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Chemical heterogeneity in the Hawaiian mantle plume from the alteration and dehydration of recycled oceanic crust

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ABSTRACT

Inter-shield differences in the composition of lavas from Hawaiian volcanoes are generally thought to result from the melting of a heterogeneous mantle source containing variable amounts or types of oceanic crust (sediment, basalt, and/or gabbro) that was recycled into the mantle at an ancient subduction zone. Here we investigate the origin of chemical heterogeneity in the Hawaiian mantle plume by comparing the incompatible trace element abundances of tholeiitic basalts from (1) the three active Hawaiian volcanoes (Kilauea, Mauna Loa, and Loihi) and (2) the extinct Koolau shield (a compositional end member for Hawaiian volcanoes). New model calculations suggest that the mantle sources of Hawaiian volcanoes contain a significant amount of recycled oceanic crust with a factor of ~ 2 increase from ~ 8 – 16% at Loihi and Kilauea to ~ 15 – 21% at Mauna Loa and Koolau. We propose that the Hawaiian plume contains a package of recycled oceanic crust (basalt and gabbro, with little or no marine sediment) that was altered by interaction with seawater or hydrothermal fluids prior to being variably dehydrated during subduction. The recycled oceanic crust in the mantle source of Loihi and Kilauea lavas is dominated by the uppermost portion of the residual slab (gabbro-free and strongly dehydrated), whereas the recycled oceanic crust in the mantle source of Mauna Loa and Koolau lavas is dominated by the lowermost portion of the residual slab (gabbro-rich and weakly dehydrated). The present-day distribution of compositional heterogeneities in the Hawaiian plume cannot be described by either a large-scale bilateral asymmetry or radial zonation. Instead, the mantle source of the active Hawaiian volcanoes is probably heterogeneous on a small scale with a NW–SE oriented spatial gradient in the amount, type (i.e., basalt vs. gabbro), and extent of dehydration of the ancient recycled oceanic crust.

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1. Introduction

The deep recycling of oceanic crust at ancient subduction zones and its eventual return towards the surface by upwelling mantle plumes is thought to be one of the major controls on the compositional heterogeneity of the Earth's mantle (e.g., Chauvel et al., 1992; Hofmann and White, 1982; Stracke et al., 2003; Weaver, 1991). Strong evidence for this recycling hypothesis comes from the chemical and isotopic diversity of basaltic lavas that are produced by partial melting of the mantle at oceanic “hotspots”, such as Samoa (e.g., Jackson et al., 2007), Iceland (e.g., Chauvel and Hémond, 2000; Kokfelt et al., 2006), and the Canary Islands (e.g., Gurenko et al., 2009). Like other ocean-island basalts

(OIB), lavas from Hawaiian shield volcanoes display relatively large variations in major and trace element abundances, and Pb, Sr, Nd, and O isotope ratios that have been interpreted to result, in large part, from the melting of a heterogeneous mantle source (e.g., Frey et al., 1994; Frey and Rhodes, 1993; Huang and Frey, 2003; Jackson et al., 2012; Ren et al., 2009; Tanaka et al., 2008; Tatsumoto, 1978; Weis et al., 2011). Many of these compositional features, such as the unusually high SiO_2 and Ni abundances and high $\delta^{18}\text{O}$ values of lavas from the extinct Koolau shield, seem to require the presence of ancient recycled oceanic crust in the Hawaiian plume (e.g., Hauri, 1996; Herzberg, 2006; Sobolev et al., 2005; Wang et al., 2010). This recycled oceanic crust may be composed of a mixture of lower crustal gabbro, mid-ocean ridge basalt (MORB), and marine sediment that was metamorphosed to eclogite or pyroxenite during subduction.

Hawaiian shields form two parallel chains (“Kea” and “Loa”) that are named after the largest volcanoes in each trend, Mauna Kea and Mauna Loa (Fig. 1). Lavas from Kea- and Loa-trend

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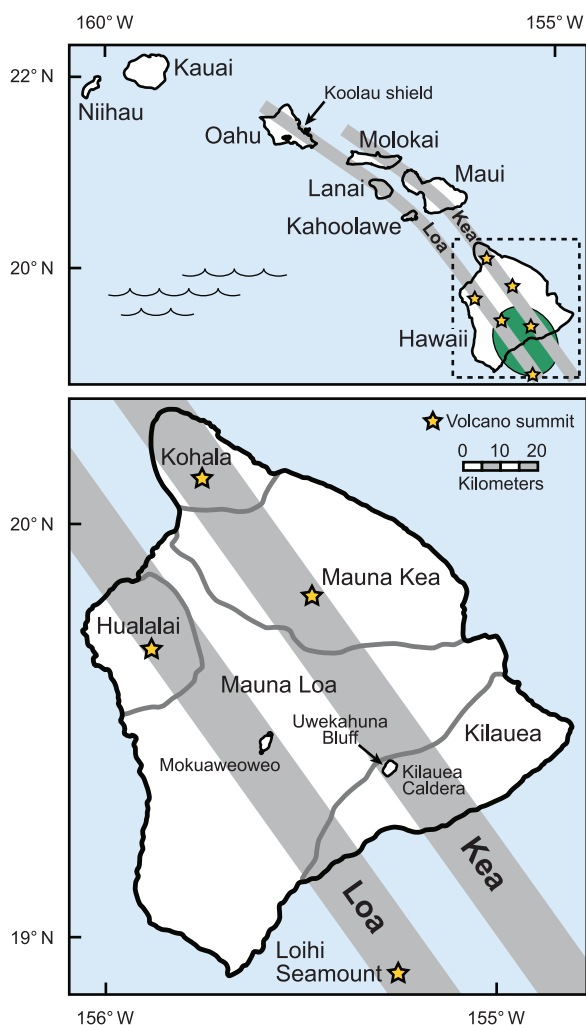


