0.20	0.32	0.31	0.28	0.35	0.22
Cr <sub>2</sub> O <sub>3</sub>	0.20	0.19	0.21	0.20	0.23	0.18	0.17	0.19	0.22	0.16	0.04	0.23	0.25	0.21
Mg#	67.1	66.1	65.9	67.4	67.1	67.3	67.0	70.4	66.3	66.4	62.2	67.9	68.6	70.2
Fo olivine	86.3	85.7	85.5	86.6	86.4	86.4	86.1	88.1	85.8	85.9	83.7	86.4	87.0	87.9

(continued on next page)

Table 6 (continued)

	KOO-CF													
	21	22	23	24	25	26	27	28	29	30	31	32	33	34
SiO <sub>2</sub>	51.81	52.78	51.31	51.57	51.68	52.02	52.07	50.93	51.90	52.38	51.78	51.68	52.33	51.87
TiO <sub>2</sub>	1.94	1.76	1.82	1.82	1.83	1.59	1.68	1.79	1.83	1.39	1.68	1.66	1.77	1.69
Al <sub>2</sub> O <sub>3</sub>	13.48	13.40	13.07	13.35	13.10	12.76	13.06	12.99	12.81	13.10	12.78	12.95	12.78	12.69
FeO total	10.85	10.77	10.82	10.80	10.82	10.82	10.83	10.83	10.84	10.79	10.82	10.83	10.80	10.81
Fe <sub>2</sub> O <sub>3</sub>	1.21	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
FeO	9.76	9.69	9.73	9.72	9.74	9.74	9.75	9.74	9.75	9.71	9.74	9.75	9.72	9.73
MnO	0.09	0.10	0.09	0.06	0.14	0.05	0.05	0.03	0.14	0.18	0.12	0.15	0.08	0.12
MgO	9.83	9.94	11.23	10.69	10.18	11.66	10.38	11.83	11.13	9.39	11.33	11.32	11.86	11.24
CaO	7.87	8.78	7.90	7.85	8.41	7.88	8.24	7.87	7.96	10.48	7.95	7.81	7.83	8.04
Na <sub>2</sub> O	2.85	1.50	2.41	2.46	2.42	2.42	2.46	2.57	2.45	1.44	2.37	2.43	1.54	2.38
K <sub>2</sub> O	0.68	0.40	0.67	0.73	0.65	0.33	0.60	0.50	0.47	0.30	0.57	0.57	0.38	0.57
P <sub>2</sub> O <sub>5</sub>	0.34	0.36	0.39	0.33	0.42	0.17	0.28	0.38	0.19	0.19	0.33	0.34	0.27	0.30
Cr <sub>2</sub> O <sub>3</sub>	0.15	0.09	0.19	0.19	0.23	0.16	0.23	0.16	0.16	0.23	0.15	0.14	0.22	0.17
Mg#	64.2	64.6	67.3	66.2	65.1	68.1	65.5	68.4	67.0	63.3	67.5	67.4	68.5	67.3
Fo olivine	84.9	84.3	86.5	85.9	85.2	86.8	85.4	87.2	86.3	83.6	86.5	86.5	86.6	86.4
	35	36	37	38	39	40	41	42	43	44	45	46	47	
SiO <sub>2</sub>	52.49	51.25	52.00	51.70	51.87	50.28	51.86	53.95	51.69	53.50	51.74	51.02	53.08	
TiO <sub>2</sub>	1.49	1.69	1.67	1.91	1.74	1.54	2.03	1.15	1.65	1.48	1.69	1.64	1.71	
Al <sub>2</sub> O <sub>3</sub>	12.70	14.21	13.64	13.45	13.50	13.84	13.89	13.30	13.18	12.30	12.72	12.20	12.34	
FeO total	10.80	10.77	10.76	10.82	10.84	10.82	10.77	10.75	10.82	10.81	10.82	10.80	10.81	
Fe <sub>2</sub> O <sub>3</sub>	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.19	1.20	1.20	1.20	1.20	1.20	
FeO	9.72	9.69	9.69	9.74	9.76	9.74	9.69	9.68	9.74	9.73	9.74	9.72	9.73	
MnO	0.04	0.23	0.15	0.14	0.13	0.11	0.10	0.13	0.15	0.14	0.08	0.08	0.11	
MgO	11.19	7.15	10.16	10.06	10.01	10.38	8.15	8.87	11.14	10.56	11.39	13.34	11.50	
CaO	7.89	9.81	9.05	8.07	8.24	9.83	9.25	7.90	7.65	7.64	8.10	7.44	7.58	
Na <sub>2</sub> O	2.28	3.29	1.36	2.53	2.46	2.17	2.53	2.81	2.48	2.34	2.41	2.30	2.04	
K <sub>2</sub> O	0.54	0.82	0.39	0.67	0.53	0.59	0.70	0.58	0.58	0.42	0.51	0.51	0.37	
P <sub>2</sub> O <sub>5</sub>	0.33	0.35	0.43	0.35	0.38	0.28	0.40	0.26	0.35	0.48	0.22	0.38	0.22	
Cr <sub>2</sub> O <sub>3</sub>	0.14	0.32	0.28	0.17	0.18	0.02	0.20	0.18	0.17	0.21	0.20	0.18	0.14	
Mg#	67.2	56.8	65.1	64.8	64.6	65.5	60.0	62.0	67.1	65.9	67.6	71.0	67.8	
Fo olivine	86.2	80.6	84.6	85.1	84.9	85.7	82.2	83.1	86.3	85.2	86.6	88.4	86.3	

Nb and Sr/Ba ratios that span the range observed for Mauna Loa and Kilauea (Figs. 8 and 11).

