Shield stage alkalic volcanism on Mauna Loa Volcano, Hawaii

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Abstract

Alkalic lavas have been discovered at two young (~15–20 ka) submarine radial vents on the western flank of Mauna Loa, a volcano that was thought to have produced only tholeiitic lavas for at least the last ~240,000 years. Major and trace element data show that the lavas from only one of these eruptions have undergone lower degrees of partial melting, the assumed dominant process for creating alkalic lavas on Hawaiian volcanoes. However, major and trace element analyses also suggest that lavas from both of the alkalic eruptions are evolved and have experienced moderate-pressure (~1.0 GPa) fractionation of pyroxene, an alternative mechanism for producing an alkalic magma from a tholeiitic parent. Pyroxene fractionation is also indicated by MELTS modeling and phase diagram projections. Although lavas with similar compositions have been erupted from neighboring Mauna Kea and Hualālai volcanoes, Pb isotope and trace element data indicate that the submarine alkalic lavas were produced from the same source generating Mauna Loa tholeiites. Thus, these are the first alkalic lavas to be identified from this volcano. Holocene eruptions of Mauna Loa have all produced tholeiitic lavas and eruption rates have remained relatively high. Thus, the volcano has probably not yet entered the postshield stage of Hawaiian volcanism, which is characterized by alkaline lavas and less frequent eruptions. The occurrence of the alkalic lavas only at radial vents may indicate that these magmas bypassed the primary conduit, which supplies the summit reservoir with predominantly tholeiitic magma.
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1. Introduction

Mauna Loa, the largest volcano on earth (~74,000 km³, Robinson and Eakins, this issue), has been producing tholeiitic lavas for hundreds of thousands of years during its shield building stage of volcanism. Thus, the discovery of two young alkalic cones and associated lava flows on the volcano's western flanks was completely unexpected (Fig. 1). These alkalic cones, Akihimoana and Mo'ikeha, were discovered along with four tholeiitic radial vents, in the fall of 2002 (Wanless et al., in press). Both of these alkalic vents are relatively young (<20 ka), based on the thickness of microscopic Mn-coatings and sparse sediment cover (Wanless et al., in press). Attempts to obtain the ages of all ten of these flows using the K–Ar unspiked method, which has been successful for some young submarine Hawaiian lavas (Guillou et al.,
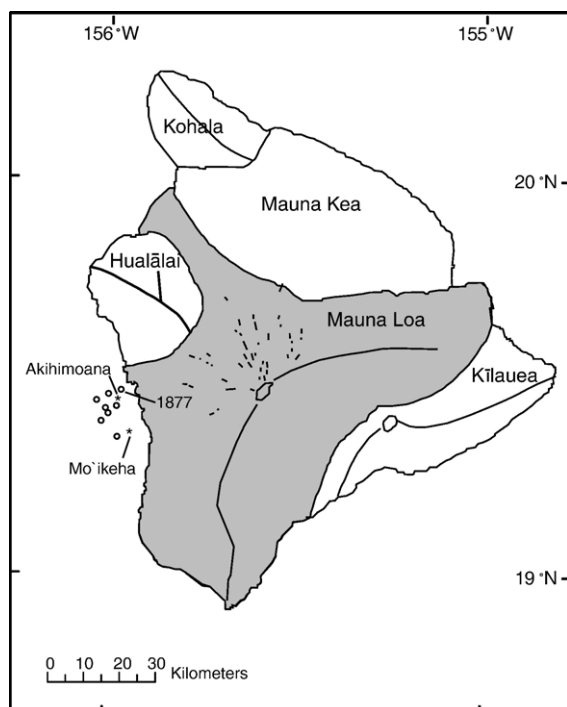
Fig. 1. Map of the island of Hawai'i showing its five shield volcanoes, the locations of their rift zones (thick lines) and summit calderas (Peterson and Moore, 1987). The locations of Mauna Loa's 44 subaerial radial vents are drawn as short dashes on its northern and western flanks. Submarine tholeiitic radial vents on the western flank of Mauna Loa, including the location of the 1877 eruption are shown as open circles. The two vents on the submarine flanks of Mauna Loa that produced alkalic lavas are noted by asterisks.

1997), have been unsuccessful (H. Guillou, 2004, pers. comm.).

Hawaiian volcanoes typically experience four phases of volcanism during their lifecycle: the preshield, shield, postshield, and the rejuvenation stages (Clague and Darymple, 1987), although evidence for the pre-shield stage is limited to the youngest Hawaiian volcanoes (e.g., Moore et al., 1982; Coombs et al., this issue). The appearance of alkalic lavas on older Hawaiian shield volcanoes is thought to signal the end of the shield building stage of volcanism and the beginning of the postshield stage, when eruptions are less frequent and mostly alkalic in composition (Macdonald et al., 1983). The switch from tholeiitic to alkalic lavas in Hawai'i is interpreted to reflect a gradual decrease in the amount of partial melting as the volcano drifts away from the center of the plume (e.g., Frey et al., 1990).

On some other oceanic islands, tholeiitic and alkalic volcanism are coeval. Examples include the Galápagos (Naumann and Geist, 1999; Geist et al., 1998), Kerguelen (Damasceno et al., 2002) and Reunion islands (Albarède et al., 1997). The occurrence of alkalic

lavas on these islands is explained by moderate (0.5 to 1.5 GPa) to high pressure (>1.5 GPa) fractionation of pyroxene. This mechanism was also advocated by Murata (1960) and Macdonald (1968) for the origin of some Hawaiian alkalic lavas. Here, major, trace element, and isotopic data are used to evaluate the volcanic source for the alkalic radial vent lavas on the submarine western flank of Mauna Loa, and to examine their petrogenesis. We show that the alkalic lavas have geochemical signatures characteristic of Mauna Loa, and present evidence that lower degrees of partial melting occurred only in the formation of the Mo'ikeha lavas, while moderate pressure pyroxene fractionation played a role in the petrogenesis of both alkalic suites.

2. Regional geology

Mauna Loa is one of five subaerial volcanoes that make up the island of Hawai'i. It has erupted 39 times since 1832 (the earliest written account of Mauna Loa's eruptive history; Barnard, 1995), producing only tholeiitic lavas (Rhodes, 1995). Like most Hawaiian shield volcanoes, Mauna Loa has two primary rift zones (Fig. 1). Additionally, 44 vents (Trusdell, 2004 pers. comm.) are radially distributed on the western and northern subaerial flanks of the volcano, including three post-1832 eruptions (1852, 1859 and 1877; Fornari et al., 1980; Macdonald et al., 1983). A radial vent eruption is any eruption that is oriented radially to the summit caldera and is located outside the summit and rift zone regions. The 1877 eruption was the only known submarine radial vent prior to a 1999 dredging cruise on the western flank of Mauna Loa, when three of the ten cones in the area were discovered and sampled (Davis et al., 2003). Six cones were discovered during our 2002 survey.

The ten submarine radial vents are almost equidistant from the summit of both Mauna Loa and Hualālai volcanoes (Fig. 1). Hualālai volcano is in its postshield stage of volcanism and the entire subaerial portion of the volcano has been covered with alkalic lavas (Moore and Clague, 1991) with ages between 203 years (1801 A.D.) and 105 ka (Moore et al., 1987; Cousens et al., 2003). The newly discovered submarine alkalic vents lie 17–20 km west of Hualālai's southeast rift zone (Fig. 1). Thus, one of the goals of this study is to determine which shield volcano was their source.

