



Enriched components in the Hawaiian plume: Evidence from Kahoolawe Volcano, Hawaii

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[1] The geochemical differences between individual Hawaiian shields provide clues to the magma source components in the Hawaiian plume. Lavas from Koolau (Makapuu-stage) and Kahoolawe volcanoes define the enriched, i.e., relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$, extreme for Hawaiian shield lavas. There are, however, important geochemical differences between these shields; Kahoolawe lavas lack the relatively high SiO_2 , low CaO , and high Sr/Nb and La/Nb that are characteristic of Makapuu-stage Koolau lavas, and they are offset from other Hawaiian shield lavas to high $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$. Consequently, a varying role for recycled plagioclase-rich gabbro is inferred, in particular, lower amounts of the low $^{87}\text{Sr}/^{86}\text{Sr}$ component in Kahoolawe lavas. Also, lavas from Loa-trend volcanoes, such as Kahoolawe, define trends ranging toward high $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ and $^{87}\text{Sr}/^{86}\text{Sr}$ and low $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$. Such trends are consistent with variable amounts of recycled sediment sampled by Loa-trend volcanoes, with the largest proportion in Makapuu-stage Koolau lavas. Therefore the enriched component in the Hawaiian plume, the Koolau component, is recycled oceanic crust, which is heterogeneous because of varying proportions of sediment, basalt, and gabbro. Hawaiian shield-stage lavas range widely in $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, $^{176}\text{Hf}/^{177}\text{Hf}$, and $^{206}\text{Pb}/^{204}\text{Pb}$, but they have similar ratios of Sr/Nd , Nd/Hf , and Hf/Pb , each varying by a factor of <3 among the Hawaiian shields. This observation has important consequences. Namely, the similar Hf/Pb ratios are inconsistent with a two-component (i.e., Kea and Koolau) mixing model for explaining the hyperbolic trend of $^{176}\text{Hf}/^{177}\text{Hf}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ defined by shield lavas. Such a model requires end-members with very different Hf/Pb (a factor of 15 to 40), but this is not observed; therefore a third component must be involved. On the basis of trends of $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ versus $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, and $^{176}\text{Hf}/^{177}\text{Hf}$, we infer that Loa and Kea trend shield lavas contain variable amounts of the Loihi source component.

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1. Introduction

[2] Radiogenic isotope ratios of Sr, Nd, Hf, Pb and Os are quite variable in Hawaiian shield lavas. Clearly their source, dominantly the Hawaiian plume, is geochemically heterogeneous. Among Hawaiian shields, lavas from the surface of the Koolau shield (Makapuu-stage) define an extreme in geochemical characteristics. Specifically, Makapuu-stage Koolau lavas have the highest $^{87}\text{Sr}/^{86}\text{Sr}$, La/Nb and SiO_2 content, and the lowest $^{143}\text{Nd}/^{144}\text{Nd}$, $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ coupled with low CaO and total iron content. These extreme geochemical characteristics are inferred to reflect small amounts of ancient recycled oceanic crust in the Hawaiian plume [e.g., Frey *et al.*, 1994; Roden *et al.*, 1994; Hauri, 1996; Lassiter and Hauri, 1998; Blichert-Toft *et al.*, 1999; Jackson *et al.*, 1999; Huang and Frey, 2005]. Lavas from two other Hawaiian volcanoes, Kahoolawe and Lanai, share some but not all of these distinctive geochemical characteristics [e.g., West *et al.*, 1987; Frey *et al.*, 1994; Basu and Faggart, 1996].

[3] Radiogenic isotope data for Kahoolawe lavas have been reported by West *et al.* [1987] (Sr, Nd and Pb), Blichert-Toft *et al.* [1999] (Hf), and Abouchami *et al.* [2005] (high precision Pb). West *et al.* [1987] showed that Kahoolawe lavas range more widely in Sr, Nd and Pb isotopic ratios than most other Hawaiian shields, and that Kahoolawe lavas range to the high $^{87}\text{Sr}/^{86}\text{Sr}$, and low $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ that define the end-member Makapuu-stage Koolau lavas. Abouchami *et al.* [2005] confirmed that Kahoolawe lavas range widely in Pb isotopic ratios, e.g., $^{206}\text{Pb}/^{204}\text{Pb}$ from 17.95 to 18.40, but in detail the Kahoolawe $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ trend differs from Makapuu-stage Koolau lavas. Leeman *et al.* [1994] in a further study of the Kahoolawe samples studied by West *et al.* [1987] used complex trends

between ratios of highly incompatible elements, e.g., Th/Ta, and Sr, Nd and Pb isotopic ratios to argue for three source components contributing to Kahoolawe lavas, i.e., plume, asthenosphere and lithospheric mantle. Blichert-Toft *et al.* [1999] found that in a $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{176}\text{Hf}/^{177}\text{Hf}$ plot, Kahoolawe lavas lie on the Hawaiian shield trend, but that Kahoolawe lavas are not as extreme as Makapuu-stage Koolau lavas.

[4] In this paper, we report major and trace element abundances for 25 shield stage and 2 caldera filling lavas from Kahoolawe Volcano (Table 1); one shield stage lava, KAH-73, has a K-Ar age of 1.25 ± 0.15 My [Fodor *et al.*, 1992]. Isotopic ratios for Sr, Nd, Hf and Pb are reported for a subset of 13 shield stage and 1 caldera filling lavas (Table 2). Our objective is to define and use the geochemical similarities and differences between Kahoolawe and other Hawaiian shield lavas to understand the origin and processes that created the enriched components in the Hawaiian plume. Important results are as follows: (1) An ancient recycled plagioclase-rich gabbroic crust component, characterized by low $^{87}\text{Sr}/^{86}\text{Sr}$, is present in the Hawaiian plume; compared with other Hawaiian shield lavas, Kahoolawe lavas contain lesser amounts of this component. (2) Kahoolawe volcano is a Loa-trend volcano (Figure 1). Lavas from Loa-trend volcanoes range to high $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ and $^{87}\text{Sr}/^{86}\text{Sr}$ coupled with low $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$; consequently, we infer that Loa-trend lavas contain variable amounts of a recycled sedimentary component that is not present in Kea-trend lavas. (3) All Hawaiian shield lavas contain the Loihi source component.

2. Samples and Analytical Procedures

[5] Twenty-five shield stage samples and two caldera-filling lavas were collected by R. V. Fodor and

Table 1 (Representative Sample). Major and Trace Element Abundances in Kahoolawe Shield and Caldera Filling Lavas^a [The full Table 1 is available in the HTML version of this article at <http://www.g-cubed.org>]

Sample	KAH 13	KAH 13	KAH 13	KAH 14 ^b	KAH 16 ^b	KAH 18 ^b	KAH 21	KAH 23 ^b	KAH 24	KAH 24	KAH 25	KAH 26	KAH 28	KAH 31	KAH 65	KAH 67
Shatter box ^c	WC	agate	WC	WC	WC	WC	agate	WC	agate	WC	agate	agate	agate	agate	agate	agate
Location	Kanapou bay	Kanapou bay	Kanapou bay	Kanapou bay	Kanapou bay	Kanapou bay	Kanapou bay	Kanapou bay	Kanapou bay	Kanapou bay	Kanapou bay	Kanapou bay	Kanapou bay	Kanapou bay	Waikahalulu bay	Waikahalulu bay
Elevation, m	215	215	192	171	143	113	98	90	90	90	86	68	47	30	8	20
SiO ₂	51.8	51.8	50.7	49.1	51.2	50.1	50.1	50.1	50.1	50.1	48.5	50.2	48.9	51.9	51.9	50.5
TiO ₂	2.62	2.62	2.52	2.54	2.25	2.60	2.60	1.52	1.52	1.52	2.08	2.35	3.18	2.38	2.38	2.33
Al ₂ O ₃	13.6	13.6	15.4	14.0	12.8	14.1	14.1	11.8	11.8	11.8	12.6	14.4	14.3	13.7	13.7	13.9
Fe ₂ O ₃	12.9	12.9	13.2	13.1	12.2	13.2	13.2	12.2	12.2	12.2	13.05	12.82	14.75	12.3	12.3	12.5
MnO	0.18	0.18	0.18	0.17	0.16	0.18	0.18	0.17	0.17	0.17	0.18	0.18	0.21	0.18	0.18	0.16
MgO	6.14	6.14	6.17	8.30	9.06	6.32	6.32	13.9	13.9	13.9	12.2	7.76	5.52	6.71	6.71	7.24
CaO	10.0	10.0	9.3	10.1	9.1	10.6	10.6	8.18	8.18	8.18	9.44	9.71	9.99	10.5	10.5	11.0
Na ₂ O	2.15	2.15	2.08	2.35	2.21	2.38	2.38	1.65	1.65	1.65	2.14	2.14	2.59	1.98	1.98	2.08
K ₂ O	0.40	0.40	0.17	0.11	0.61	0.18	0.18	0.18	0.18	0.18	0.09	0.22	0.28	0.26	0.26	0.18
P ₂ O ₅	0.29	0.29	0.27	0.31	0.34	0.36	0.36	0.16	0.16	0.16	0.12	0.26	0.36	0.23	0.23	0.22
TOTAL	100.1	100.1						99.8	99.8	99.8	100.0	99.9	100.0	100.1	100.1	100.2
LOI ^d	0.83	0.83	1.94	1.64	1.11	1.07	1.07	0.75	0.75	0.75	1.15	1.61	0.61	0.49	0.49	0.02
Sc	33	33	32	31	29	34	34	23	23	23	23	30	31	34	34	34
Rb	5.3	5.3	0.38	0.26	9.4	1.20	1.20	3.0	3.0	3.0	0.232	0.70	3.1	2.90	2.69	2.15
Sr	306	304	295	376	409	331	360	208	208	208	247	300	394	320	282	288
Y	32.3	31.6	32.1	31.7	28.1	32.4	33.5	20.6	20.6	20.6	19.2	30.5	37.2	31.1	29.3	28.1
Zr	162	161	155	161	159	143	172	95	94	94	123	146	204	149	136	132
Nb	11.4	11.2	11.1	13.6	13.4	10.2	14.0	6.34	6.25	6.25	8.93	9.84	16.7	10.7	10.5	10.4
Ba	98.4	98.5	94.3	105	190	79.9	67.2	71.2	70.3	70.3	39	72	103	64	74	62
La	11.8	11.6	13.6	14.7	13.5	12.1	13.3	6.70	6.61	6.61	6.50	10.2	16.5	12.1	9.44	9.27
Ce	27.9	27.6	29.5	33.4	30.2	26.5	33.2	16.7	16.6	16.6	14.1	24.2	40.5	28.9	23.3	24.0
Pr	4.5	4.4	4.5	5.1	4.7	4.6	5.0	2.5	2.5	2.5	2.7	4.1	5.9	4.6	3.7	3.5
Nd	21.2	21.3	21.4	23.7	22.1	21.8	22.9	12.1	11.3	11.3	13.2	20.1	27.3	21.5	17.8	17.0
Sm	6.1	5.9	5.9	6.2	5.8	6.1	6.2	3.4	3.3	3.3	3.9	5.7	7.0	6.0	4.9	5.0
Eu	1.97	1.97	1.98	2.05	1.94	2.05	2.04	1.17	1.15	1.15	1.38	1.91	2.32	2.16	1.66	1.67
Tb	1.01	1.00	0.992	1.03	0.91	1.07	1.05	0.64	0.61	0.61	0.67	0.98	1.18	1.03	0.89	0.88
Gd	6.3	6.2	6.3	6.4	6.1	6.7	6.7	3.8	3.8	3.8	4.0	6.1	7.3	6.4	5.4	5.4

^aMajor element contents are reported in %, and trace element abundances are reported in ppm.

^bMajor element contents are taken from *Fodor et al.* [1992] by converting FeO to Fe₂O₃. Major element contents are renormalized to 100% after converting FeO to Fe₂O₃.

^cSample powders prepared by *Fodor et al.* [1992] were crushed in a WC shatter box. To avoid the possible Ta and Pb contamination arising from using a WC shatter box, most of the samples that we analyzed were crushed in an agate shatter box. Two samples (KAH-13 and -24) were prepared in both WC and agate shatter boxes; trace element abundances agree within 10%, even for Ta and Pb! However, Nb/Ta in six other samples prepared in a WC shatter box have low Nb/Ta (2.5–8.5) and Ce/Pb (2.2–11.3), relative to the Nb/Ta (14.2–15.5) and Ce/Pb (12.5–29.0) in 21 samples crushed in an agate shatter box.