#### 4. Discussion

##### 4.1. Compositional modification by quenching and diffusive equilibration

A common problem facing the use of melt inclusions to reconstruct primary magma compositions is the tendency for inclusions to undergo compositional modification during quenching and through diffusive interaction with the host crystal (Sobolev, 1996; Danyushevsky et al., 2000; Gaetani and Watson,

2000). At slow cooling rates, a melt inclusion and its host olivine can approach local equilibrium, with the composition of the inclusion changing through crystallization and Fe/Mg exchange (Danyushevsky et al., 2000). Relative to the original trapped melt composition, the inclusion becomes depleted in Fe and enriched in elements that are incompatible in olivine, with the degree of compositional modification being proportional to the extent of equilibration between the host and the inclusion (Danyushevsky et al., 2000). The extreme compositions found in some of the naturally quenched melt inclusions from Mauna Loa and Kilauea, including very low FeO and MgO, and high SiO<sub>2</sub>, CaO, and Al<sub>2</sub>O<sub>3</sub> result from diffusive equilibration of the inclusions with their host olivines

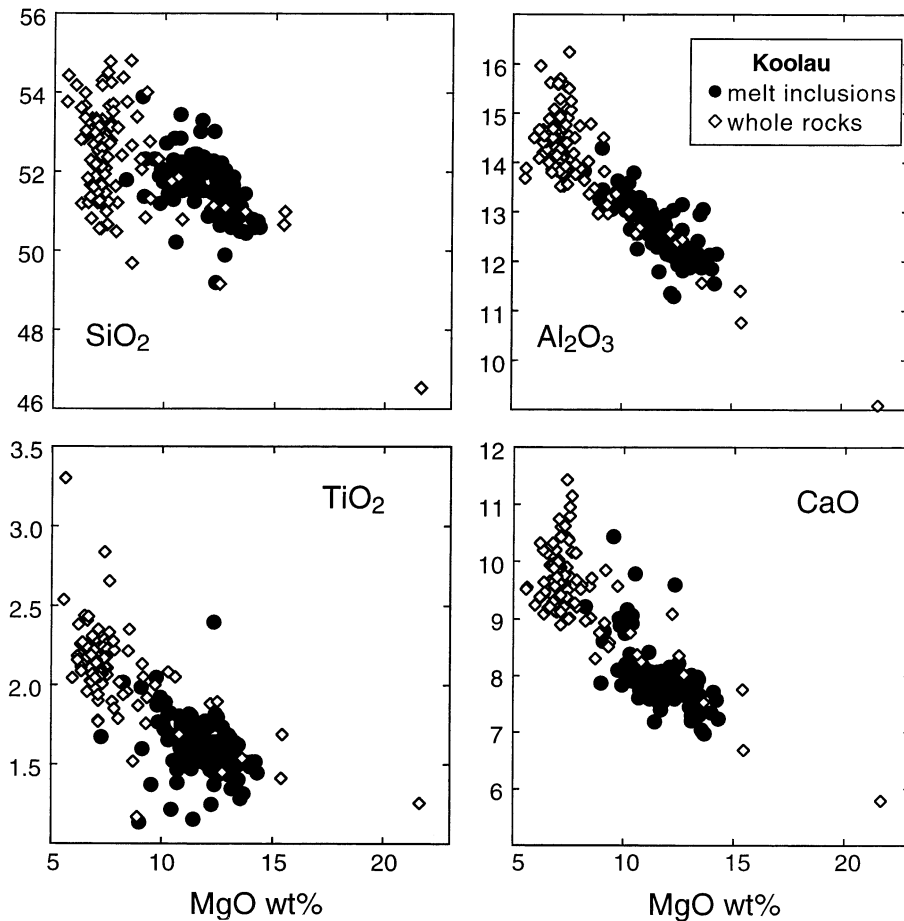


Fig. 4. MgO vs.  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ , and CaO contents of experimentally melted inclusions from Koolau (filled circles) compared to whole rock compositions of Koolau lavas (open diamonds). Koolau compositions have been corrected as described in the text and in Fig. 3. The corrected compositions of Koolau melt inclusions follow trends established by the whole rock compositions.

prior to eruption. The wide range of FeO contents of the Kilauea and Mauna Loa inclusions, and the negative correlations between FeO and, e.g., CaO,  $\text{Al}_2\text{O}_3$ , and  $\text{TiO}_2$  in these inclusions (not shown) indicates variable degrees of diffusive equilibration between the melt inclusions and host olivines.

The limited variation of MgO in the Kilauea inclusions around a value similar to that of the matrix glass (Fig. 1; Table 1) shows that these inclusions were perfectly quenched on eruption with only minor crystallization of olivine on the walls of the inclusion during cooling of the lava. In contrast, the trend to lower MgO in the Mauna Loa inclusions suggests that these were more strongly modified by quench crys-

tallization of olivine during eruption (cf. Danyushevsky et al., 2000). The evolved, high-Si compositions found in the Mauna Loa inclusions, therefore, likely reflect post-entrapment modification of the melt inclusions rather than exotic magmatic compositions. We have not attempted to correct for the effects of quench olivine crystallization on the trace element compositions of these melt inclusions, but the higher abundances of incompatible elements in the Mauna Loa inclusions with <6% MgO (Fig. 10) would be qualitatively consistent with this process.

It is commonly assumed that equilibration is limited to exchange between the host and the inclusion, and that the host-inclusion system was isolated from

