



Geochemistry of Kauai shield-stage lavas: Implications for the chemical evolution of the Hawaiian plume

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[1] We measured He, Sr, Nd, Pb, and Os isotope ratios and major and trace element concentrations in stratigraphically and paleomagnetically controlled shield-stage lavas from Kauai, Hawaii. The range of $^3\text{He}/^4\text{He}$ ratios (17–28 R_A) from Kauai is similar to that reported from Loihi and thus challenges the prevailing notion that high $^3\text{He}/^4\text{He}$ ratios are restricted to the preshield stage of Hawaiian magmatism. $^3\text{He}/^4\text{He}$ ratios vary erratically with stratigraphic position, and chronostratigraphic control from paleomagnetic data indicates very rapid changes in the $^3\text{He}/^4\text{He}$ ratios (up to 8 R_A in $\sim 10^2$ years). These variations in helium isotopic ratios are correlated with variations in radiogenic isotope ratios, suggesting rapid changes in melt composition supplying the magma reservoir. A three-component mixing model, previously proposed for Hawaiian shield lavas, does not adequately explain the isotopic data in Kauai shield lavas. The addition of a depleted-mantle (DM) component with the isotopic characteristics similar to posterosional basalts explains the isotopic variability in Kauai shield lavas. The DM component is most apparent in lavas from the Kauai shield and is present in varying proportion in other Hawaiian shield volcanoes. Shield lavas from Kauai sample a high $^3\text{He}/^4\text{He}$ end-member (Loihi component), but while lavas from western Kauai have a larger contribution from the Kea component (high $^{206}\text{Pb}/^{204}\text{Pb}$, anomalously low $^{207}\text{Pb}/^{204}\text{Pb}$ relative to $^{206}\text{Pb}/^{204}\text{Pb}$), lavas from eastern Kauai have a larger proportion of an enriched (Koolau) component. The systematic isotopic differences between eastern and western Kauai reflect a gradual migration of the locus of volcanism from west to east, or alternatively east and west Kauai are two distinct shield volcanoes. In the latter case, the two shield volcanoes have maintained distinct magma supply sources and plumbing systems. Our new geochemical data from Kauai are consistent with the existence of a single high $^3\text{He}/^4\text{He}$ reservoir in the Hawaiian plume and suggest that the proportion of the different mantle components in the plume have changed significantly in the past 5 Myr. The long-term evolution of the Hawaiian plume and the temporal variability recorded in Kauai lavas require more complex geochemical heterogeneities than suggested by radially zoned plume models. These complexities may arise from heterogeneities in the thermal boundary layer and through variable entrainment of ambient mantle by the upwelling plume.

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1. Introduction

[2] The geochemistry of oceanic island basalts (OIBs), such as those from Hawaii, provides information on the composition of the mantle, and the processes and dynamics of mantle melting. The Hawaiian Emperor chain of volcanoes represents one of the best examples of hot spot volcanism [Wilson, 1963; Morgan, 1971] commonly explained by thermal upwelling of deep mantle material. Individual Hawaiian volcanoes are thought to evolve systematically through different stages that are indicated by differences in magma production rates and chemistry of the lavas [Clague and Dalrymple, 1989]. Temporal geochemical variability within a single volcano and differences in geochemistry between the different shield volcanoes provide information about the nature of the Hawaiian plume. Here we present new geochemical data from the shield building stage of Kauai, one of the oldest of the main Hawaiian islands that offer new insights into the mantle sources of Hawaiian magmatism and into the chemical evolution of the plume.

[3] Isotopic variability in Hawaiian shield lavas is usually interpreted as mixing between at least three distinct mantle components present in the Hawaiian plume [Staudigel et al., 1984; Stille et al., 1986; West et al., 1987; Kurz et al., 1995; Eiler et al., 1996; Hauri, 1996]. To explain the temporal evolution of individual volcanoes and the difference in chemistry of Loa and Kea trend volcanoes (Figure 1), models of the Hawaiian plume mostly favor a cylindrically zoned structure [Kurz et al., 1995, 1996; Hauri et al., 1996; Lassiter et al., 1996]. The spatial distributions of the components within

the plume and their location in the mantle, however, are subject to debate [Hofmann et al., 1986; Kurz et al., 1995, 1996; Hauri et al., 1996]. Hauri [1996] suggested that the core of the plume is composed of recycled material (referred to as the Koolau component) rising from either the core–mantle boundary or from the lower mantle. The buoyant, upwelling plume entrains lower mantle material (Loihi component), and surrounding the entrained material is passively upwelling asthenosphere (Kea component) [Hauri, 1996; Lassiter et al., 1996]. Kurz et al. [1995, 1996], however, argued that the relatively undegassed lower mantle (Loihi component) is the plume core rather than the entrained material.

[4] Helium is a useful tracer of the different mantle source components of OIBs and, in combination with other radiogenic isotope tracers, can potentially constrain the spatial and temporal geochemical variability within the Hawaiian plume and the origin of chemical heterogeneities in the mantle [e.g., Kurz et al., 1995; Hauri and Kurz, 1997; Farley and Neroda, 1998]. Previous studies have shown that Hawaiian lavas have high $^3\text{He}/^4\text{He}$ ratios (6–32 R_A) [Kurz et al., 1982, 1983, 1995; Rison and Craig, 1983] compared to mid-ocean ridge basalt (MORB) glasses that are removed from influences of hot spot volcanism (8–10 R_A) [e.g., Kurz et al., 1982; Graham et al., 1992, 1996], with Loihi Seamount having the highest ratios (~ 20 –32 R_A). Such high ratios are usually attributed to sampling of a relatively undegassed mantle source with high time-integrated $^3\text{He}/(\text{U} + \text{Th})$ ratio. In particular, correlations between lithophile isotope ratios and $^3\text{He}/^4\text{He}$ ratios suggest to some investigators [e.g., Kurz et al., 1983; Farley

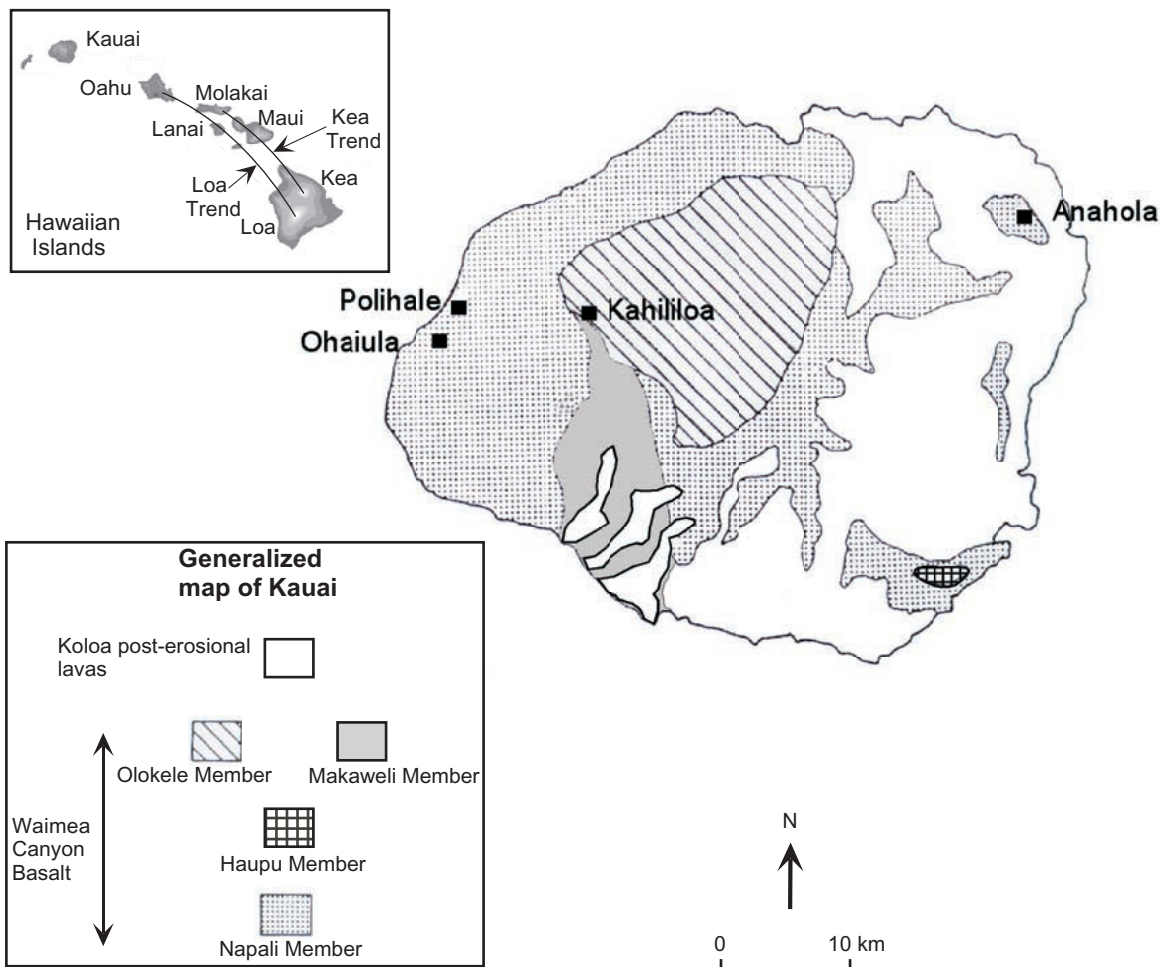


Figure 1. Generalized geological map of Kauai [Macdonald *et al.*, 1960]. Anahola (east Kauai), Kahililoa (central Kauai), and Ohaiula and Polihale (west Kauai) are the sampling sites [see also Bogue and Coe, 1984].

et al., 1992] that high $^3\text{He}/^4\text{He}$ ratios provide the best if not the only evidence for the survival of a portion of the mantle that has largely escaped melt extraction and addition of recycled components. Some studies have suggested that helium is decoupled from the lithophile tracers and, hence, does not provide information about the mantle sources of magmas [Condomines *et al.*, 1983; Zindler and Hart, 1986; Hilton *et al.*, 1995; Valbracht *et al.*, 1996]. These studies have interpreted helium isotopic variations as reflecting shallow level magmatic degassing, contamination, and radiogenic ingrowth of ^4He in magma chambers. However, He-Sr-Nd-Pb isotopic data obtained over the last 10 years are generally inconsistent with such interpretations [e.g., Farley *et al.*, 1992; Kurz *et al.*, 1987, 1995; Eiler *et al.*, 1998].

[5] Combined He, Sr, Nd, and Pb isotopic data from older Hawaiian islands, like Kauai (Figure 1), are useful for understanding the long-term geochemical evolution of the Hawaiian plume. Kauai (Figure 1) has generally been interpreted as a single large shield volcano [Macdonald *et al.*, 1960] although field relations between shield lavas exposed in different parts of the island are often obscured by posterosional lava flows (Figure 1) and heavy forest cover. The shield building stage lasted from 5.1 to 4.3 Ma [McDougall, 1979; Clague and Dalrymple, 1988]. Recent geochemical data, however, suggest a more complicated structure for Kauai including the presence of two different shield volcanoes on the island [Holcomb *et al.*, 1997; Reiners *et al.*, 1998]. To our knowledge, only two published helium isotopic analysis from

the Kauai shield exist [Rison and Craig, 1983; Scarsi, 2000]. The reported $^3\text{He}/^4\text{He}$ ratios of 24 R_A [Rison and Craig, 1983] and 25 R_A [Scarsi, 2000] are surprisingly high compared to other Hawaiian shield volcanoes, which dominantly have $^3\text{He}/^4\text{He}$ ratios $<20 R_A$. This study was undertaken to identify temporal and spatial variations in helium isotopic compositions on Kauai, gain insights into the mantle sources of Kauai lavas, and understand the origin of chemical heterogeneities in the mantle through a combined study of helium isotopic ratios, lithophile isotope tracers (e.g., Sr, Nd, and Pb) and major and trace elements.

2. Samples and Analytical Techniques

[6] Our samples are paleomagnetic cores (diameter = 1.5 cm, length = 6–10 cm) from subaerial shield-stage lava flows, which were previously studied for paleomagnetic intensity and direction [Bogue and Coe, 1984]. The shield-stage lavas belong to the Waimea Canyon Basalt Group [Macdonald *et al.*, 1960]. The Waimea Canyon Basalt is subdivided into four members, the oldest and most widespread of which is the Napali Member (Figure 1) [Macdonald *et al.*, 1960]. Next in surface area is the Olokele Member exposed in the central part of Kauai (Figure 1). Lavas of the Olokele Member are younger than the Napali Member and are comprised of thick, flat lying flows [Macdonald *et al.*, 1960]. The Makaweli and Haupu Members (Figure 1) are the two other constituents of the Waimea Canyon Basalt Group, but were not sampled for this study.

[7] Samples from stratigraphic sections at Polihale, Ohaiula, Kahililoa, and Anahola were analyzed during this study (Figure 1). The Polihale, Ohaiula, and Anahola sections belong to the Napali Member, while the Kahililoa section belongs to the Olokele Member. The Polihale and Ohaiula ridge sections have been superimposed to construct a single composite stratigraphic section, which we term the west Kauai section. Correlation of these two sections comes from tracing a Reverse-Normal (R-N) polarity transition that appears at the top of the Polihale ridge section and near the base of the Ohaiula ridge section [Bogue and Coe, 1982]. The

Kahililoa section in the Olokele Member records a Normal-Reverse (N-R) polarity transition. Lava flows of the Olokele Member pond up against flows of the Napali Member (west Kauai), thereby, indicating that the Kahililoa section is younger than the west Kauai section [see also Macdonald *et al.*, 1960; Reiners *et al.*, 1998]. We designate the Kahililoa section as the central Kauai section. The Anahola section in the eastern part of the island, which also records a R-N polarity transition, is termed the east Kauai section. The total number of flows in the west, central, and east Kauai sections are 48, 25, and 19 [see Bogue and Coe, 1984], although we sampled only the olivine-rich flows. Using the mean recurrence interval of 0.5 kyr/flow unit estimated for the tholeiitic shield lavas from the pilot hole of the Hawaii Scientific Drilling Project (HSDP) at Mauna Kea [Sharp *et al.*, 1996], the total time represented by the west, central, and east Kauai sections are likely to be ~25, 13, and 10 kyr, respectively.

[8] Based on the similarity in virtual geomagnetic pole (VGP) sequence across the R-N polarity transition in the east and west Kauai section, previous workers had correlated the two sections [Bogue and Coe, 1982, 1984]. Recently, based on observed differences in the isotopic composition of the lavas across the R-N transition in the eastern and western parts of Kauai, Holcomb *et al.* [1997] suggested while the R-N transition might be temporally correlated, east and west Kauai are two different shield volcanoes. Field relations alone are not sufficient to evaluate this hypothesis and there are no absolute ages of the R-N transition in the west and east Kauai sections. Thus, the volcanologic relationship between east and west Kauai sections is not clear.

2.1. Methods

[9] The paleomagnetic cores were crushed and olivine phenocrysts 1–3 mm in diameter were hand picked. The olivine crystals were inspected under a binocular microscope to ensure that they were free from alteration products and adhering matrix. The crystals were ultrasonically cleaned in distilled water and then in acetone and dried in an oven at 100°C for 1–2 hours. Gases from melt and fluid inclusions were liberated by crushing in

vacuum $\sim 0.2\text{--}0.9$ g of olivine crystals for 3–4 min with an electromagnetic crusher [see *Patterson et al.*, 1997 for details]. Following crushing, some of the powders were fused to check for the presence of cosmogenic or radiogenic helium. Gas purification and mass spectrometric techniques were described by *Patterson et al.* [1997]. Typical ^4He crusher blanks were $< 3 \times 10^{-11}$ cm³ STP and averaged 1% of the sample measurements. ^3He crush blanks were always less than 1×10^{-15} cm³ STP, in all cases $< 1\%$ of the sample. The uncertainty in the computed $^3\text{He}/^4\text{He}$ ratio is 3.3% based on the reproducibility of MM standards of similar size to the samples.

