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Intershield geochemical differences among Hawaiian volcanoes: implications for source compositions, melting process and magma ascent paths

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As Hawaiian volcanoes develop, their lavas systematically change in composition and isotopic ratios of Sr, Nd and Pb. These trends provide important constraints for understanding plume-related volcanism as a volcano migrates away from the hotspot. There are also geochemical differences between Hawaiian shields. In particular, lavas from adjacent shields such as Kilauea and Mauna Loa on Hawaii and Koolau and Waianae on Oahu have significant differences in abundances of some major and incompatible elements and isotopic ratios of Sr, Nd and Pb. Some incompatible element abundance ratios, such as Zr/Nb and Sr/Nb, are correlated with intershield differences in Sr and Nd isotope ratios, but these isotopic ratios are not correlated with intershield differences in major element composition, or even parent/daughter abundance ratios such as Rb/Sr and Sm/Nd. Moreover, at Kilauea and Mauna Loa the intershield differences have apparently persisted for a relatively long time, perhaps 100 ka. These intershield geochemical differences provide important constraints on plume volcanism. Specifically, (i) each volcano must have distinct magma ascent paths from the region of melt segregation; (ii) the 25–50 km distance between adjacent, but geochemically distinct, shields requires that the sources vary on a similar scale, and that the melt production region is similarly restricted. The absence of correlations between lava compositions and radiogenic isotope ratios provides evidence for significant differences in melting process such as each shield forming by a different mean extent of melting with melt segregation at different mean pressures.

Two types of models are consistent with the intershield geochemical differences: (i) a relatively large radius, *ca.* 40 km, plume conduit with a systematic spatial distribution of geochemical heterogeneities; or (ii) a small radius, less than 20 km, plume conduit composed of geochemically distinct diapirs. Because relatively small radius diapirs of limited vertical extent are too small to create the large Hawaiian shields, a possible alternative is a continuous conduit containing solitary waves which transport geochemically distinct packets of material.

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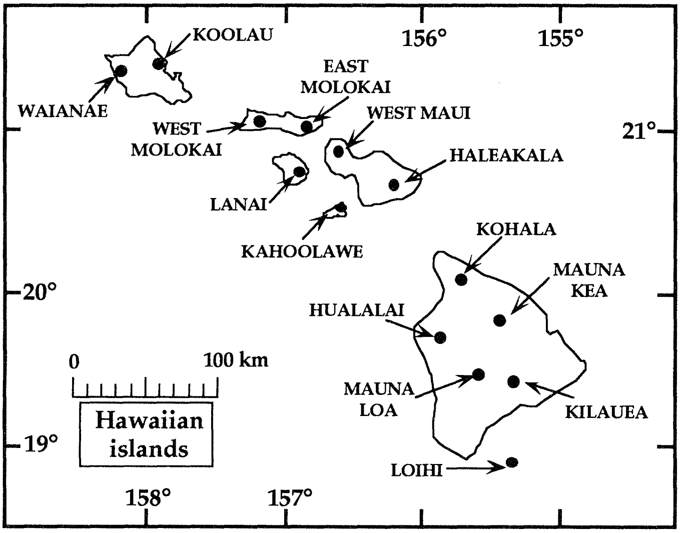

Figure 1. Location of the youngest Hawaiian volcanoes ranging from Waianae and Koolau on Oahu in the northwest to Loihi Seamount in the southeast (from Clague & Dalrymple 1987).

1. Introduction

The volcanoes comprising the Hawaiian Ridge formed as the Pacific plate migrated over a stationary magma source, a hotspot, that is created by a hot, upwelling mantle plume (Wilson 1963; Morgan 1971). Individual Hawaiian volcanoes evolve through well-characterized growth stages involving systematic temporal changes in lava composition (Stearns 1940; Clague & Dalrymple 1987; Frey & Roden 1987) and radiogenic isotope ratios of He, Sr, Nd and Pb (Chen & Frey 1985; Stille *et al.* 1986; West *et al.* 1987; Kurz & Kamner 1990). Most of the mass, 95–98%, of Hawaiian volcanoes are formed during the shield-building stage as a consequence of relatively high eruption rates (Clague & Dalrymple 1987). Therefore, the shield-forming lavas are likely to provide the most direct information about the plume composition and dynamics. These shields are interpreted to be dominantly composed of tholeiitic basalt because such basalts form the surfaces of the active shields, Kilauea and Mauna Loa, and they are the major rock type in exposures of older, eroded Hawaiian shields.

In this paper we focus on adjacent and approximately coeval Hawaiian shields composed of geochemically distinct tholeiitic basalts. These geochemical differences are manifested in major and trace element abundances as well as radiogenic isotope ratios. They provide information about the mantle source of Hawaiian shields and the magmatic processes associated with plume-related volcanism. Our objectives are (i) to evaluate the relative role of processes and differences in source in causing the intershield differences, and (ii) to identify the constraints on plume dynamics resulting from intershield geochemical differences.

We discuss adjacent pairs of Hawaiian shields: Kilauea and Mauna Loa on the island of Hawaii and Koolau and Waianae on the island of Oahu (figure 1). Kilauea and Mauna Loa are actively growing shields, and there is an abundance of high quality geochemical data. The Koolau–Waianae pair is older, *ca.* 1.8–2.7 Ma for Koolau shield lavas and *ca.* 3.0–3.9 Ma for Waianae shield lavas (Langenheim & Clague 1987), and their formation may not have been coeval. This pair was chosen because Koolau lavas define an extreme in the range of major element compositions (Frey *et al*. 1993) and heavy radiogenic isotope ratios (Roden *et al*. 1984, 1993; West *et al*. 1987).