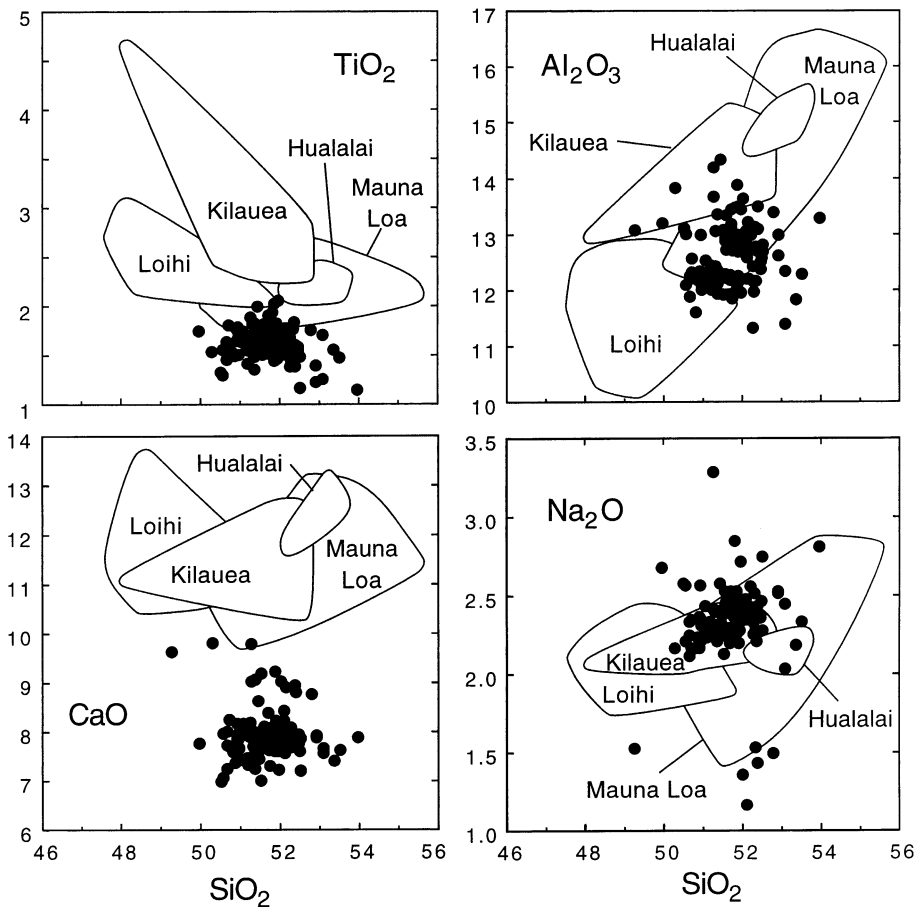


Fig. 5. Major element compositions of olivine-hosted melt inclusions from Hawaiian picrites. Koolau melt inclusions (corrected compositions; black circles) have lower CaO and  $\text{TiO}_2$  contents compared to naturally quenched inclusions from the other volcanoes.

the surrounding melt (e.g., Danyushevsky et al., 2000). This may not be a valid assumption, however, if the inclusion is open with respect to the external melt through lattice diffusion in the host crystal (Gaetani and Watson, 2000). Equilibration of an inclusion with an external fluid depends on time, temperature, diffusivity, and the partition coefficient of the species between the melt and the host, so the assumption that an inclusion remained isolated from equilibration with the host magma is valid only for slow-diffusing incompatible trace elements. Equilibration between an olivine-hosted inclusion and outside magma becomes more likely for elements such as Fe, Mg, and Ca as cooling rates drop below  $1^\circ\text{C}/\text{year}$  (Qin et al., 1992; Gaetani and Watson, 2000).

The Ca content of an olivine-hosted melt inclusion is potentially subject to modification by diffusive re-equilibration with the host magma due to the relatively rapid rate of Ca diffusion and the high  $D_{\text{Ca}}$  for olivine. Several examples of melt inclusions with anomalously high Ca contents ( $\text{CaO} > 14 \text{ wt.}\%$   $\text{CaO}/\text{Al}_2\text{O}_3 > 1$ ) have been reported from MORB lavas (Kamenetsky et al., 1998; Kamenetsky and Crawford, 1998) although such values are exceedingly rare in populations of lavas (Melson et al., 1999). These inclusions with high Ca/Al cannot be attributed to crystallization of olivine alone, but are possibly related to high pressure interaction with clinopyroxene-rich lithologies (Kamenetsky et al., 1998). However, an increase in CaO and Ca/Al might also reflect



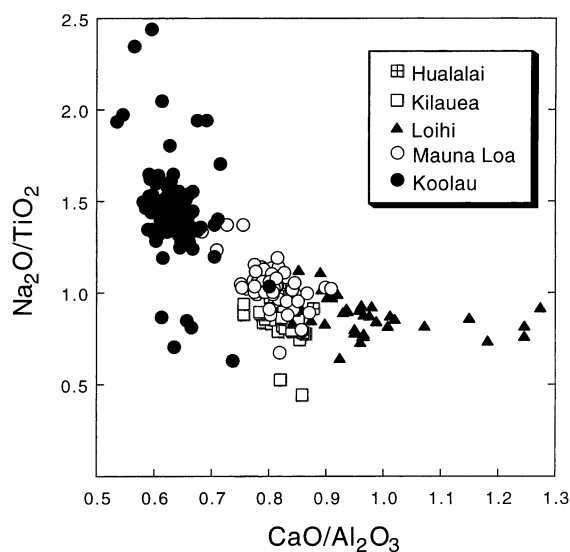


Fig. 6. Plot of  $\text{CaO}/\text{Al}_2\text{O}_3$  vs.  $\text{Na}_2\text{O}/\text{TiO}_2$  for melt inclusions from Hawaiian picrites. Low  $\text{CaO}/\text{Al}_2\text{O}_3$  and high  $\text{Na}_2\text{O}/\text{TiO}_2$  contents characterize most Koolau inclusions. Ratios of these elements should be independent of olivine fractionation.

diffusive equilibration of the inclusion with the host magma under certain conditions.

The high CaO and  $\text{CaO}/\text{Al}_2\text{O}_3$  contents in some of the Loihi inclusions (Figs. 1 and 6) raise the possibility that these unusual compositions reflect diffusive modification of these inclusions rather than primary magmatic values. However, high CaO contents and  $\text{CaO}/\text{Al}_2\text{O}_3$  values similar to those of the Loihi inclusions are also found in whole rock compositions from this volcano (Garcia et al., 1995b). The  $\text{FeO}^*$  contents of the Loihi inclusions have not been strongly modified from their magmatic values (Fig. 2; Table 1), which supports the

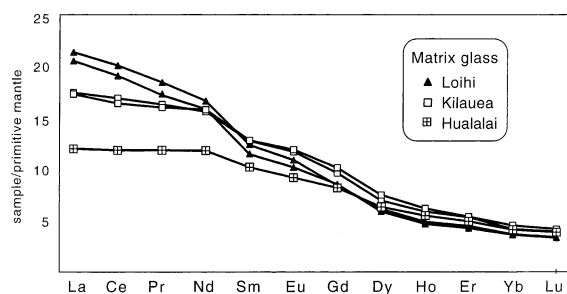


Fig. 7. REE compositions of matrix glass from the Loihi, Kilauea, and Hualalai picrites. Data by laser ablation ICPMS (Table 1).