Fig. 1. Map of the Hawaiian Islands (top) and the Island of Hawaii (bottom) showing the locations of the active volcanoes (Kilauea, Mauna Loa, and Loihi) and extinct shields (e.g., Koolau). The small oval shows the approximate location of the Hawaiian mantle plume. The Kea and Loa trends are defined primarily by the summits of the youngest Hawaiian volcanoes (Jackson et al., 1972), but these trends are thought to extend at least to the Islands of Oahu (Loa trend) and Molokai (Kea trend). The Uwekahuna Bluff section is located on the northwest wall of Kilauea Caldera at the summit of this volcano (Casadevall and Dzurisin, 1987; Marske et al., 2007). Mokuaweoweo is the summit caldera of Mauna Loa.

volcanoes display systematic differences in their Pb, Sr, and Nd isotope ratios. For example, lavas from the Koolau, Lanai, and Kahoolawe shields (members of the Loa trend, along with Mauna Loa and Loihi Seamount) have relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and low $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios. These end-member Loa-type isotopic signatures are thought to reflect a greater abundance of recycled sediment-bearing upper oceanic crust in the source of these lavas (e.g., Gaffney et al., 2005; Huang et al., 2005; Huang and Frey, 2005; Lassiter and Hauri, 1998). In contrast, lavas from Mauna Kea and Kilauea (members of the Kea trend) have low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and high $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios that do not trend towards East Pacific Rise MORB (e.g., Pietruszka and Garcia, 1999). This observation has led to the idea that the source of end-member Kea-type lavas is dominated by a long-term depleted component that is compositionally distinct from the ambient Pacific upper mantle (e.g., Bryce et al., 2005; Lassiter and Hauri, 1998; Pietruszka and Garcia, 1999; West et al., 1987). The exact nature of this depleted Hawaiian plume component is a matter of debate, but explanations range from a deep mantle peridotite that is essentially free of recycled oceanic crust (e.g.,

Hauri, 1996; Lassiter et al., 1996) to recycled oceanic lithosphere that is dominated by hydrothermally altered lower crust and lithospheric upper mantle (e.g., Gaffney et al., 2005; Lassiter and Hauri, 1998). In the latter case, the distinctive chemistry of Kea- and Loa-type lavas might result from sampling different portions of a package of ancient recycled oceanic lithosphere.

The recycled oceanic crust in the Hawaiian plume would most likely occur as veins, blobs, or filaments in a matrix of ambient mantle peridotite (e.g., Farnetani and Hofmann, 2010). Such small-scale compositional heterogeneity (e.g., Frey and Rhodes, 1993) is consistent with the short-term fluctuations of Pb, Sr, and Nd isotope ratios in lavas from Kilauea (Marske et al., 2007, 2008; Pietruszka and Garcia, 1999) and Mauna Loa (Kurz et al., 1995; Rhodes and Hart, 1995). These fast isotopic variations over years to decades probably result from rapid changes in the pathways that melt follows from each volcano's source region (which is heterogeneous on a small scale) to the surface (Pietruszka et al., 2006). In addition, the Hawaiian plume is thought to be heterogeneous on a large scale with either a NE–SW oriented bilateral asymmetry (Abouchami et al., 2005; Weis et al., 2011) or a radial zonation (e.g., Bryce et al., 2005; Hauri, 1996; Lassiter et al., 1996). The “bilateral asymmetry” model is based mostly on the observation that lavas from Loa-trend volcanoes tend to have higher $^{208}\text{Pb}/^{204}\text{Pb}$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$ compared to lavas from Kea-trend volcanoes (Fig. 2A). This spatial dichotomy of Pb isotope ratios is thought to have existed for at least 5 Myr, and may result from the deep entrainment of recycled oceanic crust into the Loa side of the Hawaiian plume (Weis et al., 2011). The “radial zonation” model invokes a heterogeneous core of upwelling plume material (dominated by recycled oceanic crust) that is sheathed by entrained ambient lower to upper Pacific mantle peridotite. In this scenario, Mauna Loa is located above the plume core, whereas Loihi and Kilauea are passing over the distal ring of entrained mantle (e.g., Bryce et al., 2005).