2. Intershield geochemical differences

(*a*) *Major elements*

At low pressures olivine is the liquidus phase of Hawaiian shield lavas, and the wide range in MgO content (*ca*. 5.5–23% in figure 2) reflects olivine accumulation and segregation (Powers 1955; Wright 1971). Intershield compositional differences are apparent in MgO variation plots (figure 2). We focus on lavas with more than 7% MgO because lavas with less than 7% MgO contain several phenocryst phases, and their compositions have been affected by post-melting segregation of clinopyroxene and plagioclase in addition to olivine; e.g. the abrupt changes of slope at *ca*. 6–7% MgO in the CaO–MgO and TiO_2–MgO trends (figure 2*a*). At more than 7% MgO, historic Kilauea and Mauna Loa lavas overlap in abundances of Al_2O_3 and Na_2O, but historic Kilauea lavas have higher CaO, TiO_2 and K_2O contents and lower SiO_2 contents (figure 2*a*). Because these intershield differences are not a function of MgO content, they represent differences in primary magma compositions (primary magmas have compositions that have not been changed by post-melting processes). Although abundances of major elements in older Hawaiian shield lavas are affected by low temperature alteration (Lipman *et al*. 1990; Frey *et al*. 1993), there are also important major element abundance differences between lavas from the adjacent Koolau and Waianae shields. Specifically, at *ca*. 7% MgO, Koolau lavas range to higher SiO_2 but lower TiO_2 and CaO contents (figure 2*b*). Relative to Kilauea and Mauna Loa lavas, Koolau lavas range to higher SiO_2 and Al_2O_3 and lower CaO contents (figure 2).

(*b*) *Incompatible elements*

In general, Kilauea lavas are more enriched in incompatible elements than Mauna Loa lavas (e.g. K_2O and TiO_2 in figure 2*a*; Rb, Sr, Zr, and Nb in figure 3*a*; La and Th, not plotted (also Tilling *et al*. 1987)). Especially good discriminants between historic Kilauea and Mauna Loa lavas are TiO_2 and Nb contents; in fact, TiO_2 is a better discriminant than the more incompatible oxides Na_2O, K_2O and P_2O_5 (figure 2*a*). Abundance ratios, such as K/Nb, Sr/Nb and Zr/Nb which are nearly uniform in genetically related basalts are also excellent intershield discriminants (figure 4). Utilizing such discriminants, Rhodes *et al*. (1989) found that some prehistoric lavas with Mauna Loa-like compositions were erupted on Kilauea from *ca*. 2.1 Ma to 300 years. Although a change in the Kilauea source composition could be inferred, Rhodes *et al*. (1989) favoured the interpretation that Kilauea's shallow magmatic plumbing system was occasionally invaded by magmas from Mauna Loa. An important observation is that the incompatible element abundance differences between historic Kilauea and Mauna Loa lavas are also characteristic of the oldest, subaerial lavas exposed at each volcano (e.g. Nb in figure 3*a*; Zr/Nb in figure 4). Although their ages are not well constrained, Hilina Basalt at Kilauea is *ca*. 31–100 ka (Easton *et al*. 1987) and Ninole Basalt at Mauna Loa is *ca*. 31–200 ka (Lipman *et al*. 1990). Therefore, these intershield differences have persisted for *ca*. 100000 years, a significant fraction of the shield growth stage.

Although at *ca*. 7% MgO most Waianae lavas have slightly higher TiO_2 and Nb contents than Koolau lavas, abundances of other incompatible elements such as Zr