3. Location and sample collection

A detailed multibeam survey of the region was conducted off the west coast of the island of Hawai'i in the fall of 2002 (Wanless et al., in press). This survey,

which covers over 300 km^2, revealed a total of ten submarine radial vents on the flanks of the volcano, two of which are alkalic in composition. Twenty-six samples were collected from the two alkalic radial vents using the ROV Jason2. Akihimoana vent, with a summit at ~1080 mbsl, stands ~160 m above the surrounding seafloor, covering a surface area of 3.8 km^2, with a volume of 400×10^6 m^3 ($\pm 10\%$) of lava. Mo'ikeha vent, with a shallower summit (~780 mbsl) and a taller cone (~280m), has a smaller total surface area (~1.6 km^2), and smaller volume (~163×10^6 m$^3 \pm 10\%$), although it produced a ~60 m thick lava flow.

4. Petrography and geochemistry results

4.1. Outcrops and samples

The submarine radial vent lavas are composed primarily of striated bulbous and elongate pillow lavas. They range in color from black to reddish brown and have glassy rims of variable thickness. Six samples were collected from Akihimoana and 19 from Mo'ikeha using the Jason2 ROV.

4.2. Petrography

The submarine alkalic lavas are petrographically simple, with sparse olivine and plagioclase phenocrysts. The Akihimoana vent lavas contain 1.2 vol.% olivine phenocrysts (>0.5 mm) and 0.9 vol.% plagioclase phenocrysts, based on 500 points per sample (six samples examined; Table 1). Lavas from Mo'ikeha (19 samples examined) have somewhat lower amounts of olivine (0.4 vol.%) but similar plagioclase abundances as Akihimoana lavas (Table 1). Most plagioclase and olivine phenocrysts are euhedral to subhedral. No pyroxene phenocrysts or microphenocrysts were observed in lavas from either vent. Vesicularity is low (<0.1–4.0 vol.%) in these predominantly glassy lavas (65–87 vol.%; Table 1). Microscopic manganese–iron (Mn–Fe) coatings are visible on lavas collected from both alkalic vents, with a maximum Mo'ikeha thickness of 0.049 ± 0.001 mm and a maximum Akihimoana thickness of 0.039 ± 0.001 mm.

4.3. Glass analysis

Fifteen glasses were analyzed for major elements and sulfur (Table 1) using the University of Hawai'i Cameca SX-50 electron microprobe following methods described in Garcia et al. (1995b). The Mo'ikeha glasses have lower SiO$_2$ and higher alkalis than the Akihimoana glasses (Fig. 2; Table 1) but both groups of glasses are alkalic (Fig. 2). The Mo'ikeha glasses are hawaiites with high total alkalies (~5.5 wt.%; Fig. 2). Compared to other Mauna Loa lavas, the alkalic glasses are evolved with low MgO (<4.9 wt.%) and CaO/Al$_2$O$_3$ ratios (<0.65) but high total iron as FeO (14.8–15.5 wt.%) and TiO$_2$ (4.0–5.4 wt.%). Mo'ikeha vent glasses also have low sulfur values (<0.04 wt.%; Fig. 3), similar to subaerially erupted Hawaiian basalts (e.g., Swanson and Fabbi, 1973; Davis et al., 2003). Akihimoana glasses and those from the nearby (tholeiitic) 1877 eruption (Moore et al., 1985) have higher sulfur contents (>0.09 wt.%; Fig. 3), which are typical for lavas erupted at >1000 m water depths (Moore and Fabbi, 1971). Naturally quenched glass inclusions in olivine and plagioclase phenocrysts were analyzed to determine if the Mo'ikeha magmas degassed prior to or during eruption. The phenocrysts contain melt inclusions with higher sulfur values (0.05 to 0.20 wt.%). This suggests that degassing of the Mo'ikeha lavas occurred after crystallization of the phenocrysts phases but prior to the eruption. All of the Akihimoana glass inclusions were undegassed.

4.4. XRF

Major and trace element analyses were made on 26 whole rock samples (Table 1) at the University of Massachusetts using methods described by Rhodes and Vollinger (2004). These analyses confirm the alkalic nature of the lavas from the two cones. The lavas have higher total alkalis (Na$_2$O+K$_2$O=3.6–4.8 wt.%) at a given SiO$_2$ than previously observed for Mauna Loa lavas (Fig. 2), well above the alkalic/tholeiitic line of Macdonald and Katsura (1964). The Mo'ikeha lavas have higher total alkalies (4.3 to 4.8 wt.%) than the Akihimoana lavas (total alkalies=3.6 to 3.8 wt.%). Both of the alkalic lavas are distinct from Mauna Loa tholeiites in their lower CaO/Al$_2$O$_3$ (Fig. 4) and higher TiO$_2$ (Table 1) with Mo'ikeha lavas having lower CaO/Al$_2$O$_3$ (0.54 to 0.57) and higher TiO$_2$ (3.43 to 3.56 wt.%) than the Akihimoana lavas (CaO/Al$_2$O$_3$=0.61–0.66; TiO$_2$=2.84–3.12 wt.%).

Incompatible element abundances are higher in the alkalic versus the tholeiitic submarine radial vent samples despite their similar MgO contents (Table 1). Zr, Sr, Nb, Rb, and Ce abundances are significantly higher, whereas Zn, Y, Ba, La, and K are slightly higher in the alkalic lavas compared to other Mauna Loa tholeiite lavas (Fig. 5). The more alkalic Mo'ikeha lavas have higher Rb, Ba, Nb, La, Ce, Sr, and Zr than the Akihimoana lavas. In comparison, Hualālai and Mauna Kea

Table 1
Petrography, microprobe, and XRF analyses of representative alkalic radial vents

Vent	Mo'ikeha					Akihimoana		
Sample	J2-15-13	J2-17-05	J2-17-10	J2-17-14	J2-13-10	J2-14-04	J2-14-07	J2-14-08
Petrography (modal percent)								
Oliv ph	0.2	0.0	0.4	0.4	2.4	0.8	1.4	1.6
Oliv mph	3.0	4.0	4.0	5.4	1.8	5.8	3.4	5.0
Plag ph	1.0	0.2	0.8	1.6	4.4	1.4	1.2	0.2
Plag mph	15.4	8.2	10.2	12.6	4.8	14.4	11.6	20.2
Opaques	0.2	<0.1	0.4	<0.1	<0.1	<0.1	<0.1	<0.1
Ves	0.2	<0.1	<0.1	<0.1	<0.1	3.2	4.0	2.0
Matrix	80.0	87.4	84.2	79.8	85.0	73.0	77.8	69.6
Glass (wt.%)								
SiO_2	45.97	46.11	45.93	45.79	–	47.69	47.38	47.42
TiO_2	4.94	4.89	4.90	5.42	–	4.01	4.14	4.27
Al_2O_3	13.96	14.24	14.07	13.37	–	13.47	13.23	13.08
FeO	15.15	14.83	14.87	15.46	–	15.01	15.18	15.30
MnO	0.17	0.17	0.19	0.20	–	0.21	0.21	0.20
MgO	4.59	4.68	4.74	4.33	–	4.95	4.87	4.80
CaO	9.15	9.12	8.91	9.00	–	9.72	9.75	9.80
Na_2O	4.14	4.24	4.19	4.19	–	3.35	3.27	3.19
K_2O	1.24	1.16	1.18	1.44	–	0.77	0.81	0.79
P_2O_5	0.64	0.59	0.59	0.64	–	0.49	0.49	0.49
S	0.03	0.02	0.02	0.02	–	0.13	0.14	0.10
Total	99.98	100.05	99.59	99.87	–	99.79	99.47	99.44
XRF majors (wt.%)								
SiO_2	46.70	46.54	46.56	46.91	48.32	47.50	47.28	47.08
TiO_2	3.512	3.432	3.507	3.495	3.12	2.898	2.878	2.844
Al_2O_3	15.74	15.66	15.61	15.73	14.82	15.51	15.45	15.42
Fe_2O_3	14.07	13.89	14.19	13.99	13.93	13.81	13.84	13.73
MnO	0.16	0.16	0.17	0.17	0.20	0.18	0.18	0.18
MgO	5.92	6.22	6.01	6.06	5.40	6.54	6.83	6.78
CaO	8.80	8.58	8.85	8.59	9.77	9.62	9.35	9.55
Na_2O	3.68	3.86	3.63	3.71	3.20	2.98	3.14	3.23
K_2O	0.87	0.847	0.87	0.89	0.63	0.63	0.594	0.587
P_2O_5	0.54	0.528	0.57	0.54	0.40	0.38	0.377	0.366
Total	100.00	99.72	99.96	100.08	99.77	100.05	99.92	99.77
XRF traces (ppm)								
Rb	12.3	12.1	12.8	12.5	9.3	8.8	8.4	8.3
Ba	186	182	185	178	137	126	113	119
Nb	20.1	19.5	20.1	19.8	14.5	13.5	13.3	13.2
La	18	17	19	18	13	11	13	11
Ce	50	50	54	49	39	37	35	34
Sr	663	648	659	665	414	459	452	459
Zr	263	259	267	264	208	192	189	189
Y	28.0	27.9	29.7	28.2	35.5	30.9	30.2	30.0
Zn	162	162	163	160	140	134	136	133
V	263	265	273	262	326	293	289	284
Ni	93	103	99	95	61	108	113	108
Cr	71	88	84	72	87	86	89	94