Hawaiian lavas also record temporal and spatial variations in ratios of trace elements that are incompatible during partial melting of the mantle. Relatively large short-term fluctuations of some trace element ratios (e.g., La/Yb and Nb/Y) in lavas from individual volcanoes (up to a factor of ~ 2) probably result mostly from changes in the degree of partial melting (e.g., Hofmann et al., 1984; Pietruszka and Garcia, 1999; Rhodes and Hart, 1995). These melting-related trace element variations are superimposed on enigmatic inter-shield differences in ratios of highly incompatible trace elements, such as Nb/La or Ba/Th (e.g., Frey et al., 1994; Hémond et al., 1994; Hofmann and Jochum, 1996). The Nb/La and Ba/Th ratios of tholeiitic Hawaiian basalts (and similar ratios, like Th/La) are thought to preserve any relative variations in the mantle source composition (despite a range in the degree of partial melting; Hofmann and Jochum, 1996). Thus, the inter-shield differences in these trace element ratios indicate that the source of Hawaiian lavas is chemically heterogeneous. Most of this chemical heterogeneity is thought to be an ancient source characteristic (Huang et al., 2005; Huang and Frey, 2003) rather than an effect of recent source depletion as observed during the Puu Oo eruption of Kilauea Volcano (Pietruszka et al., 2006). A comprehensive model to explain the ancient source-related trace element signatures of Hawaiian lavas has remained elusive. However, the variations of some highly incompatible trace element ratios may track the presence of recycled plagioclase-rich oceanic gabbro (based on high Ba/Th and low Th/La; Hofmann and Jochum, 1996) and/or marine sediment (based on low Nb/La; Huang and Frey, 2005) in the Hawaiian plume.

In this study, we investigate the origin of chemical heterogeneity in the Hawaiian plume using the incompatible trace element abundances of a suite of prehistoric (AD 900–1400) Kilauea lavas that were collected from the northwest wall of the