[10] Major and minor elements were measured by X-ray fluorescence at the GeoAnalytical Laboratories, Washington State University (Pullman). Details of the analytical procedures are given by *Johnson et al.* [1999]. In addition, a subset of the samples was analyzed for Sr, Nd, Pb, and Os isotopes. Samples were multiply leached in hot 6N HCl prior to digestion for Sr, Nd, and Pb isotope analysis. Analytical methods for these measurements were presented previously [*Lassiter et al.*, 2000, and references therein].

3. Results

3.1. Major and Trace Element Composition

[11] The Kauai lavas investigated in this study are tholeiites (Table 1 and Figure 2). Hawaiian tholeiites with $\text{K}_2\text{O}/\text{P}_2\text{O}_5 < 1$ are considered to have undergone post-eruptive alteration [*Lipman et al.*, 1990; *Frey et al.*, 1994]. Most of the samples we analyzed have $\text{K}_2\text{O}/\text{P}_2\text{O}_5 < 1$, suggesting that they have undergone alteration.

[12] The MgO content of the Kauai lavas varies from 29.7 to 7.7 wt.% and the variation most likely reflects olivine fractionation or accumulation. Abundances of MgO are inversely correlated with other major element oxides (e.g., SiO_2 , CaO, and Al_2O_3) (Figure 3 and Table 1) and the linear trends seen in Figure 3 are consistent with olivine addition or subtraction [e.g., *Frey and Rhodes*, 1993; *Yang et al.*, 1996]. Concentrations of Ni (157–1721 ppm) and Cr (385–1704 ppm), elements

compatible in olivine and Cr-spinel, are positively correlated with the MgO contents. In comparison, Sc (an element compatible in clinopyroxene) is inversely correlated with MgO (Figure 3), indicating that fractionation of clinopyroxene was not a dominant factor in controlling major element composition of Kauai lavas. Abundances of incompatible trace elements such as Nb, Zr, P_2O_5 , and Sr positively correlated with each other (Figure 4). Such correlations have been observed in other Hawaiian shield volcanoes and have been interpreted to reflect magmatic processes [e.g., *Frey et al.*, 1994].

3.2. Helium Isotopic Ratios

[13] Before interpreting the helium isotopic data from Kauai as a mantle signature, we first discuss the potential effect of post-eruptive cosmogenic or radiogenic helium on the measured $^3\text{He}/^4\text{He}$ ratios. The helium concentration in the Kauai lavas varies from 0.5 to 34×10^{-9} cm³ STP g⁻¹ (Table 2) and is within the normal range of helium concentration in olivine phenocrysts from Hawaii [*Kurz et al.*, 1987, 1996]. There is no correlation between the measured $^3\text{He}/^4\text{He}$ ratios and the helium concentration of the phenocrysts (Figure 5a), suggesting that the helium isotopic ratios are not strongly influenced by post-eruptive He production.

[14] *Kurz* [1986a, 1986b] demonstrated that crushing under vacuum is effective at separating magmatic helium trapped in fluid inclusions from post-eruptive components, which reside in the matrix of the mineral, although intense pulverization of the sample may lead to some matrix-hosted cosmogenic/radiogenic helium being released [*Hilton et al.*, 1993]. Our crushing time of 3–4 min is shorter or comparable to those normally used by other workers [e.g., *Kurz*, 1986a, 1986b; *Patterson et al.*, 1997] and, therefore, should not have released cosmogenic or radiogenic helium [see also *Scarsi*, 2000]. To verify this assertion we fused a set of crushed powders. Cosmogenic helium was detected in most of the fused powders and radiogenic ^4He was detected in one sample (Table 3). Cosmogenic ^3He concentrations varied from 1.3×10^{-13} to 9.4×10^{-15} cm³ STP g⁻¹ and $^3\text{He}_{\text{cosmogenic}}/^3\text{He}_{\text{crush}}$ ratios varied from 0.02 to 3.15, similar to ratios

Table 1. Major and Trace Element Data From Kauai Shield Lavas^a

	West Kauai (Napali Member)										Central Kauai (Olokele Member)										East Kauai (Napali Member)									
	PB1	PB10	PB12	PB16	PB17	PB18	PB19	PB20	PB21	OR1	OR3	OR5	OR18	OR27	OK9	OK19	OK20	OK22	OK25	A2	A3	A9	A11	A14	A16	A17	A19			
SiO ₂	48.19	46.29	46.24	49.58	49.46	45.61	46.06	48.57	49.97	49.09	47.48	46.18	46.23	45.91	52.04	46.19	46.54	48.35	52.04	50.12	51.48	48.69	48.47	44.49	47.13	44.98	48.15			
TiO ₂	1.87	1.47	1.49	2.56	2.49	1.37	1.71	1.90	2.33	2.11	1.83	1.46	1.44	1.32	2.30	1.31	1.60	1.74	2.30	2.23	2.56	2.23	2.13	0.93	2.18	1.22	2.30			
Al ₂ O ₃	10.01	8.12	8.14	13.12	12.62	7.37	8.57	11.11	12.97	11.69	9.94	7.87	7.23	7.14	13.11	7.58	8.70	9.92	13.11	13.65	13.88	12.02	11.95	6.29	10.93	6.59	12.72			
FeO ^b	11.70	11.93	12.43	11.80	11.98	11.99	12.15	11.65	11.52	11.90	11.68	12.38	12.53	11.89	9.53	12.15	11.80	11.43	9.53	10.43	10.27	11.64	12.34	12.48	12.40	11.97	12.23			
MnO	0.17	0.17	0.18	0.18	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.18	0.17	0.17	0.16	0.17	0.18	0.17	0.16	0.18	0.16	0.18	0.16	0.18	0.19	0.17	0.18			
MgO	17.79	23.57	23.14	9.24	9.95	25.71	22.11	15.27	9.69	13.19	18.90	23.67	24.86	26.15	10.11	25.18	22.74	18.32	10.11	10.04	7.67	13.56	13.84	29.66	16.48	28.75	12.38			
CaO	8.33	6.77	6.76	10.87	10.58	6.12	7.18	9.15	10.78	9.66	8.07	6.67	6.04	5.98	9.88	5.86	6.76	7.87	9.88	10.86	10.85	9.45	8.95	4.81	8.57	5.06	9.65			
Na ₂ O	1.58	1.37	1.36	2.15	2.21	1.36	1.63	1.85	2.13	1.81	1.60	1.27	1.18	1.19	2.32	1.26	1.42	1.75	2.32	2.14	2.48	1.87	1.82	1.01	1.78	1.07	2.08			
K ₂ O	0.17	0.16	0.10	0.23	0.28	0.14	0.22	0.16	0.21	0.17	0.15	0.17	0.17	0.11	0.33	0.15	0.11	0.25	0.33	0.11	0.39	0.15	0.09	0.05	0.12	0.07	0.10			
P ₂ O ₅	0.19	0.15	0.15	0.26	0.26	0.16	0.20	0.17	0.22	0.20	0.17	0.15	0.16	0.13	0.23	0.14	0.15	0.19	0.23	0.23	0.26	0.22	0.25	0.10	0.22	0.11	0.21			
Sc	23	15	25	32	27	24	26	25	30	30	28	20	13	20	11	25	18	22	25	25	28	24	24	15	29	15	20			
V	224	193	203	305	275	172	211	244	281	272	225	188	174	175	154	274	171	199	219	268	292	274	258	132	251	154	264			
Cr	902	1400	1374	522	559	1365	1232	848	525	726	1058	1186	1581	1428	1704	620	1294	1332	1173	578	385	813	862	1249	798	1283	540			
Ni	821	1137	1163	253	278	1280	1039	645	243	476	915	1181	1407	1390	1721	313	1419	1183	904	245	157	480	593	1592	697	1676	493			
Cu	101	66	86	117	114	55	60	105	111	76	77	47	57	58	53	77	46	79	90	105	108	91	91	51	86	56	119			
Zn	102	98	97	101	102	97	99	99	102	101	96	98	96	89	98	82	102	102	101	96	97	107	104	103	107	99	109			
Ga	14	14	10	17	18	13	13	15	20	21	14	13	11	10	8	19	13	13	14	18	18	19	18	7	19	10	20			
Sr	235	184	185	319	310	189	245	235	291	261	216	176	179	161	137	292	161	185	235	307	332	275	251	128	274	144	280			
Y	22	17	21	30	27	17	19	23	27	24	24	17	18	16	13	25	19	19	20	26	27	25	25	15	23	18	29			
Zr	104	80	79	141	137	78	99	100	125	113	98	80	82	72	57	128	73	85	97	121	138	120	112	48	114	61	123			
Nb	12	8	9	16	15	10	13	11	13	13	11	10	9.5	8.9	8	12	6	8	10	13	14	10	10	5	11	6	12			
Ba	44	36	54	54	74	57	79	46	44	39	42	44	28	28	50	62	35	40	63	100	82	45	58	29	39	34	45			
Ce	11	17	12	42	41	11	21	26	26	25	21	6	5	8	9	35	14	21	8	33	27	28	18	17	16	20	30			

^aMajor elements are reported in wt.%, volatile-free.

^bDenotes total iron. Trace element concentrations are in ppm. Details of analytical procedures are given by *Johnson et al.* [1999].

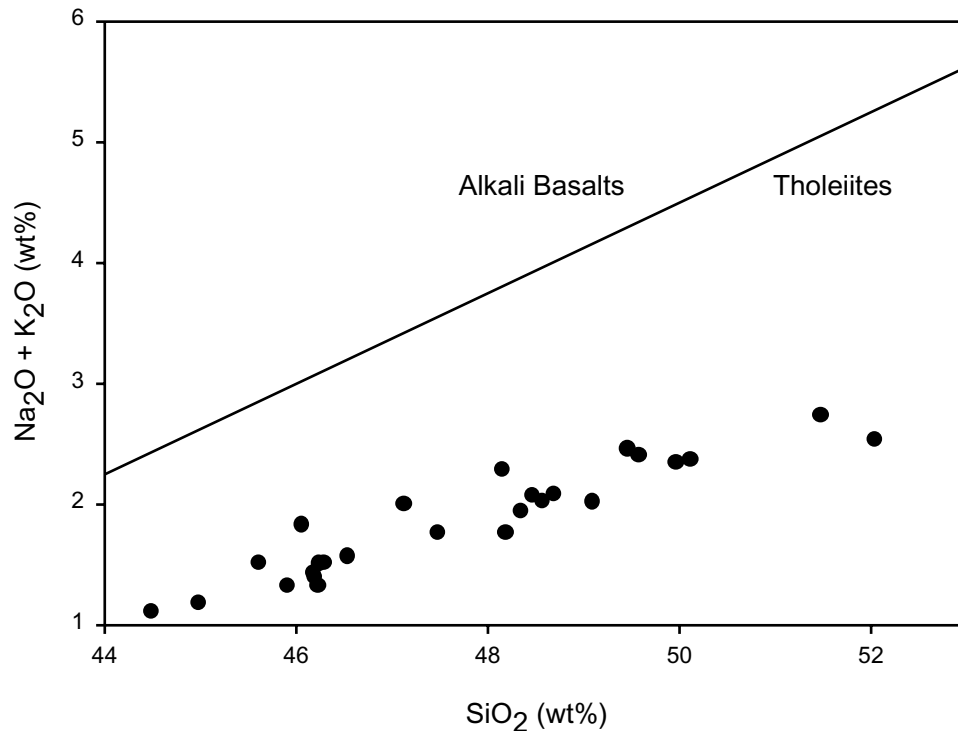


Figure 2. SiO₂ versus alkalis in Kauai shield lavas. Note that all the Kauai samples plot in the tholeiite field.

found in Haleakala basalts [Kurz, 1986b, 1987]. In addition, Patterson *et al.* [1997] obtained typical ³He/⁴He ratios of 4–7 R_A on crushing olivine and clinopyroxene phenocrysts from island arc lavas at Papua New Guinea, which had significantly higher ³He_{cosmogenic}/³He_{crush} ratios, between 1.6 and 12.2. Based on the above arguments, we find no evidence that cosmogenic ³He affected the ³He/⁴He ratios we obtained on crushing the sample.

[15] The concentrations of cosmogenic ³He can be utilized to obtain exposure ages of the lavas. The samples were collected on a sloping ridge crest, and were typically drilled normal to a steeply inclined outcrop surface well below any obvious flow top [see also Bogue and Coe, 1984; Bogue, 2001]. The specimens analyzed for this study came from the middle sections of cores and so were usually about 5 cm in from the outcrop surface. Correcting for the sample depth and the absolute elevation (Table 3), the cosmogenic ³He concentrations imply apparent exposure ages of 2–34 kyr for the Kauai lavas. These exposure ages likely reflect erosion rates along ridges and cliffs and do not constrain the recurrence interval of lava flows.

The primary purpose of this study was to investigate the mantle sources of Kauai lavas and more detailed interpretation of the exposure ages is beyond the scope of this work.

[16] Step crushing experiments are a potential way of verifying if ³He/⁴He ratios in the original crush have been affected by the presence of cosmogenic ³He [Hilton *et al.*, 1993]. Because sample PB12 had the highest ³He/⁴He ratio of the fusion analyses (Table 3), we took a second aliquot of the sample and subjected it to step crushing. The results are shown in Figure 5b. The ³He/⁴He ratio in the 2 and 4 min steps was 26 R_A, identical to the original crush ratio. Although the 6 min step suggests an increase in the ³He/⁴He ratio, it is within uncertainty of the earlier steps. The large error bar on this step reflects its very low He yield (99% of the helium was extracted in the first two crushing steps). A step crushing experiment on olivine phenocrysts from Kauai by Scarsi [2000] also documents no variation in the ³He/⁴He ratio after 30 min of crushing. The crusher design used by Scarsi [2000] is similar to that used at Caltech. Thus, we conclude that the range of ³He/⁴He

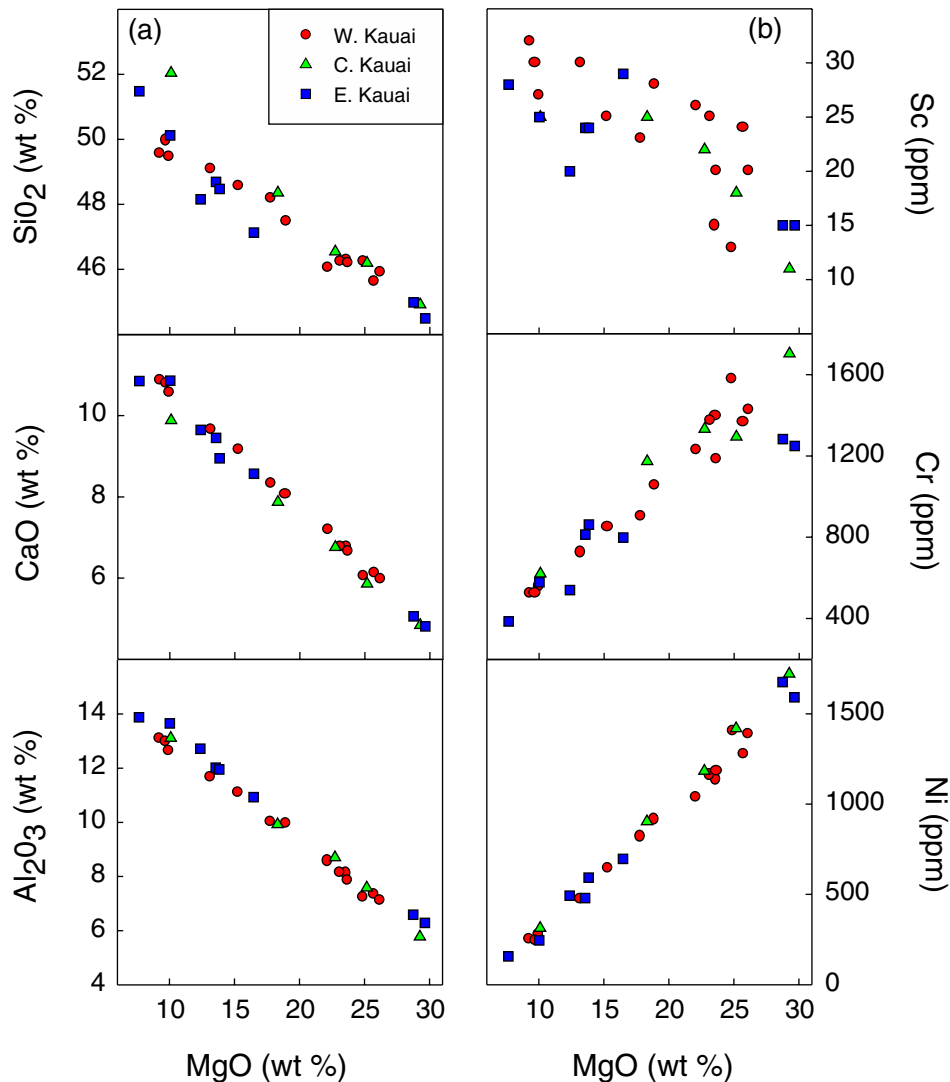


Figure 3. (a) Major oxide abundance and (b) concentration of transition metals trace versus MgO content of Kauai lavas. The linear trends reflect the olivine control line.

values obtained from Kauai is indicative of the composition of the mantle sources of these lavas.