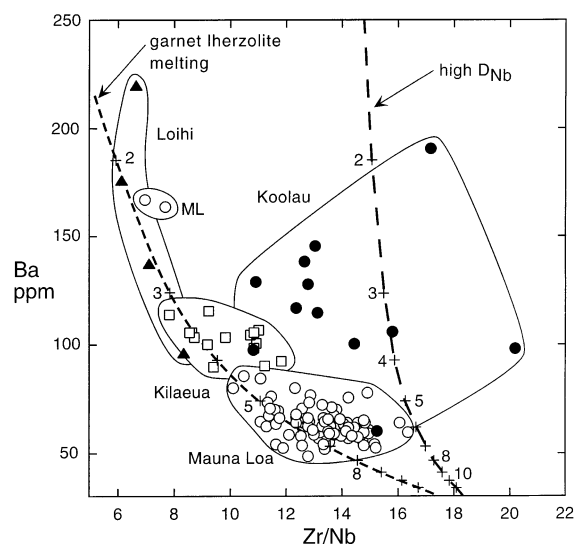


Fig. 8.  $\text{Zr}/\text{Nb}$  vs. Ba contents of melt inclusions from Hawaiian picrites. Symbols are the same as for previous figures. Dashed lines indicate trends for accumulated incremental melting of garnet lherzolite (Table 8). The trend labelled “high  $D_{\text{Nb}}$ ” is the same melting model except that  $D_{\text{Nb}}=0.045$  (Norman and Garcia, 1999).

idea that the high CaO in these inclusions are primary. The lack of compositional modification observed in the Loihi melt inclusions may indicate a brief interval between crystallization of the olivines and eruption of these lavas.

#### 4.2. Melting models

Systemic variations in the whole rock trace element compositions of Hawaiian picrites appear to be controlled primarily by melting of a garnet lherzolite plume source (Norman and Garcia, 1999). Here, we test and extend this model using the compositions of melt inclusions from these lavas. The trends of decreasing La/Yb and increasing  $\text{Zr}/\text{Nb}$ ,  $\text{Zr}/\text{La}$ , and  $\text{Sr}/\text{Ba}$  ratios for the Loihi, Kilauea, and Mauna Loa matrix glasses and melt inclusions are compatible with either increasing degrees of partial melting of a common source, or melt generation from an increasingly depleted source. Melt inclusions from Loihi, Kilauea, and Mauna Loa all have relatively constant Ba/Nb ratios ( $\sim 6-8$ ) that are less than the primitive mantle value ( $\sim 10$ ; McDonough and Sun, 1995) (Fig. 9). The similarity of the Ba/Nb ratios among these volcanoes suggests that the lavas were derived

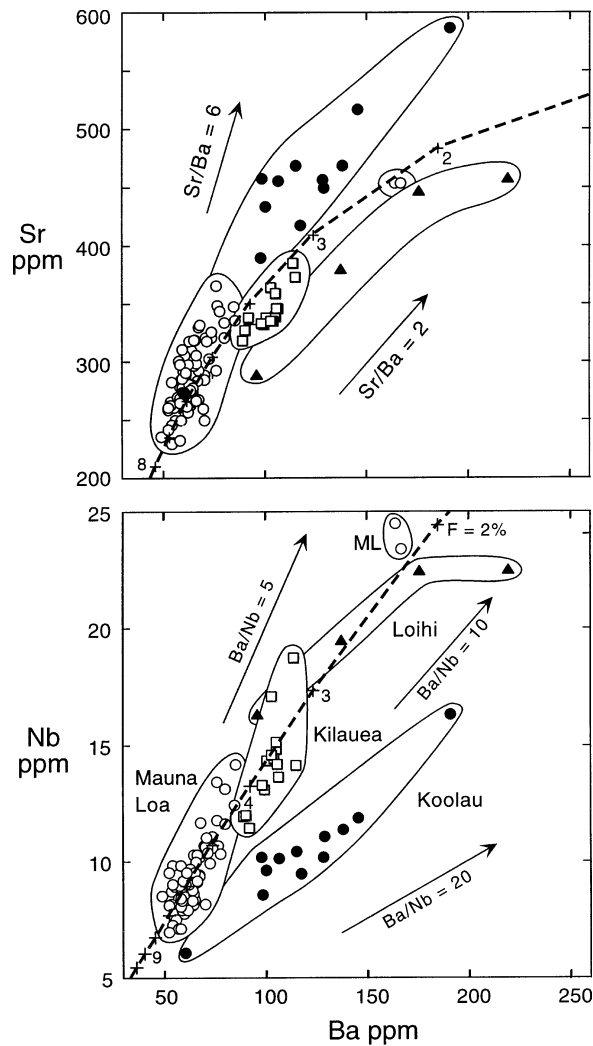


Fig. 9. Plots of Ba vs. Sr and Nb contents of melt inclusions from Hawaiian picrites. Symbols are the same as for previous figures. Mauna Loa, Kilauea, and Loihi samples are characterized by similar Ba/Nb ratios, whereas those from Koolau have distinctly higher values. Variable degrees of melting of a garnet lherzolite source (dashed line) accounts for most of the compositions variation observed in the Mauna Loa, Kilauea, and Loihi inclusions, whereas a distinct source is indicated for Koolau.

from plume source components that were isotopically distinct but which had similar trace element characteristics. Internally consistent results can be obtained from a simple model involving variable degrees of melting of a moderately depleted garnet lherzolite (Table 8).