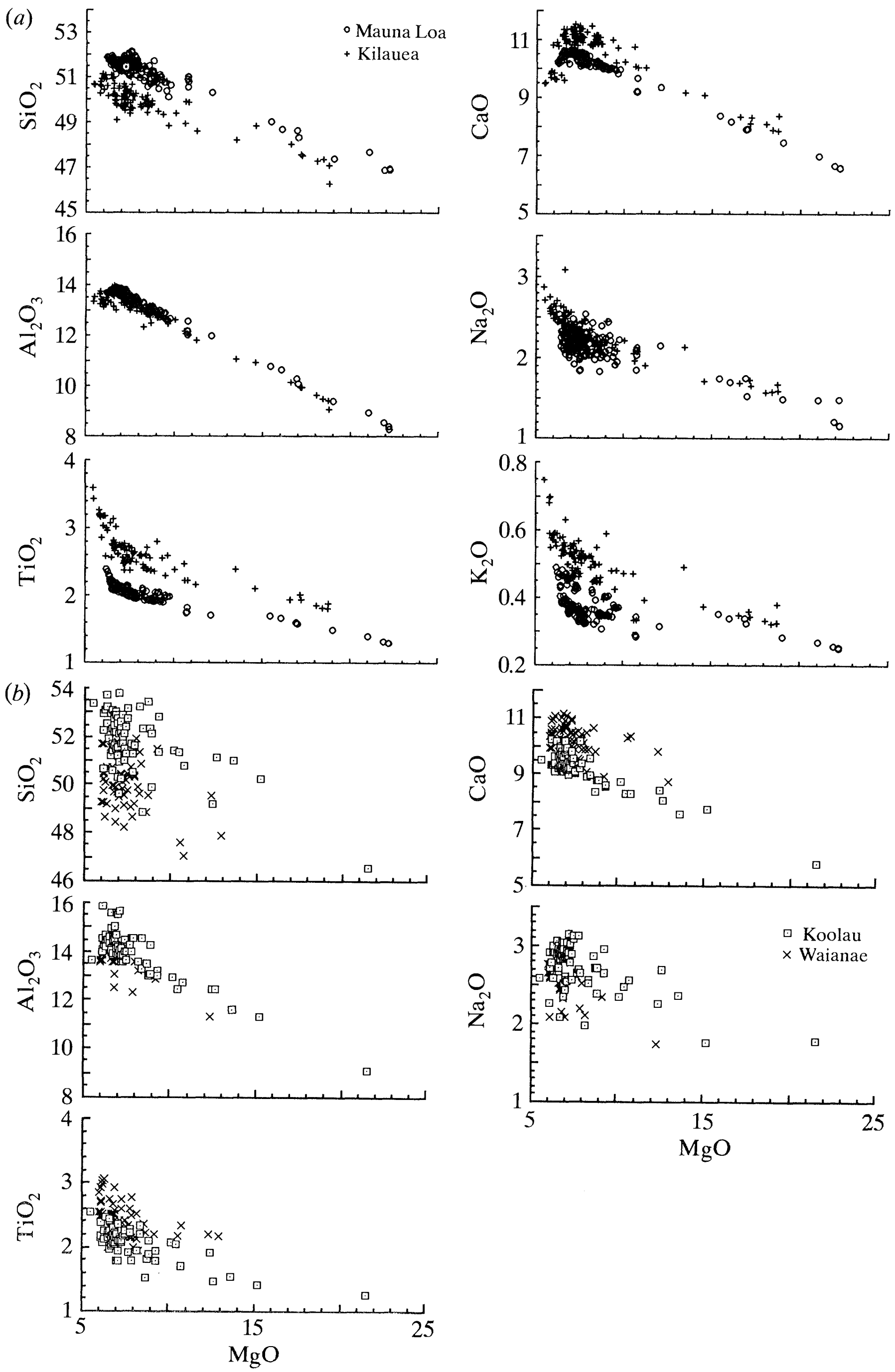

Figure 2. MgO variation plots for major elements (all in wt %). Rather than plotting only samples with a particular range in MgO content or correcting lava compositions to a common MgO content, we plot all of our data because (i) the effects of low pressure fractionation are clearly indicated at less than 7 % MgO, and (ii) it is evident that intershield differences are not a function of calculations that attempt to correct for the effects of post-melting, mineral-melt fractionation. (*a*) Comparison of historic Kilauea and Mauna Loa lavas (Rhodes, unpublished data). For lavas with more than

and Sr are similar in both shields (figures 2*b* and 3*b*); therefore, Zr/Nb and Sr/Nb abundance ratios in most Koolau lavas are higher than in most Waianae lavas (figure 4). Also relative to all Kilauea lavas and most Mauna Loa lavas, Koolau lavas have higher Zr/Nb and Sr/Nb (figure 4).

(*c*) *Isotopes*

Despite considerable isotopic variability within individual shields (West *et al.* 1987; Kurz & Kamner 1991; Roden *et al.* 1992), intershield differences in radiogenic isotopic ratios of Sr, Nd and Pb are large (figure 5). Moreover, isotopic data for the oldest lavas from Kilauea (Hilina Basalt) and Mauna Loa (Ninole Basalt) show that these isotopic differences have, like differences in incompatible element abundance ratios, persisted for *ca.* 100 ka. Note that Kilauea lavas have lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ than Mauna Loa lavas. Because Kilauea lavas have higher Rb/Sr (figure 4) and Nd/Sm (Budahn & Schmitt 1985; Tilling *et al.* 1987) than Mauna Loa lavas, these isotopic differences are inconsistent with the differences in parent/daughter abundance ratios.

The isotopic differences between Koolau and Waianae lavas are even larger. Koolau shield lavas are isotopically heterogeneous, but they define the high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ and low $^{206}Pb/^{204}Pb$ extremes for Hawaiian lavas (Roden *et al.* 1993). In contrast, lavas forming the adjacent Waianae shield have $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ similar to Kilauea lavas but $^{206}Pb/^{204}Pb$ similar to Mauna Loa lavas (figure 5).

3. Interpretations

Although all studied Hawaiian shield lavas have Sr and Nd radiogenic isotope ratios between the fields for MORB and bulk Earth (West *et al.* 1987; Roden *et al.* 1993), the intershield isotopic differences are large (figure 5), and require that the sources of each shield contained isotopically distinct components, perhaps different proportions of the same components. Based on limited data for the oldest subaerial basalts from Kilauea and Mauna Loa (figure 5), these isotopic differences persist for a long time, perhaps at least 100 ka. Among Hawaiian shield lavas, those from Koolau volcano define an isotopic extreme (relatively low $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ and high $^{87}Sr/^{86}Sr$ (Roden *et al.* 1993)), and they are also extreme in several major element characteristics such as high SiO_2, low CaO (figure 2) and low total iron contents (not plotted). However, there is no systematic correlation between isotopic ratios of Sr, Nd and Pb and major element abundance characteristics. Specifically, West *et al.* (1987) found that lavas from Kahoolawe Volcano are isotopically similar to Koolau lavas, but Kahoolawe shield lavas do not

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7% MgO there are distinct intervolcano differences for TiO_2, K_2O, CaO and SiO_2. (*b*) Comparison of Waianae and Koolau basalts. The most distinct differences are in SiO_2 and CaO. K_2O data are not shown because of K_2O loss caused by low-temperature alteration. (Koolau data from Frey *et al.* (1993); Waianae data for samples with more than 6% MgO from Macdonald & Katsura (1964), Zbinden & Sinton (1988), Sinton & Presley unpublished). All abundance data for lavas from Kilauea, Mauna Loa and Koolau volcanoes in this and subsequent figures were determined by a combination of X-ray fluorescence at the University of Massachusetts and instrumental neutron activation analysis at the Massachusetts Institute of Technology. Therefore, the compositional differences between these shields are not a result of systematic interlaboratory errors. Abundance data for Al_2O_3 and Na_2O in Waianae lavas reported by Macdonald & Katsura (1964) were not plotted because they are systematically different from more recent data for Waianae lavas.