^dLOI, loss on ignition. ~0.2 g samples were ignited at 1000°C for over 8 hours. LOI was calculated using (weight loss during ignition/weight before ignition)*100%.



Table 2. Sr, Nd, Pb, and Hf Isotopic Ratios in Kahoolawe Shield and Caldera Filling Lavas

Sample	$^{87}\text{Sr}/^{86}\text{Sr}$	2 sigma	$^{143}\text{Nd}/^{144}\text{Nd}$	2 sigma	$^{206}\text{Pb}/^{204}\text{Pb}$	2 sigma	$^{207}\text{Pb}/^{204}\text{Pb}$	2 sigma	$^{208}\text{Pb}/^{204}\text{Pb}$	2 sigma	$^{176}\text{Hf}/^{177}\text{Hf}$	2 sigma
KAH 13	0.704049	0.000008	0.512873	0.000008	18.009	0.001	15.438	0.001	37.797	0.002	0.283046	0.000007
KAH 14	0.704226	0.000008	0.512819	0.000012	18.004	0.001	15.426	0.001	37.785	0.002	0.283001	0.000006
KAH 21	0.704161	0.000010	0.512834	0.000007	17.999	0.001	15.429	0.001	37.780	0.002	0.283008	0.000006
KAH 24	0.704300	0.000008	0.512796	0.000008	17.867	0.001	15.414	0.001	37.685	0.003	0.282968	0.000009
KAH 25	0.704091	0.000008	0.512862	0.000006	18.060	0.001	15.436	0.001	37.817	0.002	0.283015	0.000007
KAH 28	0.704090	0.000008	0.512828	0.000007	17.998	0.001	15.424	0.001	37.778	0.002	0.283002	0.000008
KAH 31	0.704073	0.000007	0.512863	0.000007	18.021	0.001	15.438	0.001	37.808	0.002	0.283004	0.000006
KAH 36	0.704167	0.000011	0.512821	0.000007	17.992	0.001	15.427	0.001	37.791	0.002	0.283010	0.000006
KAH 67	0.704093	0.000008			18.095	0.001	15.439	0.001	37.888	0.002	0.283010	0.000008
KAH 71	0.703937	0.000010	0.512902	0.000007	18.109	0.001	15.426	0.001	37.838	0.001	0.283050	0.000009
KAH 75	0.704160	0.000010	0.512855	0.000010	18.028	0.001	15.423	0.001	37.829	0.002	0.282988	0.000006
KAH 181	0.704139	0.000008	0.512852	0.000008	17.945	0.001	15.423	0.001	37.760	0.002	0.283002	0.000007
KAH 182	0.704139	0.000008	0.512860	0.000009	17.952	0.001	15.427	0.001	37.758	0.002	0.282990	0.000006
KAH 185	0.704190	0.000008	0.512832	0.000022	18.029	0.001	15.448	0.001	37.908	0.002	0.282981	0.000007

G. R. Bauer [Fodor *et al.*, 1992] from three stratigraphic sections on Kahoolawe Island, Hawaii, which was originally mapped by Stearns [1940] (Figure 1). Major element contents were determined by X-ray fluorescence analysis at the University of Massachusetts at Amherst following the procedure described by Rhodes [1996]. Trace element abundances were determined by ICP-MS at MIT following the procedure described by Huang and Frey [2003]. Sr-Nd-Pb isotopic ratios were obtained on acid-leached powders at MIT following the procedures described by Huang *et al.* [2005]. Hf isotopic ratios were obtained on unleached powders in Lyon following the procedure described by Blichert-Toft *et al.* [1997]. $^{176}\text{Hf}/^{177}\text{Hf}$ was normalized for mass fractionation relative to $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ and $^{176}\text{Hf}/^{177}\text{Hf}$ of the JMC-475 Hf standard averaged 0.282160 ± 0.000010 (2 sigma). The Hf standard was run systematically after every two samples. Hf total procedural blanks were less than 25 pg.

3. Results

3.1. Major Elements

[6] Kahoolawe shield and caldera-filling lavas are tholeiitic basalt. Among Hawaiian shield lavas, tholeiitic basalt forming the Makapuu-stage of the Koolau shield is distinctive because of its relatively high SiO_2 and low CaO content (Figure 2); these are features attributed to a dacitic melt component derived from recycled oceanic crust [Hauri, 1996; Huang and Frey, 2005]. Consistent with the conclusions of Frey *et al.* [1994], Kahoolawe lavas do not have the distinctively high SiO_2 and low CaO contents that distinguish Makapuu-stage Koolau lavas from other Hawaiian shield lavas; after applying a $\text{K}_2\text{O}/\text{P}_2\text{O}_5 > 1$ alteration filter to reject samples whose compositions have been affected by low-temperature alteration [e.g., Huang and Frey, 2003], the SiO_2 and CaO contents of Kahoolawe shield and caldera-filling lavas scatter widely (Figure 2).

3.2. Trace Elements

[7] Relative to primitive mantle compositions, tholeiitic basalt forming Hawaiian shields, is characterized by increasing relative enrichment as the incompatibility of the element increases; typical highly incompatible elements, such as Ba, La and

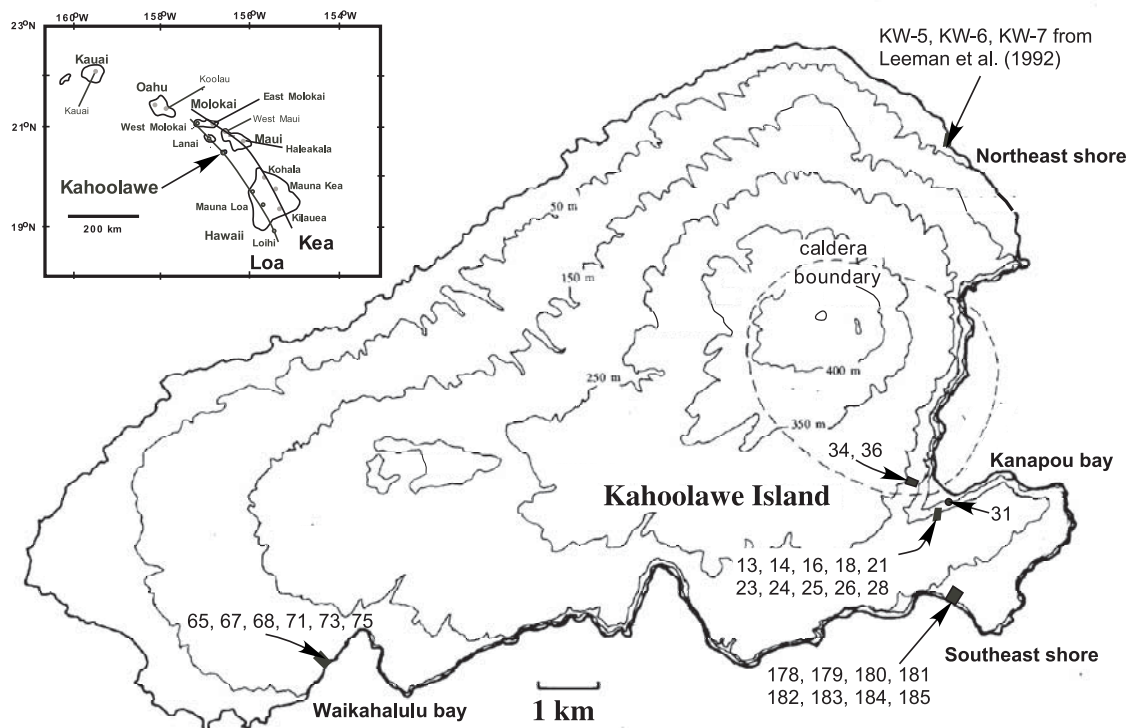


Figure 1. Map of Kahoolawe Island showing sample locations. Location for samples KW-5, KW-6, and KW-7 from *Leeman et al.* [1994] is also shown. The inset shows Loa and Kea volcano trends; Kahoolawe Volcano is a Loa-trend volcano.

Ce, are enriched by factors of >9 whereas less incompatible elements, such as heavy rare earth elements (REE), are enriched by factors of 3 to 5 (Figure 3). In a primitive-mantle normalized multi-element diagram, tholeiitic basalts from Kahoolawe have trace element abundances similar to Makapuu-stage Koolau lavas, and range to higher incompatible element abundances than Mauna Loa lavas (Figure 3).

[8] Also, some abundance ratios, such as Ba/Th, distinguish Hawaiian shield lavas from mid-ocean ridge basalts (MORB) and most other ocean island basalts (OIB) [e.g., *Hofmann and Jochum*, 1996; *Yang et al.*, 2003]. Consistent with this result, (Ba/Th)_{PM} in Kahoolawe lavas (with $K_2O/P_2O_5 > 1$) ranges from 1.5 to 3.0. Other ratios, such as La/Nb, in Hawaiian shield lavas are variable and correlated with radiogenic isotopic ratios [e.g., *Huang and Frey*, 2003, Figure 14]. Among Hawaiian shield lavas, Makapuu-stage Koolau lavas have the highest La/Nb and Sr/Nb; such ratios are inferred to reflect a recycled sedimentary component in the source of Makapuu-stage lavas [*Jackson et al.*, 1999; *Huang and Frey*, 2005]. In contrast, Kahoolawe

shield and caldera-filling lavas have lower La/Nb and Sr/Nb and largely overlap the field for Mauna Loa lavas (Figure 4). The difference between Makapuu-stage Koolau lavas and Kahoolawe lavas is especially clear for Sr/Nb. Since Kahoolawe caldera-filling lavas have similar geochemical compositions as Kahoolawe shield lavas (e.g., Figures 2 and 4), we do not distinguish them in the following discussion and figures.

3.3. Sr-Nd-Hf-Pb Isotopic Ratios

[9] Our data for $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ in Kahoolawe lavas define an inverse trend with considerably less scatter than previously published data (Figure 5). In part, this is a result of higher precision, but most importantly, except for 3 of the 11 shield lavas, the isotopic data for Kahoolawe lavas reported by *West et al.* [1987] were obtained on powders that were not acid-leached. It is now recognized that $^{87}\text{Sr}/^{86}\text{Sr}$ of Hawaiian lavas can be significantly modified, typically increased, by residence in the tropical marine environment of Hawaii [e.g., *Roden et al.*, 1994]. Nevertheless, the new data confirm that Kahoolawe lavas, like

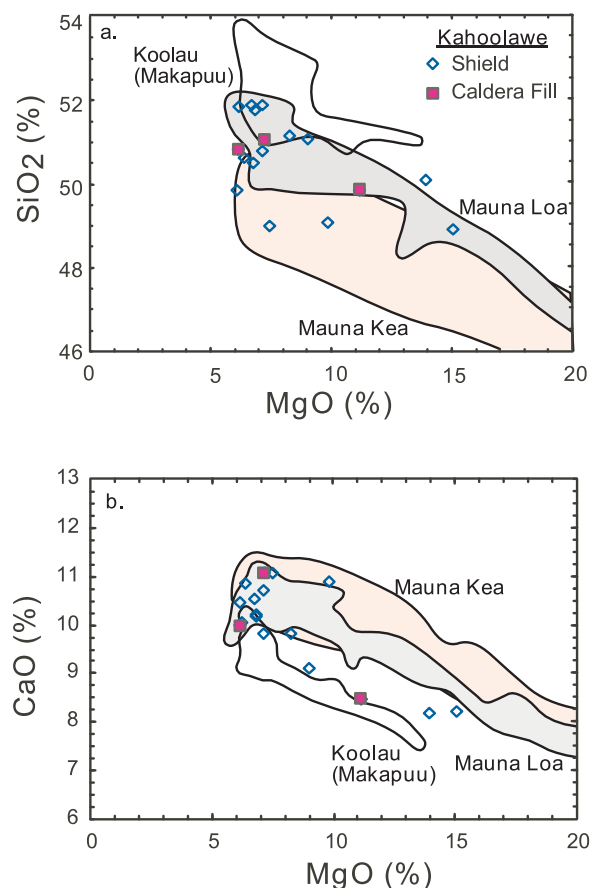


Figure 2. MgO versus SiO₂ and CaO (all in %) for Kahoolawe shield and caldera-filling lavas. Since SiO₂ and CaO are sensitive to postmagmatic alteration, only relatively unaltered lavas with K₂O/P₂O₅ > 1 are plotted. Kahoolawe lavas scatter widely; most are not in the field for Makapuu-stage Koolau lavas (~40 samples). Data sources: Kahoolawe: *Fodor et al.* [1992], *Leeman et al.* [1994], this study; Mauna Kea: *Rhodes* [1996], *Rhodes and Vollinger* [2004]; Mauna Loa: *Garcia et al.* [1995a], *Rhodes* [1995, 1996], *Rhodes and Hart* [1995], *Rhodes and Vollinger* [2004]; Koolau (Makapuu-stage): *Frey et al.* [1994].