Oliv = olivine; Plag = plagioclase; Ves = vesicles; ph = phenocrysts; mph = microphenocrysts.

alkalic lavas have higher Nb and Ba contents for a given K content compared to the submarine radial vent lavas (Fig. 5). The radial vent alkalic lavas have similar abundances of Ni but lower abundances of Cr than Mauna Loa radial vent tholeiites.

4.5. ICPMS

Five alkalic lavas were analyzed by solution ICPMS at the Australian National University (Table 2) using methods described by Norman et al. (1998).
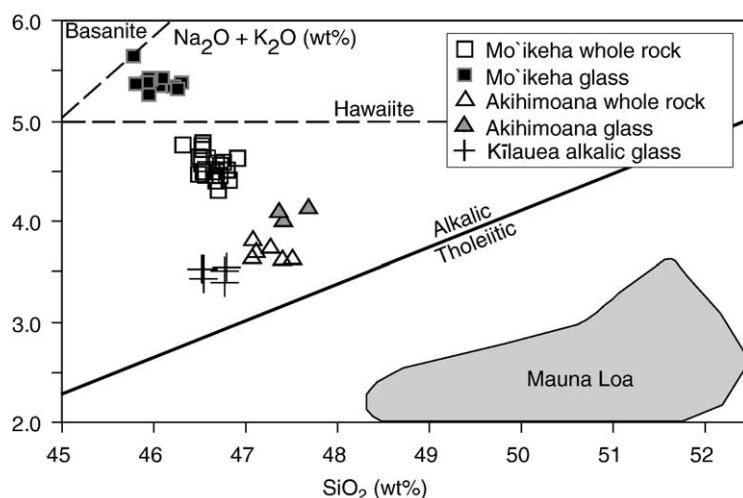
Fig. 2. The total alkalies versus silica classification diagram (LeBas et al., 1986) with alkalic–tholeiitic line (Macdonald and Katsura, 1964) for Mauna Loa tholeiites, lavas and glasses from the two alkalic radial vents, and glasses from Puna Ridge (Kīlauea) alkalic lavas. The radial vent alkalic lavas (>3.5 wt.% total alkalies) are distinct from the other Mauna Loa samples, which fall within the gray Mauna Loa field. Kīlauea glass data from Johnson et al. (2002). Data for Mauna Loa fields from Rhodes and Hart (1995), Rhodes (1995), and Rhodes and Vollinger (2004), and Rhodes (unpub. data).

Compared to Mauna Loa tholeiites, the more alkalic Mo'ikeha lavas have steeper REE patterns with similar abundances of HREE, yielding higher La/Yb ratios (Figs. 6,7). In contrast, the Akihimoana lavas have REE patterns that are generally parallel to that of the tholeiites but with higher abundances of all elements and lower La/Yb ratios compared to the Mo'ikeha lavas (Figs. 6,7). Thus, there is no simple correlation of La/Yb with alkalinity for these lavas compared to Mauna Loa tholeiites, although the more alkaline Mo'ikeha lavas have the highest ratio and the highest alkalinity index (Fig. 7). The lack of an Eu anomaly
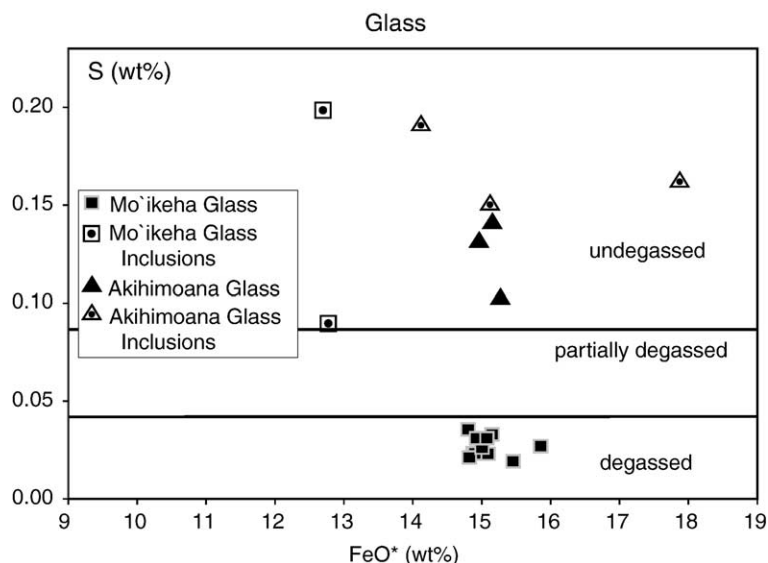