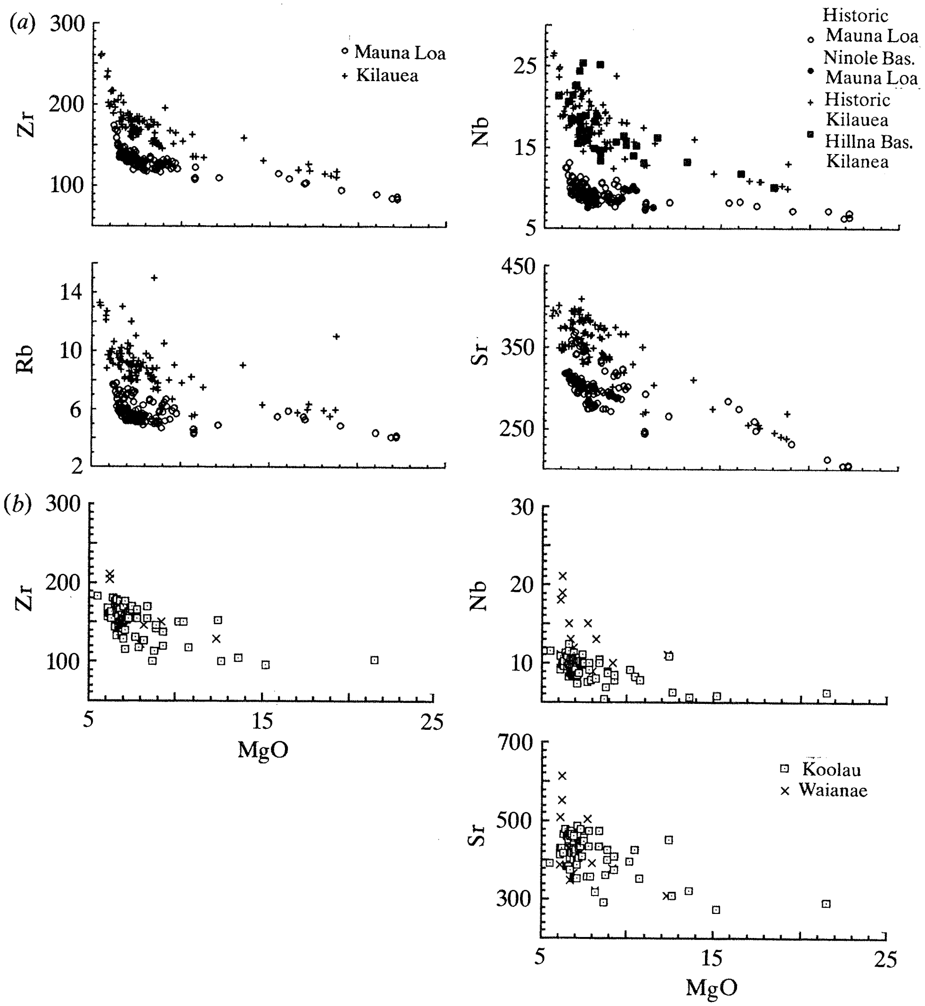

Figure 3. Abundances of the incompatible elements of Rb, Sr, Zr and Nb (all in p.p.m.) against MgO (wt %). (*a*) Comparison of historic Kilauea and Mauna Loa lavas (Rhodes, unpublished data). The Nb panel includes data for the oldest basalts from Kilauea (Hilina) and Mauna Loa (Ninole) (Ninole data from Lipman *et al.* (1990); Hilina data from Chen, Frey and Rhodes, unpublished). (*b*) Comparison of Waianae and Koolau basalts (Koolau data from Frey *et al.* (1993); Waianae data from Sinton & Presley, unpublished, and Feigenson, unpublished.) Rb data not shown because of the Rb loss caused by alteration of old shield lavas.

have the distinctive major element compositions that characterize Koolau lavas (Frey *et al.* 1993). In fact, in several respects, such as relatively high SiO_2 content, Koolau and Mauna Loa lavas are similar (greater than 51 % SiO_2 at 7 % MgO, figure 2), but they are isotopically very different (figure 5). Consequently, we conclude that the intershield differences in major element composition were not controlled by the components creating intershield isotopic differences.

Do the intershield differences in major element compositions reflect differences in process rather than differences in source composition? Klein & Langmuir (1987) used abundances of SiO_2, total iron, Al_2O_3 and Na_2O in regionally averaged mid-ocean ridge basalt (MORB) combined with experimental results for partial melting of spinel

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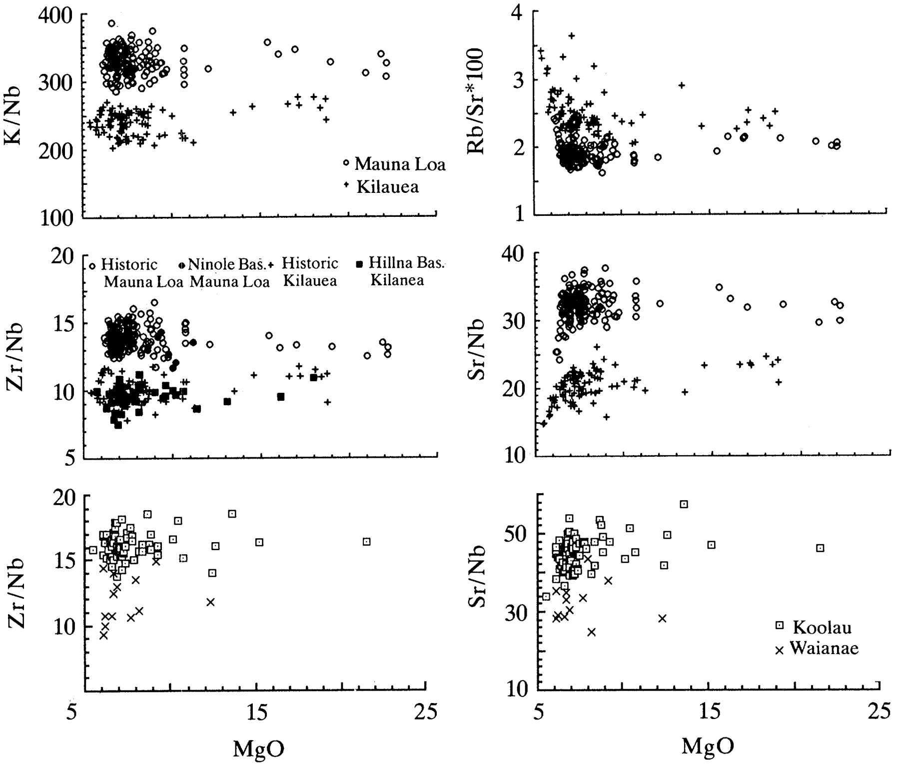