3.2.1. Temporal Variability in Helium Isotopic Ratios

[17] $^3\text{He}/^4\text{He}$ ratios in shield lavas from all three Kauai sections vary erratically with stratigraphic position (Figure 6 and Table 2). For example in west Kauai, the $^3\text{He}/^4\text{He}$ ratio decreases from 26.8 R_A in flow PB16 to 19.5 R_A in PB17 and then increases from 17.9 R_A in PB19 to 24.9 R_A in PB20 (Table 2). Previously published paleodirection and paleointensity measurements on the Kauai samples [Bogue and Coe, 1982, 1984] provide us

with a time constraint on the variations in $^3\text{He}/^4\text{He}$ ratios. Bogue [2001] grouped individual flows from west Kauai that differ by no more than 5% in paleodirection and 10% in paleointensity into vector groups (Figure 6). Based on Holocene records of the secular variation of the geomagnetic field, a vector group represents on the order of 100 years [Holcomb *et al.*, 1986; Bogue, 2001]. As discussed by Mankinen *et al.* [1986], the geomagnetic secular variation during the Holocene is lower (by about a factor or two) than the average for the last 5 million years, suggesting that the estimate of vector group duration above is conservative, i.e., some vector groups may represent intervals consid-

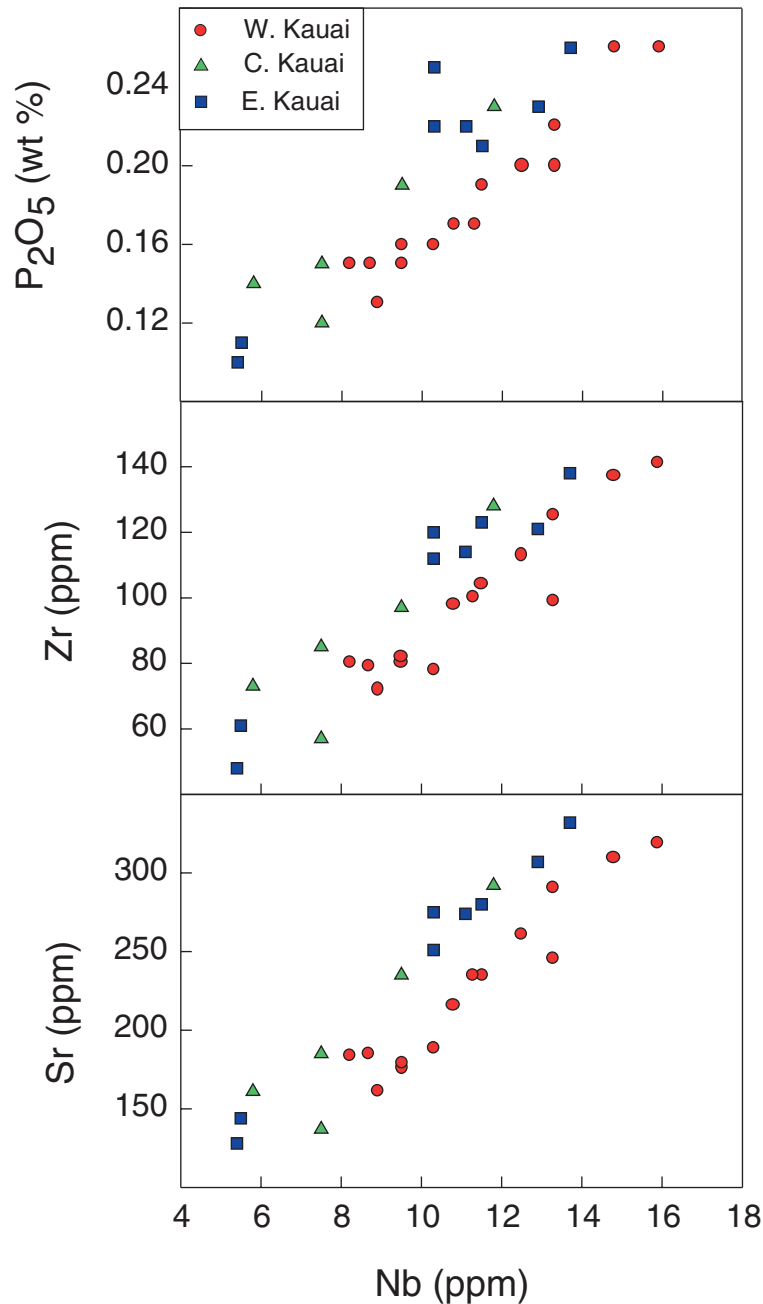


Figure 4. Concentrations of incompatible trace elements and minor oxides (P_2O_5) in Kauai shield lavas. Nb, Sr, Zr, and P_2O_5 abundances correlate well with each other and such correlations observed on other Hawaiian shield volcanoes are interpreted to reflect magmatic processes [Frey *et al.*, 1994]. Therefore, while the alkalis may have been lost (reflected by the low K/P ratios) during postmagmatic weathering processes, trace element ratios, such as Zr/Nb, reflect magmatic values.

erably shorter than 100 years. Within the time interval represented by a single vector group the $^3\text{He}/^4\text{He}$ ratio varies by 7 R_A (Figure 6). Therefore, we conclude that the variations in $^3\text{He}/^4\text{He}$ ratios in west Kauai lavas between ~ 77 and 143 m (Figure 6)

occur on a timescale of 50 years to few hundred years. Alternatively, one may use the mean recurrence interval of lavas flows from Mauna Kea [Sharp *et al.*, 1996], to constrain the timescales of the geochemical variations on Kauai. The west

Table 2. Isotopic Composition of Kauai Shield Lavas^a

	Flow Name	Stratigraphic Height (m)	Crush ³ He/ ⁴ He (R _A)	[He] (10 ⁻⁹ cm ³ STP G ⁻¹)	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	¹⁸⁷ Os/ ¹⁸⁸ Os
West Kauai (Napali Member)	PB1	1.5	22.9	9.4						
	PB10	78.0	20.2	1.0	0.70361		18.322	15.45	37.989	
	PB11	84.0	26.7	1.9						
	PB12	90.0	27.3	10.0	0.70365	0.51297	18.320	15.45	37.998	0.1334
	PB16	114.0	26.8	1.6	0.70356		18.324	15.45	37.947	
	PB17	117.0	19.5	0.8						
	PB18	126.0	19.7	3.6	0.70351	0.51302	18.292	15.44	37.884	
	PB19	129.0	17.9	1.7	0.70345	0.51302	18.257	15.45	37.854	
	PB20	135.0	24.9	1.5	0.70368	0.51303	18.369	15.46	38.020	0.1345
	PB21	141.0	22.3	1.4	0.70364	0.51299	18.299	15.45	37.955	
	OR1	142.5	28.3	5.0	0.70365					
	OR2	145.5	24.1	1.1						
	OR3	148.5	24.6	1.8	0.70364		18.299	15.43	37.925	
	OR4	150.0	22.9	5.0						
	OR5	152.4	23.9	5.9						
	OR18	207.0	23.9	3.1	0.70364	0.51299	18.377	15.45	38.011	
	OR19	210.0	24.7	3.3						
OR27	268.5	26.8	12.7	0.70363	0.51300	18.366	15.44	37.958		
Central Kauai (Olokele Member)	OK9	30.0	25.7	5.6	0.70367	0.51298	18.25	15.44	37.9	0.1364
	OK19	70.0	23.3	0.9						
	OK20	80.0	22.9	1.0	0.70370	0.51294	18.2	15.44	37.89	0.1379
	OK22	90.0	28.3	5.8						
	OK23	92.0	24.1	0.5						
East Kauai (Napali Member)	OK25	101.0	21.4	0.6	0.70369	0.51297	18.22	15.44	37.92	0.1352
	A2	8.2	19.9	3.4	0.70371	0.51296	18.157	15.44	37.871	
	A3	16.4	21.4	1.3	0.70379	0.51296	18.22	15.45	37.91	0.1389
	A9	65.5	27.7	27.1	0.70381		18.186	15.45	37.9	
	A11	81.9	24.5	34.3	0.70378		18.102	15.42	37.813	
	A12	90.1	24.9	4.0						
	A13	98.3	26.6	3.3						
	A14	106.5	25.4	5.5						
	A16	122.9	22.1	1.2	0.70369		18.198	15.45	37.879	
	A17	131.0	26.8	6.6	0.70373	0.51296	18.14	15.43	37.84	0.1378
Postshield Alkalic Cap, Central Kauai	Olokele Member	936	7.0	0.5	0.70375	0.51295				0.1376

^a Stratigraphic height is with respect to the base of the section. Uncertainties (1σ) in ³He/⁴He ratios are 3.3%, based on reproducibility of MM standards of similar size to the samples. The MM standard is a geothermal gas from Yellowstone National Park with ³He/⁴He = 16.45 R_A. Analytical blanks for Sr, Nd, Pb, and Os are <200, <20, <100, and <1 pg, respectively. ⁸⁷Sr/⁸⁶Sr corrected for mass fractionation using ⁸⁶Sr/⁸⁸Sr = 0.1194 and reported relative to a value of 0.71025 for NBS 987. ¹⁴³Nd/¹⁴⁴Nd corrected for mass fractionation using ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219 and reported relative to La Jolla ¹⁴³Nd/¹⁴⁴Nd = 0.511860. External precisions for Sr and Nd isotopes are ±0.00003 and ±0.00002 (2σ). Pb isotopes were corrected for mass fractionation using NBS 981 values of *Todt et al.* [1996]. Reproducibility of measured ratios is better than 0.05% amu⁻¹. Analytical uncertainties for Os isotopes are 3‰ (2σ) based on ¹⁸⁷Os/¹⁸⁸Os ratios measured on a DTM in-house standard during the course of this study, which was 0.1742 (±3‰ 2σ).

Kauai tholeiites were erupted at least 136 kyr prior to eruption of postshield alkalic lavas at Kauai (Figure 6) and, therefore, we will use the mean recurrence interval of flows estimated from the tholeiitic shield stage of Mauna Kea, which is 500 years [*Sharp et al.*, 1996]. The 6–7 R_A variations in ³He/⁴He ratios from west Kauai occur in successive lava flows (Table 2) and, hence, on timescales of ~500 years. In summary, both the paleomagnetic data and the chronology obtained

from the HSDP core at Mauna Kea suggest large variations in ³He/⁴He ratios on timescales of 10² years.

[18] A postshield alkalic basalt in the Olokele Formation yielded a ³He/⁴He ratio of 7 R_A (Table 2), similar to ratios obtained from alkalic lavas at Haleakala and Mauna Kea [*Kurz et al.*, 1987, 1996] and from MORBs [e.g., *Graham et al.*, 1992, 1996]. The alkalic basalts in the Olokele

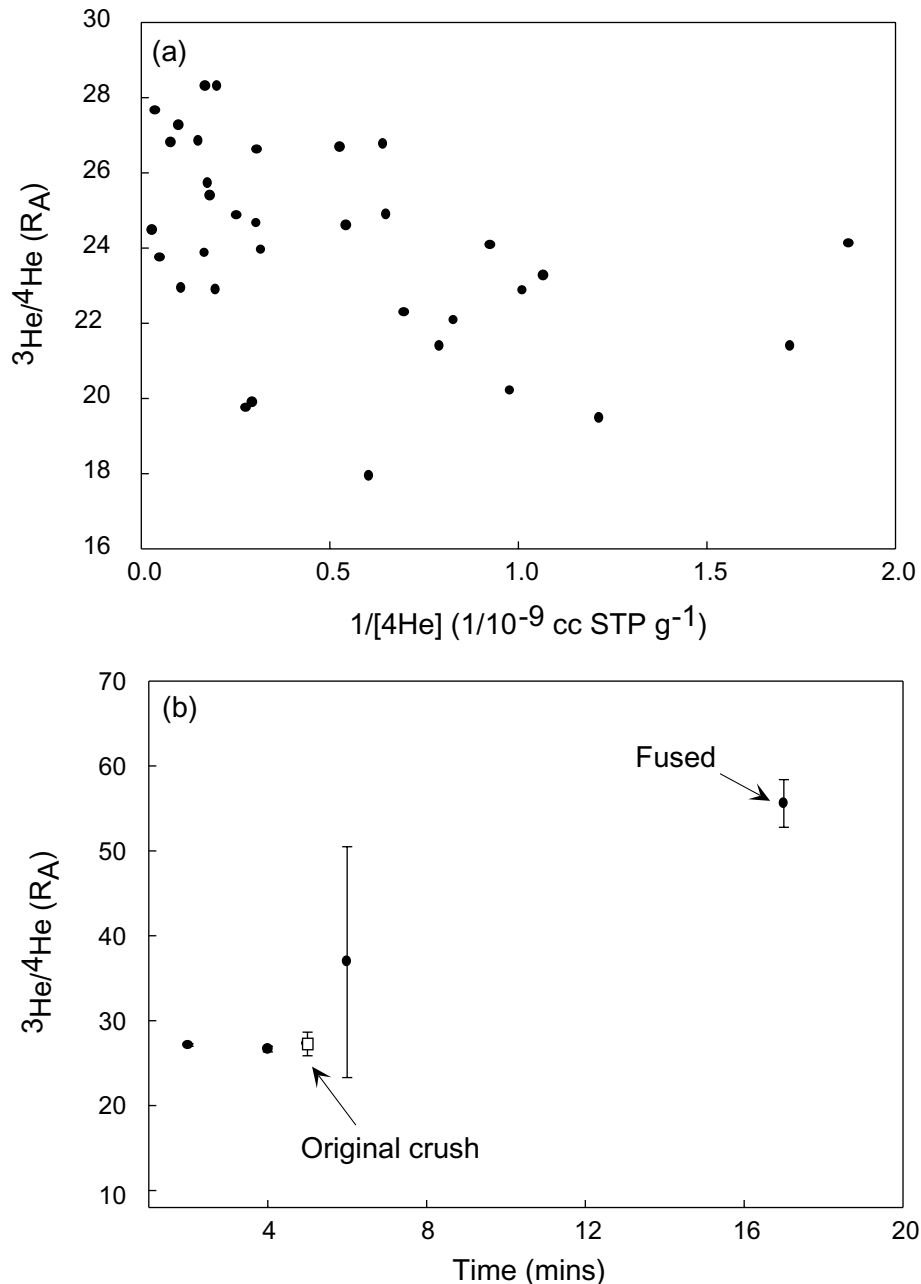


Figure 5. (a) $^3\text{He}/^4\text{He}$ ratios versus $1/[^4\text{He}]$ in olivine phenocrysts from Kauai. The lack of a correlation suggests that $^3\text{He}/^4\text{He}$ ratios are not a simple mixture between mantle sources and post-eruptive components. Note that samples with high He concentration plot on the left-hand side of the figure. (b) Step crushing experiment on PB12, the sample with the highest $^3\text{He}/^4\text{He}$ ratio in the fusion. For comparison, data from the original 4 min crush is shown and has been offset to the right for clarity. Note that the $^3\text{He}/^4\text{He}$ ratios are identical in the first two steps.