Fig. 3. Total iron (as FeO*) vs. S plot for glasses and melt inclusions from radial vent alkalic lavas. Glasses from Mo'ikeha are distinct with low S (<0.04 wt.%), similar to subaerially erupted Mauna Loa lavas (Davis et al., 2003), despite being collected in water depths sufficient enough to inhibit S degassing (Moore and Fabbi, 1971). In contrast, Akihimoana lavas are undegassed. Both Mo'ikeha and Akihimoana lavas have undegassed (>0.09 wt.%) glass inclusions in plagioclase and olivine phenocrysts, indicating that degassing occurred after phenocryst formation. Solid lines represent boundary between degassed, partially degassed, and undegassed magmas (Moore and Clague, 1987; Davis et al., 2003). Analytical error for sulfur is 2–10% depending on concentration.
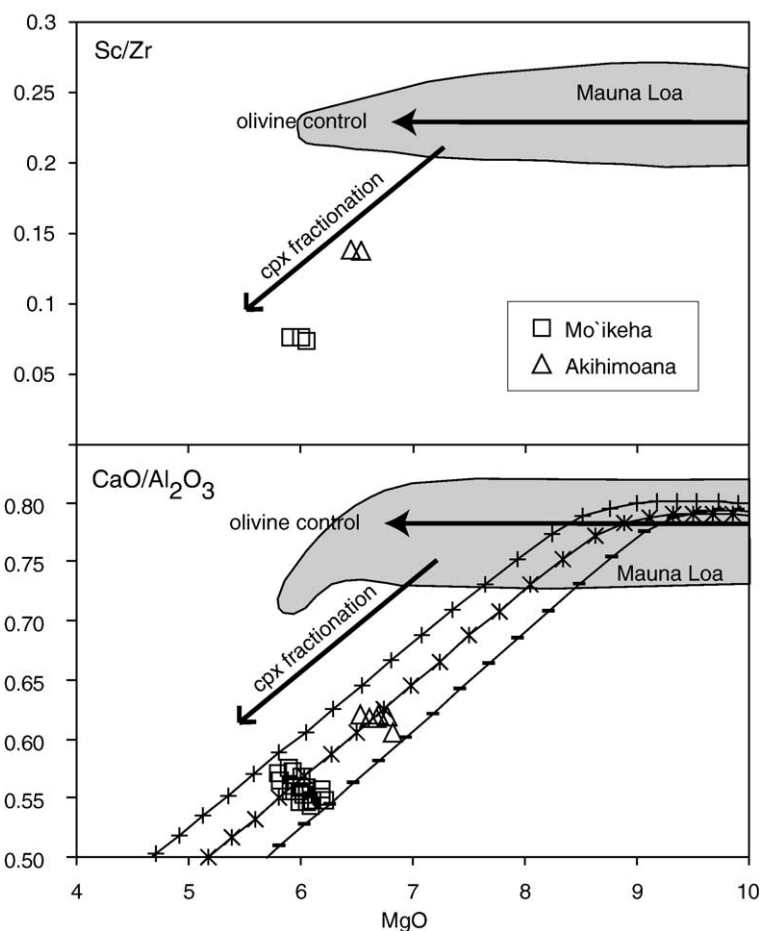
Fig. 4. MgO variation diagrams for Sc/Zr and CaO/Al$_2$O$_3$ in alkalic radial vent lavas. The alkalic radial vents have lower Sc/Zr and CaO/Al$_2$O$_3$ ratios than Mauna Loa tholeiites and lie well below their olivine control trend. The location of the alkalic samples on this plot is consistent with cpx fractionation. The three different fractionation trends shown are based on MELTS modeling (Ghiorso and Sack, 1995) of Mauna Loa compositions (for specific parameters see text). This modeling supports fractionation of clinopyroxene from a tholeiitic parent. Data for Mauna Loa fields from Rhodes and Hart (1995), Rhodes (1995), and Rhodes and Vollinger (2004), and Rhodes (unpub. data).

(Fig. 6) is consistent with the high Sr contents in these lavas (Table 1), indicating that plagioclase fractionation in these lavas was absent or minor. Sc/Zr ratios are significantly lower in both suites of alkalic lavas compared to Mauna Loa tholeiites with similar MgO values (Fig. 4).

4.6. Isotopes

Pb isotope compositions of five alkalic samples (Table 2) were measured at the University of British Columbia following methods described in Weis and Frey (1991) and Weis and Frey (2002) to evaluate the source for these lavas (i.e. Hualālai, Mauna Kea, or Mauna Loa). Pb isotope ratios for lavas from these adjacent volcanoes are distinct (Fig. 8). The ^{206}Pb/^{204}Pb and ^{208}Pb/^{204}Pb ratios of the Mo'ikeha

and Akihimoana alkalic lavas, as well as all the tholeiitic lavas from other radial vents, fall well within the field for Mauna Loa tholeiites (Fig. 8). In contrast, the Pb isotope ratios for alkalic lavas from volcano are distinctly lower (Fig. 8).

5. Discussion

5.1. Source volcano for radial vent alkalic magmas

Mauna Loa was thought to have erupted only tholeiitic lavas for at least the last 240,000 years (Rhodes and Weis, 2003; Rhodes et al., 2003; Garcia et al., 1995b). The appearance of alkalic lavas on other Hawaiian shield volcanoes has marked the onset of postshield activity and, therefore, the slow demise of the volcano over ~250,000 years (Frey et al., 1990). Before
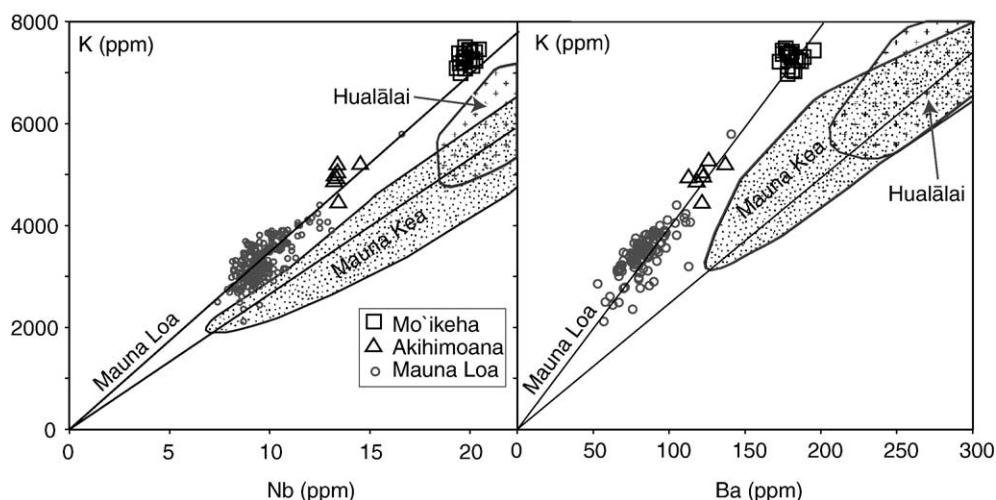
Fig. 5. K vs. Nb and Ba variations in the radial vent alkalic lavas, Mauna Loa tholeiites, and alkalic lavas from Mauna Kea and Hualālai. These highly incompatible elements define a source trend (black line) for Mauna Loa that is distinct from those for Mauna Kea and Hualālai lavas. The alkalic radial vent lavas lie along the extension of the Mauna Loa line, indicating a similar source. Data for Mauna Kea fields from Frey et al. (1991). Hualālai alkalic data from Moore et al. (1987). Fields for Mauna Loa data from Rhodes and Hart (1995), Rhodes (1995), Rhodes and Vollinger (2004) and Rhodes (unpub. data).

discussing the implications of the radial vent alkalic lavas for Mauna Loa's future, we need to demonstrate the parentage of these lavas. Another possible source for the alkalic lava is a neighboring volcano Hualālai, which has been in the alkalic postshield stage of volcanism for at least 100,000 years (Moore et al., 1987). Hualālai is a possible source due to its history of alkalic eruptions (Kauahikaua et al., 2002) and its proximity to the radial vents.

Despite its recent activity (1801; Kauahikaua et al., 2002; Moore et al., 1987), Hualālai has received limited geochemical characterization compared with the many detailed studies of active Kīlauea and Mauna Loa volcanoes. However, comparisons with available geochemical data (Park, 1990; D. Weis, 2004 unpub. data) reveal that Mo'ikeha and Akihimoana alkalic submarine radial vent lavas are geochemically distinct from Hualālai alkalic lavas. For example, the alkalic radial vent lavas have a higher K for a given Ba than Hualālai and Mauna Kea volcanoes, defining different source trends (Fig. 5). However, the radial vent alkalic lavas lie along the same trend as Mauna Loa lavas. Likewise, Pb isotope and Zr/Nb ratios for the radial vent lavas are similar to Mauna Loa tholeiitic lavas but are distinct from Hualālai alkalic lavas (Figs. 2,8). Thus, incompatible element and isotope data indicate that Mauna Loa is the probable source for the radial vent alkalic lavas, making these lavas the first alkalic lavas reported to erupt from this volcano.