The trace element compositions of Loihi inclusions and the two inclusions from Mauna Loa with high incompatible element contents are consistent

with relatively small degrees of accumulated incremental melting (2–4%), whereas the inclusions from Kilauea and most of the samples from Mauna Loa require somewhat larger degrees of melting (4–9%). These results are consistent with those obtained on the whole rock compositions, and support the idea that Hawaiian lavas reflect the integration of numerous discrete parcels of melt that are at least partially preserved as melt inclusions trapped within early

Table 7

Trace element data for Hawaiian melt inclusions

ppm	LO-02-04				KIL-1-10						
	1/1	3/1	6/1	6/3	4/1	4/3	4/4	6/2	8/1	8/2	
Ba	96	137	176	220	92	100	98	89	105	90	
La	11.6	17.4	17.0	22.3	10.5	10.3	10.8	9.7	10.5	10.3	
Nb	16.3	19.5	22.5	22.5	11.4	13.1	13.3	12.0	14.9	12.0	
Sr	289	380	447	459	338	332	333	318	339	327	
Zr	137	139	138	150	136	120	144	113	129	135	
Yb	2.18	1.47	1.53	1.63	<2.9	2.1	2.3	<2.3	2.8	<2.6	
	Kil-2-1									KOO-CF	
	1/1	1/6	1/11	2/1	2/3	2/8	2/10	3/1	1-1	2-1	
Ba	104	103	103	107	114	105	106	115	98	138	
La	10.6	11.2	11.7	11.7	13.0	11.8	11.7	11.3	8.8	11.5	
Nb	14.5	17.1	14.6	13.7	18.8	15.2	14.2	14.2	10.2	11.4	
Sr	335	336	364	346	385	359	346	373	390	470	
Zr	155	149	144	151	147	130	155	131	111	144	
Yb	2.1	2.8	2.1	<1.5	2.4	1.8	2.1	1.7	1.13	1.53	
	3-1	4-1	5-1	6-1	7-1	8-1	10a-1	11-1	13-1	15-1	
Ba	115	145	128	129	117	100	98	106	191	61	
La	11.1	10.9	9.7	11.0	10.7	9.5	13.0	13.3	19.1	6.0	
Nb	10.5	11.9	10.2	11.1	9.5	9.7	8.6	10.1	16.4	6.1	
Sr	469	517	458	450	418	434	459	457	587	274	
Zr	137	155	130	121	117	139	174	160	280	93	
Yb	1.22	1.51	1.23	1.25	1.25	1.39	2.01	1.53	2.81	1.21	
	Mauna Loa										
	182-3-6	182-3-9	182-6a	182-6-2	182-6-6	182-7-2	182-7-2h	182-7-3	182-7-4	182-7-5	
Ba	54	7.6	69	71	70	74	53	77	65	63	
La	6.8	9.4	8.9	9.4	6.5	9.2	7.5	9.8	8.6	7.7	
Nb	9.8	11.8	10.7	10.4	8.2	11.1	9.5	10.7	10.3	9.7	
Sr	230	293	260	289	250	322	260	349	274	279	
Zr	114	135	126	131	113	126	113	137	114	110	
Yb	2.66	2.16	2.08	2.37	2.01	2.28	<1.9	1.70	2.41	2.13	
	182-7-5h	182-7-6h	182-7-6	182-7-8	182-8-1	182-8-11h	182-8-1mh	182-8-1rh	182-8b-1h	182-8b-2h	
Ba	56	54	68	84	80	67	63	64	70	64	
La	6.6	7.4	8.2	10.8	10.8	7.3	7.8	7.5	8.2	8.1	
Nb	7.6	7.3	10.2	12.5	13.2	9.5	9.3	9.4	10.6	9.7	
Sr	250	246	293	348	334	268	263	277	285	277	
Zr	112	110	116	138	133	117	108	119	123	120	
Yb	<3.0	<6.4	1.70	1.63	2.22	2.70	1.85	2.68	1.92	1.67	
	182-8-3	182-8-5	182-8-7	183-3-1	183-3-2	183-3-3	183-3-5	183-3-6	183-3-13	183-3-15	
Ba	80	71	85	58	62	49	62	54	61	67	
La	10.4	10.3	12.7	6.9	7.7	6.9	6.8	7.1	7.1	8.5	
Nb	11.6	11.0	14.2	8.7	8.3	8.6	8.7	8.7	8.1	9.3	
Sr	321	322	337	266	257	236	275	266	289	284	
Zr	143	126	149	109	113	109	118	110	120	125	
Yb	2.49	2.39	2.24	1.89	1.88	<3.2	1.61	1.68	2.28	1.91	

(continued on next page)

Table 7 (continued)

ppm	Mauna Loa									
	183-3-16	183-3-17	183-3-18	183-3-19	183-3-20	183-3-21	183-3-281	183-7-1i	183-7-5	183-7-6
Ba	64	57	55	64	59	74	60	54	59	60
La	7.3	7.2	7.2	6.8	7.4	9.2	7.4	7.1	7.9	7.3
Nb	8.1	8.5	8.9	8.2	8.8	10.6	7.8	8.2	8.0	8.6
Sr	270	265	261	266	268	327	273	264	285	275
Zr	118	111	121	117	121	136	115	121	117	113
Yb	1.78	1.83	1.80	<1.4	2.12	2.39	2.42	1.54	1.89	1.72
	183-7-8	183-11-a	183-11-b	183-11-4	183-11-13	183-12-3	183-12-6	183-12-9	183-12-14	183-15-1
Ba	59	64	60	59	63	57	60	76	52	58
La	7.4	7.2	7.6	7.2	7.7	6.6	7.7	15.1	6.9	6.6
Nb	8.3	9.5	8.1	8.1	9.1	7.2	9.0	13.5	8.2	7.2
Sr	278	281	293	274	281	270	273	366	261	269
Zr	108	122	132	121	121	102	121	191	109	104
Yb	1.97	2.63	3.20	2.70	3.05	<1.3	1.47	3.13	2.46	1.92
	183-15-1h	183-15-2h	183-15-2	183-15-4	183-15-5	183-15-8	184-2-1	184-2-2	184-2-3i	184-2-5
Ba	60	62	68	65	58	66	52	64	59	66
La	7.8	7.6	8.6	7.8	6.8	8.2	6.2	10.8	6.5	8.3
Nb	8.1	8.0	9.4	8.4	8.1	10.3	7.0	9.0	8.4	9.2
Sr	274	262	330	297	234	299	242	276	250	267
Zr	120	115	129	112	105	121	106	126	101	124
Yb	1.85	1.75	3.13	2.84	1.62	2.84	1.67	2.19	1.84	<2.2
	184-2-9	184-5-2i	184-5-3	184-5-4	184-6-1	184-6-2	184-6-3	184-6-5i	184-6-12	184-7-1
Ba	58	59	68	64	66	64	71	72	62	60
La	7.4	7.5	9.7	8.0	8.5	8.6	8.5	8.2	7.8	8.3
Nb	8.5	9.0	11.7	8.3	10.0	8.8	10.4	9.9	9.1	9.1
Sr	265	286	332	310	319	310	319	304	298	306
Zr	118	123	144	134	139	130	142	132	129	128
Yb	2.20	1.84	2.53	1.59	2.99	2.97	1.82	2.00	1.45	2.57
	184-7-1a	184-7-1m	184-7-1r	184-7-11	184-7b-2h	184-7-3	184-7b-3h	184-7-5	184-7-8	184-7-10
Ba	57	63	59	58	54	65	61	164	66	167
La	8.0	8.0	7.0	8.0	7.8	8.8	8.7	24.6	8.3	24.4
Nb	9.0	9.7	9.2	9.9	9.0	9.5	9.6	24.5	9.2	23.4
Sr	301	318	311	298	283	320	291	455	306	454
Zr	131	124	125	141	121	141	124	188	117	163
Yb	2.40	2.83	1.72	1.74	1.75	2.47	1.42	2.39	1.76	1.69