Makapuu-stage Koolau lavas, range to relatively high ⁸⁷Sr/⁸⁶Sr and low ¹⁴³Nd/¹⁴⁴Nd; most importantly, relative to Makapuu-stage Koolau lavas, Kahoolawe lavas are offset to high ⁸⁷Sr/⁸⁶Sr at a given ¹⁴³Nd/¹⁴⁴Nd (Figure 5).

[10] In an ϵ_{Hf} versus ϵ_{Nd} plot, *Blichert-Toft et al.* [1999] showed that Hawaiian shield lavas define a shallower trend than the OIB array. Specifically, they found that Makapuu-stage Koolau lavas are at the extreme of the Hawaiian trend with relatively high ϵ_{Hf} at a given ϵ_{Nd} (Figure 6). They also found that the Kahoolawe sample, KW-19, with the lowest ϵ_{Nd} is offset to relatively high ϵ_{Hf} . In

contrast, our Kahoolawe data do not deviate from the OIB array; Sample KAH-24 with the lowest ϵ_{Hf} is on the OIB array (Figure 6). We are confident that these differences are not analytical artifacts because the low ϵ_{Nd} of KW-19 is consistent with its relatively high ⁸⁷Sr/⁸⁶Sr (Figure 5), and ϵ_{Hf} for KAH-24 and KW-19 were determined in the same laboratory and are within analytical uncertainty.

[11] In Pb-Pb isotopic plots, Kahoolawe lavas range to the low ²⁰⁶Pb/²⁰⁴Pb end of the array defined by Hawaiian shield lavas (Figure 7). As expected for a Loa-trend volcano, Kahoolawe lavas have relatively high ²⁰⁸Pb/²⁰⁴Pb at a given ²⁰⁶Pb/²⁰⁴Pb [*Abouchami et al.*, 2005]. However, unlike Makapuu-stage Koolau lavas, the Pb-Pb trends for Kahoolawe lavas are parallel to those for other Hawaiian shields (Figure 7).

[12] An important feature of Kahoolawe lavas is their wide range in isotopic ratios. There are no systematic geochemical variations within or between the three stratigraphic sections of shield lavas. The isotopic extremes are represented by samples studied by *West et al.* [1987]; KW-19 from a Kanapou Bay section has the highest ⁸⁷Sr/⁸⁶Sr and lowest ¹⁴³Nd/¹⁴⁴Nd (Figure 5), whereas samples KW-5 and KW-7 from the Northeast shore have the lowest ⁸⁷Sr/⁸⁶Sr, highest ¹⁴³Nd/¹⁴⁴Nd and ϵ_{Hf} , and the most radiogenic Pb isotopic ratios (Figures 5–7). Most importantly, isotopic heterogeneity is expressed on a very local scale, in terms of location and eruption age; i.e., sample KW-6 is stratigraphically situated between samples KW-5 and KW-7 (Figure 1) [*Leeman et al.*, 1994, Figure 2], but does not have extreme isotopic ratios (Figures 5–7). Among our samples, KAH-24 from Kanapou Bay has the highest ⁸⁷Sr/⁸⁶Sr and lowest ϵ_{Nd} and ϵ_{Hf} , and the least radiogenic Pb isotopic ratios (Figures 5–7).

4. Discussion

4.1. Source Components Contributing to Hawaiian Shield Lavas

[13] Among Hawaiian shield lavas, the extremes in radiogenic isotopic ratios are manifested in lavas from specific volcanoes. Lavas from Loihi and Kauai are characterized by the highest ³He/⁴He [*Kurz et al.*, 1983; *Mukhopadhyay et al.*, 2003]. Lavas from Mauna Kea, Kilauea and Kauai are characterized by the lowest ⁸⁷Sr/⁸⁶Sr and highest

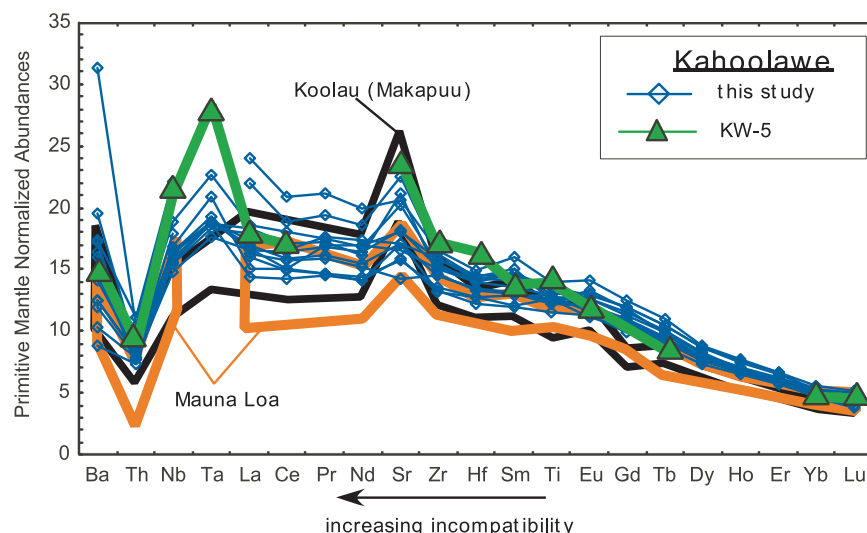


Figure 3. Primitive mantle value normalized incompatible element abundances in Kahoolawe lavas. Fields for Mauna Loa and Makapuu-stage Koolau lavas are shown for comparison. Only lavas with 7% < MgO < 10% and $K_2O/P_2O_5 > 1$ are shown. Only Sample KW-5 from *Leeman et al.* [1994] satisfies these criteria; it is important because among Kahoolawe lavas it has the largest relative Sr enrichment. Our samples crushed in a WC shatter box were contaminated with Ta (see Table 1 footnote); consequently, Ta abundances are not shown for these samples. Data sources: Mauna Loa: *Rhodes* [1995, 1996], *Cohen et al.* [1996], *Rhodes and Hart* [1995], *Rhodes and Vollinger* [2004], our unpublished instrumental neutron activation analysis data for the Mauna Loa section of the Hawaii Scientific Drilling Project Phase 2 drill core. Primitive mantle values are from *Hofmann* [1988]; Makapuu-stage of Koolau: *Frey et al.* [1994], *Huang and Frey* [2005].

$^{143}\text{Nd}/^{144}\text{Nd}$, $^{176}\text{Hf}/^{177}\text{Hf}$ and Pb isotopic ratios [e.g., *Lassiter et al.*, 1996; *Blichert-Toft et al.*, 1999; *Abouchami et al.*, 2000]. In contrast, lavas from the Makapuu-stage of Koolau, Lanai and Kahoolawe range to the highest $^{87}\text{Sr}/^{86}\text{Sr}$ and lowest $^{143}\text{Nd}/^{144}\text{Nd}$, $^{176}\text{Hf}/^{177}\text{Hf}$ and Pb isotopic ratios [e.g., *West et al.*, 1987; *Roden et al.*, 1994]. The enriched end-member, i.e., highest $^{87}\text{Sr}/^{86}\text{Sr}$ and lowest $^{143}\text{Nd}/^{144}\text{Nd}$, in Hawaiian shield lavas is defined by lavas from the Makapuu-stage of the Koolau shield [*Frey et al.*, 1994; *Roden et al.*, 1994; *Hauri*, 1996; *Lassiter and Hauri*, 1998; *Blichert-Toft et al.*, 1999; *Jackson et al.*, 1999; *Huang and Frey*, 2005]. Although an enriched component also contributed to lavas from the Lanai and Kahoolawe shields [*West et al.*, 1987; *Basu and Faggart*, 1996], we find that Kahoolawe shield lavas differ from Makapuu-stage Koolau lavas. Compared with Makapuu-stage Koolau lavas, Kahoolawe lavas are offset to higher $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$ (Figure 5). Also, they lack the distinctive major and trace element characteristics of Makapuu-stage Koolau lavas; i.e., high SiO_2 and low CaO contents attributed to a dacite melt derived from partial melting of eclogite, and high La/Nb and Sr/Nb attributed to recycled sediment [*Huang and Frey*, 2005]. Such differences provide

insights for understanding the origin of enriched components in the Hawaiian plume.

4.2. Mixing Among Different Source Components

[14] The diversity of isotopic ratios in Hawaiian shield lavas is commonly explained by variable mixing proportions of source components known as the Koolau, Loihi and Kea components [e.g., *Eiler et al.*, 1996, 1998; *Lassiter and Hauri*, 1998; *Blichert-Toft et al.*, 1999]. On the basis of isotopic data for Kauai lavas, *Mukhopadhyay et al.* [2003] proposed that a fourth component DM (depleted mantle as represented by rejuvenated-stage lavas) is necessary. Four components are also required by the Pb-Pb isotopic trends defined by Hawaiian shield lavas [*Abouchami et al.*, 2005]. With four source components, it is surprising that some isotopic trends defined by Hawaiian shield lavas are near-linear, e.g., $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ (Figure 5) and $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{176}\text{Hf}/^{177}\text{Hf}$ (Figure 6). Therefore one approach to modeling the mixing process is to assume that different source components have similar trace element abundance ratios (i.e., Sr/Nd and Nd/Hf) and, in some cases, similar trace element abundances [e.g.,

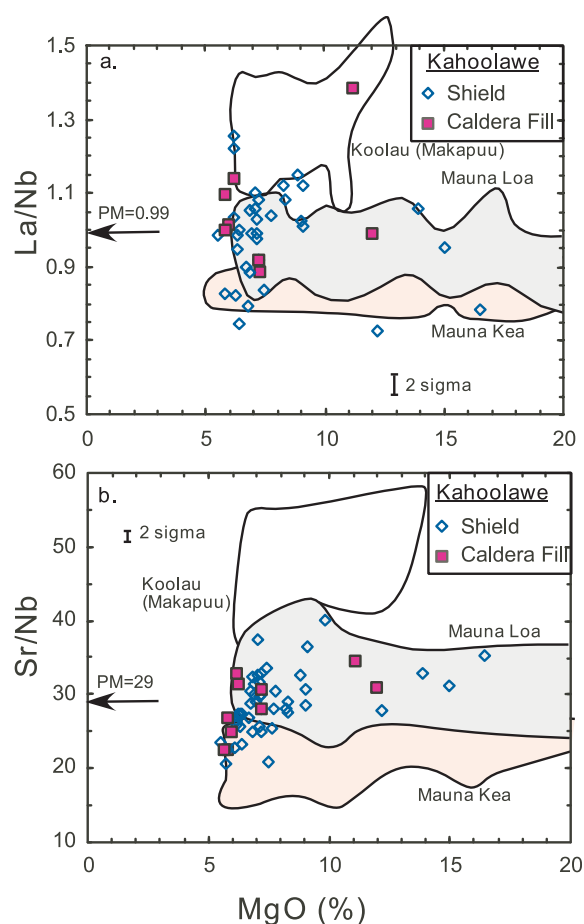


Figure 4. MgO versus La/Nb and Sr/Nb for Kahoolawe shield and caldera-filling lavas. Fields for Loa-trend shields (Makapuu-stage of Koolau and Mauna Loa) and a Kea-trend shield (Mauna Kea) are shown for comparison. These ratios are not correlated with MgO content. The important result is that most Kahoolawe lavas lack the high La/Nb and Sr/Nb that distinguish Makapuu-stage Koolau lavas. Data sources: Kahoolawe: Fodor *et al.* [1992], Leeman *et al.* [1994], this study; Makapuu-stage Koolau and Mauna Loa: see the Figures 2 and 3 captions; Mauna Kea: Rhodes [1996], Yang *et al.* [1996], Huang and Frey [2003], Rhodes and Vollinger [2004].