5.2. Origin of Mauna Loa radial vent alkalic lavas

Various mechanisms have been invoked to explain coeval tholeiitic and alkalic lavas on many ocean island volcanoes. Early ideas included the formation of tholeiitic magma from alkalic magma by crystal fractionation (Bowen, 1928) and assimilation of siliceous crust (Bailey et al., 1924). Alternatively, alkalic magmas were thought to be produced from tholeiitic magmas by assimilation of carbonates (Daly, 1933). These hypotheses have subsequently been discarded (e.g., McBirney, 1993). Experimental studies in the 1960s explored high pressure origins for tholeiitic and alkalic suites, which included eclogite fractionation (O'Hara, 1968), variable depths of partial melting (O'Hara, 1968; Green and Ringwood, 1967), and variable extents of partial melting (Green and Ringwood, 1967). A higher pressure origin (>0.4 GPa) allows hypersthene-normative tholeiitic magmas to fractionate pyroxene and form nepheline-normative alkalic magmas, whereas at low pressures a thermal divide separates alkalic and tholeiitic magmas (Yoder and Tilley, 1962).

The currently accepted mechanism for the production of both alkalic and tholeiitic magmas at Hawaiian volcanoes is variable degrees of partial melting of a peridotitic source, with tholeiites produced by larger degrees of melting compared to alkalic compositions (e.g., Feigenson et al., 1983). For Hawaiian volcanoes, an increase in the extent of partial melting has been advocated for the transition from alkalic to tholeiitic

Table 2
ICPMS and Pb isotope analyses of selected alkalic radial vent lavas

Vent	Mo'ikeha			Akihimoana	
Sample	J2-15-13	J2-17-10	J2-17-14	J2-13-10	J2-14-04
ICPMS					
Li	8.5	8.3	8.6	6.5	5.6
Sc	19.8	19.9	19.4	29.8	25.7
V	274	274	269	322	289
Cr	76	92	83	95	91
Co	61	67	63	60	59
Ni	118	130	125	73	126
Cu	59	61	60	81	65
Zn	161	161	160	133	127
Ga	27.7	27.4	27.5	23.2	22.6
Rb	13.2	13.6	13.1	9.4	9.1
Sr	689	669	662	408	457
Y	29.8	30.1	29.0	36.0	30.9
Zr	264	263	264	208	189
Nb	20.4	20.1	20.0	14.5	13.5
Mo	1.2	1.3	1.3	1.2	1.0
Cd	0.089	0.088	0.085	0.083	0.078
Sn	2.81	2.8	2.7	2.33	2.04
Sb	0.058	0.119	0.075	0.049	0.056
Cs	0.154	0.148	0.145	0.121	0.144
Ba	198	194	183	136	119
La	21.0	21.8	20.8	14.8	13.4
Ce	53.5	54.9	53.1	37.4	34.4
Pr	7.39	7.60	7.32	5.59	4.96
Nd	36.0	36.9	35.7	26.5	24.1
Sm	9.30	9.53	9.20	7.34	6.65
Eu	3.06	3.11	3.03	2.49	2.28
Gd	9.01	9.23	8.99	8.00	7.09
Tb	1.31	1.35	1.32	1.26	1.11
Dy	6.77	7.04	6.80	7.16	6.27
Ho	1.21	1.27	1.21	1.41	1.22
Er	2.75	2.93	2.77	3.73	3.09
Yb	2.09	2.27	2.10	3.03	2.58
Lu	0.29	0.31	0.29	0.43	0.37
Hf	6.33	6.39	6.30	4.98	4.55
Pb	1.69	3.39	2.58	2.48	1.82
Th	1.37	1.41	1.34	0.98	0.86
U	0.47	0.57	0.50	0.33	0.30
Pb Isotopes					
$^{206}Pb/^{204}Pb$	18.1199	18.1158	18.1769	18.1185	18.1148
2SD[*]	0.0015	0.0016	0.0025	0.0017	0.0010
$^{207}Pb/^{204}Pb$	15.4648	15.4601	15.4482	15.4586	15.4606
2SD[*]	0.0014	0.0014	0.0022	0.0014	0.0010
$^{208}Pb/^{204}Pb$	37.8871	37.8762	37.8909	37.8718	37.8746
2SD[*]	0.0035	0.0037	0.0053	0.0036	0.0029

[*] standard deviation.

volcanism at the end of the preshield stage (Moore et al., 1982; Garcia et al., 1995a; Sisson et al., 2002) and a decrease in partial melting for the transition from tholeiitic to alkalic lavas at the start of the postshield stage (e.g., Feigenson et al., 1983; Chen and Frey, 1983).

If the Mauna Loa alkalic and tholeiitic lavas formed by varying degrees of melting of a common source, as suggested by their similar Pb isotopic compositions (Fig. 8), then ratios of highly over moderately incompatible trace elements (e.g. La/Yb) in these magmas should be different (e.g., Garcia et al., 1995a). The distinct La/Yb ratios for the two alkalic radial vent lavas (5 vs. 10; Fig. 7) require different partial melting histories. The more alkalic Mo'ikeha lava has higher
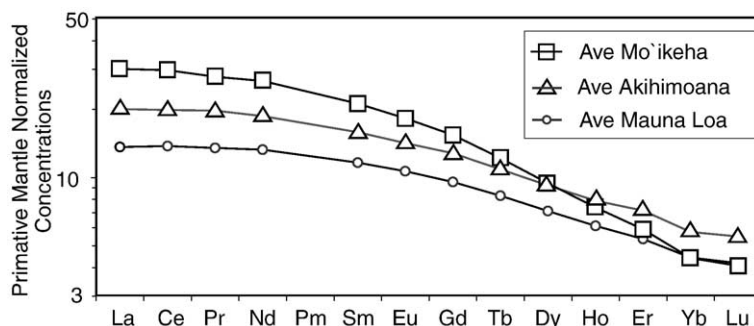
Fig. 6. Primitive mantle normalized REE diagram for Mauna Loa showing average values for lavas from the two alkalic radial vents and an average Mauna Loa tholeiite lava (Rhodes, unpubl. data). The Mo'ikeha lavas have a steeper REE pattern than typical Mauna Loa tholeiite lavas, with identical HREE abundances, which suggest lower degrees of melting of a common garnet-bearing source. In contrast, the Akihimoana lavas have a similar pattern but elevated REE compared to the average Mauna Loa tholeiite, suggesting similar degrees of melting but greater crystal fractionation. Primitive mantle normalizing values from McDonough and Sun (1995).

La/Yb ratios than the Mauna Loa tholeiites and the Akihimoana radial vent lavas, although their HREE abundances are similar (Figs. 6,7). This is consistent with an origin of the Mo'ikeha magma either by a lower degree of melting of a garnet-bearing source similar to the one for Mauna Loa tholeiites, or by a greater amount of residual garnet in the source. Zr/Nb ratios, which are similar for both alkalic suites and also overlap with Mauna Loa tholeiites, appear to be relatively insensitive to moderate variations in partial melting in Hawaiian shield lavas, and, therefore, are more indicative of mantle source composition (Rhodes et al., 1989). In contrast, the less alkaline Akihimoana lavas have lower La/Yb ratios and REE patterns parallel to those of the tholeiites, although with elevated abundances (Figs. 6,7). This is suggestive of similar degrees of melting for the Akihimoana and tholeiitic magmas to establish the slope of the REE pattern. Thus, some

mechanism other than lower degrees of partial melting is required to create the Akihimoana alkalic lavas.