crystallizing olivines. A linkage between isotopically identified source components and extent of melting within the plume is implied by the correlations of Zr/Nb with indicators of melting such as Ba abundance, La/Yb, Zr/La, and Sr/Ba ratios for Mauna Loa, Kilauea, and Loihi (Figs. 8, 9 and 11). This model does not attempt to explain the origin of isotopic heterogeneity in the Hawaiian plume, but it would suggest that the isotopically distinct source compo-

nents have generally similar trace element compositions.

Koolau compositions are unique. Trace element characteristics of the Koolau inclusions fall well off the melting trends defined by the other volcanoes (Figs. 8, 9 and 11) and Koolau tholeiites define an isotopically distinct source component (Brandon et al., 1999). A mantle source with higher  $D_{\text{Nb}}$  has been suggested based on the whole rock compositions of these Koolau

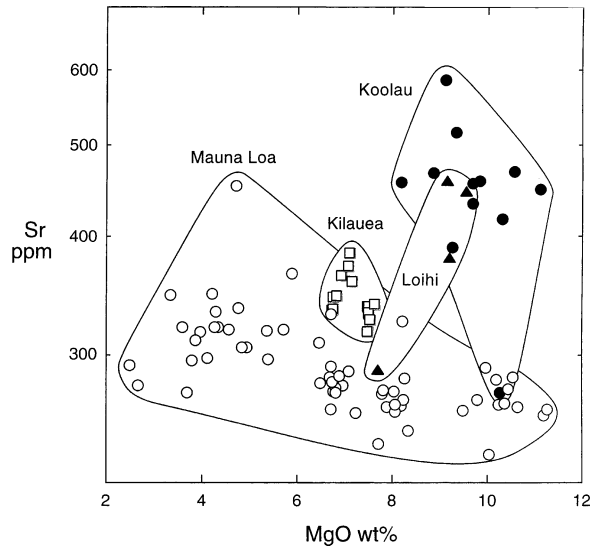


Fig. 10. MgO vs. Sr content of melt inclusions from Hawaiian picrites. The Mauna Loa inclusions with low MgO contents (<6 wt.%) tend to be enriched in incompatible element abundances. Inclusions from Koolau also have high Sr contents.

picrites (Norman and Garcia, 1999). Such a model does not reproduce the range or trend of the Koolau melt inclusion compositions (Fig. 8), although mixing between melts of a source with high  $D_{Nb}$  with melts

from a more “normal” garnet lherzolite source appears feasible based on the compositions of these melt inclusions. A more depleted source with a lower Nb contents and higher Zr/Nb would be unlikely to pro-

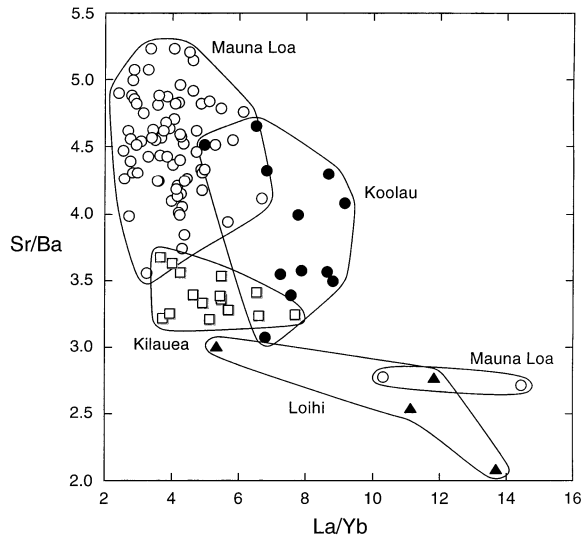


Fig. 11. Sr/Ba vs. La/Yb ratios of melt inclusions from Hawaiian picrites. High Sr/Ba and low La/Yb ratios in the Mauna Loa inclusions reflect generally higher degrees of melting for this volcano compared to Kilauea and Loihi, although the two Mauna Loa inclusions with elevated incompatible element contents, low Sr/Ba and high La/Yb ratios also indicate addition of relatively small degree melts to this volcano. Symbols are the same as previous figures.

Table 8  
Details of the garnet lherzolite melting model

	HPY (ppm)	HPY/PM	D
Ba	3.70	0.54	0.003
La	0.51	0.72	0.007
Nb	0.55	0.75	0.008
Sr	17.4	0.87	0.025
Zr	11.0	0.93	0.063
Yb	0.47	0.96	0.290

Accumulated incremental melting.

HPY = Hawaiian pyrolite plume source.

PM = primitive mantle.

D = bulk distribution coefficients.

duce the combination of higher Ba and Sr abundances and higher Ba/Nb and La/Yb ratios of the Koolau inclusions.

#### 4.3. Recycled oceanic lower crust in the plume?

Enrichments of Sr relative to LREE and depletions of Th and U relative to Ba and La in tholeiites from Mauna Loa provide evidence for recycled oceanic lower crust (now eclogite) in the plume source region (Hofmann and Jochum, 1996). Rare Sr-enriched melt inclusions from Mauna Loa may also reflect ghost plagioclase in eclogite derived from recycled oceanic lower crust in the Hawaiian plume (Sobolev et al., 2000). The trace element compositions of these Mauna Loa inclusions are characterized by unusual enrichments of Sr and severe depletions of the highly incompatible elements (e.g., LREE, K, Nb, Th, Ba) resulting in high Sr/Ba, high Zr/Nb, and low La/Yb ratios (Sobolev et al., 2000).