Eiler *et al.*, 1996, 1998; Mukhopadhyay *et al.*, 2003]. The observation that Hawaiian shield lavas have similar ratios (within a factor of 3) of Sr/Nd and Nd/Hf at a given MgO content (Figure 8) is consistent with the assumptions made by Eiler *et al.* [1996, 1998] and Mukhopadhyay *et al.* [2003], who successfully reproduced the isotopic variations in Hawaiian shield lavas using three or four source components. However, similar Sr/Nd and Nd/Hf in isotopically distinct source components is surprising if these components were created by diverse processes, ranging from partial melting to

formation of different types of sediments. A possible explanation is that the “source components” in the mixing models are mixtures of different mantle reservoirs rather than independent source components created by different processes. The mixing lines involving different mantle reservoirs may be highly curved, i.e., they have very different element abundance ratios (such as Sr/Nd), but if the mixing proportions of different mantle reservoirs vary over a small range, it is possible that the mixing lines are close to linear. As an example, the sources of Koolau lavas contain variable, but small amounts (<3%) of recycled sediment [Huang and Frey, 2005].

[15] Other isotopic ratio trends defined by Hawaiian shield lavas, most notably $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{176}\text{Hf}/^{177}\text{Hf}$ (Figure 9), are highly curved and very different Hf/Pb are inferred for the proposed mixing end-members [Blichert-Toft *et al.*, 1999]. Although Blichert-Toft *et al.* [1999] proposed that the end-members for the Koolau and Kea components differ by a factor of 40 in Hf/Pb, we find the trend of Hawaiian shield lavas is consistent with $(\text{Hf/Pb})_{\text{Kea/Koolau}} = 15$ (Figure 9). A mixing calculation using $(\text{Hf/Pb})_{\text{Kea/Koolau}} = 15$ implies that Hf/Pb in Mauna Kea and Makapuu-stage Koolau lavas differs by a factor of 5 ($8.0/1.6$) (Figure 9). In detail, other shield lava trends, such as $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$, are also best fitted by Sr/Pb and Nd/Pb that differ by factors of ~ 5 in the Koolau and Kea components (Figure 10).

[16] Given the nonlinearity of trends involving $^{206}\text{Pb}/^{204}\text{Pb}$ (Figures 9 and 10), it is surprising that Hawaiian shield lavas with $>7\%$ MgO have Sr/Pb, Nd/Pb and Hf/Pb that differ by factors less than 3 (Figure 8). If these ratios in the lavas are representative of those in the sources, a consequence is that mixing of end-members, e.g., Mauna Kea (Kea) and the Makapuu-stage of Koolau (Koolau), yields near-linear trends which do not adequately explain the curvature defined by lavas from Hawaiian shields (Figures 9 and 10). For example, the curvature in the $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{176}\text{Hf}/^{177}\text{Hf}$ plot requires that $(\text{Hf/Pb})_{\text{Kea/Koolau}} = 15$ (Figure 9), but such a difference is not observed (Figure 8). How can this contradiction be resolved? One potential problem is our assumption that Hf/Pb in lavas represents the source value. Could solid sources have quite different Hf/Pb but magmas resulting from the partial melting process have similar Hf/Pb? We evaluate this possibility.

[17] We assume that a garnet peridotite contains 10% garnet and 15% clinopyroxene, a melting

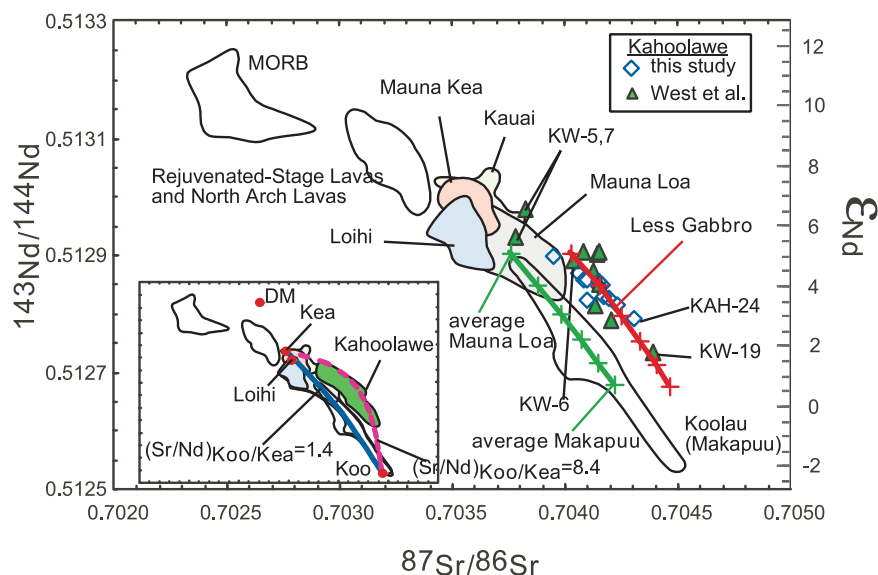


Figure 5. $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ for Kahoolawe shield lavas. Shield lavas KW-5, KW-7, and KW-19 define the extremes for Kahoolawe lavas. Fields for other Hawaiian shields, rejuvenated stage lavas, and MORB are shown for comparison. Most notable is the large range for Kahoolawe, and Makapuu-stage Koolau lavas, and the offset of Kahoolawe lavas to high $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$. The inset shows the fields for Hawaiian shields, rejuvenated stage lavas, and MORB, along with the four “source components” (red dots) of *Mukhopadhyay et al.* [2003]. Note that these four “source components” define a near-linear trend; Kahoolawe lavas are offset from this trend. The blue line is a mixing line between source components “Kea” and “Koolau,” and Sr/Nd of these two components are the average values of Mauna Kea and the Makapuu-stage Koolau lavas, 15 and 21, respectively. Note that we assume that partial melting does not significantly change Sr/Nd; consequently, Sr/Nd in the lavas reflect their source values. The red dashed line is also a mixing line between source components “Kea” and “Koolau,” using Sr/Nd of 15 and 126 for these two components, respectively. This large difference in Sr/Nd is required for the mixing line to include Kahoolawe lavas. In the large figure, two model mixing lines are also shown: the green line represents mixing between average Mauna Loa source composition and average Makapuu-stage Koolau source composition. The red line which passes through the Kahoolawe data reflects 1% subtraction of recycled gabbro from the mixtures of average Mauna Loa source and average Makapuu-stage Koolau source. Increments on the mixing lines are 20%. Modeling details are given in Table 3. Data sources: Kahoolawe lavas: *West et al.* [1987], this study; Koolau (Makapuu): *Roden et al.* [1984, 1994]; Mauna Kea: *Lassiter et al.* [1996], *Bryce et al.* [2005]; Mauna Loa: *Cohen et al.* [1996], *Kurz et al.* [1995]; Kauai: *Mukhopadhyay et al.* [2003]; Loihi: *Garcia et al.* [1993, 1995b, 1998]; rejuvenated stage lavas: *Stille et al.* [1983], *Roden et al.* [1984], *Chen and Frey* [1985], *Tatsumoto et al.* [1987], *West et al.* [1987], *Frey et al.* [2000], *Lassiter et al.* [2000]; EPR MORB: *Niu et al.* [1999], *Regelous et al.* [1999], *Castillo et al.* [2000].

reaction of 40% garnet + 40% clinopyroxene + 10% olivine + 10% orthopyroxene = 100% melt, and that 10% partial melting is required to generate tholeiitic lavas [e.g., *Feigenson et al.*, 2003]. During partial melting of peridotite, Pb partitioning is similar to Ce or Nd [e.g., *Hofmann*, 1997]; since these elements are highly incompatible in these minerals, D_{Pb} is assumed to be 0. Also, we assume that $D_{\text{Hf}}^{\text{garnet/melt}} = 0.5$, $D_{\text{Hf}}^{\text{clinopyroxene/melt}} = 0.2$, and that Hf is very incompatible in orthopyroxene and olivine. These partition coefficients are on the high end of published values [e.g., *Salter and Longhi*, 1999; *Pertermann et al.*, 2004]; therefore our calculations maximize the effect of partial melting on Hf/Pb. We find that Hf/Pb in melt generated by 10% partial melting is about 0.7 times that in the

original source. Therefore it is reasonable to assume that Hf/Pb in Hawaiian shield lavas approximates their source.

[18] However, Hawaiian shield lavas may be saturated with sulfide [e.g., *Lassiter*, 2003; *Norman et al.*, 2004]. *Norman et al.* [2004] showed that there is no correlation between Pb and S abundances in basaltic glasses from Hawaiian shields; consequently, it is unlikely that Pb abundance was affected by S devolatilization. On the basis of abundances of platinum group elements in Hawaiian shield lavas, *Lassiter* [2003] argued that the source of Hawaiian shield lavas may contain small amounts of sulfide, which may significantly affect the partition coefficient of Pb. Is it reasonable to

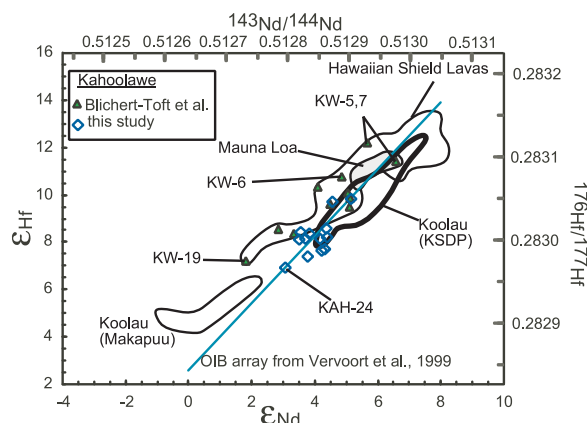


Figure 6. Nd-Hf isotopic correlation. $\epsilon_{\text{Hf}} = ((^{176}\text{Hf}/^{177}\text{Hf})_{\text{sample}} / (^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR}} - 1) \times 10000$ and $\epsilon_{\text{Nd}} = ((^{143}\text{Nd}/^{144}\text{Nd})_{\text{sample}} / (^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} - 1) \times 10000$ with $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR}} = 0.282772$ and $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} = 0.512638$. Data sources: Blichert-Toft *et al.* [1999] for the Hawaiian shield field, Kahoolawe data points (triangles), Mauna Loa and Koolau (Makapuu-stage) fields; V. J. M. Salters and J. Blichert-Toft (Isotope and trace element evidence for sampling of depleted lithosphere by the enriched Ko'olau basalts, submitted to *Contributions to Mineralogy and Petrology*, 2005; hereinafter referred to as Salters and Blichert-Toft, submitted manuscript, 2005) for Koolau (KSDP); this study for additional Kahoolawe data (diamonds). The OIB array is shown for comparison [Vervoort *et al.*, 1999].

assume $D_{\text{Pb}} = 0$? We use a Pb-Hf abundance plot to investigate their relative incompatibility during the partial melting process (Figure 11). The large data set for Mauna Kea lavas shows that Pb and Hf abundances are positively correlated, with alkalic lavas having the highest Pb and Hf abundances (Figure 11). Undoubtedly, this trend in part represents olivine accumulation and fractionation, but we infer that the large range, factor of 3, was dominantly controlled by variable extents of melting. Moreover, since the regressed line intercepts the Hf axis (Figure 11), we infer that during the partial melting process, Pb was more incompatible than Hf. Therefore we conclude that it is reasonable to assume that Hf/Pb in Hawaiian shield lavas reflects source ratios within 30%.

[19] If Hf/Pb in the lavas reflect those of the sources, a possible explanation is that the curvature of the isotopic-isotopic trends in Figures 9 and 10 reflects the involvement of a third component. Supporting evidence for this inference arises from plots of $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ versus Hf, Sr and Nd isotopic ratios for Hawaiian shield lavas (Figure 12). It is well known that the spatial arrangement of

recent Hawaiian volcanoes form two offset trends, i.e., the Kea and Loa trends [e.g., Lassiter *et al.*, 1996] (Figure 1). There are important geochemical differences between Loa and Kea trend lavas [e.g., Lassiter *et al.*, 1996]. Many of these differences are source related; e.g., Loa and Kea shield lavas define distinct arrays in a $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{208}\text{Pb}/^{204}\text{Pb}$ plot (Figure 7), thereby requiring four components with different Pb isotopic ratios [Abouchami *et al.*, 2005]. In Figure 12 we show that Kea and Loa lavas form two linear trends in plots of $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ versus Hf, Sr and Nd isotopic ratios, with Loihi lavas at the intersection of the Kea and Loa trends.