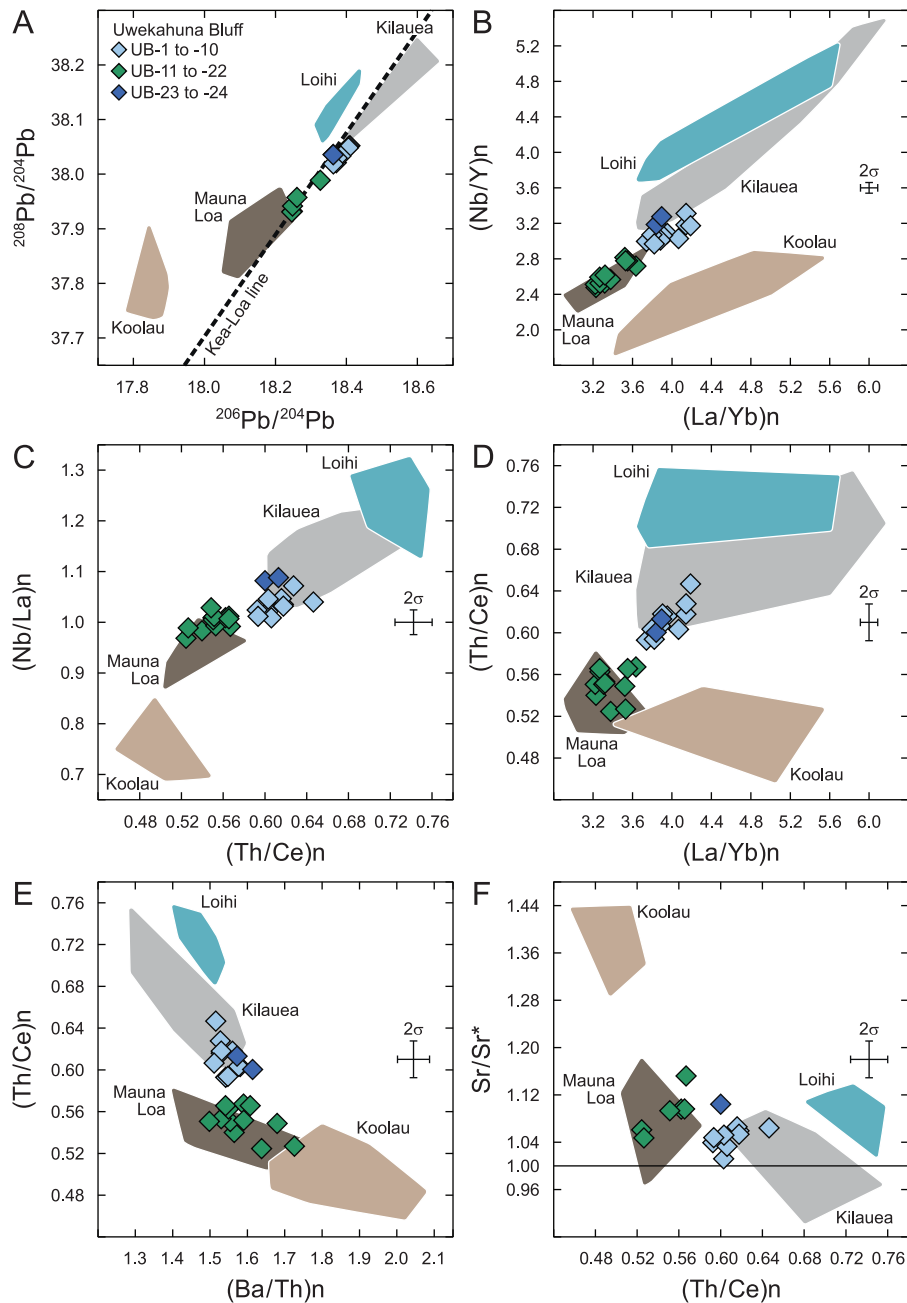


Fig. 2. Plots of the Pb isotope (A) and trace element (B–F) ratios of Hawaiian lavas. The Kea-Loa line in (A) is from [Abouchami et al. \(2005\)](#). The trace element abundances of the lavas were normalized to the primitive mantle values of [Sun and McDonough \(1989\)](#). The parameter Sr/Sr^* is defined as the Sr concentration of the sample divided by the average of its Pr and Nd concentrations (Sr^*), all normalized to the primitive mantle. A lava with no Sr anomaly will have a Sr/Sr^* value of 1.0. The data on (F) were filtered to remove any samples that have differentiated significantly beyond olivine control. Literature data sources: Kilauea ([Abouchami et al., 2005](#); [Garcia et al., 1996, 2000, 2003](#); [Marske et al., 2007, 2008](#); [Pietruszka and Garcia, 1999](#)), Mauna Loa ([Marske et al., 2007](#); [Wanless et al., 2006](#); [Weis et al., 2011](#)), Loihi tholeiitic basalts ([Garcia et al., 1998a](#); [Norman and Garcia, 1999](#); [A. Pietruszka, unpublished data, 2012](#)), and Koolau ([Abouchami et al., 2005](#); [Frey et al., 1994](#); [Huang and Frey, 2005](#); [Norman and Garcia, 1999](#); [Tanaka et al., 2002](#)). The Kilauea fields include only historical lavas (and only high precision Pb isotopic analyses), whereas the Mauna Loa fields include only historical and young prehistoric subaerial lavas ([Marske et al., 2007](#); [Weis et al., 2011](#)) and young lavas from the submarine radial vents ([Wanless et al., 2006](#)). Only Koolau lavas from the Makapuu stage of this volcano were plotted. The Oahu North-a Koolau samples from [Tanaka et al. \(2002\)](#) are included because they are compositionally similar to Makapuu-stage lavas. No alkalic lavas from Loihi Seamount were considered, which minimizes the potential effects of a very low degree of partial melting on the ratios of highly incompatible trace elements. All literature Pb isotope ratios were normalized to the same values for the NBS981 standard as described by [Marske et al. \(2007\)](#). After [Abouchami et al. \(2005\)](#) and [Weis et al. \(2011\)](#), the Pb isotope ratios of two outliers (one lava from Koolau and another from Mauna Loa) are not shown. The 2σ error bars are shown on each plot (unless they are smaller than the size of the symbols).

volcano's summit caldera at Uwekahuna Bluff ([Fig. 1](#)). These lavas display a systematic temporal fluctuation in Pb ([Fig. 2A](#)), Sr, and Nd isotope ratios that spans the compositional divide between historical Kilauea lavas, and historical and young prehistoric lavas from the neighboring volcano, Mauna Loa ([Marske et al., 2007](#)). Here we compare the chemistry of the Uwekahuna Bluff lavas to literature data for lavas from (1) the active Hawaiian volcanoes

(Kilauea, Mauna Loa, and Loihi) because they collectively provide a snapshot of the present-day compositional heterogeneity in the Hawaiian plume and (2) the well studied extinct Koolau shield because they record more extreme Pb ([Fig. 2A](#)), Sr, and Nd isotope ratios that are not expressed at the active volcanoes. The combined data are used to (1) propose a quantitative mantle source and melting model that accounts for the trace element abundances of

Hawaiian lavas in terms of the recycling hypothesis and (2) re-evaluate previous models for the origin and spatial distribution of chemical heterogeneities in the Hawaiian plume.

2. Methods

The trace element abundances of twenty-four lavas from the Uwekahuna Bluff of Kilauea Volcano (Fig. 1) were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) at the Australian National University (see Appendix A for data and methods). For comparison, literature ICP-MS trace element abundances of tholeiitic basalts from Kilauea, Mauna Loa, Loihi, and Koolau (Fig. 2) were corrected for inter-laboratory differences as described in Appendix A. Since the chemistry of Koolau lavas may have been affected by post-eruptive alteration (Frey et al., 1994; Huang and Frey, 2005), analyses of samples from this extinct shield were rejected if they failed to meet freshness criteria: loss-on-ignition < 1 wt%, $K_2O/P_2O_5 > 1.2$, $K/Rb < 1000$, and $Ba/Rb < 30$. Nevertheless, we used only the most alteration-resistant elements for Koolau lavas with the exception of Ba, a key element in this study (i.e., Rb and U were excluded). Barium is thought to be less sensitive to post-eruptive alteration than Rb and U, but it may be mobilized during tropical weathering (Albarède, 1996). Thus, the Ba abundances of the Koolau lavas should probably be regarded as minimum values.