Moderate pressure (0.5–1.5 GPa) clinopyroxene fractionation may have also played a role in the production of the Mauna Loa radial vent alkalic lavas. Several recent studies have shown that moderate pressure fractionation of pyroxene can be important in the production of alkalic magmas (e.g., Bohrson and Reid, 1995; Albarède et al., 1997; Geist et al., 1998; Naumann and Geist, 1999; Damasceno et al., 2002). Crystallization of pyroxene in basalts is enhanced when magmas fractionate at higher pressures because the pyroxene liquidus surface expands (Yoder and Tilley, 1962; O'Hara, 1968). Pressures >0.4 GPa are needed for it to be the dominate crystallizing phase in Mauna Loa composition melts, based on modeling with the MELTS program (Ghiorso and Sack, 1995). The fingerprints of clinopyroxene fractionation are
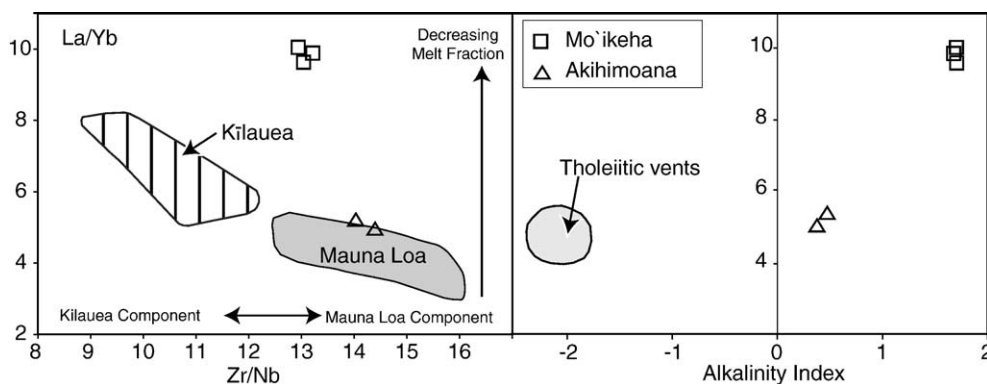

Fig. 7. La/Yb vs. Zr/Nb and alkalinity index [total alkalies − ((SiO$_2$ * 0.37) − 14.43)] (Rhodes, 1996) for Mauna Loa radial vent lavas. The alkalinity index reflects the departure of the sample composition from the alkali/tholeiite line (Rhodes, 1996). Mo'ikeha lavas are more alkaline than the Akihimoana lavas. The higher La/Yb values seen in the Mo'ikeha lavas are probably related to lower degrees of partial melting based on their high La/Yb ratios (e.g., Norman and Garcia, 1999). Zr/Nb ratios of the alkalic radial vent lavas are similar to Mauna Loa tholeiites, suggesting a similar source. Kīlauea and Mauna Loa fields from Rhodes et al. (1989). Accuracy and precision were <1% to 2% for La, Yb, Zr, and Nb based on repeat analyses of several samples.
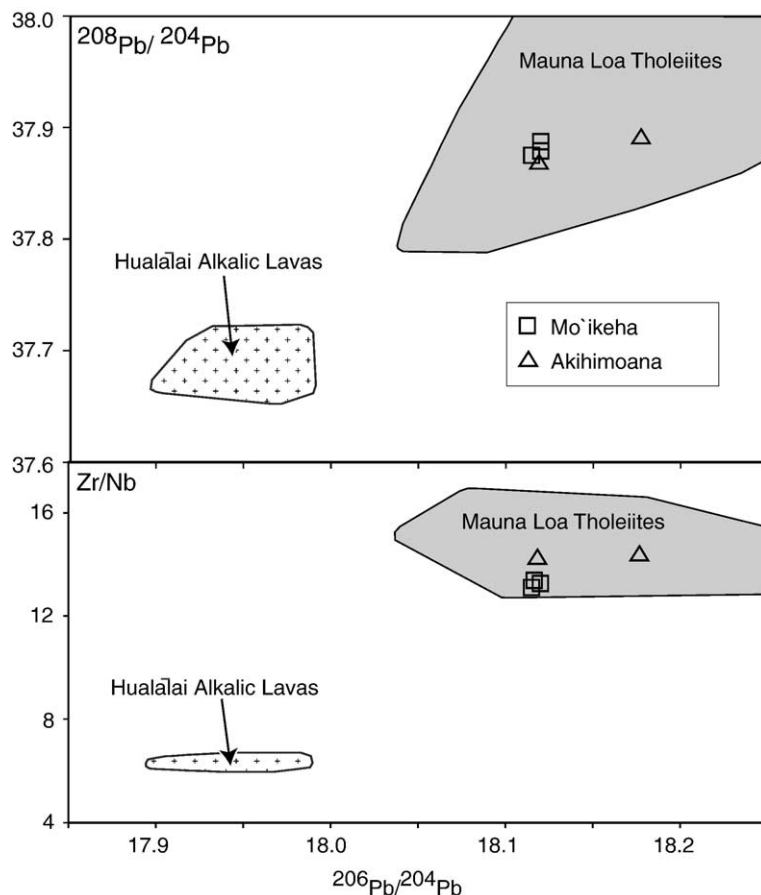
Fig. 8. Pb isotope and Zr/Nb ratio plots for radial vent alkalic lavas compared to Mauna Loa tholeiites and alkalic lavas from nearby volcano Hualālai volcano. Hualālai alkalic lavas are distinct in these plots from Mauna Loa tholeiites. The alkalic radial vent lavas plot within the Mauna Loa field for these ratios indicating they have a similar source. Data for Mauna Loa fields from Rhodes and Hart (1995) and Weis (unpub. data). Hualālai data from Park (1990) and Weis (unpub. data). Analytical errors are smaller than the symbols for all Zr/Nb and Pb isotope analyses.

seen in the major and trace element data for both the Mo'ikeha and Akihimoana lavas. CaO/Al_2O_3 and Sc/Zr ratios are sensitive to clinopyroxene fractionation because CaO and Sc are highly compatible in clinopyroxene (Henderson, 1982). These ratios are distinctly lower in the alkalic lavas compared to Mauna Loa tholeiitic lavas with similar MgO contents (Fig. 4) suggesting that these lavas have undergone clinopyroxene fractionation.

To further evaluate the role of clinopyroxene fractionation in the Mauna Loa alkalic lavas, we utilized the Grove et al. (1992) phase diagram projections. These projections draw on experimental results to show how the location of the liquidus surfaces of basaltic minerals change as a result of variable pressures. The composition of the magma, especially the TiO_2 wt.%, total alkalis, and Mg/Fe ratio, affect these projections. Therefore, we recalculated invariant points for Mauna Loa compositions following steps outlined in the ap-

pendices of Grove et al. (1992) for pressures of 1 atm, 0.5, 0.7, and 1.0 GPa. Alkalic radial vent lava compositions were normalized and projected from plagioclase onto the olivine–clinopyroxene–quartz–nepheline basalt tetrahedron (Fig. 9). Fields for evolved alkalic lavas (<7 wt.% MgO) for neighboring Mauna Kea and Hualālai volcanoes are also shown, along with Mauna Loa tholeiitic lava compositions.