Figure 4. Incompatible element abundance ratios against MgO content (wt %). Upper four panels: historic lavas from Kilauea and Mauna Loa. The Zr/Nb panel includes data for the oldest basalts from Kilauea (Hilina) and Mauna Loa (Ninole). Lower two panels: Waianae and Koolau. Because K and Rb abundances are affected by post-magmatic alteration, K/Nb and Rb/Sr data are not shown. Data sources as indicated in caption to figure 3.

peridotite to argue for regional differences in the mean depth and extent of melt segregation. Melts segregating from a mantle plume should also reflect a range in pressures and extents of melting (Ribe 1988; Wyllie 1988; Liu & Chase 1991*a*). However, based on both geophysical and geochemical arguments, Hawaiian tholeiitic magmas segregate at higher pressures than MORB. For example, Watson & McKenzie (1991) developed a numerical model of the Hawaiian plume that is consistent with the observed melt production rate, residual depth anomaly and geoid anomaly. They concluded that melt production occurs between depths of 82–136 km; consequently, Hawaiian shield lavas segregate at pressures which encompass the transition region from spinel- to garnet-peridotite (McKenzie & O'Nions 1991). Because garnet has high contents of Al_2O_3, Sc and heavy REE relative to coexisting melt, the lower Al_2O_3, Sc and heavy REE contents of Hawaiian shield lavas relative to MORB are consistent with garnet as an important residual phase during generation of Hawaiian shield lavas. The uniformity of heavy REE contents in Hawaiian tholeiites (when adjusted to a common MgO content) is also a strong argument for residual garnet (Hofmann *et al.* 1984).

As inferred by Klein & Langmuir (1987) and shown by Takahashi *et al.* (this symposium), within the stability field of spinel peridotite the SiO_2 contents of partial melts decrease with increasing pressure. Although the effect of pressure on the SiO_2

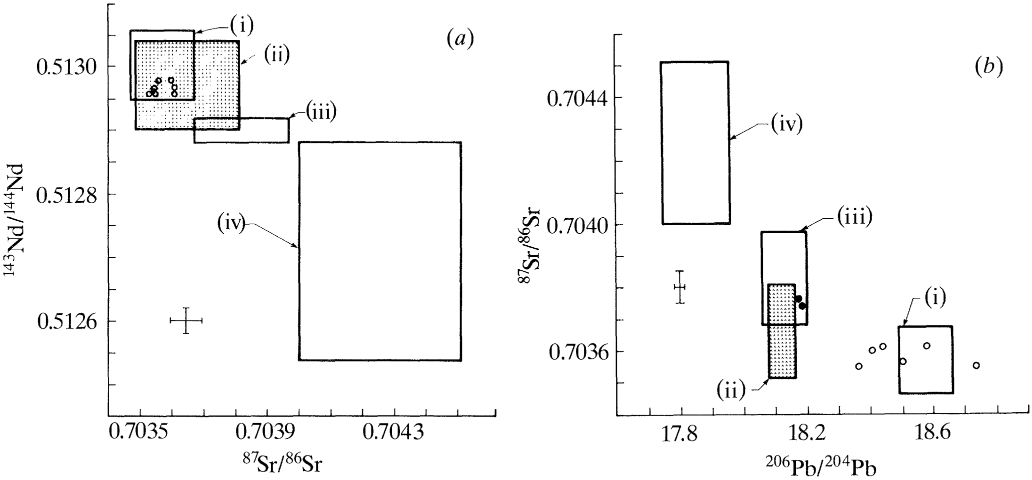

Figure 5. $^{143}Nd/^{144}Nd$ against $^{87}Sr/^{86}Sr$ and $^{87}Sr/^{86}Sr$ against $^{206}Pb/^{204}Pb$ showing the large differences between the adjacent shields. Mauna Loa–Kilauea and Waianae–Koolau. (*a*) (i) Historic Kilauea (24, 21), (ii) Waianae (16, 16), (iii) Mauna Loa (33, 5), (iv) Koolau (23, 17). (*b*) (i) Historic Kilauea (24, 5), (ii) Waianea (16, 4), (iii) Mauna Loa (33, 30), (iv) Koolau (23, 11). Numbers within parentheses indicate number of samples analysed with number for $^{87}Sr/^{86}Sr$ given first. Note that the oldest lavas from Mauna Loa, Ninole Basalt (two filled circles in right panel), lie within the field for younger Mauna Loa lavas. Also, the oldest lavas from Kilauea, Hilina Basalt (open circles in both panels), lie within or extend slightly the fields for younger Kilauea lavas. Another important point is that Mauna Loa lavas have higher $^{87}Sr/^{86}Sr$ than Kilauea lavas but they have lower Rb/Sr (figure 3*a*). Error bars in lower left indicate typical two sigma errors. Mauna Loa and Kilauea data from O'Nions *et al.* (1977), Tatsumoto (1978), White & Hofmann (1982), Hofmann *et al.* (1984), Stille *et al.* (1986), Kurz & Kamner (1991), Chen, Frey and Rhodes (unpublished data for Hilina basalt). Waianae data from White & Hofmann (1982), Stille *et al.* (1983), and Feigenson (unpublished). Koolau data from Stille *et al.* (1983) and Roden *et al.* (1993).

contents of melts in equilibrium with garnet peridotite is not as well established, the relatively higher abundances of SiO_2 in Mauna Loa and Koolau lavas (figure 2) may reflect melt segregation at a lower mean pressure than lavas from their respective adjacent volcanoes, Kilauea and Waianae. Total iron contents in partial melts increase with increasing pressure (Klein & Langmuir 1987; Takahashi *et al.*, this symposium), therefore, the atypically low total iron contents of Koolau lavas (generally lower than 11.7 % Fe_2O_3, as total iron (Frey *et al.* 1993)) are also consistent with segregation at relatively low pressure.