The inclusions studied here show well defined positive correlations between Sr and the highly incompatible elements, such that Sr enrichments are associated with higher concentrations of Ba, La, and Nb and higher La/Yb ratios (Figs. 8 and 9). Two inclusions from Mauna Loa do have anomalously high Sr concentrations, but these inclusions are also characterized by high contents of incompatible elements, high La/Yb ratios and low Sr/Ba, Sr/La, and Zr/Nb ratios (Figs. 8, 9 and 11). This differs from the ghost plagioclase inclusions, which are strongly depleted in highly incompatible elements and have high Sr/Ce and Zr/Nb (Sobolev et al., 2000), and appears to be inconsistent with an origin by melting of recycled basaltic eclogite. Alter-

natively, trace element compositions of the incompatible element enriched Mauna Loa inclusions tend to fall along melting trends (Figs. 8, 9 and 11), suggesting a contribution of relatively small degree melts to these lavas.

The ghost plagioclase melt inclusions are thought to be rare (<4%; Sobolev et al., 2000) and therefore potentially easy to miss in a reconnaissance survey of glass compositions. We analysed 80 inclusions from Mauna Loa for their trace element compositions (Table 7), so a population present at the 4% level would be expected to produce three to four inclusions with this composition. However, none are observed in this suite. The submarine lavas from the southwest rift of Mauna Loa that were studied here are most likely older than the three flows containing the Sr-enriched inclusions which are  $\leq 50$  ka (Sobolev et al., 2000), so it is possible that an eclogite pod may have entered the Mauna Loa melting regime relatively recently.

#### 4.4. Mafic source for Koolau?

The source or process responsible for the distinctive compositional characteristics of Koolau tholeiites is controversial. The high SiO<sub>2</sub> and low CaO composition of Koolau tholeiites pose particular problems for conventional peridotite mantle source compositions, and the trace element and isotopic compositions of Koolau tholeiites suggest a unique source of component for this volcano (Figs. 8, 9 and 11); also Brandon et al., 1999). Koolau tholeiites have been modelled as mixtures of primitive Hawaiian tholeiite with a sizeable fraction (10–20%) of dacitic melt derived from mafic eclogite within the plume (Hauri, 1996). Takahashi and Takeguchi (1998) extended this idea by invoking high degrees of melting of a basaltic eclogite plume component to produce primary high-Si Koolau tholeiites with 7% MgO. Compositional characteristics of a hypothetical Koolau dacitic melt were predicted from geochemistry of Hawaiian lavas (Hauri, 1996) but there is little independent evidence to suggest that such melts actually exist or that they could survive reaction with ambient peridotite and contribute to oceanic volcanism (Yaxley and Green, 1998).

However, an unusually siliceous (57.3% SiO<sub>2</sub>) glass recently discovered from the Bouvet Triple Junction

(BTJ) area in the South Atlantic (Kamenetsky et al., 2001) provides unequivocal proof that relatively primitive silicic melts with at least some of the distinctive compositional characteristics of Koolau tholeiites do occur in the upper mantle. In addition to the high  $\text{SiO}_2$  content, other compositional similarities between the BTJ glass and Koolau tholeiites include high  $\text{Na}_2\text{O}$ , and low  $\text{CaO}$ ,  $\text{CaO}/\text{Al}_2\text{O}_3$ ,  $\text{FeO}$  and  $\text{TiO}_2$  contents. Importantly, the BTJ glass also has unusually high  $\text{MgO}$  (8.5 wt.%),  $\text{Mg\#}$  and  $\text{Ni}$  contents for its  $\text{SiO}_2$ , so it appears to be a relatively primitive melt rather than an evolved fractionate.

The feasibility of such a melt contributing to the compositional variation of Hawaiian lavas is demonstrated by a mixing model that reproduces the  $\text{CaO}/\text{Al}_2\text{O}_3$  vs.  $\text{Na}_2\text{O}/\text{TiO}_2$  trends of the Koolau melt inclusions (Fig. 12).  $\text{CaO}/\text{Al}_2\text{O}_3$  and  $\text{Na}_2\text{O}/\text{TiO}_2$  ratios of the Hawaiian melt inclusions span a broad range, from 0.4 to 1.3, and there are systematic differences among the different volcanoes, with Koolau having lower  $\text{Ca}/\text{Al}$  and higher  $\text{Na}/\text{Ti}$  compared to other volcanoes (Figs. 6 and 12). Olivine gain or loss does not affect these ratios, so they should reflect magmatic characteristics regardless of any compositional mod-

ification of the inclusions. A mixture of either the BTJ glass composition or a Koolau dacitic melt (DAC; Hauri, 1996) with an average Loihi composition reproduces the trend of the melt inclusion compositions (Fig. 12). Relatively large percentages of both the BTJ (80%) and the DAC (40%) endmembers are necessary to account for the observed Koolau compositions by this model. Smaller amounts of contamination may be necessary if some the range of melt inclusion compositions is related to primary variations within the plume.