Fractionated Mauna Loa tholeiitic lavas (6–7% MgO) cluster near the 1 atm cotectic (Fig. 9). In contrast, the Mauna Loa alkalic radial vent samples plot along a trend that extends out of the silica-saturated field and into the nepheline field. They follow a trend similar to that of Mauna Kea alkalic lavas and plot between the evolved alkalic lavas (<7 wt.% MgO) from Hualālai and Mauna Kea, which are thought to have fractionated at moderate pressures from an alkalic parent (Frey et al., 1990; Fay et al., 2002; Shamberger and Hammer, in preparation). The Mo'ikeha and Aki-
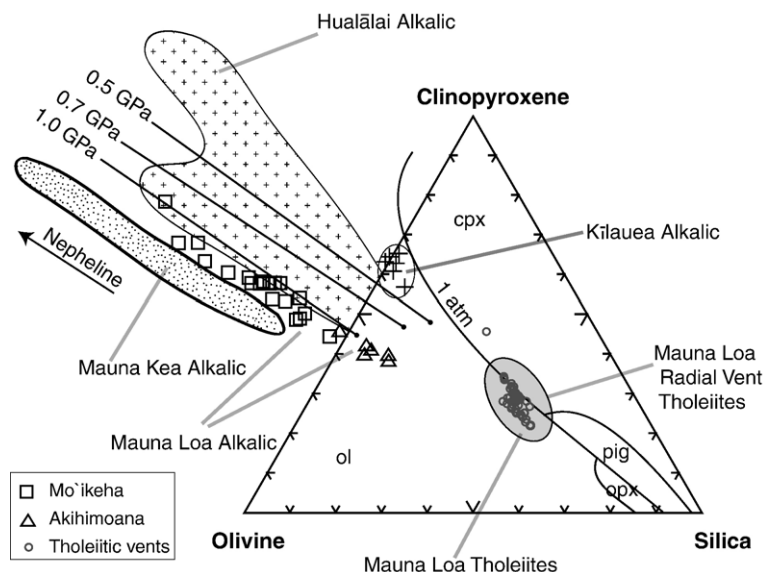
Fig. 9. Olivine–clinopyroxene–silica phase diagram projected from plagioclase. The invariant points were recalculated following procedures in Grove et al. (1992) for 1 atm, and 0.5, 0.7, 1.0 GPa of pressure. Fields for alkalic lavas from Hualālai (Moore et al., 1987), Kīlauea (Johnson et al., 2002) and Mauna Kea (Laupāhoehoe only; Frey et al., 1991) and tholeiite lavas from Mauna Loa (Rhodes and Hart, 1995; Rhodes, 1995; Rhodes and Vollinger, 2004; Rhodes, unpub. data) volcanoes are shown. Mauna Loa's alkalic radial vent lavas straddle and extend into the nepheline-normative field from the silica-saturated field. They plot along a trend that indicates clinopyroxene fractionation at ~1.0 GPa of pressure, slightly lower pressures than for Mauna Kea alkalic lavas (Frey et al., 1991).

himoana alkalic radial vent lavas appear to have fractionated at pressures ~1.0 GPa or ~33 km depths based on Grove et al. (1992) projections.

MELTS modeling (Ghiorso and Sack, 1995) was undertaken to test this interpretation. Multiple MELTS runs were run on compositions from both the submarine radial vents and other tholeiitic Mauna Loa lavas, with MgO values ranging from 6 to 13 wt.%. All Mauna Loa magmas contain some water (e.g. Davis et al., 2003), which affects their crystallization sequence. Therefore, water was added to the compositions using the formula $H_2O = K_2O * 1.2$, which is based on the Hawaiian tholeiitic parental magma estimate of Wallace and Anderson (1998) and Davis et al. (2003). The magma compositions were normalized assuming a QFM oxygen fugacity (appropriate for Mauna Loa magmas; Davis et al., 2003), and run at pressures (1 atm to 1.0 GPa) assuming fractional crystallization in a closed system. The MELTS results show that at pressures >0.4 GPa, orthopyroxene followed quickly by clinopyroxene are the dominate liquidus phases, whereas at lower pressures, olivine is the liquidus phase.

It is evident from the three approaches discussed here that moderate-pressure (~1.0 GPa) clinopyroxene fractionation probably played a significant role in the production of the alkalic lavas from both radial vents. This is supported by the low CaO/Al_2O_3 and Sc/Zr ratios of these lavas (Fig. 4), the location of the

alkalic lava compositions on the olivine–clinopyroxene–quartz–nepheline phase diagram (Fig. 9), and the MELTS modeling. However, pyroxene has not been found as a phenocryst or microphenocryst in any of the alkalic Mauna Loa radial vent lavas (Table 1). Likewise, no pyroxene was found in the evolved alkalic Laupāhoehoe lavas from Mauna Kea, which are also thought to have formed by moderate pressure clinopyroxene fractionation (Frey et al., 1990). Thus, clinopyroxene must have been removed from the magma prior to eruption, perhaps in a subcrustal magma chamber or by reaction with the magma as it becomes unstable at shallower pressures (Frey et al., 1990).

5.3. Implications of alkalic volcanism for Mauna Loa's evolution

The transition of a Hawaiian volcano from shield stage to postshield stage is typically signified by a decrease in eruption rates (e.g., Frey et al., 1991) and the gradual shift of lava compositions from tholeiitic to transitional basalts (which have compositions lower in silica and somewhat higher in total alkalis than a tholeiitic lava) and then to alkalic basalts (e.g. Feigenson and Spera, 1981). Below, we examine these indicators to determine if the discovery of the radial vent alkalic lavas on Mauna Loa is consistent with the

volcano having entered the postshield-building stage of volcanism.

Estimates of lava accumulation rates and drowned shorelines have been used to suggest that the growth rate of Mauna Loa is declining (Moore et al., 1990; Lipman, 1995), and that the volcano may be entering the postshield stage. However, eruption rates on Mauna Loa have varied markedly during the Holocene with periods of relative quiescence (e.g., 6–8 ka) alternating with periods of frequent eruptions (e.g., 1.3–1.8 ka, Lockwood, 1995). Kīlauea, which is undoubtedly in the shield building stage, has also undergone large variations in eruption rate during the last 200 years (<10 to $>100 \times 10^6$ m^3/yr; Dvorak and Dzurisin, 1993; Pietruszka and Garcia, 1999). In comparison, Mauna Kea's eruption rate during the basaltic substage of postshield volcanism decreased from 10 to 2×10^6 m^3/yr (Frey et al., 1990) and continued to decrease during its hawaiite substage ($\sim 0.4 \times 10^6$ m^3/yr; West et al., 1988). Hualālai is in the basaltic substage of postshield volcanism with an eruption rate of 2×10^6 m^3/yr (Moore et al., 1987). Thus, although there are fluctuations in Mauna Loa's Holocene eruptive activity, its post-1832 relatively high rate of eruptive activity (average of 32×10^6 m^3/yr from 1832 to 1984; Wanless et al., in press) would seem to indicate that it has not entered the postshield stage.