Formation are from an elevation of ~ 942 m above sea level, or 367 m from the base of our central Kauai section (Figure 6). The stratigraphically highest flow from which we have a helium measurement (24.1 R_A in OK25) (Table 2) in the central

Kauai section is ~ 675 m above sea level [Bogue and Coe, 1984]. Since lavas in the Olokele Formation are near horizontal, the $^3\text{He}/^4\text{He}$ ratio decreased by 14 R_A over ~ 270 m. The postshield alkalic lavas in the Olokele Formation yield an Ar-

Table 3. Comparison of Crush and Fused $^3\text{He}/^4\text{He}$ Ratios From Olivine Phenocrysts in Kauai Shield Lavas^a

Sample	Elevation (m above sea level)	$^3\text{He}/^4\text{He}$ Fusion (R_A)	$^3\text{He}/^4\text{He}$ Crush (R_A)	^4He Fusion (10^{-9} cm ³ STP g ⁻¹)	^3He Fusion (10^{-15} cm ³ STP g ⁻¹)	Cosmogenic [^3He] (10^{-15} cm ³ STP g ⁻¹)	$^3\text{He}_{\text{cosmogenic}}/$ $^3\text{He}_{\text{crush}}$	Apparent exposure age (kyr)
PB12	124.5	97.9	27.3	1.2	162.0	116.6	0.3	31.3
PB17	151.5	38.3	19.5	2.7	144.0	70.2	3.2	18.5
PB19	163.5	30.6	17.9	3.2	137.0	56.0	1.4	14.6
PB20	169.5	29.8	24.9	5.3	220.0	35.9	0.7	9.3
OR1	97.5	45.7	28.3	3.7	234.0	88.1	0.5	24.2
OR18	162.0	33.3	23.9	4.5	208.0	57.1	0.5	14.9
OR27	223.5	30.4	26.8	2.0	82.9	9.4	0.02	2.3
A2	130.2	39.2	19.9	4.7	258.0	126.3	1.4	33.8
A11	203.9	15.9	24.5	2.8	62.0	—	—	—
A17	253.0	34.6	26.8	3.8	185.0	40.5	0.2	9.9

^a Cosmogenic ^3He ($^3\text{He}_c$) was calculated using the relation $^3\text{He}_c = ^3\text{He}_{\text{fusion}} - ((^3\text{He}/^4\text{He})_{\text{crush}} * (^4\text{He}_{\text{fusion}}))$ [Kurz, 1986b]. $^3\text{He}_c$ was scaled to sea level and the surface of the rock using an exponential relation: $^3\text{He}_c(\text{sea level}) = ^3\text{He}_c(X) * \exp[(X - 1032)/L] * \exp(z/53)$, where X is the altitude in units of pressure (g cm⁻²), 1032 is the sea level altitude expressed in units of g cm⁻², L is the atmospheric attenuation length for cosmic rays (160 g cm⁻²) [Kurz et al., 1990], z is the depth of the sample from the surface (=5 cm), and 53 is the attenuation depth of cosmic rays in a basalt in cm. X is calculated using a third-order polynomial given by Lal [1991]. The exposure ages have been calculated by using a sea level ^3He production rate of 100 atoms g⁻¹ yr⁻¹ in olivine crystals at Hawaii [Kurz et al., 1990].

Ar age of 3.92 ± 0.03 Ma [Clague and Dalrymple, 1988] and, hence, were erupted during reversed polarity chron 2r. Since there is only one N-R transition in the Olokele Formation [Bogue and Coe, 1984], the normal polarity chron in our central Kauai section is 3n.1.n and the N-R magnetic reversal boundary is at 4.18 Ma (Figure 6) [Cande and Kent, 1995]. Consequently, the decrease in $^3\text{He}/^4\text{He}$ ratios from plume-like values of 21 R_A to MORB values of 7 R_A occurs in <26 kyr. Because of the lack of olivine-rich flows near the top of the Olokele section, we could not determine whether the drop in $^3\text{He}/^4\text{He}$ ratios occurred gradually or rapidly. For comparison, in the last 25 kyr of the shield building stage of Mauna Kea the $^3\text{He}/^4\text{He}$ ratio varied by only 1–2 R_A units [Kurz et al., 1996] while at Mauna Loa the $^3\text{He}/^4\text{He}$ ratio decreased from 18 to 8 R_A in ~20 kyr [Kurz et al., 1995; DePaolo et al., 2001].

[19] Helium isotopic ratios from Kauai vary from 17.9 to 28.3 R_A and the average for 34 samples is 24 R_A (Table 2). Although differences in radiogenic isotope ratios between west and east Kauai have been suggested [Holcomb et al., 1997], there is no distinction in the range of $^3\text{He}/^4\text{He}$ ratios from the different geographical localities.

[20] Absolute ages of postshield alkalic lavas at the top of the Olokele Formation (Figures 1 and

6) provide a minimum estimate of the total time over which the high $^3\text{He}/^4\text{He}$ ratios were sampled at Kauai. As discussed above, the reversed polarity chron in the central Kauai section is 2r and the normal polarity chron is 3n.1.n (Figure 6). The R-N transition in west Kauai and N-R transition in central Kauai section (Figure 6) is very likely a back-to-back R-N-R reversal pair [Bogue and Coe, 1982, 1984]. Hence, the normal polarity chron in west Kauai (Figure 6) is also 3n.1.n. Based on the Cande and Kent [1995] timescale the total duration of chron 3n.1.n is 110 kyr. Therefore, the He isotope ratios documented from Kauai represent tapping of a high $^3\text{He}/^4\text{He}$ component in the shield-stage, at least episodically but possibly continuously, for >110 kyr.

3.3. Radiogenic Isotope Ratios

[21] Our new isotopic data extends the Kauai field in Sr, Nd, and Pb space and provides the first Os isotopic measurements from the shield building stage of Kauai (Figures 7–10). The erratic variations in $^3\text{He}/^4\text{He}$ ratios with stratigraphic position are also seen in Sr, Nd, and Pb isotope ratios (Figure 6 and Table 2). For example, the decrease in $^3\text{He}/^4\text{He}$ ratios from ~25 to 17 R_A and the subsequent recovery to 25 R_A between 112 and 143 m in west Kauai are correlated with variations in Sr isotope ratios

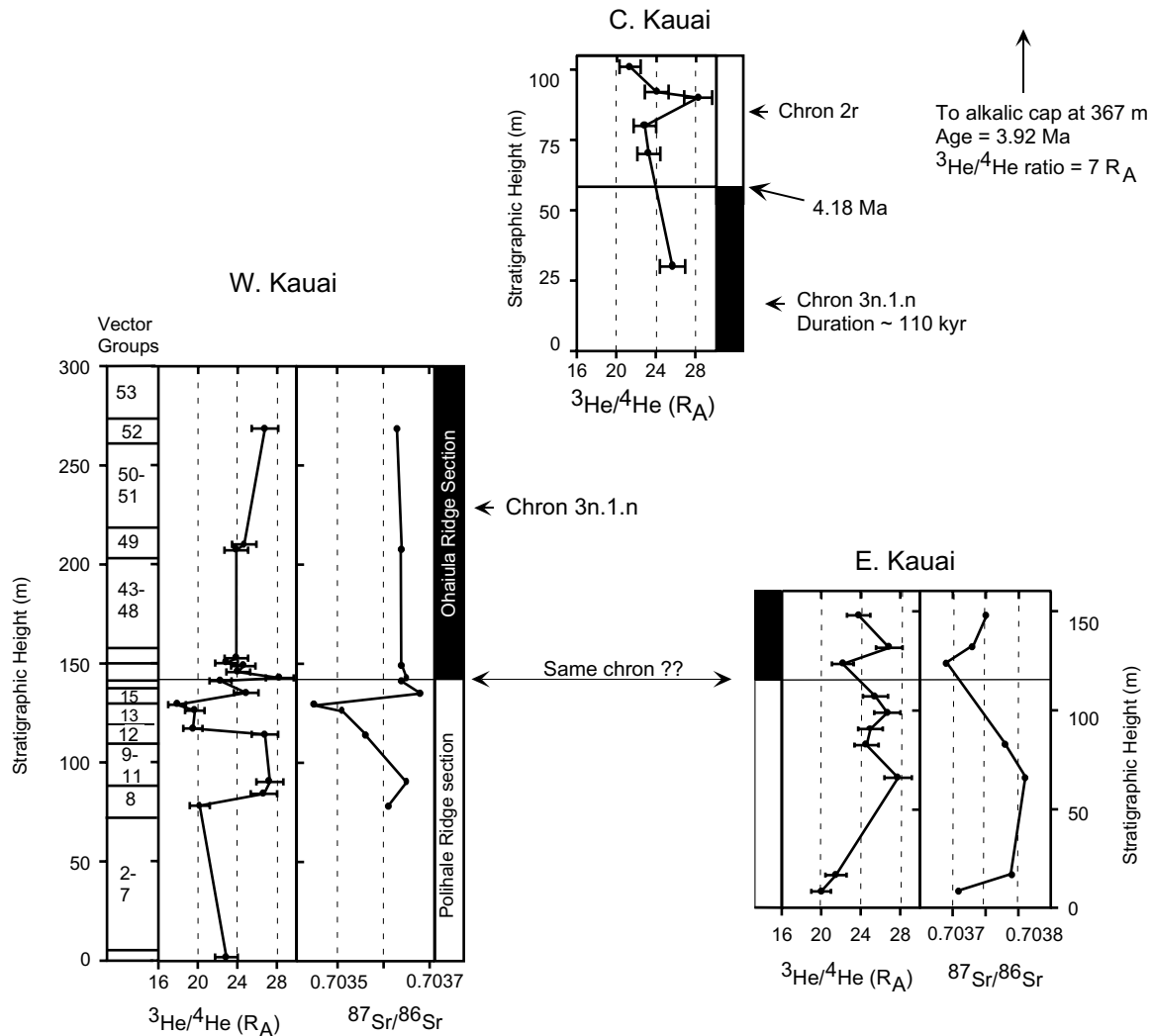


Figure 6. Stratigraphic variations in He and Sr isotope ratios from west, central, and east Kauai. West Kauai represents a composite stratigraphic section, constructed by superposing the Polihale (reverse polarity) and Ohaiula sections (normal polarity). Stratigraphic height is relative to the base of the section (and not with respect to elevation above sea level). Age of the postshield alkalic basalt is from the study of *Clague and Dalrymple* [1988] and the age of the N-R transition is from the study of *Cande and Kent* [1995]. Note the rapid variations in $^3\text{He}/^4\text{He}$ ratios particularly from west Kauai and the correlation in He and Sr isotope ratios. The normal chron in west and central Kauai is 3n.1.n (see text), which implies that Loihi-like $^3\text{He}/^4\text{He}$ ratios are sampled only 136 kyr prior to the eruption of the postshield alkalic lavas. Such consistently high $^3\text{He}/^4\text{He}$ ratios in the late shield building stage have not been observed on other Hawaiian volcanoes.

(Figure 6). Similar variations in $^3\text{He}/^4\text{He}$ ratios and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are also seen in east Kauai lavas (Figure 6).

[22] The Sr, Nd, and Os isotopic composition of west Kauai lavas are similar to those from Loihi (Figures 7 and 8a). In addition, our new data suggest that Sr isotope ratios in some west Kauai rocks are among the most unradiogenic (0.70345)

from Hawaiian shield building lavas (Figures 8 and 9). East Kauai lavas have more enriched $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ composition compared to west Kauai lavas (Figure 8b). In general, east Kauai lavas are similar in Sr and Nd isotopic composition to those from Mauna Loa although for a given Sr isotopic composition east Kauai lavas have higher $^{187}\text{Os}/^{188}\text{Os}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios than those from Mauna Loa (Figures 7 and 8b).

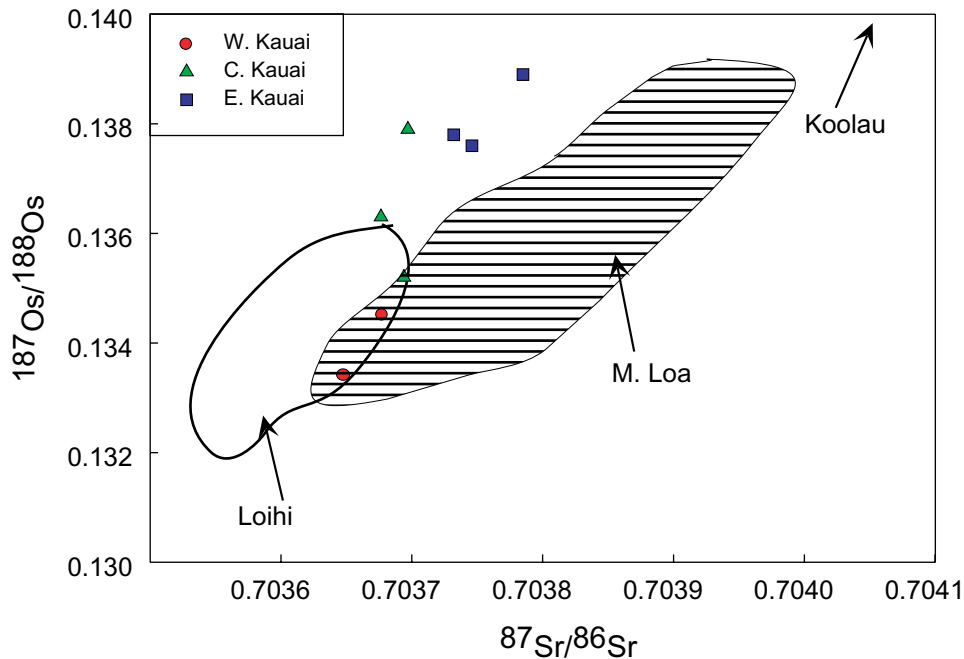


Figure 7. Sr versus Os isotopic ratios in Kauai lavas. Melt–mantle reaction tends to decouple Os from Sr [Hauri *et al.*, 1996]. Hence, the correlation between Sr and Os argues against significant chromatographic element fractionation during melt transport. Data for the Loihi and Mauna Loa fields were retrieved from the GEOROC database (<http://georoc.mpch-mainz.gwdg.de>).

[23] Hawaiian shield lavas in general show a negative correlation between Sr and Pb isotopic ratios (Figure 8a). Although shield lavas from east Kauai display a broad negative correlation, those from west Kauai show a positive correlation and appear to trend toward MORB. The similarity between west Kauai and Loihi lavas is further borne out in He–Sr and He– $^{206}\text{Pb}/^{204}\text{Pb}$ space (Figure 9). Note that both Loihi and west Kauai lavas appear to trend toward the MORB field with decreasing $^3\text{He}/^4\text{He}$ ratios. While lavas from east Kauai have similar $^3\text{He}/^4\text{He}$ ratios as those from west Kauai, the east Kauai field is shifted toward higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (Figure 9).

[24] In $^{207}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ space east and west Kauai lavas form distinct fields and central Kauai lies between the two (Figure 10a). West Kauai overlaps with the Loihi field while east Kauai overlaps with the Mauna Loa field, consistent with observations from Figure 8. In $^{208}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ space (Figure 10b), east and west Kauai

display steep subparallel arrays. Unlike in all other isotope spaces, west Kauai and Loihi lavas are distinct in $^{208}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ space with lavas from west Kauai systematically lower in $^{208}\text{Pb}/^{204}\text{Pb}$ for a given $^{206}\text{Pb}/^{204}\text{Pb}$ ratio, compared to lavas from Loihi.