The higher K_2O and TiO_2 contents of Kilauea lavas (figure 2*a*) are accompanied by higher abundances of incompatible trace elements (figure 3*a*). If the sources of Kilauea and Mauna Loa lavas were similar in incompatible element content, Kilauea lavas were derived by lower extents of melting (F). In this context, the similar Al_2O_3 and Na_2O contents of Kilauea and Mauna Loa lavas at a given MgO content (figure 2*a*) are surprising, because in regionally averaged MORB, these oxides have been used as sensitive indicators of F (Klein & Langmuir 1987). However at the higher pressures of melt segregation inferred for Hawaiian shield lavas, Al_2O_3 and probably Na_2O become more compatible in residual minerals, and their abundances are not as sensitive to extent of melting.

Abundances of CaO are also a good intershield discriminant; e.g. at a given MgO content, CaO decreases in the order Kilauea > Mauna Loa ≈ Waianae > Koolau (figure 2). Within the stability field of spinel peridotite, CaO contents of melts increase with F until clinopyroxene is exhausted from the residue (Kinzler & Grove 1992). If a similar trend is valid at higher pressures, the relatively high CaO content of Kilauea lavas is inconsistent with the inference based on incompatible element abundances that Kilauea lavas formed by a lower mean extent of melting than Mauna Loa lavas. This paradox is resolved, if the Kilauea source had relatively higher abundances of incompatible elements. It is also possible that the CaO contents of melts in equilibrium with clinopyroxene and garnet are sensitive to pressure in the 25–45 kb range; however, there are insufficient experimental data to evaluate this hypothesis. Another possibility is that CaO abundances reflect differences in volatile content (Wyllie 1988). In particular, the effect of CO_2 is to lower SiO_2 and increase CaO in partial melts (Eggler 1978); possibly, Kilauea lavas were derived from a source with higher CO_2 content (Garcia *et al.* 1989).

In summary, the limited experimental data for the compositions of partial melts in equilibrium with garnet peridotite preclude confident interpretations of intershield differences in major element composition. However, it is possible that these compositional differences reflect variations in mean depth and extent of melting, and perhaps variations in volatile content.

A difficulty in using lava composition to constrain melting processes is that erupted magmas are probably mixtures of melts formed over a range in pressure and extent of melting (Thompson 1987). Eggins (1992*a*) concluded that picritic Hawaiian tholeiites with *ca.* 16% MgO (Clague *et al.* 1991) are not in equilibrium with garnet peridotite at any pressure or temperature, but that they are in equilibrium with harzburgite at 20 kb. How can this constraint be consistent with control of some trace element abundances by residual garnet? Eggins (1992*b*) inferred that the rate of melting must decrease as the plume approaches the lithosphere. Therefore he proposed that the bulk of the shield lavas formed by relatively low F in the presence of garnet, but because of equilibration during ascent by porous flow the major element compositions reflect equilibration with harzburgite at the top of the melting column. Perhaps the incompatible element-rich Kilauea lavas contain more of these low F melts than Mauna Loa lavas. Because the extent of melting in a plume must decrease radially from the relatively high temperature plume axis toward the relatively cool periphery, a possible explanation is that the source of Kilauea lavas is offset from the plume axis. If the relatively low SiO_2 contents of Kilauea lavas reflect melt segregation at higher pressures, then magmas derived from the plume periphery reflect a lower F and higher pressure of melt segregation.

McKenzie & O'Nions (1991) proposed a different interpretation for the relative incompatible element enrichment of Kilauea lavas. They proposed that as a Hawaiian shield ages, partial melts of asthenosphere percolate through and interact with the overlying plume matrix. During this process abundance ratios among incompatible elements are changed because of chromatographic effects. This model was proposed to explain the lower abundances of light REE and other incompatible elements such as Sr (figure 3*a*) in Mauna Loa lavas relative to Kilauea lavas. However, this model predicts that Mauna Loa lavas should be more MORB-like in isotopic ratios; consequently, the model does not satisfactorily explain the higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ of Mauna Loa lavas (figure 5). In addition, West *et al.* (1987) concluded that the $^{87}Sr/^{86}Sr$–$^{206}Pb/^{204}Pb$ trend defined by Hawaiian shield lavas is inconsistent with an important role for a MORB-like component. Moreover, the McKenzie & O'Nions model implies that the youngest shield lavas on extinct Hawaiian shield should also have relatively low abundances of incompatible elements, but this is not observed (Leeman *et al.* 1980; Budahn & Schmitt 1985). Therefore, this model does not satisfactorily explain intershield geochemical differences.

Abundance ratios of incompatible elements are relatively insensitive to fractional crystallization, and it is unlikely that the intershield differences in K/Nb, Zr/Nb and Sr/Nb (figure 4) reflect shallow processes, such as fractionation and mixing in a replenished magma chamber (Loubet *et al.* 1988; Nielsen 1990). In particular, ratios such as Zr/Nb and Sr/Nb are correlated with $^{87}Sr/^{86}Sr$; e.g. all decrease in the order Koolau > Mauna Loa > Waianae $\geqslant$ Kilauea (figures 4 and 5); therefore, some of intershield variations in incompatible element abundances may reflect source differences. However, there is evidence that intershield differences in incompatible element abundance ratios do not reflect long-term differences in sources. For example, relative to Mauna Loa lavas, Kilauea lavas have higher Rb/Sr but lower $^{87}Sr/^{86}Sr$ and lower Sm/Nd but higher $^{143}Nd/^{144}Nd$ (figures 4 and 5). This decoupling between parent/daughter ratio and isotopic ratio cannot be a long-lived effect and requires a recent change in parent/daughter abundance ratios caused by processes such as partial melting, mixing and metasomatism. The absence of a correlation between parent/daughter abundance ratio and isotopic ratio is even more dramatic for Koolau volcano which has unusually low $^{143}Nd/^{144}Nd$ (figure 5) but Sm/Nd ratios that encompass the range of Kilauea and Mauna Loa lavas (Frey *et al.* 1993).