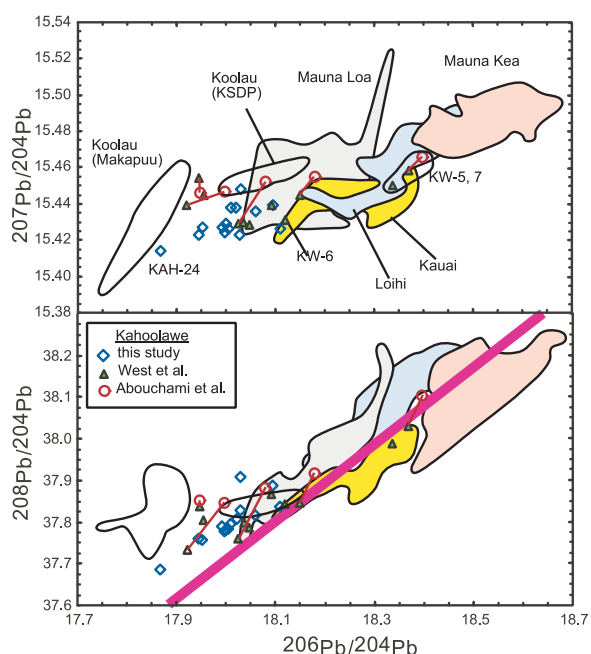


Figure 7. Pb-Pb isotopic ratios for Kahoolawe shield lavas. Five Kahoolawe lavas previously analyzed by West *et al.* [1987] were reanalyzed by Abouchami *et al.* [2005] and are connected by brown lines. Generally, lavas from Loa trend volcanoes have higher $^{208}\text{Pb}/^{204}\text{Pb}$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$ than lavas from Kea trend volcanoes, and the thick pink line in the bottom panel marks the boundary between Loa and Kea lavas (see Abouchami *et al.* [2005] for a detailed discussion). Data sources: Kahoolawe lavas: West *et al.* [1987], Abouchami *et al.* [2005], this study; Koolau (Makapuu): Roden *et al.* [1994], Abouchami *et al.* [2005]; Koolau (Koolau Scientific Drilling Project (KSDP)): Z. Fekiacova *et al.* (manuscript in preparation, 2005); Mauna Kea: Abouchami *et al.* [2000], Blichert-Toft *et al.* [2003], Eisele *et al.*, 2003; Mauna Loa: Cohen *et al.* [1996], Kurz *et al.* [1995], Abouchami *et al.* [2000]; Kauai: Mukhopadhyay *et al.* [2003]; Loihi: Garcia *et al.* [1993, 1995b, 1998].

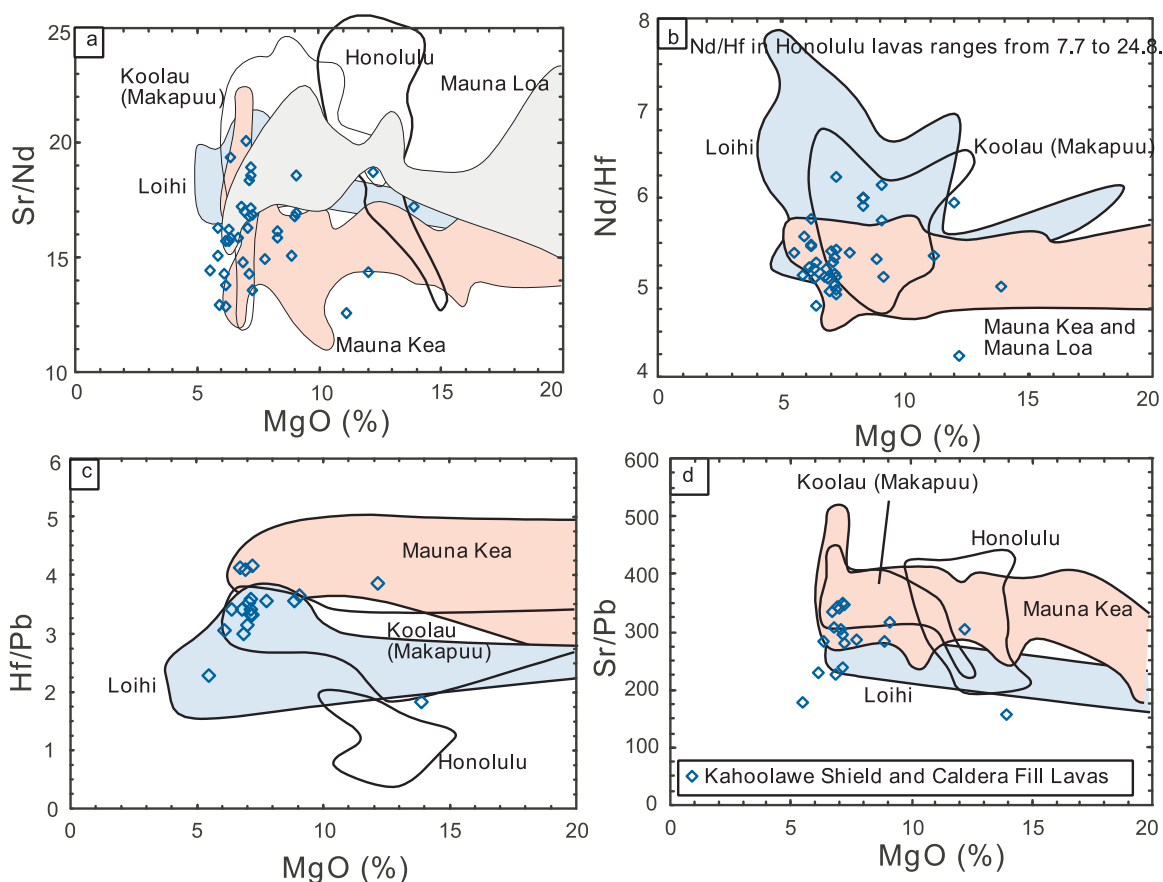


Figure 8. MgO (%) versus Sr/Nd, Nd/Hf, Hf/Pb, and Sr/Pb for Hawaiian shield lavas that define the isotopic end-members for Hawaiian shields (i.e., Mauna Kea, Loihi, and the Makapuu-stage of Koolau). It is surprising that these abundance ratios vary by less than a factor of 3 (at MgO > 7%). Even the alkalic, rejuvenated stage lavas of the Honolulu Volcanics derived by low extents of partial melting [e.g., *Yang et al.*, 2003] have Sr/Nd and Sr/Pb overlapping the shield fields. In contrast, Nd/Hf and Hf/Pb for the Honolulu lavas do not overlap the shield fields because Hf was controlled by residual oxides [Clague and Frey, 1982; *Yang et al.*, 2003]. Data sources: See the Figures 2–4 captions, plus Loihi data from *Frey and Clague* [1983], *Garcia et al.* [1993, 1995b, 1998], *Norman and Garcia* [1999], and Honolulu Volcanics data from *Clague and Frey* [1982] and *Yang et al.* [2003].

Specifically, lavas from Kea trend volcanoes have variable $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ but relatively constant $^{176}\text{Hf}/^{177}\text{Hf}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$; consequently, they form a near-horizontal trend. In contrast, lavas from Loa trend volcanoes form a steep trend. The extremes of the Kea and Loa trends at relatively low and high $^{208}\text{Pb}^*/^{206}\text{Pb}^*$, i.e., the Kea and Koolau components respectively, are consistent with Loa trend sources containing a small and variable recycled sedimentary component characterized by relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ coupled with low $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$, i.e., the Koolau component. The Koolau component is absent in Kea trend lavas, and the Kea component is absent in Loa trend lavas. In addition to the Kea and Loa extremes, a third component is required. This third component is best manifested by Loihi lavas; that is,

the field for Loihi lavas is at the intersection of the straight lines that define the Loa and Kea trends in Figures 9, 10, and 12.

[20] Random sampling of three isotopically distinct source components, i.e., Koolau, Kea and Loihi, should result in a triangle in 2-D isotopic plots. *Douglass and Schilling* [2000] showed that under certain conditions mixing between three components can result in linear trends in isotopic ratio space, i.e., a pseudo-binary mixing array. The formation of a pseudo-binary mixing array requires that “1. the mass fraction of at least two of the three end-members (source components) must covary linearly, and 2. the elemental enrichment of the different isotopes in a given end-member relative to the third end-member must be the same” [Douglass and Schilling, 2000]. The second re-

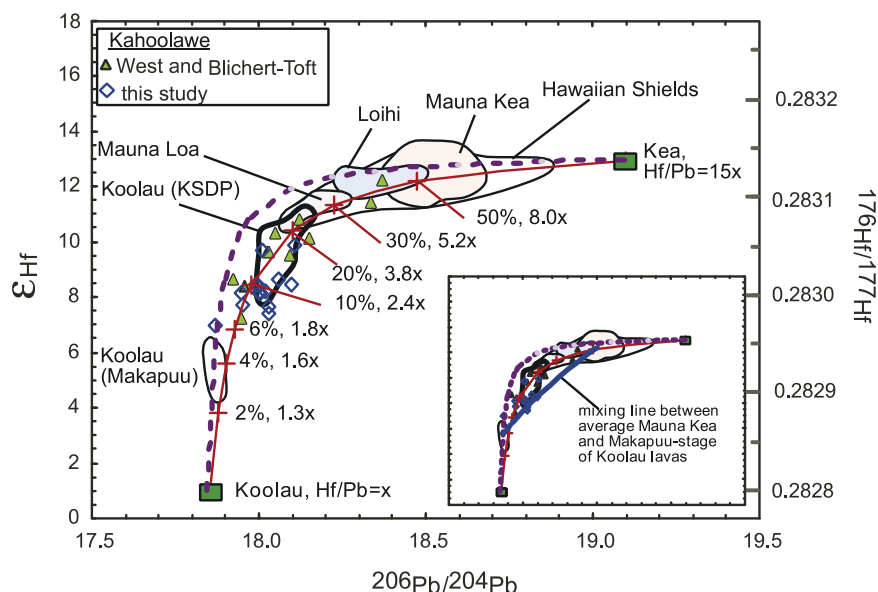


Figure 9. $^{206}\text{Pb}/^{204}\text{Pb}$ - ϵ_{Hf} . The isotopic ratios of the two source components, “Kea” and “Koolau,” are from Blichert-Toft *et al.* [1999], who inferred that the highly curved trend of Hawaiian shield lavas represents a mixing line between two components with very different Hf/Pb (a ratio of 40 shown by the dashed purple line). The Hawaiian trend can be fitted using $(\text{Hf}/\text{Pb})_{\text{Kea}/\text{Koolau}} = 15$. For simplicity, we assume that these two components have the same Pb abundance, and we let $\text{Hf}/\text{Pb} = x$ in the “Koolau” component. The red line with ticks shows the mixing line between these two components with $(\text{Hf}/\text{Pb})_{\text{Kea}/\text{Koolau}} = 15$. The proportions of the “Kea” component and Hf/Pb in the mixtures are labeled. This two-source component model implies that Hf/Pb in Mauna Kea lavas (8.0x) is ~ 5 times that in Makapuu-stage Koolau lavas (1.6x). The blue line in the inset shows the mixing line between average Mauna Kea source composition (Hf/Pb = 4.0) and Makapuu-stage Koolau source composition (Hf/Pb = 3.0). Clearly, this mixing line cannot explain the highly curved Hawaiian trend. Data sources: Blichert-Toft *et al.* [1999], Frey *et al.* [2005], Salters and Blichert-Toft (submitted manuscript), this study.

quirement is necessary only if the mixing array is linear. If only the first requirement is satisfied, mixing of three source components may result in a linear or curved trend [e.g., Douglass and Schilling, 2000, Figure 3], similar to Figures 6 and 9.

[21] What are the physical conditions that lead to pseudo-binary mixing arrays? A possible explanation is that sampling of the proposed source components is controlled by their different solidi. Consider upwelling mantle consisting of several different lithologies; since heat diffuses much faster than atoms, it is possible that this geochemically heterogeneous mantle is in thermal equilibrium throughout the upwelling process [Phipps Morgan, 2001]. Consequently, during upwelling the melting extent of each lithology is determined by its solidus, the potential temperature of this geochemically heterogeneous mantle and the final depth where upwelling terminates [see Phipps Morgan, 2001, Figure 9]. The effect of this process on the isotopic compositions of pooled magmas is discussed by Ito and Mahoney [2005].