Typically, Hawaiian volcanoes erupt transitional basalts and alkalic lavas as they begin the postshield stage (e.g., Chen et al., 1991). These basalts are intercalated with tholeiitic lavas on Mauna Kea and Haleakalā (e.g., Frey et al., 1990; Chen et al., 1991). This change in major element chemistry is thought to reflect a gradual decrease in partial melting as these volcanoes drift off the center of the hotspot and enter the post-shield stage (Feigenson et al., 1983). In contrast, there have been numerous eruptions on Mauna Loa, including 39 historical eruptions (Barnard, 1995), since the emplacement of the alkalic lavas. In fact, with the exception of these alkalic lavas, the overall major element composition of Mauna Loa lavas has not changed significantly in 240,000 years (Rhodes and Weis, 2003; Rhodes et al., 2003; Garcia et al., 1995b). Thus, despite the appearance of alkalic lavas on the flanks of Mauna Loa, we suggest that the volcano has not entered the postshield stage of volcanism.

The eruption of alkalic magma on the flanks of a Hawaiian volcano during the shield stage, although rare, is not unique to Mauna Loa. At the base of Kīlauea's east rift zone, the Puna Ridge, sidescan sonar images (Holcomb et al., 1988; Clague et al., 1995) revealed a relatively young, large lava flow (~ 70 km^2), which was subsequently sampled by submersible and shown to be alkalic in composition (Johnson et al., 2002). Unlike the Mauna Loa alkalic lavas, these Kīlauea alkalic lavas plot near the 1 atm cotectic on the olivine–clinopyroxene–quartz–nepheline phase diagram (Fig. 9), an indication that clinopyroxene fractionation probably did not play a significant role in their petrogenesis. However, the discovery of Kīlauea alkalic lavas supports the hypothesis that Hawaiian shield stage volcanoes can produce and erupt alkalic magmas.

5.4. structural implications of Mauna Loa's alkalic volcanism

It is commonly assumed that during shield-building volcanism magma ascends through a primary conduit from the mantle into a crustal magma reservoir, from where it may erupt in the summit region or along rift zones (e.g. Tilling and Dvorak, 1993). With the normally high eruption rates, magma is thought to be nearly continuously flowing through Hawaiian shield volcanoes and mixing in their summit reservoirs (e.g. Dvorak and Dzurisin, 1993; Pietruszka and Garcia, 1999). Thus, if a relatively small volume of alkalic magma entered Mauna Loa's plumbing system, it would be overwhelmed by the more voluminous tholeiites. To avoid mixing with tholeiitic magma, the alkalic magmas must either bypass the highly active main conduit and the summit reservoir or be formed during periods of much lower magma production. We believe that the voluminous activity in the main conduit of a shield-stage volcano would not allow for the preservation of the alkalic magmas and therefore, we favor the separate conduit model. This would allow the magmas to undergo clinopyroxene fractionation at ~ 30 km depth prior to eruption, which has not been observed in other Mauna Loa lavas.

A schematic diagram of Mauna Loa illustrates a scenario for the occurrence of alkalic lavas on Mauna Loa's flank during the main shield stage (Fig. 10). Alkalic magmas ascended outside of the main mantle conduit, and fractionated pyroxene during ascent at ~ 30 km or storage within the upper mantle. Ascent into the volcanic edifice continued along subsidiary conduits. Sulfur concentrations indicate that the Mo'ikeha magma degassed just prior to eruption (Fig. 3), but the water pressures where it erupted are too great to allow for this degassing. Therefore, the Mo'ikeha magma must have been near the surface of the volcano (<300 m depths) prior to eruption. After degassing, this magma was intruded along a radial dike to the submarine flank of the volcano.
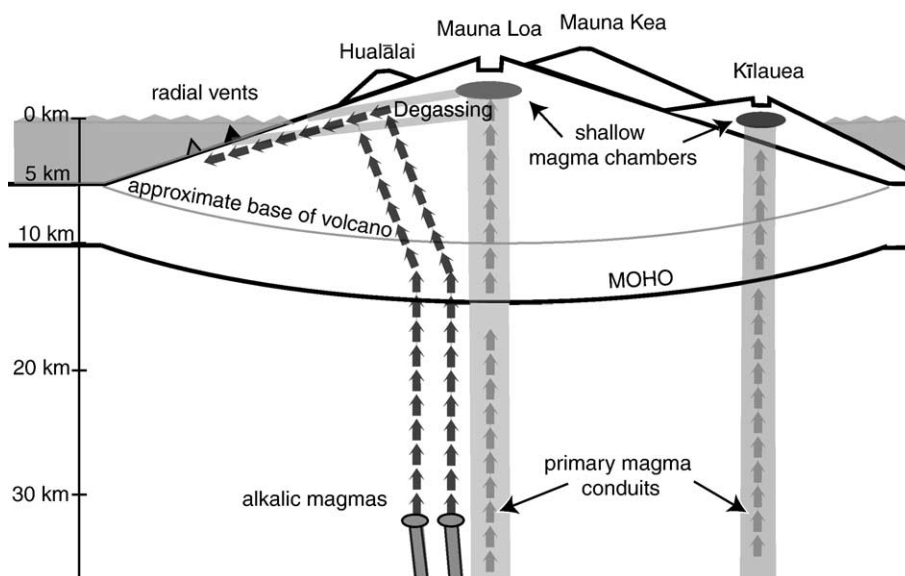
Fig. 10. Cartoon illustrating a model for the ascent and eruption of Mauna Loa's alkalic radial vent lavas. Alkalic magmas are produced from Mauna Loa's source by lower degrees of partial melting and/or moderate pressure fractionation of clinopyroxene (at ~33 km) prior to intrusion into the crust. These magmas branch off and bypass the main conduit system of the volcano and avoid mixing with the voluminous tholeiitic magmas. They then rise into the edifice of the volcano. The Mo'ikeha vent lavas are degassed, so they must have risen to near the surface where they could degassed before eruption. The magmas then followed radial fractures to the submarine flanks of Mauna Loa, erupting at a depth > 800 m below sea level.

Alkalic magmas may also be generated routinely during fluctuations in melt production for Hawaiian shield volcanoes and be injected into the primary conduit. This idea can be tested by examining the compositions of melt inclusions in early-formed olivine crystals from tholeiitic lavas erupted from the summit reservoir. However, hundreds of such inclusions in olivine phenocrysts have been analyzed with no sign of alkalic magmas (Norman et al., 2002).

6. Conclusions

Field and geochemical data point to Mauna Loa, not neighboring Hualālai volcano, as the source of the alkalic lavas from the two newly discovered radial vents on the submarine western flanks of the island of Hawai'i. Thus, these are the first alkalic lavas reported from Mauna Loa. Moderate-pressure fractionation of clinopyroxene played an important role in the petrogenesis of lavas from both vents. However, the high La/Yb and incompatible element abundances of the lavas from Mo'ikeha vent indicate that lower degrees of partial melting from a common mantle plume source were also important in their formation. In contrast, the Akihimoana lavas were formed from similar degrees of melting to typical Mauna Loa tholeiites and they gained their alkalic signature from moderate-pressure fractionation of clinopyroxene from a tholeiitic parent. This interpretation is supported by CaO/Al_2O_3, Sc/Zr, REE, isotope data, phase diagram projections, and MELTS modeling. While the onset of alkalic eruptions typically accompanies the beginning of the postshield building stage, there has been no long-term change in the major element chemistry of Mauna Loa lavas in the last 240,000 years and no other alkalic or transitional basalts are known despite numerous Holocene eruptions and hundreds of chemical analyses (Rhodes and Hart, 1995; Rhodes, 1995; Rhodes and Vollinger, 2004; Rhodes, unpub. data). Thus, Mauna Loa has not entered the postshield stage of volcanism. These shield stage alkalic magmas were able to erupt by avoiding the highly productive mantle magma conduit, which is dominated by voluminous tholeiitic magmas.

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