3. Results

The prehistoric Kilauea lavas from Uwekahuna Bluff display small, but significant, ranges in ratios of incompatible trace elements that expand the known compositional range for this volcano. Ratios of highly over moderately incompatible trace elements (e.g., Nb/Y vs. La/Yb) show the most variation, and range from values similar to historical Kilauea lavas to values that overlap with lavas from Mauna Loa (Fig. 2B). A similar behavior is observed for ratios of highly incompatible trace elements (e.g., Nb/La vs. Th/Ce), although the magnitude of the variation is smaller (Fig. 2C). In general, Uwekahuna Bluff lavas from the middle of the sampled stratigraphic section (UB-11 to 22) have Mauna Loa-like trace element ratios, whereas lavas from the upper (UB-1 to 10) and lower (UB-23 to 24) portions of the section have compositions that are similar to historical Kilauea lavas. Thus, these prehistoric Kilauea lavas display a temporal fluctuation in trace element ratios that links the otherwise distinctive chemistry of Kilauea and Mauna Loa lavas.

4. Chemical heterogeneity in the Hawaiian plume

Kilauea lavas display a strong melting-related correlation between ratios of highly over moderately incompatible trace elements (Fig. 2B) with a factor of ~ 2 variation in their Nb/Y and La/Yb ratios (cf., Pietruszka and Garcia, 1999). Lavas from the other Hawaiian volcanoes display similar trends (of variable magnitude) that may be offset to somewhat higher (Loihi) or lower (Koolau) Nb/Y ratios at a given La/Yb ratio (Fig. 2B). These offsets reflect systematic source-related variations in ratios of highly incompatible trace elements, such as Nb/La and Th/Ce (Fig. 2C). Loihi and Kilauea lavas have relatively high Nb/La and Th/Ce ratios, whereas Mauna Loa and Koolau lavas (especially the Makapuu-stage lavas from Koolau, hereafter referred to simply as “Koolau” lavas) have relatively low Nb/La and Th/Ce ratios. A source control on the Nb/La and Th/Ce ratios of Hawaiian lavas is verified by the fact that neither parameter correlates with trace element ratios (e.g., Nb/Y or La/Yb) that would be dominated by

the melting process (Fig. 2D). In this section, we review and reinterpret the origin of these source-related trace element signatures.

4.1. Thorium and uranium depletions from altered oceanic crust

Hawaiian lavas from both Kea-trend (Fig. 3A) and Loa-trend (Fig. 3B) volcanoes display pronounced negative anomalies of Th and U relative to Ba, Nb, and the light rare-earth elements (LREE) on a primitive mantle normalized trace element diagram (Hofmann and Jochum, 1996; Huang and Frey, 2003; Ren et al., 2009). These Th–U depletions are reflected in the relatively high Ba/Th and low Th/La (or Th/Ce) ratios of Hawaiian lavas (Fig. 2E) compared to most other OIB and the primitive mantle (Hofmann and Jochum, 1996), with the notable exceptions of basalts from Iceland (e.g., Chauvel and Hémond, 2000; Kokfelt et al., 2006) and the Galapagos Islands (Saal et al., 2007). This behavior for Ba, Th, and La (or Ce, because these LREE behave in a nearly identical fashion during magmatic processes) does not follow the normal order of trace element incompatibility during partial melting (or depletion) of the mantle (Fig. 2E).

Hofmann and Jochum (1996) proposed that the high Ba/Th and low Th/La ratios of Hawaiian lavas are a signature of recycled oceanic gabbro (now eclogite or pyroxenite) in the mantle source because Ba and La are expected to be enriched (relative to Th and U) in gabbros that have accumulated plagioclase. If the high Ba/Th and low Th/La ratios result from the melting of recycled plagioclase-rich gabbro, then Hawaiian lavas should have larger positive anomalies of Sr (that correlate with Ba/Th and Th/La) due to the compatibility of Sr in plagioclase (Ba and the LREE are only moderately incompatible in this mineral; Bindeman and Davis, 2000). Although positive Sr anomalies up to $\sim 350\%$ have been observed in rare melt inclusions trapped by olivines from Mauna Loa picrites (Sobolev et al., 2000), most olivine-controlled Hawaiian lavas (Fig. 2F) have relatively small Sr anomalies ($< 10\%$ excess Sr) and even the relatively Sr-rich Koolau lavas reach only $\sim 40\%$ excess Sr (cf., Ba/Th ratios elevated by 30–100% compared to the primitive mantle; Fig. 2E). Neither the Th/La (or Th/Ce, as plotted here in Fig. 2F) nor the Ba/Th (not shown) ratios of Hawaiian lavas correlate with the magnitude of their Sr anomalies. Furthermore, lavas from Kilauea, Mauna Loa, and Loihi have Rb/Th ratios (Fig. 3A and B) that are similar to or (like Ba/Th) greater than the primitive mantle (up to a factor of ~ 1.4 for Rb/Th). An enrichment of Rb (relative to Th) cannot result from the melting of recycled plagioclase-rich gabbro because Rb (like Th and U) is expected to be highly incompatible in plagioclase (Bindeman and Davis, 2000).