Other geochemical features of Koolau that might be explained by such a model include depletion of HREE compared to tholeiites from other Hawaiian volcanoes (Frey et al., 1994; Jackson et al., 1999), and isotopic compositions consistent with long-term (2 Ga) isolation of a crustal source (Hauri et al., 1996; Bennet et al., 1996). The BTJ glass is strongly depleted in HREE, consistent with the presence of significant residual garnet in its source, and its Sr, Nd, and Pb isotopic compositions match those of Proterozoic or older continental crust (Kamenetsky et al., 2001). In detail, the trace element composition of this specific sample of BTJ glass does not provide a

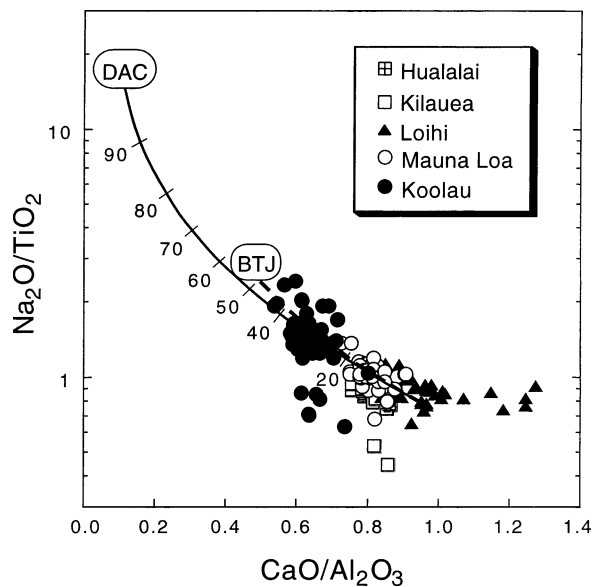


Fig. 12. Mixing models showing that the  $\text{CaO}/\text{Al}_2\text{O}_3$  vs.  $\text{Na}_2\text{O}/\text{TiO}_2$  compositions of melt inclusions in Hawaiian picrites can be reproduced by adding relatively large amounts of silicic melt compositions to an average Loihi composition. BTJ indicates the composition of a primitive, high-Si glass composition from the Bouvet Triple Junction (Kamenetsky et al., 2001). DAC represents a hypothetical Koolau dacitic melt component (Hauri, 1996). The Loihi inclusions with high  $\text{CaO}/\text{Al}_2\text{O}_3$  cannot be explained by this model and require an alternative explanation.

simple direct analogue of Koolau magmatism because it is depleted in highly incompatible elements such as  $K_2O$ , Rb, Nb, and the LREE, but this probably reflects recent melt depletion of an originally more enriched BTJ source (Kamenetsky et al., 2001).

Mafic sources contributing to Koolau volcanism might be entrained in the plume, or occur as accidental components in the upper mantle which are unrelated to the plume. Most Hawaiian tholeiites have Na/Ti ratios lower than those of N-MORB consistent with initiation of melting at greater depths in a hot plume (Putirka, 1999). Within the suite of Hawaiian basalts, however, Na/Ti varies systemically with isotopic composition, decreasing in the sequence Koolau > Mauna Loa > Kilauea > Loihi (Putirka, 1999). A similar trend is observed in the melt inclusions (Fig. 12). Based on melting models describing trace element abundances and Na/Ti ratios, Putirka (1999) concluded that garnet pyroxenite and eclogite are unlikely source components in the Hawaiian plume, and proposed a vertically stratified melting regime for Hawaiian tholeiites. In this model, Koolau tholeiites with higher Na/Ti formed by initiation of melting at shallower depths, possibly due to lower temperatures of this source component in the plume.

A shallower depth of melting for Koolau tholeiites may be consistent with a lithospheric or upper mantle origin for the Koolau component. The Bouvet glass is thought to reflect the presence of Precambrian continental lithosphere stranded in the upper mantle during opening of the Atlantic Ocean (Douglass and Schilling, 2000; Kamenetsky et al., 2001), and a similar process might have contributed unusual melt compositions to Koolau volcanism, along with picritic melts from the plume. Pods of ancient lithosphere trapped within the modern oceanic mantle have been discovered at subduction zones (Parkinson et al., 1998), and entrainment of ancient lithospheric mantle into the ocean basins may account for the subchondritic  $^{187}\text{Os}/^{188}\text{Os}$  isotopic compositions found in some abyssal periodotites (Brandon et al., 2000). Interaction of the Hawaiian plume with ancient mafic lithologies in the upper mantle may provide an alternate possibility to recycling of subducted oceanic crust into the plume to account for the distinctive compositional characteristics of Koolau tholeiites.

## 5. Conclusions

(a) Melt inclusions in tholeiitic picrites from Hawaiian volcanoes show that magmas feeding these volcanoes exhibit a much greater compositional diversity than indicated by the whole rock compositions of erupted lavas.

(b) Major element compositions of naturally quenched olivine-hosted inclusions from Kilauea, Mauna Loa, and Hualalai have been modified by interaction with their host olivine, but are consistent with magmatic trends observed in erupted lavas.

(c) Melt inclusions in picrites from Loihi have not been strongly affected by interaction with their host olivines, perhaps indicating insignificant cooling after growth of the olivine, and a brief interval between crystallization of the olivines and eruption of these lavas. Unusually high CaO contents of some Loihi inclusions appear to be a primary magmatic feature rather than resulting from diffusive equilibration of the inclusions with the host melt.

(d) Experimentally melted inclusions from two Koolau picrites have corrected major element compositions similar to magmatic trends observed in erupted lavas from this volcano. These inclusions represent trapped Koolau melts with up to 14% MgO.

(e) Trace element compositions of melt inclusions from Mauna Loa, Kilauea, and Loihi can be explained by systematic variations in the extent of melting of a moderately depleted garnet lherzolite source. Compositions of the Koolau inclusions suggest a unique source component for this volcano.

(f) Correlations between source characteristics inferred from Zr/Nb ratios and the extent of melting indicated by incompatible trace element compositions of the melt inclusions imply a linkage between the melting regime and isotopically defined source components in the plume. Lavas from Mauna Loa volcano are produced by generally greater degrees of melting compared to lavas from Kilauea and Loihi, although contributions from smaller degree melts are also found at Mauna Loa.

(g) No evidence was found for Sr-enriched, incompatible element depleted inclusions that may have formed from recycled basaltic or gabbroic eclogite in the plume.

(h) The major and trace element characteristics of Koolau magmas may reflect contributions from ancient



lithosphere, either within the plume or entrained in the upper mantle.

## Acknowledgements

We thank Leonid Danyushevsky for enlightening discussions, comments on the manuscript, and correction of the Koolau major element data, and Daniel Bombardieri and Maya Kamenetsky for assistance with sample preparation. Hugh O'Neill generously conducted the Koolau batch melting experiments at the Research School of Earth Sciences, Australian National University. Journal reviews by Peter Reiners, Alex Sobolev, and David Clague are appreciated. This work was supported by the Australian Research Council and the National Science Foundation (OCE-9729894). This is SOEST contribution no. 5854.

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