[22] For Hawaii, the Koolau component defined by Makapuu-stage Koolau lavas has been proposed to be an eclogitic component formed from recycled oceanic crust including sediments (see Hauri [1996] and Huang and Frey [2005] for a detailed discussion). Consequently, the Koolau component has a lower solidus temperature than mantle peridotites. We infer that the Kea and Loihi components are peridotites. The Loihi component may have higher H_2O content than the Kea component based on the volatile contents of Mauna Kea glasses [Seaman *et al.*, 2004]. Specifically, a subset of submarine Mauna Kea glasses have Pb and He isotopic signatures similar to Loihi lavas. They also have higher water content and $\text{H}_2\text{O}/\text{K}_2\text{O}$ than typical Mauna Kea glasses. This difference is inferred to be a source signature. Consequently, we speculate that the Loihi component may have a higher water content than the Kea component; therefore the Loihi component has a lower solidus temperature than the Kea component.

[23] We propose that the Hawaiian plume contains three geochemically distinct source components: Koolau, Kea and Loihi. During upwelling

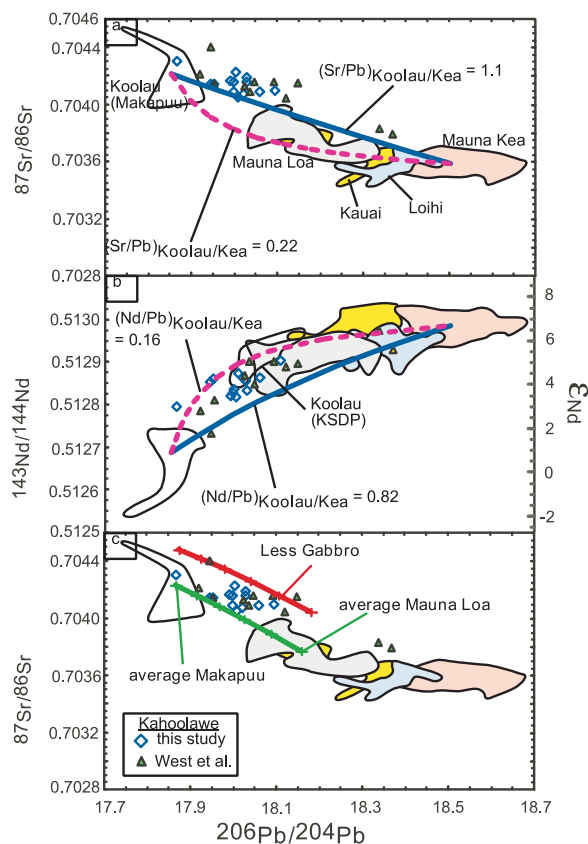


Figure 10. $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ for Hawaiian shield lavas. As in Figure 9, Hawaiian shield lavas define curved trends in plots of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$. The blue solid lines in Figures 10a and 10b show the mixing lines between average Mauna Kea and Makapuu-stage Koolau source compositions, with $(\text{Sr}/\text{Pb})_{\text{Koolau/Kea}} = 1.1$ and $(\text{Nd}/\text{Pb})_{\text{Koolau/Kea}} = 0.82$. The pink dashed lines in Figures 10a and 10b show mixing lines between two source components with the same isotopic ratios as those of average Mauna Kea and Makapuu-stage Koolau lavas, and $(\text{Sr}/\text{Pb})_{\text{Koolau/Kea}} = 0.22$ and $(\text{Nd}/\text{Pb})_{\text{Koolau/Kea}} = 0.16$, which are 5 times lower than the measured ratio of average Koolau/Mauna Kea lavas. The curved trends of Hawaiian shield lavas, excluding the Kahoolawe lavas in the plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$, can be explained by such mixing lines, but they are not consistent with the observed similarity of Sr/Pb and Nd/Pb in Hawaiian shield lavas. In Figure 10c (same axes as Figure 10a), two model mixing lines are shown: the green line represents mixing between average Mauna Loa and Makapuu-stage Koolau source compositions. The red line represents subtraction of 1% recycled gabbro (see text) from the mixtures of average Mauna Loa source and average Makapuu-stage Koolau source composition (the green line). The offset of Kahoolawe lavas can be explained by the red line. Increments on the mixing lines are 20%. Modeling details are in Table 3. Data sources are in Figures 5 and 7 captions.

of the Hawaiian plume, the Koolau component, having the lowest solidus, begins to melt at the greatest depth. Consequently, initial partial melts from the geochemically heterogeneous source have the isotopic characteristics of the Koolau component. Then, with further upwelling to a shallower depth, the Loihi component begins to melt. Consequently, partial melts from this geochemically heterogeneous source reflect two lithologies, the Koolau and Loihi components; i.e., the isotopic ratios of partial melts trend from the Koolau component to the Loihi component. Finally, with further upwelling, the Kea component begins to melt. The isotopic ratios of these low-pressure partial melts trend toward the Kea component isotopic composition. Consequently, partial melts from different depths of a geochemically heterogeneous mantle may form trends rather than triangles in isotopic ratio plots.

[24] A further complication that may be important is that during progressive melting of a given lithology, the solidus temperature increases [e.g., *Phipps Morgan*, 2001]. Therefore it is possible that at the depth where the Kea component begins to melt, the Koolau component becomes too refractory to melt. The consequence is that partial melts from this geochemically heterogeneous mantle generated at high pressure sample only the Koolau and Loihi components, whereas those generated at shallower depths sample only the Loihi and Kea

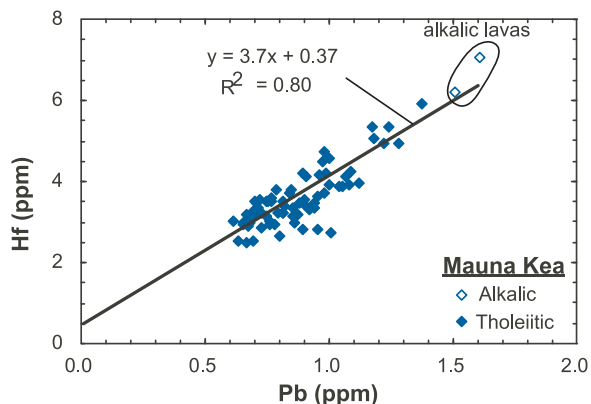


Figure 11. Pb versus Hf abundances (in ppm) for Mauna Kea (HSDP2) lavas. Samples with $>20\%$ MgO are not plotted because their low Pb contents are especially sensitive to contamination during sample preparation [e.g., *Eisele et al.*, 2003; *Huang and Frey*, 2003]. The regression line intercepts the Hf axis, implying that Pb is more incompatible than Hf during partial melting generating Mauna Kea lavas. Data source: *Huang and Frey* [2003].

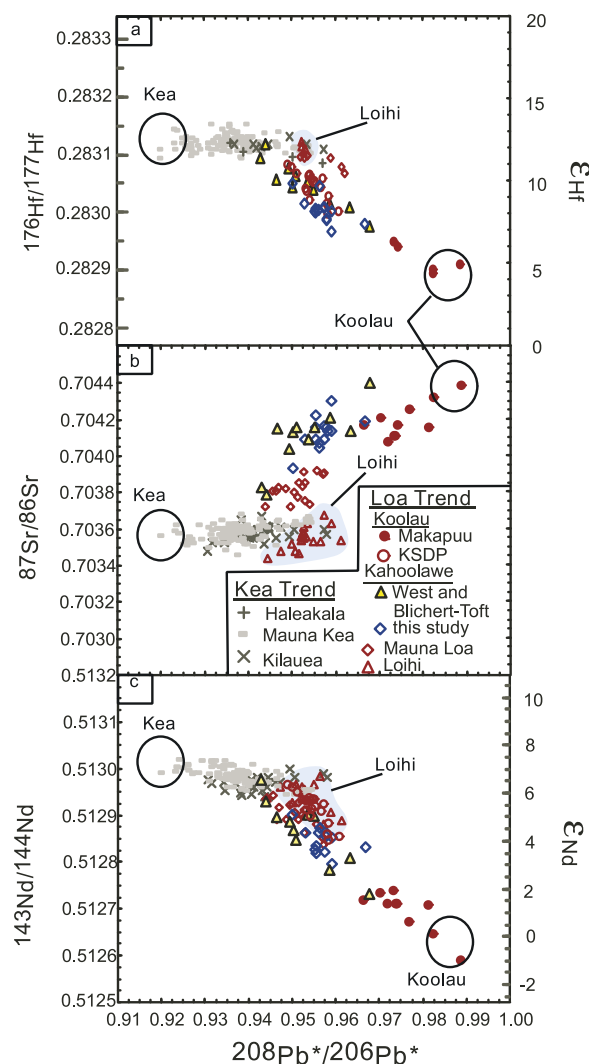


Figure 12. $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ versus $^{176}\text{Hf}/^{177}\text{Hf}$, $^{87}\text{Sr}/^{86}\text{Sr}$, and $^{143}\text{Nd}/^{144}\text{Nd}$ for Hawaiian shield lavas. $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ represents the time-integrated $^{232}\text{Th}/^{238}\text{U}$ since the Earth's formation and is defined as $[(^{208}\text{Pb}/^{204}\text{Pb})_{\text{sample}} - 29.475]/[(^{206}\text{Pb}/^{204}\text{Pb})_{\text{sample}} - 9.307]$ [Galer and O'Nions, 1985]. Lavas from Loa and Kea trend volcanoes define different trends in these plots. Lavas from the Kea trend have relatively constant $^{176}\text{Hf}/^{177}\text{Hf}$, $^{87}\text{Sr}/^{86}\text{Sr}$, and $^{143}\text{Nd}/^{144}\text{Nd}$, and consequently, they define near-horizontal trends. In contrast, lavas from the Loa trend define a steep trend. Loihi lavas, highlighted by blue fields, are at the intersection of Loa and Kea trend lavas and define the Loihi component. The Koolau and Kea components (open circles) are also labeled in the figure. Data sources are in the Figure 5, 6, and 7 captions.

components. The net result is that partial melts of a three-component mantle may form a trend in isotopic ratio space.

4.3. Source Components Contributing to Kahoolawe Lavas

[25] *Leeman et al.* [1994] found that some abundance ratios involving only highly incompatible elements are highly variable in Kahoolawe lavas, e.g., $\text{Nb}/\text{Th} = 9\text{--}24$ and $\text{Th}/\text{Ta} = 0.5\text{--}1.2$. Using Th/Ta versus isotopic ratios of Sr, Nd and Pb, they argued for three source components contributing to Kahoolawe lavas. However, our new data for Kahoolawe lavas do not show such variability; in fact, Th/Ta in Hawaiian and Emperor Seamount shield lavas (over 300 samples) ranges only from 0.7 to 1.1, much less than the Th/Ta range for 11 Kahoolawe tholeiitic lavas analyzed by *Leeman et al.* [1994] (Figure 13). Therefore we conclude that the three source components proposed by *Leeman et al.* [1994] for Kahoolawe lavas are not plausible. In particular, we note that their component with anomalously low Th/Ta of 0.5 is defined by two MgO-rich, picritic lavas (Figure 13); their low Th abundances, ~ 0.3 ppm, determined by instrumental neutron activation analysis may not be accurate.

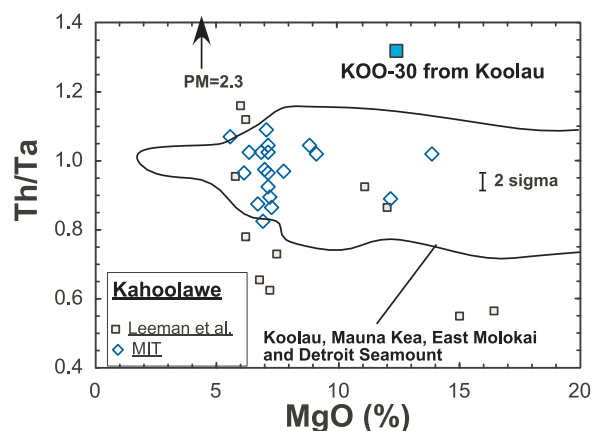


Figure 13. MgO (%) versus Th/Ta for Kahoolawe shield lavas. The field is for lavas from several Hawaiian shields and Detroit Seamount which were analyzed in our laboratory by ICP-MS. The Th/Ta range in 11 Kahoolawe tholeiitic lavas analyzed by *Leeman et al.* [1994] exceeds that of over 300 samples that define the field. For unknown reasons, sample KOO-30 from Koolau has anomalously high Th/Ta [Huang and Frey, 2005]. Because of the possible fractionation by Fe-Ti oxides, highly fractionated lavas, e.g., hawaiite, are excluded from this plot. Data sources: *Leeman et al.* [1994], this study, *Yang et al.* [1996], *Huang and Frey* [2003, 2005]; *Huang et al.* [2005]; *Xu et al.* [2005].