4. Implications

During the growth of a Hawaiian volcano there are important temporal trends in geochemical characteristics. The transition from the shield stage to post-shield and rejuvenated stages has been studied at several volcanoes, and the geochemical trends have provided important constraints for understanding the evolution of Hawaiian volcanoes as they move away from the hotspot. Although the geochemical characteristics of lavas forming a shield may also vary systematically as a function of eruption age (Rhodes 1983; Kurz & Kamner 1991), we emphasize that lavas from adjacent and approximately coeval Hawaiian volcanoes (Mauna Loa and Kilauea on Hawaii, Koolau and Waianae on Oahu) have significant differences in major and incompatible element abundances and radiogenic isotope ratios, and the differences between Mauna Loa and Kilauea have persisted for a significant fraction of shield stage growth. Moreover, most intershield geochemical differences are larger than known intrashield geochemical variations.

The systematic geochemical differences between the lavas forming adjacent shields lead to constraints on the processes involved in creation of Hawaiian shields, and they have the following important implications for plume models.

(*a*) Each volcano must have distinct magma ascent paths. This requirement has not been recognized from the locations of earthquakes at depths of more than 40 km (Klein 1987).

(*b*) The 25–50 km distance between adjacent calderas requires that the source regions of Hawaiian volcanism vary on a similar scale. Although geochemical heterogeneity on this length scale is not surprising, the large volumes of Hawaiian shields requires that substantial volumes of source material remain geochemically distinct, possibly throughout growth of the shield stage, *ca.* 0.5–1 Ma. Extraction of melts from large plumes, more than 50 km in diameter, cannot explain the intershield differences unless the plume has a systematic distribution of heterogeneities. If such heterogeneities exist in the source, they may be preserved in the overlying volcanoes (Eggins 1992*b*) because melts ascend nearly vertically in the fluid dynamic model for plumes proposed by Ribe & Snooke (1987). Entrainment of asthenospheric wallrocks might also create heterogeneity on an intershield scale (Griffiths & Campbell 1991), but the isotopic and incompatible element characteristics of adjacent shields, such as Kilauea and Mauna Loa, do not indicate that one shield contains more of an asthenospheric, MORB-related component.

(*c*) Because intershield differences in radiogenic isotopic ratios are not correlated with abundances of major elements, there is also evidence for differences in the melting process. For example, intershield differences in SiO_2 and total iron contents (e.g. relatively high SiO_2 and low total iron in Koolau lavas), may reflect differences in mean pressure of melt segregation. In addition, the absence of correlations between Rb/Sr and $^{87}Sr/^{86}Sr$ and Sm/Nd and $^{143}Nd/^{144}Nd$ indicate that the parent/daughter abundance ratios were affected by the partial melting process (e.g. different mean extents of melting for each shield) or the source compositions were recently affected by an enrichment (metasomatic?) process. Also, the intershield differences in incompatible element abundances are not consistent with the order of incompatibility typically inferred for partial melts of spinel peridotite (Sun & McDonough 1989, fig. 1). For example, Ti is a better intershield discriminant than Na or P, and Nb is a better discriminant than K or Rb (figures 2 and 3). Either the sources have variable Ti and Nb contents or the transition from partial melting of spinel peridotite to garnet peridotite increases the relative compatibility of K, Rb, Na and P. Unfortunately, rigorous assessment of how much of the intershield compositional differences reflect variations in pressure of melt segregation is not yet possible, because there are insufficient experimental data for melts in equilibrium with garnet peridotite.

5. Structure of the Hawaiian plume

Possible explanations for intershield differences in isotopic ratios of Sr, Nd and Pb are: (i) shallow mixing processes involving plume and oceanic lithosphere components; (ii) geochemical heterogeneities within a large plume, either intrinsic or resulting from entrainment of wallrocks during ascent; or (iii) relatively small, closely spaced, geochemically distinct diapirs with each shield forming from a different diapir.

In a $^{87}Sr/^{86}Sr$–$^{206}Pb/^{204}Pb$ plot, data for Hawaiian shield lavas do not trend toward the MORB field; therefore, West *et al.* (1987) concluded that shield lavas do not contain a significant amount of oceanic lithosphere or entrained MORB-related asthenosphere. However, a plume conduit, *ca.* 40 km radius, with systematic spatial geochemical heterogeneities could explain the intershield differences, especially if the melt ascent paths are nearly vertical (Ribe & Smooke 1987). If these spatial heterogeneities are inherited from the boundary layer source, it is surprising that these small-scale variations can be preserved during ascent over 100s of kilometres. An alternative is that entrainment of wallrocks, perhaps lower mantle (Hart *et al.* 1992), creates the spatial geochemical heterogeneity. If interaction of the plume conduit with the lithosphere results in tilting of the conduit and asymmetry in the extent of melting contours, then intershield differences in mean extent and pressure of melting are expected (figure 6*a*, *b*).