4. Discussion

[25] A striking feature of our Kauai data is the very high $^3\text{He}/^4\text{He}$ ratios (17–28 R_A), similar to those from Loihi (Loihi range \cong 18–32 R_A). The average $^3\text{He}/^4\text{He}$ ratio in shield lavas from Kauai is 24 R_A , indistinguishable from Loihi average and significantly higher than the average value of 16 R_A from Mauna Loa and Kilauea, and 12 R_A from Mauna Kea [DePaolo *et al.*, 2001]. In the following section, we discuss (1) possible origins of the isotopic trends observed, particularly the different mantle components that may explain the geochemical data in Kauai shield lavas, (2) the temporal and spatial geochemical variability in Kauai shield

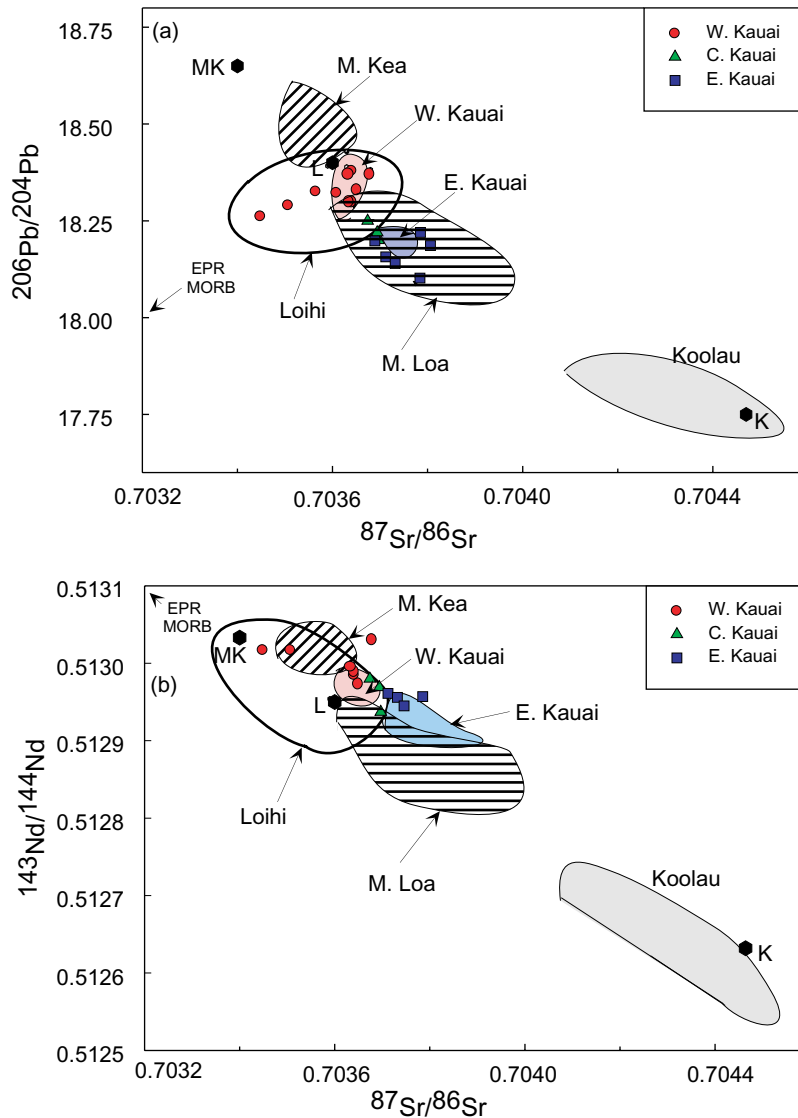


Figure 8. (a) $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ and (b) $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ from Kauai. Individual points represent our new data while the fields, including the east and west Kauai fields, are from literature sources available from the GEOROC database (<http://georoc.mpch-mainz.gwdg.de>). For clarity, only the fields for Loihi, Mauna Kea, Koolau, Kauai, and Mauna Loa are shown. K, L, and MK are the composition of the Koolau, Loihi, and Mauna Kea end-members as defined by *Eiler et al.* [1996, 1998]. The west Kauai data significantly overlaps with the Loihi field, while east Kauai is similar to Mauna Loa. Note that the west Kauai data appears to trend toward EPR MORB.

lavas, and (3) the implications of our data for models of the Hawaiian plume.

4.1. Isotopic Composition of Kauai Lavas: Three or Four Mantle Components?

[26] The isotopic variability in Kauai lavas could be generated by mixing between distinct mantle sources [Staudigel *et al.*, 1984; Stille *et al.*, 1986; West *et al.*, 1987; Kurz *et al.*, 1995; Eiler *et al.*,

1996; Hauri, 1996] or through magma–mantle reaction during melt transport to the surface [McKenzie and O’Nions, 1991; DePaolo, 1996]. The correlation between Sr and Os in Kauai lavas (Figure 7), however, strongly argues against the latter, since melt–mantle reaction would produce horizontal or vertical arrays in Sr–Os space [Hauri *et al.*, 1996]. Hence, following previous interpretations from other Hawaiian shield volcanoes

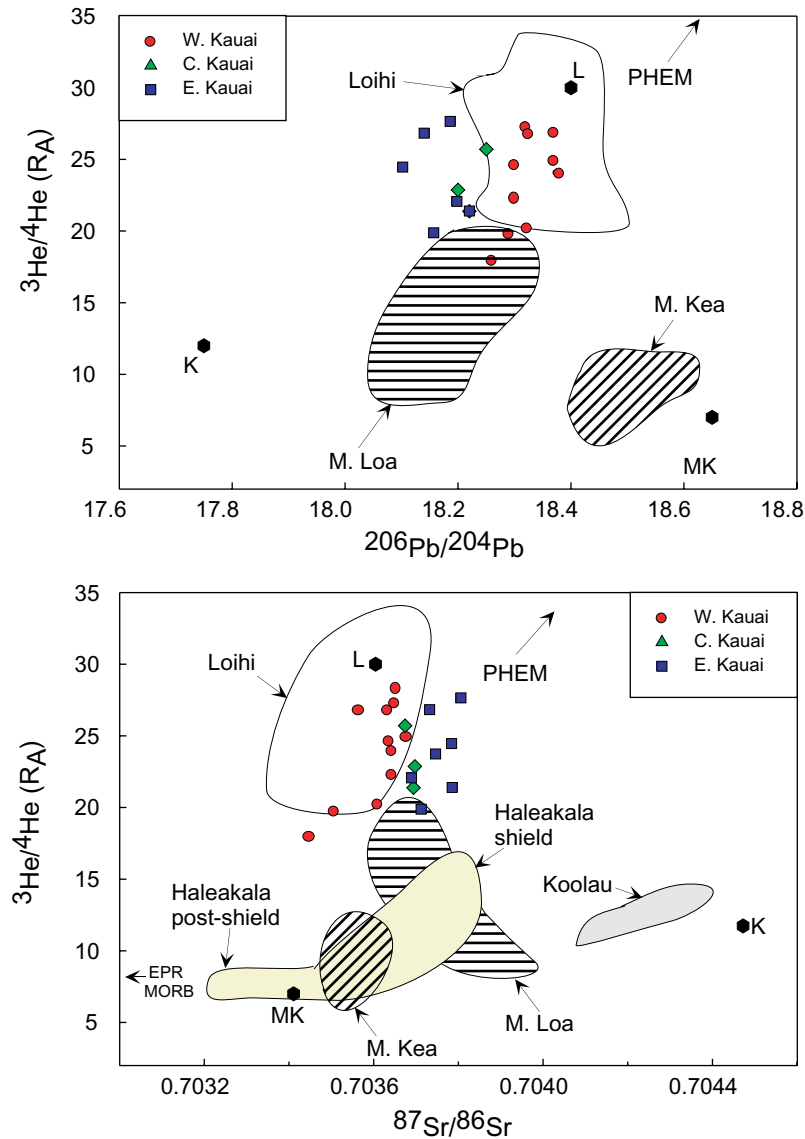


Figure 9. $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^3\text{He}/^4\text{He}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^3\text{He}/^4\text{He}$. Symbols and fields as in Figure 8. The west Kauai data once again significantly overlaps with the Loihi field. Note that in the He-Sr plot west Kauai trends toward a depleted component that is commonly sampled in posterosional lavas.

[Staudigel *et al.*, 1984; Kurz *et al.*, 1995; Eiler *et al.*, 1996; Hauri *et al.*, 1996], we explain the isotopic variability and the correlations among the isotopic ratios of Sr, Nd, Pb, and Os in Kauai shield lavas by mixing between distinct mantle sources.

[27] At least three distinct mantle components are required to explain the isotopic variability in Hawaiian shield lavas [Staudigel *et al.*, 1984; Stille *et al.*, 1986; West *et al.*, 1987; Kurz *et al.*, 1995;

Eiler *et al.*, 1996; Hauri, 1996]. The three components are referred to as Loihi, Koolau, and Kea, for the volcanoes where the geochemical signatures of these components are most strongly manifested. The compositions of these three end-members [Eiler *et al.*, 1996, 1998] have been plotted in Figures 8–10. To investigate if the most recent three-component model [Eiler *et al.*, 1996, 1998] can successfully explain isotopic variability of Kauai lavas, we fit the isotopic composition of He, Sr, Nd, and Pb simultaneously in Kauai lavas

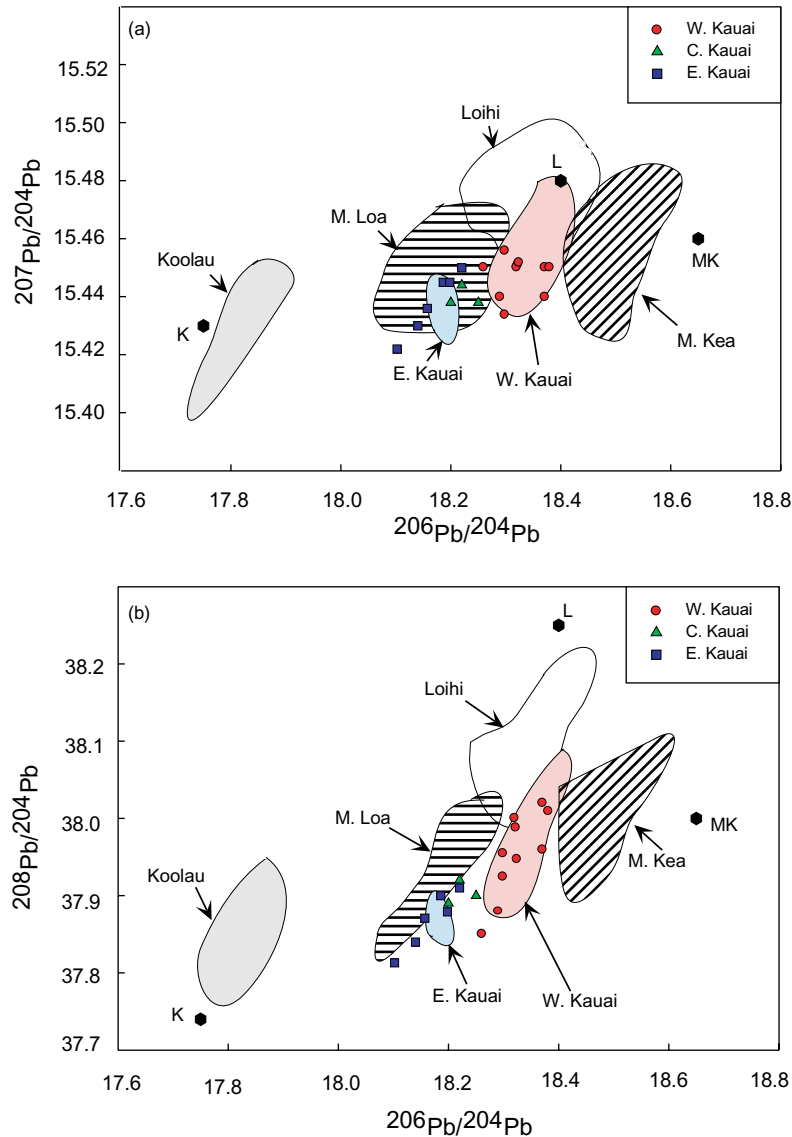


Figure 10. Pb-Pb correlations in Hawaiian shield basalts. In $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ space, Kauai defines an elongated field between the Mauna Loa and Mauna Kea fields. Although the west Kauai and Loihi fields overlap in $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{207}\text{Pb}/^{204}\text{Pb}$ space, there is almost no overlap in $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ space. Symbols and fields are as in Figure 8.

by a least squares mixture of the three defined components [see *Eiler et al.*, 1996 for details]. However, the sums of the three components are frequently negative, indicating that the Kauai samples lie outside the triangle and off the plane defined by the three components (Figure 11).

[28] Recently, *Abouchami et al.* [2000] demonstrated that the three-component mixing model of *Eiler et al.* [1996, 1998] does not explain Pb

isotope ratios of Hawaiian shield lavas. Therefore, we conducted a principal component analysis based on our new He, Sr, Nd, and Pb data and the literature data (see Appendix A). Only samples with combined He-Sr-Nd-Pb data were selected and we did not include Os in the analysis, as this would considerably decrease the size of the database. To weight the different isotope systems equally, isotopic ratios were normalized (subtract population mean and divide by the population

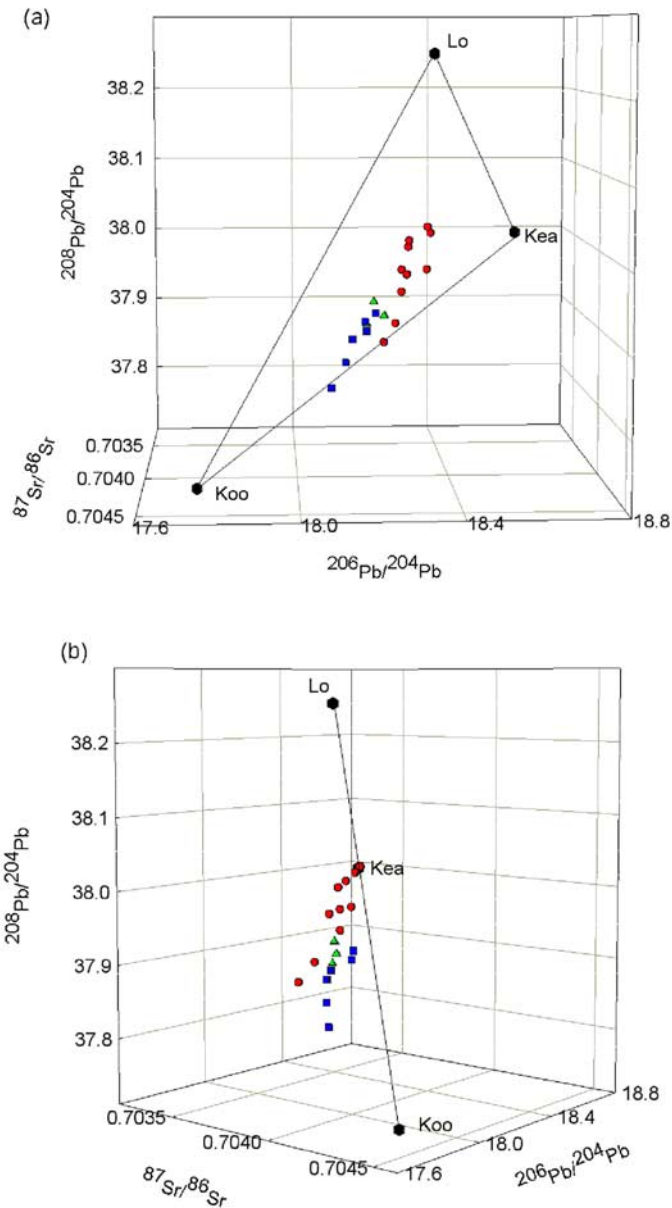


Figure 11. (a) The Kauai data plotted in $^{87}\text{Sr}/^{86}\text{Sr}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{208}\text{Pb}/^{204}\text{Pb}$ space. Symbols for Kauai samples as in previous figures. Also shown are the Loihi (Lo), Kea, and Koolau (Koo) components as defined by *Eiler et al.* [1996, 1998]. The figure is then rotated (b) to view the plane through the three end-members edge on (i.e., the plane through the three components runs vertical out of the plane of the paper). The Kauai data lie outside the plane containing the Loihi, Kea, and Koolau components, suggesting that the Kauai lavas sample an additional component.

standard deviation) [LeMaitre, 1982]. The principal component analysis indicates that the first three eigenvectors account for 56%, 18%, and 16% of the variance, respectively, and a total of 90% of the variance in the data set (the next eigenvector accounts for $\sim 4\%$ of the variance). Therefore, four components are required to explain

the variability in Hawaiian shield lavas. To demonstrate that four components in the Hawaiian shield lavas are required even without the helium data, the principal component analysis was repeated using only Sr, Nd, and the three Pb isotopic ratios. While the first two eigenvectors account for 87% of the variance, the third vector accounts for $\sim 6\%$ of the

Table 4. End-Member Compositions for the Four-Component Mixing Model

End-member	$^{87}\text{Sr}/^{86}\text{Sr}$	ϵNd	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^3\text{He}/^4\text{He}$
Koolau	0.70444	-2.0	17.68	15.42	37.77	10.3
Loihi	0.70353	6.8	18.40	15.49	38.22	38.7
Kea	0.70347	7.5	18.61	15.52	38.19	2.6
DM	0.70321	11.3	18.38	15.41	37.67	7.8

variance and is too large to be explained by analytical uncertainties.