The trace element patterns of Hawaiian lavas (Fig. 3A and B) are thought to reflect a combination of two main processes (e.g., Hofmann et al., 1984; Hofmann and Jochum, 1996; Norman and Garcia, 1999): (1) a range in the degree of partial melting to variably enrich the melt in the more incompatible elements (e.g., Rb, Ba, Th, U, Nb, and the LREE) and (2) the presence of residual garnet in the source to retain the HREE and Y. Superimposed on this overall pattern of trace element enrichment (as the incompatibility of the elements increase) is a reversal towards lower abundances of the most highly incompatible elements from U (Nb for Koolau lavas) to Rb (Fig. 3A and B). This reversal, and especially the low Th and U abundances relative to Nb and the LREE, can be explained if Hawaiian lavas are derived from a source that is depleted in highly incompatible elements (e.g., Pietruszka and Garcia, 1999). A depleted source is consistent with the observation by Hofmann (1986) that the U/Nb and Th/Nb ratios of Hawaiian lavas are similar to MORB, and both are significantly lower than the primitive mantle. This depleted source might include a mixture of recycled MORB and oceanic

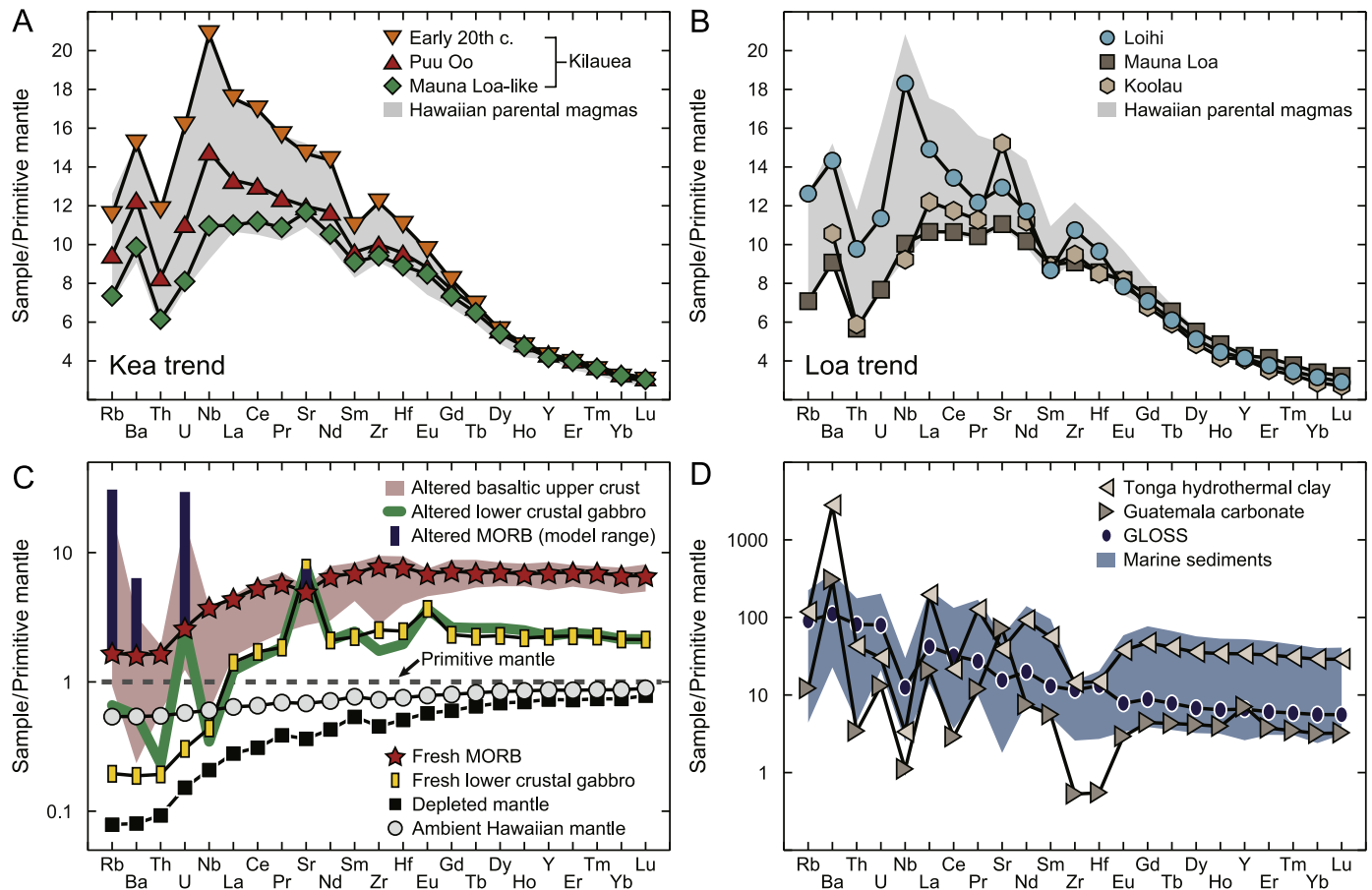


Fig. 3. Primitive mantle normalized trace element diagrams for Hawaiian parental magmas from volcanoes on the Kea (A) and Loa (B) trends, and potential source components in the Hawaiian mantle plume (C and D). All of the trace element abundances were normalized to the primitive mantle values of Sun and McDonough (1989). The compositions of the parental magmas and mantle source components were estimated as described in Appendix A. Three parental magmas for Kilauea were chosen to represent the wide range in the chemistry of lavas from this Kea-trend volcano (Fig. 2), whereas average parental magma compositions were used for each of the Loa-trend volcanoes. The three parental magmas for Kilauea represent (1) lavas from the Puu Oo eruption, (2) early 20th century summit lavas, and (3) the Mauna Loa-like lavas from the Uwekahuna Bluff. For comparison, the fields on (A) and (B) show the range for all of the Hawaiian parental magmas. The ambient Hawaiian mantle is assumed to be a 50:50 mixture of depleted (Workman and Hart, 2005) and primitive (Sun and McDonough, 1989) mantle. The field on (C) shows the range in the composite chemistry of the basaltic “upper crust” (dominated by variably altered MORB) drilled from the oceanic crust at Site 417/418 (Staudigel et al., 1996), Site 504B (Bach et al., 2003), and Site 801 (Kelley et al., 2003). The vertical bars on (C) show the maximum enrichment of Rb, Ba, U, and Sr during alteration of fresh MORB that was permitted for the model. The other trace element abundances for altered MORB were assumed to be identical to the average of fresh MORB (Hofmann, 1988; Sun and McDonough, 1989; Salters and Stracke, 2004). The composition of fresh lower crustal gabbro was calculated from the composite chemistry of altered gabbros drilled from the lower oceanic crust at Site 735B (Bach et al., 2001) by comparison with fresh MORB to remove the effects of low-temperature alteration on Rb, Ba, and U, while preserving positive anomalies of Sr and Eu (the latter signatures are thought to be related to plagioclase accumulation). On (D), two types of marine sediment, carbonate from Guatemala and hydrothermal clay from Tonga, are compared with GLOSS and the field for bulk sediments being subducted regionally at individual trenches worldwide (Plank and Langmuir, 1998).