[26] In addition to the commonly proposed Koolau, Kea and Loihi components for Hawaiian lavas, *Mukhopadhyay et al.* [2003] showed that isotopic data for Kauai shield lavas and perhaps all Hawaiian shield lavas require a fourth component (DM), namely the depleted component that controls the isotopic characteristics of rejuvenated-stage lavas. In addition, *Mukhopadhyay et al.* [2003] assumed that these four components have the same Sr/Nd, Sr/Pb and He/Pb. The validity of assuming similar trace element abundance ratios for these source components with such diverse origins can be questioned, especially the He/Pb. Nevertheless, the limited variations of Sr/Nd and Sr/Pb in Hawaiian shield lavas shown in Figure 8 are consistent with this assumption. In detail, the calculation of component proportions in Figure 14 of *Mukhopadhyay et al.* [2003] also assumed uniform Sr, Nd, Pb and He abundances in these four source components. This assumption, however, is not needed to assess the suitability of the four chosen source components to explain the observed isotopic variations. Since Kahoolawe lavas were not considered by *Mukhopadhyay et al.* [2003], we ask whether their model can explain the isotopic variations in Kahoolawe lavas. The four source components are close to a line in a $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ plot (see the inset in Figure 5). Since most Hawaiian shield lavas, except for Kahoolawe lavas, form a near-linear trend in a $^{87}\text{Sr}/^{86}\text{Sr}$ - $^{143}\text{Nd}/^{144}\text{Nd}$ plot, these source components are consistent with most data (Figure 5). Kahoolawe lavas, however, cannot be modeled as mixtures of these four source components. Although the $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ trend of Kahoolawe lavas can be reproduced by a curved mixing line between the Koolau and Kea components, the curvature requires that Sr/Nd of the Koolau component is ~ 8 times that of the Kea component (inset in Figure 5); this inference is inconsistent with the similar Sr/Nd in Hawaiian shield lavas (Figure 8a). Therefore the range in $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$ in Hawaiian shield lavas, especially Kahoolawe versus Makapuu-stage Koolau lavas (Figure 5), can be explained either by introducing an additional source component in the Hawaiian plume, or as we argue later, $^{87}\text{Sr}/^{86}\text{Sr}$ heterogeneity in the Koolau component.

[27] Additional evidence for this complexity arises from correlations between highly incompatible element abundance ratios and isotopic ratios. Comparisons of Hawaiian shields show that some abundance ratios involving only highly incompat-

ible elements, such as La/Nb, are correlated with isotopic ratios [Roden *et al.*, 1994; Huang and Frey, 2003, 2005] (Figure 14). The $^{87}\text{Sr}/^{86}\text{Sr}$ of Kahoolawe lavas is not highly correlated with La/Nb; $\sim 50\%$ of these lavas deviate from the inter-shield trend to high $^{87}\text{Sr}/^{86}\text{Sr}$ (Figure 14a). As with $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ (Figure 5), a curved mixing line can be postulated, but a Sr/Nb range of 10 is required to encompass Kahoolawe lavas with high $^{87}\text{Sr}/^{86}\text{Sr}$ and relatively low La/Nb (Figure 14a). However, the range of Sr/Nb in all Hawaiian shield lavas (with MgO > 7%) is less than 4 (Figure 4b).

[28] In summary, in most plots involving isotopic ratios and isotopic ratios versus a highly incompatible element abundance ratio, Kahoolawe lavas fall on the trends defined by other Hawaiian shield lavas (Figures 6, 7, 9, 10b, 14c, and 14d). However, in plots involving $^{87}\text{Sr}/^{86}\text{Sr}$, Kahoolawe lavas are offset from the trends of other Hawaiian shield lavas toward higher $^{87}\text{Sr}/^{86}\text{Sr}$ (Figures 5, 10a, and 14a). This offset requires a component that only affects $^{87}\text{Sr}/^{86}\text{Sr}$.

4.4. Nature of the $^{87}\text{Sr}/^{86}\text{Sr}$ Heterogeneity in the Koolau Component

[29] In the previous section, we showed that Kahoolawe lavas are offset from other Hawaiian shield lavas only in plots involving $^{87}\text{Sr}/^{86}\text{Sr}$. This offset may be explained by introducing an additional source component in the Hawaiian plume. We infer that this source component is characterized by very high Sr/X (where X designates incompatible elements such as Nb, REE, Hf, Pb); this component is a spike source of Sr. Is it necessary to introduce an additional mantle reservoir to explain this source component and, if so, what is its nature? Previous studies of Hawaiian shield lavas have inferred ancient recycled oceanic lithosphere, including carbonate-rich or hydrothermal sediment, basaltic crust, gabbroic crust and lithospheric mantle, as components in the Hawaiian plume [Hauri, 1996; Lassiter and Hauri, 1998; Blichert-Toft *et al.*, 1999; Jackson *et al.*, 1999; Sobolev *et al.*, 2000; Frey *et al.*, 2005; Huang and Frey, 2005].

[30] Because of the distinctive geochemical characteristics in Makapuu-stage lavas, such as high Sr/Nb and La/Nb, Huang and Frey [2005] argued that their source contained a recycled carbonate-rich or hydrothermal sedimentary component. Strontium is compatible in calcium carbonate and sulphate phases, which are abundant in carbonate-rich and hydrothermal sediments, respectively. Conse-

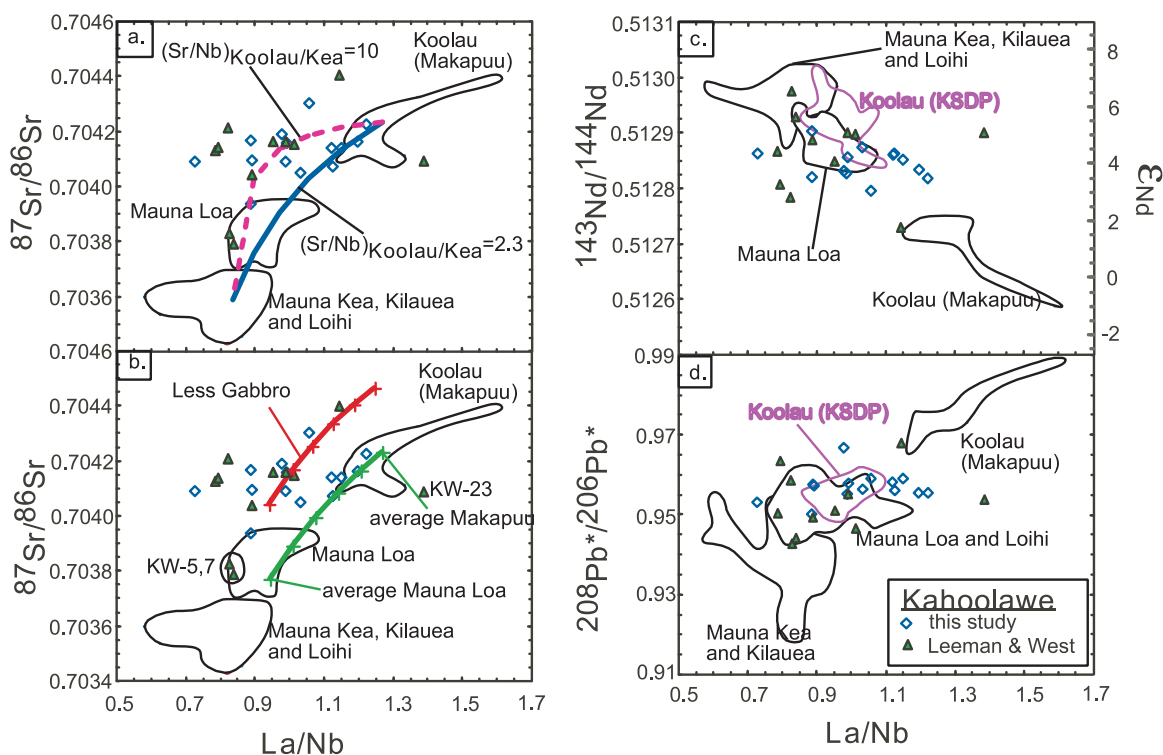


Figure 14. La/Nb versus $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, and $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ for Hawaiian shield lavas. Generally, Hawaiian shields form linear trends in these plots, with the extreme defined by Makapuu-stage Koolau lavas (see Huang and Frey [2005] for a detailed discussion). Kahoolawe lavas are offset from the shield trend to higher $^{87}\text{Sr}/^{86}\text{Sr}$ in Figure 14a. The blue solid line in Figure 14a represents mixing between average Mauna Kea source composition and Makapuu-stage Koolau source composition with $(\text{Sr}/\text{Nb})_{\text{Koolau/Kea}} = 2.3$. The pink dashed line is a mixing line between two source components which have La/Nb and $^{87}\text{Sr}/^{86}\text{Sr}$ equal to average Mauna Kea and Makapuu-stage Koolau lavas, but have $(\text{Sr}/\text{Nb})_{\text{Koolau/Kea}} = 10$. In Figure 14b, two model mixing lines are shown: the green line is a mixing line between average Mauna Loa source composition and average Makapuu-stage Koolau source composition. The red line represents subtraction of 1% recycled gabbro from the mixtures of average Mauna Loa source composition and average Makapuu-stage Koolau source composition (the green line). The offset of Kahoolawe lavas can be explained by the red line. Increments on the mixing lines are 20%. Modeling details are given in Table 3. Data sources are in the Figure 4, 5, and 7 captions. La/Nb from Garcia et al. [1993, 1995b] are adjusted using reported BHVO data of Garcia et al. [1993] and Huang and Frey [2005].

quently, they are characterized by high Sr/X [e.g., Plank and Langmuir, 1998; Chavagnac et al., 2005]. In order to explain the rare Sr-enriched melt inclusions in Mauna Loa olivine phenocrysts, Sobolev et al. [2000] proposed that recycled plagioclase-rich gabbroic crust is present in the Hawaiian plume. Sr is highly compatible in plagioclase [e.g., Blundy and Wood, 1991]; consequently, recycled gabbro with cumulate plagioclase is characterized by extremely high Sr/X [e.g., Zimmer et al., 1995].

[31] Since recycled carbonate-rich and hydrothermal sediments and plagioclase-rich gabbros have high Sr/X, they can act as a spike source of Sr. However, recycled carbonate-rich and hydrothermal sediments and plagioclase-rich gabbros have very different $^{87}\text{Sr}/^{86}\text{Sr}$. Since $^{87}\text{Sr}/^{86}\text{Sr}$ in ancient (2 Ga) seawater was ~ 0.705 [Ray et al., 2002,

Figure 3], ancient carbonate-rich and hydrothermal sediments, which inherited $^{87}\text{Sr}/^{86}\text{Sr}$ from seawater, are characterized by initially high $^{87}\text{Sr}/^{86}\text{Sr}$ that was further increased by ingrowth during aging. In contrast, recycled plagioclase-rich gabbro has the very low $^{87}\text{Sr}/^{86}\text{Sr}$ of ancient oceanic crust and because of its very low Rb/Sr, there is insignificant ingrowth during aging [e.g., Zimmer et al., 1995].