[29] While the mantle end-members are not precisely defined by the principal component analysis, the eigenvectors indicate that the previously defined Loihi, Koolau and Kea components [e.g., *Eiler et al.*, 1996, 1998; *Hauri*, 1996], and a depleted mantle (DM) component with MORB-like Sr, Nd, Pb, and He would be appropriate end-members (Table 4). The isotopic composition of the DM component is similar to the end-member sampled during posterosional stages of Hawaiian volcanism [*Stille et al.*, 1986; *Kurz et al.*, 1987; *West et al.*, 1987; *Reiners and Nelson*, 1998]. Note that our principal component analysis was conducted only on Hawaiian *shield-stage* lavas. Thus, our proposed fourth component for the shield lavas is not a new component in Hawaiian volcanism but one that is normally sampled during the posterosional stage. The DM component is discussed later in this section.

[30] To test if the four-component model can successfully describe the isotopic variability in Hawaiian shield lavas, each sample was fit by a least squares mixture of the four components (Table 4) using He, Sr, Nd, and Pb isotopic data. This calculation assumes linear mixing between the different components (i.e., elemental ratios such as Pb/Sr are the same in the different components), a reasonable assumption based on the linearity of isotope arrays in Hawaiian lavas [see also *Eiler et al.*, 1996]. As shown in Figure 12, all the isotope ratios in Kauai shield lavas, and Hawaiian shield lavas in general, can be fitted simultaneously and to within a small multiple of the analytical precision, illustrating the success of the four-component model and suggesting good coupling of He to the other lithophile tracers.

Thus, unlike the three-component model, our four-component model can explain the isotopic variability in Kauai lavas and, furthermore, significantly improves the fit to the isotopic data in other Hawaiian shield lavas. For example, the three-component mixing model by *Eiler et al.* [1996] systematically underestimates ϵNd and overestimates $^{206}\text{Pb}/^{204}\text{Pb}$ ratios.

[31] To test the predictive capability of our four-component model, we computed the proportions of the components in shield lavas using the measured $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios and then predicted their $^3\text{He}/^4\text{He}$ ratio [see also *Eiler et al.*, 1998]. The predicted He isotope ratios, on average, deviate from the measured values by $\sim 10 R_A$. However, if we constrain the proportions of the four components using $^3\text{He}/^4\text{He}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios (along with another isotopic ratio such as ϵNd) we successfully predict the other isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios) (Figure 13). In fact, the best predictions are obtained when both $^3\text{He}/^4\text{He}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios are used to compute the proportions of the components (compare Figures 13a and 13b). Hence, the inability to predict He isotopic ratios does not imply decoupling of He from other isotopic systems. Rather the predictions in Figure 13 imply that the Loihi component is best characterized by $^3\text{He}/^4\text{He}$ ratios and has well defined Sr, Nd, and uranium-Pb isotopic composition that are intermediate between the Kea and Koolau end-members (Table 4).

[32] Based on the least squares fit to each sample (Figure 12), we computed the average proportion of the four components in different Hawaiian shield volcanoes (Figure 14). While four components are required to explain the isotopic data from all Hawaiian shield-stage lavas, only three components can reasonably explain the isotopic compo-

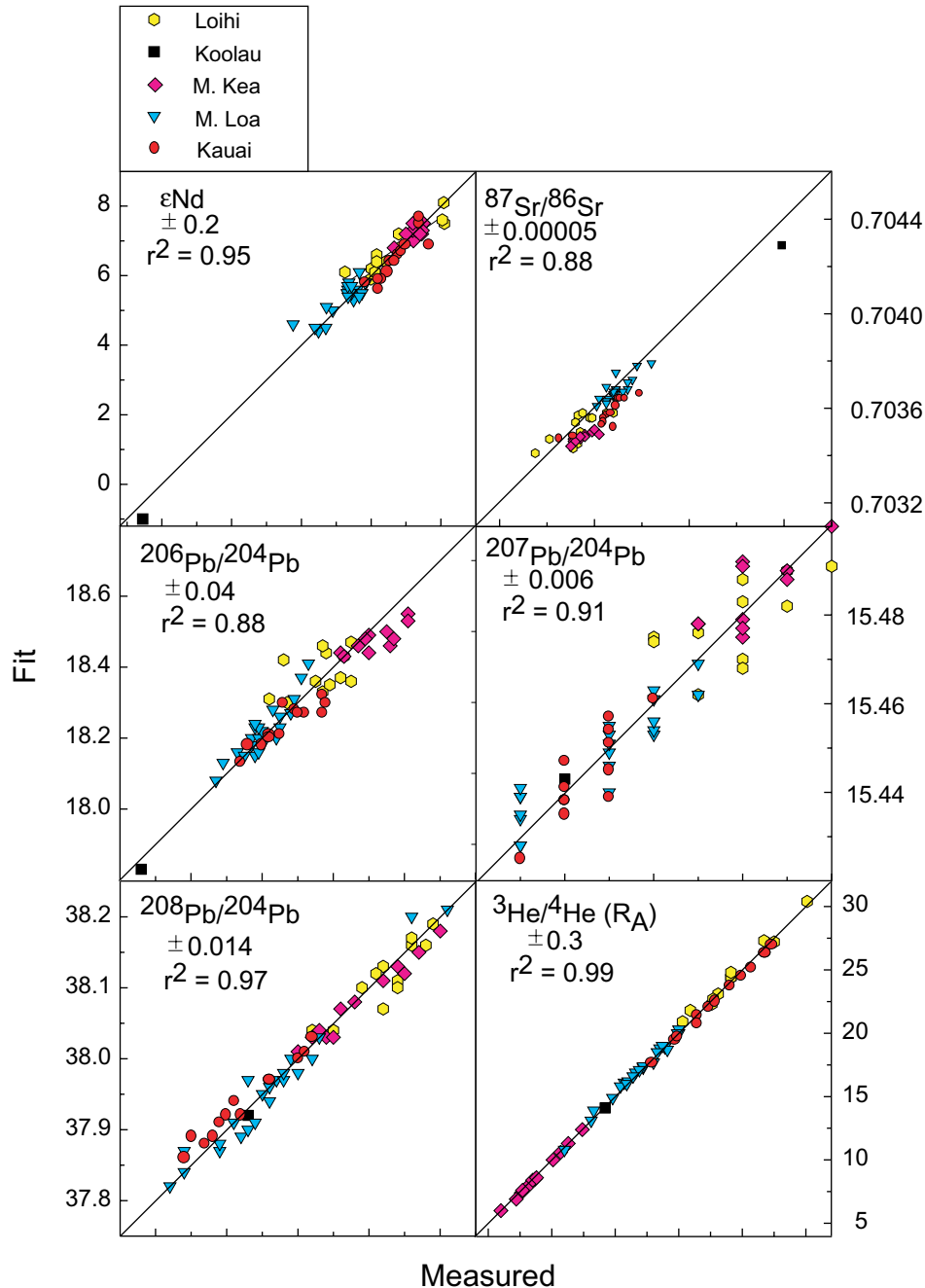


Figure 12. Comparison between measured Nd, Sr, Pb, and He isotopic ratios with a best fit of the samples to a mixture of the four components in Table 4. All isotope ratios have been fit simultaneously. \pm indicates average difference between measured and fit values. Unlike previous three component models, our four-component model can explain the isotopic data from Kauai and also improves the fit to other Hawaiian shield lavas (compare with the study of *Eiler et al.* [1996, Figure 4]). For the data set used in the figure, see Appendix A.

sition of Kauai shield-stage lavas (Figure 14). However, a *different set* of three components is required to explain the Kauai data (Loihi, Koolau and DM) than the previously proposed Loihi, Koolau and Kea components [e.g., *Eiler et al.*,

1996; *Hauri*, 1996]. In addition, our principal component analysis indicates that Hawaiian shield volcanoes sample different proportions of the mantle components (Figure 14), which has been previously suggested [*Frey and Rhodes*, 1993; *Frey et*

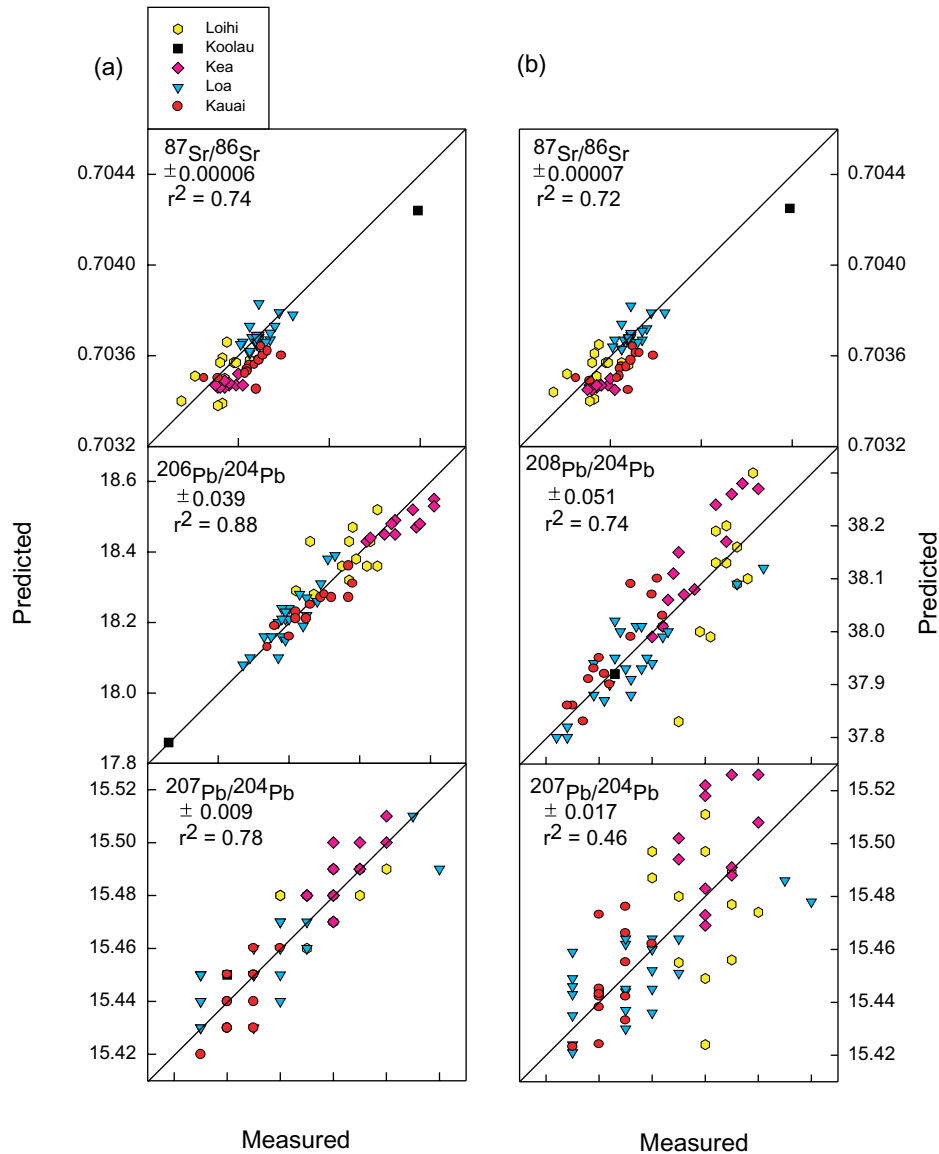


Figure 13. (a) Predicted $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios in Hawaiian shield lavas. We first computed the proportions of the four components from the measured $^{208}\text{Pb}/^{204}\text{Pb}$, He, and Nd isotopic composition and the relation $X_{\text{Koolau}} + X_{\text{Loihi}} + X_{\text{Kea}} + X_{\text{DM}} = 1$. The $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios were then predicted simultaneously using the end-member compositions in Table 4. (b) Predicted $^{87}\text{Sr}/^{86}\text{Sr}$, $^{208}\text{Pb}/^{204}\text{Pb}$, and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios in Hawaiian shield lavas. He, $^{206}\text{Pb}/^{204}\text{Pb}$, and ϵNd data were used to calculate the proportions of the components. Note the significantly better $^{207}\text{Pb}/^{204}\text{Pb}$ prediction in (a), which indicates that $^3\text{He}/^4\text{He}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios best identify the Loihi component.

al., 1994; Pietruszka and Garcia, 1999]. The implications of this result for models of the Hawaiian plume are discussed later.

4.1.1. The DM Component

[33] The DM component could be assimilated Pacific crust, Pacific lithospheric mantle, or asthe-

nosphere entrained by the upwelling plume. Correlations between Os and Sr (Figure 7) and Os and O in Hawaiian lavas argue against crustal assimilation [Lassiter and Hauri, 1998; Lassiter *et al.*, 2000]. Although our isotopic data cannot distinguish between Pacific lithospheric mantle and entrained asthenosphere, as noted earlier, the DM component is isotopically similar to the component sampled in

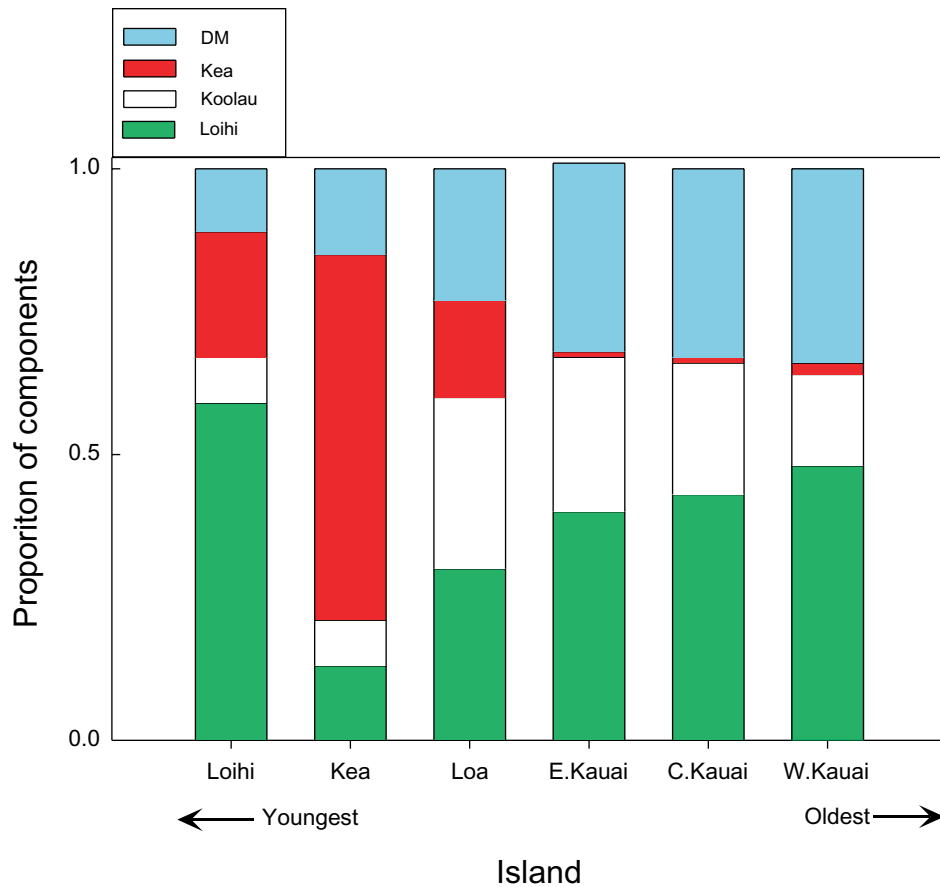


Figure 14. Average proportion of the Loihi, Koolau, Kea, and DM components in shield lavas from different Hawaiian volcanoes. The proportions of the four components were calculated by simultaneously fitting the Nd, Sr, Pb, and He isotopic data using least squares regression.