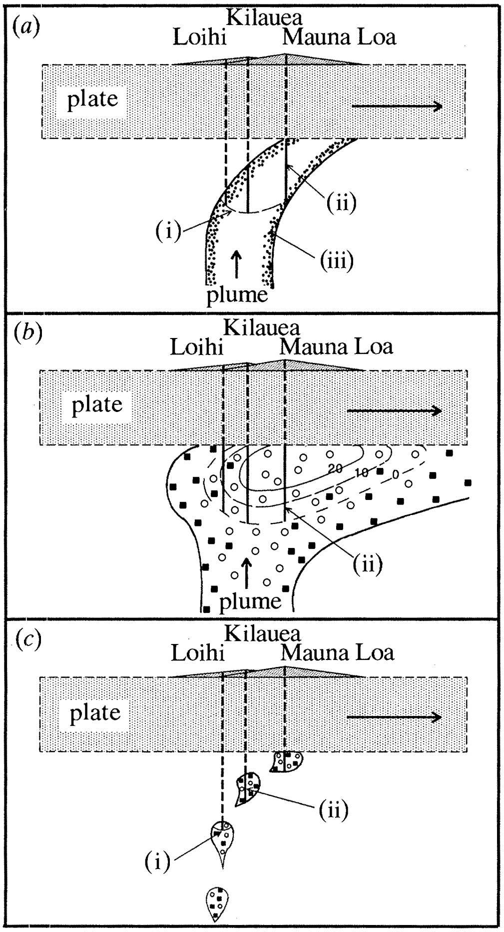

Figure 6. Plume models that could explain the observed intershield geochemical differences. In each sketch, the oceanic lithosphere (plate) is 70 km thick and melting initiates at a depth of 130 km (Watson & McKenzie 1991). (i) Beginning of melting; (ii) melting column; (iii) entrained mantle. In (*a*) the plume conduit has relatively cool margins which are a mixture of plume material and entrained wallrock. Within the conduit, melting initiates at the solidus labelled (i). Some of the intershield geochemical differences are a result of conduit tilting at shallow depths, i.e. within 70 km of the lithosphere–asthenosphere contact. Because the centre of the conduit is at a higher temperature than the margins, lavas derived from the centre (Kilauea shield) segregate at a higher mean pressure than lavas derived from the margin (Mauna Loa shield). However, the melting column for Mauna Loa lavas is longer than that for Kilauea lavas; therefore, Mauna Loa lavas reflect a larger, mean extent of melting, consistent with their lower abundances of incompatible elements relative to Kilauea lavas. An implication of this model is that the geochemical characteristics of a shield should change as it moves from the position of Loihi to Mauna Loa. In (*b*) the plume configuration is similar to (*a*) except that the plume conduit contains intrinsic geochemical heterogeneities (indicated by the varying proportion of open circles and closed squares) and interaction between the plume conduit and lithosphere is more extensive resulting in distortion of the axisymmetric extent of melting contours (labelled 0, 10 and 20 in figure) illustrated in fig. 12 of Watson & McKenzie (1991). Mauna Loa lavas reflect a larger mean extent of melting than Kilauea lavas. In (*c*) the plume is composed of discrete diapirs which may reflect discontinuous input from the plume source or transformation of a continuous conduit into discrete diapirs as the plume ascends and interacts with the mantle (Liu *et al.* 1991). An attractive aspect of this model is that geochemical differences between shields are expected because each diapir could be different in composition (indicated by variable proportion of open circles and closed squares),

An alternative hypothesis is that the plume conduit is discontinuous and is defined by a series of distinct diapirs. For example, Skilbeck & Whitehead (1978) proposed that tilting of the plume conduit may be sufficient to create diapiric instability. Although Griffiths & Richards (1989) used the sharpness of the bend in the Hawaiian Emperor chain to conclude that the tilt of the Hawaiian plume conduit is not sufficient to cause diapiric instability, Whitehead & Helfrich (1990) note that this conclusion is dependent on the assumed radius of the plume conduit and the viscosity of the surrounding mantle. Moreover, there are other mechanisms for creating a non-continuous plume conduit (Olson 1990). For example, the supply of buoyant material in the plume source may be episodic rather than continuous, or diapir chains can develop as a continuous conduit passes through a phase change during ascent (Liu *et al.* 1991). From a geochemical perspective, creation of each shield from an individual diapir is attractive because in addition to likely intrinsic geochemical differences between diapirs, differences in size and temperature of each diapir would lead to differences in mean extent and depth of melting. There is, however, a serious volume problem with small diapirs. Diapirs with radii of less than 20 km and limited vertical extent (figure 6*c*) are not large enough to create the voluminous Hawaiian shields, typically 25000–50000 km^3 (Frey & Roden 1987). A possible alternative model (not shown in figure 6) is that solitary waves develop in a small radius plume conduit. Because these waves have closed streamlines, each wave can transport large amounts of geochemically distinct material from the source region (Whitehead & Helfrich 1990). Interaction of this conduit with the lithosphere might result in each shield forming from a different solitary wave.

An important aspect of the models in figure 6 is that the radius of the plume conduits are small, not more than 40 km, compared to the large, more than 1000 km topographic anomaly of the Hawaiian swell. However, this anomaly may result from horizontal divergence of the plume as it encounters the lithosphere (Loper 1991). Moreover, consideration of thermal-chemical plumes shows that the thermal effects are dispersed much more widely than the compositional effects (Liu & Chase 1991*b*).

6. Conclusions

The intershield geochemical differences between Hawaiian shields provide several important constraints on plume dynamics, especially the processes that convert a deep mantle plume into discrete shield volcanoes. Specifically, (i) adjacent shields must have long-lived, and distinct magma ascent paths and (ii) melt formation must be restricted to a zone less than 50 km in width. Also the plume is heterogeneous in isotopic ratios and incompatible element abundance ratios involving Ti, Sr and Nb. Because Rb/Sr and Sm/Nd are not correlated with ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd, source heterogeneity was created relatively recently or the melting process changed these trace element abundance ratios. The processes occurring during melt formation and migration probably control intershield differences in major element contents. Finally, interaction of the plume conduit with the lithosphere must enable adjacent shields to form from geochemically different sources and enable each shield to be

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size and temperature, thereby leading to intershield differences in extent of melting and mean pressure of melt segregation. However, this model has a significant problem stemming from the size of the shields. A conservative estimate for large shield, like Mauna Loa, is 45000 km^3. If the mean extent of melting is not more than 20%, a small radius diapir is not large enough to form a volcanic shield.

characterized by a different mean extent of melting and pressure of melt segregation. Although the validity of these inferences requires further evaluation, it is evident that Hawaiian shields did not form from a geochemically homogeneous plume.

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