[32] In Figure 15, we plot $^{87}\text{Sr}/^{86}\text{Sr}$ versus Ce/Sr for Hawaiian shield lavas with $\text{MgO} > 7\%$ and $\text{K}_2\text{O}/\text{P}_2\text{O}_5 > 1$; Hawaiian lavas with $\text{MgO} > 7\%$ typically have not fractionated plagioclase [e.g., Huang and Frey, 2003]. Since only tholeiitic lavas are plotted, it is reasonable to assume that Ce/Sr in these lavas was not fractionated by the partial melting process. The Hawaiian shields, the Makapuu-stage of Koolau, Mauna Loa and Mauna Kea,

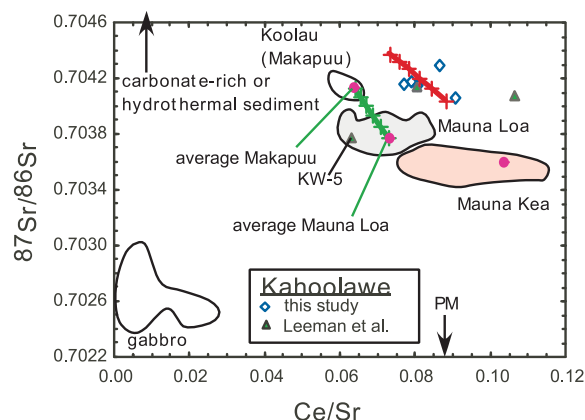


Figure 15. Ce/Sr versus $^{87}\text{Sr}/^{86}\text{Sr}$. We plot Ce/Sr instead of Nd/Sr because Nd data are less abundant in *Leeman et al.* [1994]. To minimize the effects of plagioclase fractionation and alteration on Ce/Sr, only lavas with MgO > 7% and $\text{K}_2\text{O}/\text{P}_2\text{O}_5 > 1$ are plotted. Two model mixing lines are shown: the green line represents mixing between average Mauna Loa source composition and average Makapuu-stage Koolau source composition. The red line, which passes through most Kahoolawe data, reflects 1% subtraction of recycled gabbro from the mixtures of average Mauna Loa and Makapuu-stage Koolau source compositions (the green line). Note that KW-5, with the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ among analyzed Kahoolawe lavas (Figure 5), is within the Mauna Loa field; KW-7, which has the second-lowest $^{87}\text{Sr}/^{86}\text{Sr}$, has MgO < 7% and is not plotted in this diagram. Increments on the mixing lines are 20%. Except for average Makapuu-stage Koolau lavas, modeling details are given in Table 3. In this figure, the average of Makapuu-stage Koolau source composition ($^{87}\text{Sr}/^{86}\text{Sr} = 0.704120$, [Sr] = 36 ppm, and [Ce] = 2.3 ppm) is calculated for lavas with MgO > 7% and $\text{K}_2\text{O}/\text{P}_2\text{O}_5 > 1$. The primitive mantle value of Ce/Sr is shown for comparison [Hofmann, 1988]. Data sources: Hawaiian shields (see Figure 4, 5 and 7 captions); gabbro (Table 3); carbonate-rich and hydrothermal sediments: Ce/Sr from *Plank and Langmuir* [1998] and *Chavagnac et al.* [2005], respectively, and $^{87}\text{Sr}/^{86}\text{Sr}$ is assumed to be 0.705 (see text for details).

define a negative trend on this plot, and most Kahoolawe lavas are offset from this trend toward higher Ce/Sr. In detail, Kahoolawe lavas have $^{87}\text{Sr}/^{86}\text{Sr}$ similar to Makapuu-stage Koolau lavas, but most Kahoolawe lavas have higher Ce/Sr. A possible, but speculative interpretation is that Hawaiian shield lavas generally sampled an ancient plagioclase-rich gabbroic component, whereas Kahoolawe lavas sampled comparatively less of this component (Figures 5, 10c, 14b, and 15); i.e., Kahoolawe lavas do not contain an additional component, but rather they contain less of a low Ce/Sr and low $^{87}\text{Sr}/^{86}\text{Sr}$ component.

[33] We present a simple calculation to test this idea. Following the approach used by many researchers [e.g., *Hauri*, 1996; *Mukhopadhyay et al.*, 2003], we assume that sources of Hawaiian shield lavas are mixtures of several end-member source components, and that partial melting does not significantly change incompatible element abundance ratios (Sr/Nd, Hf/Pb, Sr/Nb, ...). In Figures 5, 10c, 14b, and 15, the green line shows mixtures between average Mauna Loa and Makapuu-stage Koolau source compositions. If 1% recycled gabbro (Table 3) is subtracted from mixtures of average Mauna Loa and Makapuu-stage Koolau source compositions, this trend (the solid red line in Figures 5, 10c, 14b, and 15) passes through the field of Kahoolawe lavas. That is, compared with Kahoolawe lavas, Mauna Loa and Makapuu-stage Koolau lavas sampled more of a recycled gabbroic component.

[34] We emphasize that source components are not equivalent to mantle reservoirs. For example, we propose that the Koolau component is eclogite formed from a mixture of recycled oceanic basaltic crust with associated sediment and plagioclase-rich gabbroic lower crust [see also *Hauri*, 1996; *Huang and Frey*, 2005]. However, Loa trend volcanoes sample a Koolau component containing variable proportions of sediment, basalt and gabbro. For example, the Koolau component in Kahoolawe lavas contains lesser amounts of gabbroic crust. Kahoolawe lavas also lack the trace element signatures of recycled sediment, i.e., the high Sr/Nb and La/Nb that is characteristic of Makapuu-stage Koolau lavas (Figure 4). The negative trend formed by lavas from Koolau, Mauna Loa and Mauna Kea in a plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus Ce/Sr (Figure 15) reflects sampling various amounts of the Koolau component with constant proportions of recycled oceanic basaltic crust, sediment and plagioclase-rich gabbroic lower crust. Although these three lithologies have very different $^{87}\text{Sr}/^{86}\text{Sr}$ and Ce/Sr, their mixture (the Koolau component) is characterized by relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ and low Ce/Sr. Most Kahoolawe lavas deviate from this trend (Figure 15) because they have a lower proportion of low $^{87}\text{Sr}/^{86}\text{Sr}$ gabbroic crust.

[35] A direct consequence of our hypothesis is that a recycled gabbroic component is generally present in Hawaiian shield lavas. Is there any evidence supporting this argument? The most direct evidence is the Sr-enriched melt inclusions in Mauna Loa olivine phenocrysts [*Sobolev et al.*, 2000]. In addition, both Mauna Loa and Koolau (Makapuu-stage and Kalihi-stage) lavas show a positive Sr

Table 3. Input Parameters for Mixing Lines in Figures 5, 10, 14, and 15^a

	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	²⁰⁶ Pb/ ²⁰⁴ Pb	[Sr]	[Nd]	[Pb]	[La]	[Ce]	[Nb]	[Th]
Average Koolau lavas (Makapuu) ^b	0.704226	0.512680	17.868	384	18.3	1.1	10.3	25.8	8.1	0.58
Average source composition of Koolau (Makapuu) ^c	0.704226	0.512680	17.868	38.4	1.83	0.11	1.03	2.58	0.81	0.058
Average Mauna Loa lavas ^d	0.703767	0.512904	18.162	272	14.2	0.85	7.5	19.9	8.0	0.50
Average source composition of Mauna Loa ^c	0.703767	0.512904	18.162	27.2	1.42	0.085	0.75	1.99	0.80	0.050
Average gabbro ^e	0.702596	0.512936	17.523	562	2.75	0.31	1.43	3.81	0.87	0.046

^aSince we argue that Loa-trend volcanoes do not sample the Kea component (e.g., Figure 12), we compare Kahoolawe lavas with mixtures between two other Loa-trend volcanoes, the Makapuu-stage of Koolau and Mauna Loa.

^bIsotopic ratios are from Roden *et al.* [1994], Lassiter and Hauri [1998], and Abouchami *et al.* [2005]. Trace element data (ppm) are from Huang and Frey [2005].

^cTrace element abundances in source are inferred assuming solid/melt partition coefficients are $\ll 0.1$ and 10% partial melting. Although Hawaiian shield lavas form by variable extents of melting, assuming a constant melting extent does not change the mixing lines in Figures 5, 10, 14, and 15). Variable extents of melting only change the relative proportions of different sources (Mauna Loa versus Makapuu-stage of Koolau).

^dIsotopic ratios are from Kurz *et al.* [1995], Cohen *et al.* [1996], Abouchami *et al.* [2000], and Blichert-Toft *et al.* [2003].

^eData source: Gabbros from Zimmer *et al.* [1995].

anomaly in a primitive mantle normalized multiple element diagram [Huang and Frey, 2005, Figure 2] (Figure 3). Since only high-MgO lavas are plotted (MgO > 7 for Figure 3 and MgO > 6.5 for Figure 2 of Huang and Frey [2005]), the Sr enrichment in these lavas should be a source characteristic, a result consistent with a recycled plagioclase-rich gabbroic component in the sources of these lavas. In detail, Huang and Frey [2005] argue that high Sr/Nb in Makapuu-stage Koolau lavas reflects a recycled carbonate-rich or hydrothermal sedimentary component. That is, the Sr enrichment in Hawaiian shield lavas may have two origins: recycled carbonate-rich or hydrothermal sediment and recycled plagioclase-rich gabbro. In detail, some atypical Kahoolawe lavas, such as KW-5 (Figures 5 and 7), are also characterized by Sr enrichment (Figure 3), and KW-5 is within the Mauna Loa field in Figure 15. Like other Hawaiian shield lavas, KW-5 may also sample a recycled plagioclase-rich gabbroic component. The relatively high SiO₂ content in several Loa-trend shields, including Mauna Loa and Makapuu-stage Koolau lavas [e.g., Hauri, 1996, Figure 2], is inferred to be a result of sampling a dacitic magma generated from partial melting of an eclogite component that formed from recycled oceanic crust [Hauri, 1996; Huang and Frey, 2005]. This inference is also consistent with a recycled plagioclase-rich gabbroic lower crust component in the Hawaiian plume.

5. Summary

[36] 1. Like Makapuu-stage Koolau lavas, Kahoolawe shield lavas range widely in radiogenic isotope ratios, and among Hawaiian shield lavas they extend to high ⁸⁷Sr/⁸⁶Sr with low ¹⁴³Nd/¹⁴⁴Nd, ¹⁷⁶Hf/¹⁷⁷Hf and ²⁰⁶Pb/²⁰⁴Pb. However, the

enriched component in the source of Kahoolawe lavas differs from that sampled by Makapuu-stage Koolau lavas [Huang and Frey, 2005]. Specifically, Kahoolawe lavas are offset to high ⁸⁷Sr/⁸⁶Sr from the trends of Hawaiian shield lavas. We interpret this offset as a result of varying proportions of a recycled plagioclase-rich gabbroic lower crust in the Hawaiian plume; that is, Kahoolawe lavas sampled a lower proportion of this low ⁸⁷Sr/⁸⁶Sr component. We conclude that the enriched component in the Hawaiian plume is derived from ancient recycled oceanic crust, but that Koolau (Makapuu-stage) and Kahoolawe lavas sampled different proportions of recycled sediment, basalt and gabbro.

[37] 2. Shield lavas from Loa and Kea trend volcanoes define intersecting linear trends in plots of ²⁰⁸Pb*/²⁰⁶Pb* versus ⁸⁷Sr/⁸⁶Sr, ¹⁴³Nd/¹⁴⁴Nd and ¹⁷⁶Hf/¹⁷⁷Hf; they converge at the field defined by Loihi lavas, implying that all Hawaiian shield lavas sample the Loihi component. The trend of Loa lavas to high ²⁰⁸Pb*/²⁰⁶Pb* and ⁸⁷Sr/⁸⁶Sr and low ¹⁴³Nd/¹⁴⁴Nd and ¹⁷⁶Hf/¹⁷⁷Hf is consistent with variable amounts of a recycled sedimentary component that is not present in Kea-trend lavas.

[38] 3. Hawaiian shield lavas range widely in radiogenic isotope ratios of Sr, Nd, Hf and Pb, but they have similar abundance ratios, within a factor of three, of Sr/Nd, Sr/Pb and Hf/Pb. A consequence is that the hyperbolic trend of ²⁰⁶Pb/²⁰⁴Pb versus ¹⁷⁶Hf/¹⁷⁷Hf defined by Hawaiian shield lavas requires three component mixing rather than mixing of two components with very different Hf/Pb. It is, however, surprising that isotopically distinct mantle reservoirs, presumably created by very different processes, have similar Sr/Nd, Sr/Pb and Hf/Pb. We postulate that source

components inferred from trends defined by isotopic ratios, e.g., $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$, are mixtures of reservoirs with very different Sr/Nd, Sr/Pb and Hf/Pb ratios, but that limited ranges of mixing proportions yield mixtures with similar ratios.

[39] 4. Despite evidence for more than two isotopically distinct source components contributing to Hawaiian shield lavas, these lavas commonly define trends in two dimensional isotopic ratio plots (e.g., Figures 9, 10, and 12). This observation can be explained if the isotopically different source components have significantly different solidus temperatures.

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