gabbro (in addition to some form of “depleted mantle”) because each of these materials are expected to have low Th and U abundances (relative to Nb and the LREE) as part of an overall trace element pattern that is depleted in highly incompatible elements (Fig. 3C).

An enrichment of Ba (and Rb to a lesser extent) relative to Th and U in Hawaiian lavas is superimposed upon this pattern of source depletion. These signatures might result from the alteration of the recycled oceanic crust by interaction with seawater or hydrothermal fluids prior to subduction. This process is known to selectively increase the abundances of Rb, Ba, Sr, and depending on redox conditions, U in altered MORB and oceanic gabbro (Fig. 3C) with little or no effect on the REE or elements such as Th, Nb, Zr, Hf, and Y (e.g., Bach et al., 2003; Kelley et al., 2003; Staudigel et al., 1996). If the elevated Rb and Ba abundances of such altered oceanic crust (at least partially) survived the process of subduction, the recycled oceanic crust in the source of Hawaiian lavas would be enriched in Rb and Ba relative to Th and U. Partial melting of this altered oceanic crust would yield parental magmas with apparent Th–U depletions

(along with high Ba/Th and low Th/La or Th/Ce ratios relative to the primitive mantle).

4.2. Niobium anomalies from dehydrated oceanic crust

The Nb/La ratios of Hawaiian lavas straddle the primitive mantle value (Fig. 2C). Koolau lavas have relatively low Nb/La ratios compared to other Hawaiian lavas (e.g., Frey et al., 1994; Huang and Frey, 2005) and the primitive mantle. Huang and Frey (2005) proposed that the relatively low Nb abundances of Koolau lavas (along with other chemical signatures, such as low Th/La and Nb/Sr ratios) are controlled mostly by the presence of recycled marine sediment in the mantle source of this volcano. In their model, two types of marine sediment, similar to either carbonate from Guatemala (< 3% required) or hydrothermal clay from Tonga (< 0.25% required), were suggested based partly on the low Nb/La and Th/La ratios of these materials. However, marine sediments (Fig. 3D), including the specific examples used by Huang and Frey (2005), are characterized by negative Nb

anomalies relative to Th, U, and the LREE (Plank and Langmuir, 1998). Mass balance calculations suggest that bulk addition of either type of sediment (Guatemala carbonate or Tonga hydrothermal clay; Plank and Langmuir, 1998) in the amounts proposed by Huang and Frey (2005) to a 50:50 mixture of depleted (Workman and Hart, 2005) and primitive (Sun and McDonough, 1989) mantle would create negative anomalies of Nb ($\sim 30\%$ relative to Th and La) that are preserved when the source is melted (because Th, Nb, and La are highly incompatible during partial melting of the mantle). Negative Nb anomalies are not observed in Koolau or other Hawaiian lavas (Fig. 3A and B).