Hawaiian posterosional basalts [Chen and Frey, 1985; Stille *et al.*, 1986; Kurz *et al.*, 1987; West *et al.*, 1987; Reiners and Nelson, 1998]. Geochemically, both asthenospheric and lithospheric origin is permissible for posterosional basalts [e.g., Chen and Frey, 1985; Reiners and Nelson, 1998; Lassiter *et al.*, 2000]. However, seismic evidence [Woods *et al.*, 1991] and numerical modeling of plume–lithosphere interaction [Ribe and Christensen, 1994] argue against lithospheric erosion during the shield-stage and, therefore, we favor an asthenospheric origin for the DM component. Irrespective of the precise origin of posterosional basalts, our principal component analysis indicates that melts from this source(s) are present during the shield building stage of Kauai and also present in other Hawaiian shield volcanoes, albeit varyingly (Figure 14). Future $\delta^{18}\text{O}$ and Os isotopic studies in Kauai

lavas may more positively identify the character of the DM component.

4.2. Major Element Chemistry of Kauai Tholeiites: Source Heterogeneity or Melting Effects?

[34] While the isotopic variability in Kauai and other Hawaiian shield volcanoes demonstrates the presence of mantle components with distinct isotopic signatures in the Hawaiian plume, an important question is whether these components are also characterized by distinctive major element chemistry. Previous studies on Hawaiian volcanoes noted systematic intervolcano differences in major element chemistry [Frey and Rhodes, 1993; Frey *et al.*, 1994; Yang *et al.*, 1996]. Based on correlations between isotopic ratios and major element composition of shield lavas, Hauri [1996] suggested that

Table 5. Major Element Data Corrected for Olivine Fractionation

	West Kauai					Central Kauai			East Kauai
	PB10	PB17	PB19	OR5	OR18	OK19	OK20	OK25	A3
SiO ₂	47.5	47.4	46.7	47.2	47.5	50.5	47.8	48.4	49.0
TiO ₂	1.8	1.9	1.9	1.7	1.8	2.0	1.7	1.7	2.0
Al ₂ O ₃	9.7	9.7	9.5	9.2	8.8	11.3	9.6	9.9	10.7
FeO ^a	11.8	11.8	12.1	12.4	12.5	9.6	12.0	11.4	10.5
MnO	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.1
MgO	18.9	18.8	19.3	19.7	20.0	15.4	19.3	18.3	16.8
CaO	8.1	8.1	8.0	7.8	7.4	8.5	7.4	7.9	8.4
Na ₂ O	1.6	1.7	1.8	1.5	1.4	2.0	1.6	1.8	1.9
K ₂ O	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.3	0.3
P ₂ O ₅	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

^aDenotes total iron. Major element oxides are in wt.%.

major element variability might be related to source heterogeneity within the Hawaiian plume. However, most studies generally interpret differences in major elements to reflect variable degrees of melting of a source homogeneous in its bulk chemistry [e.g., *Frey and Rhodes, 1993; Frey et al., 1994; Yang et al., 1996*].

[35] To infer the parental magma composition of Kauai lavas, we corrected the major element data for olivine fractionation. The MgO content of primary Hawaiian magmas is between 16 and 18 wt.% [*Clague et al., 1991; Garcia et al., 1995; Hauri, 1996; Yang et al., 1996*] and, hence, we adjusted the major element data to an MgO content of 17 wt.% by adding or subtracting olivine in 1% increments [see *Yang et al., 1996* for details]. Only samples with K₂O/P₂O₅ >1 were used for this exercise. Note that using alternative methods to correct for olivine fractionation, such as recalculating the major elements to a constant Mg/(Mg + Fe²⁺) ratio (Mg#) [*Hauri, 1996*], will not significantly alter the results.

[36] The olivine fractionation corrected data are presented in Table 5 and Figure 15. It should be noted that because of the very small data set the results should be treated as tentative. There are small but systematic differences in the major element data between west, central, and east Kauai. For example, west Kauai lavas have lower SiO₂, CaO, Al₂O₃, and higher FeO contents than central and east Kauai lavas (Table 5). Major element differences between east and west Kauai tholeiites can

also be inferred from CaO/Al₂O₃ ratios. Tholeiites from east Kauai have systematically lower CaO/Al₂O₃ ratios than those from west Kauai. While weathering may have decreased CaO/Al₂O₃ ratios in east Kauai lavas, the correlation between CaO/Al₂O₃ and Zr/Nb ratios (Figure 16) argue against such an interpretation because Zr and Nb are immobile during post-eruptive alteration [*Lipman et al., 1990; Frey et al., 1994*]. Furthermore, correlations between radiogenic isotope ratios and CaO/Al₂O₃ ratios in individual samples (Figure 16) suggest that CaO/Al₂O₃ ratios reflect magmatic values.

[37] SiO₂ and FeO contents in basalts are sensitive indicators of the degree and mean pressure of melting [*Klein and Langmuir, 1987*]. For example, higher extent of melting leads to higher SiO₂ and lower FeO contents in the melt [*Klein and Langmuir, 1987; Frey et al., 1994; Yang et al., 1996*]. In Hawaiian lavas, mean pressure of melt segregation and extent of melting are inversely correlated [*Frey et al., 1994; Yang et al., 1996*]. The SiO₂ and FeO contents in Kauai tholeiites (Figure 15) indicate that east Kauai lavas are derived from lower mean pressures and higher degrees of melting than west Kauai lavas. However, variable degrees of melting of a source, homogenous in its mineralogy and bulk chemistry, cannot explain all the differences in major element composition of Kauai lavas. First, since Al₂O₃ contents increase with decreasing pressure of melting and Ca/Al ratios increase with the degree of melting [*Herzberg and Zhang, 1996; Walter, 1998*], east Kauai lavas should also have higher Al₂O₃ contents and Ca/Al ratios than west

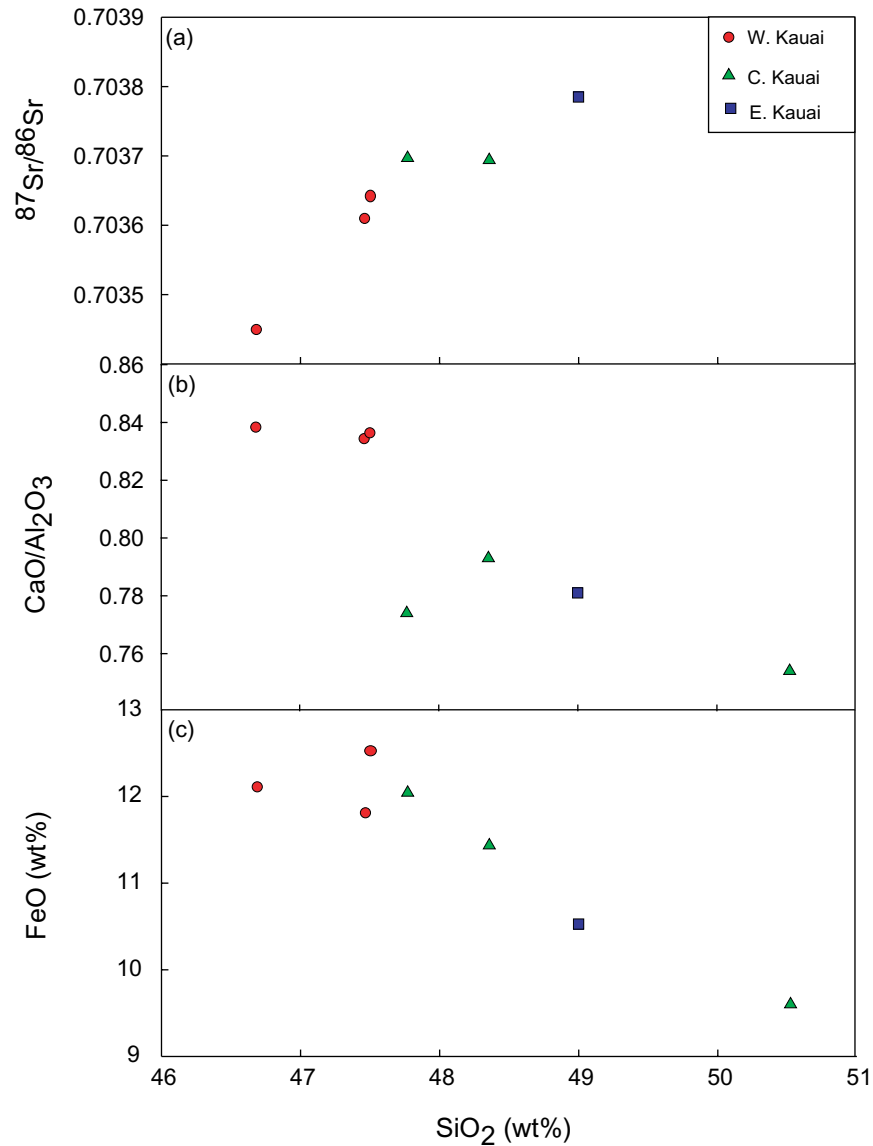


Figure 15. Fractionation corrected SiO₂ versus (a) Sr isotopic ratios, (b) CaO/Al₂O₃, and (c) FeO. Note that the SiO₂ versus CaO/Al₂O₃ trend is opposite to that expected from differences in extent of melting. In addition, the correlation between isotopes and major elements indicates that differences in major element chemistry are (at least) partly due variations in mineralogy and/or bulk chemistry.

Kauai lavas. While lavas from east Kauai have higher Al₂O₃ contents they have lower Ca/Al ratios compared to west Kauai lavas (Figures 15 and 16). Fractionation of clinopyroxene is not a feasible explanation for the lower Ca/Al ratios in east Kauai lavas, since this would lead to a higher FeO content [Klein and Langmuir, 1987]. In addition, because Sc is compatible in clinopyroxene, the correlation between Sc and MgO (Figure 3) also argues against clinopyroxene fractionation. Second, in

Hawaiian lavas Zr/Nb ratios increase with increasing degree of melting [Frey *et al.*, 1994; Yang *et al.*, 1996] and, as a result, the inverse correlation between Ca/Al and Zr/Nb (Figure 16) is not likely to reflect a melting trend.

[38] The correlations between isotope ratios and major elements (Figures 15 and 16) in Kauai lavas indicate that the different mantle components in the Hawaiian plume may be associated with distinctive

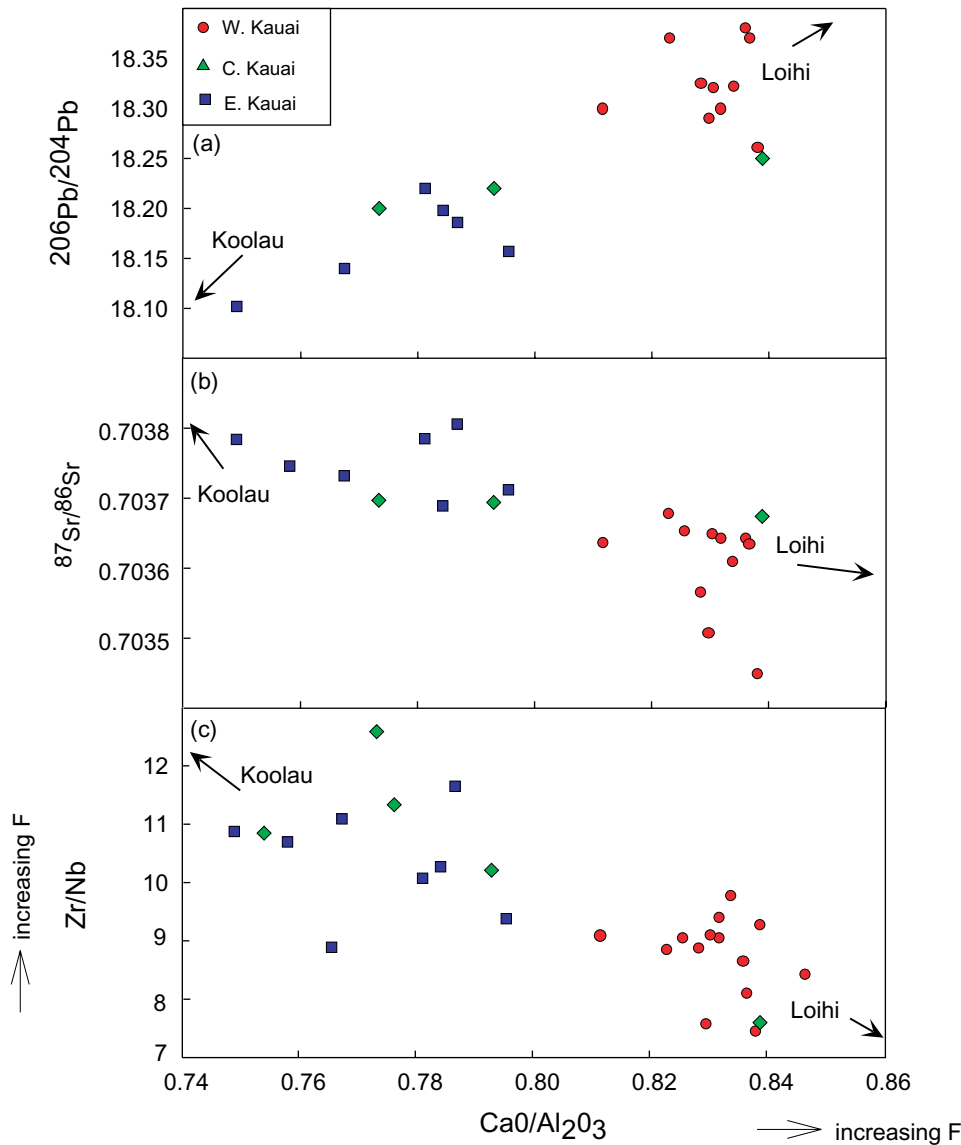


Figure 16. Correlation between $\text{CaO}/\text{Al}_2\text{O}_3$ and (a) $^{206}\text{Pb}/^{204}\text{Pb}$, (b) $^{87}\text{Sr}/^{86}\text{Sr}$, and (c) Zr/Nb . All samples with combined major elements, trace elements, and isotopic data are plotted (Tables 1 and 2). The correlations indicate that the lower Ca/Al ratios in east Kauai lavas are not an artifact of post-eruptive alteration processes. Note that the correlation between Zr/Nb and $\text{CaO}/\text{Al}_2\text{O}_3$ cannot be explained by variable degrees of melting of a homogeneous source.

bulk chemistry and mineralogy [see also *Hauri and Kurz, 1997*]. Both the MELTS algorithm [*Ghiorso and Sack, 1995*] and experiments on depleted peridotites show that, for a given degree of melting, depleted peridotites generate melts with higher Ca/Al , lower SiO_2 , and higher FeO contents [*Hirschmann et al., 1999; Wasylenki, 1999*] than fertile peridotites. Thus, mixing between melts generated from fertile and depleted peridotites may explain the major element variability in Kauai

lavas. This would imply that the source of west Kauai lavas sampled a higher proportion of the depleted peridotite component, consistent with the more depleted isotopic signature in west Kauai lavas (Figure 8).

[39] Variability in major element chemistry of Kauai lavas may alternatively be explained by melting of a peridotite mixed with varying proportions of eclogite or pyroxenite component. The presence of a

recycled eclogite or pyroxenite component in the Hawaiian plume has been suggested to explain the major element chemistry and enriched isotopic signatures of some Hawaiian lavas, particularly those from Koolau [Hauri, 1996; Lassiter and Hauri, 1998]. Partial melting of pyroxenite with MORB-like bulk composition at 3 GPa produces basaltic andesites rich in SiO₂ and low in FeO and CaO/Al₂O₃ ratios [Pertermann and Hirschmann, 1999]. Furthermore, the major element composition of melts derived from pyroxenites or eclogites will be associated with the enriched isotopic signatures of recycled material [Hauri, 1996]. Thus, the higher SiO₂ content, the lower Ca/Al ratio, and the enriched isotopic signature in east Kauai lavas compared to lavas from west Kauai is consistent with a larger contribution from a pyroxenite/eclogite component. Rare Earth element data can more rigorously test the two hypotheses we have suggested to explain the difference in major element chemistry between east and west Kauai lavas and the correlation between Ca/Al and radiogenic isotope ratios. For example, for similar degrees of melting, melts derived from pyroxenites would have larger Lu-Hf and smaller Sm-Nd fractionation compared to peridotite melts [e.g., Stracke et al., 1999]. Irrespective of whether the difference in major element composition between east and west Kauai lavas reflects source depletion or presence of pyroxenite, the Kauai data strongly support Hauri's [1996] suggestion of major element heterogeneity in the Hawaiian plume.

4.3. Spatial and Temporal Isotopic Variability of Kauai Lavas

[40] The high ³He/⁴He ratios in Kauai lavas can be attributed to the presence of the Loihi component in the source of Kauai shield lavas (Figures 8 and 14). The isotope ratios of Sr, Nd, Pb, and Os indicate that west Kauai lavas have a larger proportion of the Loihi component, while east Kauai lavas are more "Mauna Loa-like," reflecting a larger contribution from the Koolau component (Figures 7–10). Such a conclusion is quantitatively supported by our principal component analysis (Figure 14). The systematic variation in isotopic composition between west, central, and east Kauai may represent a change in the mantle sources from more Loihi-like to more

Koolau-like as the locus of volcanism moved from west to east. A transition from Loihi-like to Koolau-like composition with time has been observed at Mauna Loa and has been interpreted to reflect the translation of the volcano over a radially zoned Hawaiian plume [Kurz et al., 1995; Hauri and Kurz, 1997]. However, the possibility that the geochemical variations at Mauna Loa (and possibly at Kauai) are due to heterogeneities in the vertical dimension of the plume cannot be ruled out.

[41] Alternatively, east and west Kauai may be two different shield volcanoes [Holcomb et al., 1997]. The systematic differences in west and east Kauai lavas then imply that magma sources and plumbing systems of the two shields were distinct. Previous studies [Frey and Rhodes, 1993; Frey et al., 1994; Lassiter et al., 1996; Hauri and Kurz, 1997] have attributed the lateral variations in isotopic composition of Hawaiian lavas to the length scales of geochemical heterogeneities in the Hawaiian plume. If so, the source region of Kauai lavas must have been heterogeneous on length scales of ~20–25 km, and east and west Kauai must have maintained distinct magmatic plumbing systems. These length scales are consistent with previous suggestions from other Hawaiian shield volcanoes [e.g., Frey and Rhodes, 1993].

[42] On the Kauai shield, geochemical variations are erratic and occur on timescales of 10² years (Figure 6). The erratic geochemical variations in Kauai shield lavas likely arise from rapid changes in the composition of the parental magma supplying the magma reservoir, which must reflect the heterogeneous distribution of the mantle components in the source. At Samoa high ³He/⁴He ratios (up to 24 R_A) are also associated with large and rapid temporal variations [Farley et al., 1992]. Recently, Kurz and Curtice [2000] documented variations from 24 to 11 R_A in 10³ years at Mauna Kea. The range of ³He/⁴He ratios at Loihi is also quite large (>14 R_A) [Kurz et al., 1982, 1983] although the timescale of the variations is not clear. Thus, it appears that high ³He/⁴He ratios are associated with rapid temporal variations. A possible explanation of this observation is that the high ³He/⁴He component is not the volumetrically major constituent of mantle plumes and Loihi-like ³He/⁴He ratios can be

observed only when the mantle components in the plume are not thoroughly homogenized.

4.4. Implications for the Hawaiian Plume

[43] Models for the Hawaiian plume are often based on the notion that the highest $^3\text{He}/^4\text{He}$ ratios occur in the oldest (Loihi-stage) tholeiites [e.g., Kurz *et al.*, 1995, 1996; Valbracht *et al.*, 1996]. To explain this observation, Valbracht *et al.* [1996] proposed a model that invokes early separation of a CO_2 dominated melt phase from the plume at depths of about 100 km. The noble gases, but not the lithophile tracers, partition into this gas-rich melt. The melt phase migrates ahead of the buoyantly upwelling plume and metasomatizes the lithosphere. Conductive heating by the ascending plume then induces melting of the metasomatized lithosphere forming the preshield Loihi stage, characterized by high $^3\text{He}/^4\text{He}$ ratios ($30 R_A$) and depleted Sr and Nd isotopic composition. Subsequent melting of the helium-depleted plume and mixing with asthenospheric material then yields the shield-stage tholeiites dominated by lower $^3\text{He}/^4\text{He}$ ($<20 R_A$) and more enriched Sr, Nd, and Pb isotopic composition manifested in lavas from Mauna Loa and Koolau. However, our new $^3\text{He}/^4\text{He}$ data from the shield building stage of Kauai strongly argues against this hypothesis. $^3\text{He}/^4\text{He}$ ratios of 17–28 R_A observed in Kauai tholeiites demonstrate that high $^3\text{He}/^4\text{He}$ ratios are not restricted to the preshield (Loihi) stage of Hawaiian volcanism and can be sampled during the shield building stage. In addition, the model by Valbracht *et al.* [1996] suggests decoupling of helium from other lithophile tracers but is not supported by our work and He, Sr, Nd and Pb isotopic ratios from other Hawaiian volcanoes [e.g., Kurz *et al.*, 1995; Eiler *et al.*, 1996].

[44] Passage of the Pacific lithosphere over a radially zoned Hawaiian plume has been used to explain temporal geochemical variability of Hawaiian shield volcanoes [Kurz *et al.*, 1995; Hauri *et al.*, 1996; Lassiter *et al.*, 1996]. Kurz *et al.* [1995] suggested that primitive undegassed mantle (Loihi component) is the plume source material, which entrains passively upwelling mantle material. He, Sr, Nd, and Pb are incompatible elements and Kurz

et al. [1995] have suggested that due to melting of the buoyantly upwelling plume these elements become increasingly depleted in the plume material at shallower depths. The geochemical difference between lavas at Loihi, Kilauea, and recent Mauna Loa results from tapping of the plume at progressively shallower depths and by dilution of the plume signal by melts from entrained mantle and asthenosphere. This model [Kurz *et al.*, 1995] suggests a steady decrease in the isotopic signatures of the Loihi component during the evolution of a single volcano. For example, $^3\text{He}/^4\text{He}$ ratios would be highest in the preshield stage (Loihi; 20–30 R_A), intermediate in the shield-stage (Kilauea; 10–20 R_A), and decreasing to MORB values of 8 R_A at the end of the shield building stage (recent Mauna Loa lavas). Because only the last 10–15% of a volcano's history is exposed subaerially [Stolper *et al.*, 1996] the model by Kurz *et al.* [1995] would not predict Loihi-like $^3\text{He}/^4\text{He}$ ratios to be present in subaerial Kauai shield lavas.

[45] Hauri *et al.* [1996] and Lassiter *et al.* [1996] suggested an alternative distribution of the components in the Hawaiian plume. They proposed that the Koolau component comprises the core of the plume and is surrounded by entrained lower mantle material (Loihi component). However, models that suggest that the mantle components are distributed radially predict smooth and systematic changes in the isotopic composition of the lavas with time. The rapid excursions in isotopic composition of Kauai lavas (Figure 6) indicate that the different mantle components were not sampled systematically during the evolution of the Kauai shield and thus cannot be explained by any simple radially zoned plume model [Kurz *et al.*, 1995; Hauri *et al.*, 1996; Lassiter *et al.*, 1996]. In summary, although entrainment of ambient mantle by rising plumes might produce heterogeneities in the plume, a radially zoned plume that has remained in steady state, cannot explain the temporal evolution of all Hawaiian volcanoes.

[46] In a more recent model of the Hawaiian plume, DePaolo *et al.* [2001] inverted the spatial isotopic distribution of He and Nd in lavas from the island of Hawaii to infer the structure of the plume.

Based on their model, *DePaolo et al.* [2001] suggest that high $^3\text{He}/^4\text{He}$ ratios are restricted to the core of the plume (20–25 km radius) and that the plume He signal is lost during the early stages of melting. Therefore, as with previous models by *Kurz et al.* [1995, 1996] and *Valbracht et al.* [1996], *DePaolo et al.*'s model does not offer a potential explanation for why $^3\text{He}/^4\text{He}$ ratios as high as 27 R_A are present at Kauai, <136 kyr from the end of the shield stage (Figure 6).

[47] The isotopic compositions of Kauai lavas combined with our principal component analysis suggest that the proportion of the Loihi component in the Hawaiian plume has changed significantly over the past 5 Myr (Figure 14). While progressive depletion of incompatible elements in the plume probably occurs during the evolution of a single volcano [*Kurz et al.*, 1995; *DePaolo et al.*, 2001], geochemical variations in the vertical dimension of the Hawaiian plume is an important factor in determining the average composition of each shield and the intershield isotopic differences. Such variations could result from heterogeneities in the deep mantle from where the Hawaiian plume originates [*DePaolo et al.*, 2001; *Fouch et al.*, 2001] or through time-varying entrainment of ambient mantle by the upwelling plume. Seismic velocity anomalies and anisotropies reflect thermal, and possibly chemical, heterogeneities in deep mantle layers. [*Sidorin et al.*, 1999; *Fouch et al.*, 2001]. Since the rate of entrainment of material by an upwelling plume is proportional to the temperature difference between the plume head and ambient mantle and inversely proportional to the viscosity of the plume material [*Griffiths and Campbell*, 1990], a consequence of the thermal heterogeneities in the plume would be *variable* entrainment of ambient mantle by the upwelling plume. Thus, the proportion and vertical distribution of the components in the Hawaiian plume would be expected to change with time.

5. Conclusion

[48] We measured He, Sr, Nd, Pb, Os, and major and trace elements in stratigraphically controlled lavas from Kauai. Based on our data we conclude:

1. High $^3\text{He}/^4\text{He}$ ratios (>20 R_A) are present during the shield building stage of Hawaiian volcanism. This observation strongly argues against helium depletion in the plume by early melts that are sampled during the preshield stage of Hawaiian volcanism [e.g., *Valbracht et al.*, 1996].

2. Mixing between the Koolau, Kea, and Loihi components [e.g., *Eiler et al.*, 1996; *Hauri*, 1996] does not explain isotopic variability in Kauai shield lavas. Addition of a fourth component with the isotopic characteristic of Hawaiian posterosional basalts can explain the isotopic composition of Kauai shield lavas.

Appendix A. Compiled Sr, Nd, Pb, and He Data for Hawaiian Shield Lavas

Island	$^{87}\text{Sr}/^{86}\text{Sr}$	ϵNd	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^3\text{He}/^4\text{He}$		
Loihi	0.70353	6.01	18.22	15.48	38.09	30.1		
	0.70352	6.16	18.35	15.47	38.14	26.7		
	0.70354	6.81	18.43	15.49	38.16	23.1		
	0.70358	6.42	18.27	15.47	38.02	27.5		
	0.70368	5.99	18.45	15.48	38.19	32.1		
	0.70365	6.11	18.42	15.48	38.12	22.6		
	0.70353	8.10	18.38	15.49	38.11	22.7		
	0.70341	6.79	18.37	15.50	38.16	24.1		
	0.70335	8.08	18.26	15.48	38.05	20.9		
	0.70351	8.04	18.45	15.49	38.18	24.1		
	0.70355	5.25	18.37	15.46	38.14	24.1		
	0.70359	6.16	18.39	15.46	38.12	20.3		
	Koolau	0.70439	-0.55	17.86	15.44	37.93	14.2	
		Mauna Kea	0.70351	7.5	18.42	15.48	38.00	7.6
			0.70352	7.35	18.50	15.49	38.08	6
0.70351			7.5	18.47	15.48	38.03	8.7	
0.70356			7.45	18.43	15.48	38.02	8.2	
0.70354			7.47	18.49	15.49	38.06	7.2	
0.70359			7.21	18.55	15.50	38.14	7.7	
0.70356			7.29	18.50	15.47	38.04	8.5	
0.70352			7.19	18.61	15.50	38.20	10.1	
0.70360			6.66	18.56	15.48	38.15	12.4	
0.70362	7.4		18.53	15.47	38.05	8.8		
Mauna Loa	0.70350	7.2	18.61	15.49	38.17	11.3		
	0.70354	7	18.57	15.48	38.12	10.7		
	0.70384	4.49	18.07	15.43	37.82	13.1		
	0.70378	4.39	18.09	15.45	37.84	11.0		
	0.70369	3.76	18.17	15.46	37.93	18.0		
	0.70369	5.40	18.17	15.45	37.91	14.8		
	0.70374	5.50	18.19	15.45	37.95	20.0		
	0.70372	5.60	18.20	15.43	37.92	15.7		
	0.70368	5.85	18.13	15.43	37.84	16.0		
	0.70369	5.44	18.20	15.45	37.96	15.4		
	0.70376	4.90	18.18	15.43	37.93	18.5		
	0.70369	5.74	18.18	15.46	37.96	17.2		
	0.70368	5.33	18.25	15.45	37.97	18.9		
0.70366	5.36	18.24	15.43	37.94	20.0			
0.70365	5.66	18.33	15.52	38.16	19.1			
0.70368	5.40	18.25	15.46	38.02	16.6			

Appendix A. (continued)

Island	$^{87}\text{Sr}/^{86}\text{Sr}$	ϵNd	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^3\text{He}/^4\text{He}$
	0.70369	5.31	18.15	15.43	37.89	18.7
	0.70368	5.33	18.19	15.43	37.89	19.9
	0.70362	5.44	18.23	15.46	38.00	13.3
	0.70365	5.83	18.29	15.47	38.03	15.9
	0.70361	5.66	18.28	15.45	37.98	17.2
	0.70368	5.34	18.19	15.46	37.98	18.3
	0.70374	4.70	18.31	15.51	38.21	16.9
	0.70365	4.72	18.18	15.47	37.99	16.4
Kauai	0.70365	6.53	18.32	15.45	38.00	27.3
	0.70351	7.37	18.29	15.44	37.88	19.7
	0.70345	7.39	18.26	15.45	37.85	17.9
	0.70368	7.65	18.37	15.46	38.02	24.9
	0.70364	6.77	18.30	15.45	37.96	22.3
	0.70364	6.85	18.38	15.45	38.01	24.0
	0.70363	6.98	18.37	15.44	37.96	26.8
	0.70367	6.67	18.25	15.44	37.90	25.7
	0.70370	5.83	18.20	15.44	37.89	22.9
	0.70369	6.46	18.22	15.44	37.92	21.4
	0.70371	6.30	18.16	15.44	37.87	19.9
	0.70379	6.22	18.22	15.45	37.91	21.4
	0.70373	6.20	18.14	15.43	37.84	26.8

Only samples that have combined He, Sr, Nd, and Pb isotopic data were selected.

References: *Abouchami et al.*, 2000; *Hauri et al.*, 1996; *Lassiter et al.*, 1996; *Lassiter and Hauri*, 1998; *Kurz et al.*, 1983, 1995, 1996; *Roden et al.*, 1994; *Staudigel et al.*, 1984. Kauai data is from this work.

3. Correlated shifts in isotopic ratios and Ca/Al ratios in Kauai tholeiites support the hypothesis that the sources of Hawaiian lavas are heterogeneous in their major element chemistry [*Hauri*, 1996; *Hauri and Kurz*, 1997].

4. Systematic differences in geochemistry of east and west Kauai lavas may reflect a progressive sampling from the Loihi component to the Koolau component, which has previously been attributed to the spatial distribution of the mantle components in the Hawaiian plume [*Hauri and Kurz*, 1997]. Alternately, east and west Kauai are two distinct shield volcanoes [*Holcomb et al.*, 1997] that maintained different magma sources and plumbing systems.

5. The distribution, particularly of the high $^3\text{He}/^4\text{He}$ component, has changed significantly over the evolution of the Hawaiian plume. Coupled with the rapid variation in geochemical variations seen in west Kauai, our data require complex geochemical heterogeneities that are not accounted for in the radially zoned plume models.

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