The depletion of Nb (relative to La) in Koolau lavas is part of a smooth trend of decreasing abundances of highly incompatible trace elements that extends from La to Nb to Th (Fig. 3B). Although it is possible that the Koolau source contains a very small amount of sediment (insufficient to create a negative Nb anomaly), this trace element pattern is consistent with a simpler origin from a source that is depleted in highly incompatible elements (analogous to our interpretation based on the Th–U depletions of Hawaiian lavas). Again, this depleted source (with Nb/La, Th/Nb, and Th/La ratios less than the primitive mantle) might include a mixture of recycled MORB and oceanic gabbro (in addition to some form of “depleted mantle”) that was altered to increase its Rb and Ba abundances (because Koolau lavas have elevated Ba/Th ratios like other Hawaiian lavas). Thus, we conclude that recycled marine sediment is not required to account for the trace element signatures of Koolau or other Hawaiian lavas, and may even be prohibited (depending on the amount and composition of the sediment).

Unlike Koolau lavas, Nb is anomalously enriched in Loihi (e.g., Garcia et al., 1998a) and Kilauea lavas (Fig. 3A and B), which display Nb/La ratios greater than the primitive mantle (Fig. 2C). The parameter Nb/Nb* (defined as the Nb concentration of the sample divided by the average of its Th and La concentrations, all normalized to the primitive mantle) is a measure of the size of the Nb anomaly. The average Nb/Nb* values of Hawaiian lavas increase from Koolau (~ 1.0 , or no anomaly) to Mauna Loa and the Mauna Loa-like prehistoric Kilauea lavas (~ 1.2 – 1.3) to historical Kilauea lavas (~ 1.4) to the highest values at Loihi (~ 1.5). These positive Nb anomalies cannot be explained simply by partial melting of a depleted source that contains altered oceanic crust (as discussed above). An additional process or source component is required.

Positive Nb anomalies are a common feature of OIB (e.g., Jackson et al., 2008). This signature is typically explained by the presence of recycled oceanic crust (in the OIB mantle source) that was dehydrated (or even partially melted) during subduction (probably in the presence of residual rutile) to create a residual slab that is relatively enriched in Nb (e.g., Hofmann, 1997; Jackson et al., 2008; Weaver, 1991). Observations of island-arc basalt chemistry (e.g., Elliott et al., 1997) and experimental studies (Kessel et al., 2005; Kogiso et al., 1997) suggest that fluid-immobile elements like Nb are preferentially retained in the oceanic crust as it is subducted and dehydrated, whereas fluid-mobile elements (especially Rb, Ba, U, Pb, and Sr, but also Th and the LREE based on the experimental studies) are variably lost to the overlying mantle wedge. The preferential retention of Nb and other fluid-immobile high field-strength elements (HFSE) in the residual slab would be strongly enhanced (e.g., Kessel et al., 2005) by the presence of residual rutile (a common phase in refractory eclogites from metamorphosed oceanic crust; Becker et al., 2000) because the HFSE are highly compatible in this mineral (e.g., Xiong et al., 2005). Thus, the high Nb/La ratios of Loihi and Kilauea lavas (and their positive anomalies of Nb) most likely result from the presence of recycled oceanic crust in the Hawaiian plume that was dehydrated during subduction. In this scenario, the recycled

oceanic crust in the source of Koolau lavas would have been the least dehydrated (to preserve a relatively simple pattern of source depletion in the highly incompatible trace elements), whereas the recycled oceanic crust in the source of Loihi lavas would have been the most dehydrated (to create the largest positive anomalies of Nb and highest Nb/La ratios observed in Hawaiian shield lavas).

5. A quantitative recycling model for Hawaiian lavas

In this section, we present a quantitative model for the origin of chemical heterogeneity in the Hawaiian plume. The goal was to (1) match the incompatible trace element abundances of six parental magmas from four Hawaiian volcanoes (Fig. 3A and B) by partial melting of altered and variably dehydrated oceanic crust (in a matrix of ambient depleted Hawaiian mantle; Fig. 3C) and (2) infer the incompatible trace element abundances in the mantle source of each parental magma (prior to melting). Two different scenarios were modeled: (1) melting of a lithologically homogeneous peridotite source and (2) melting of a lithologically heterogeneous source composed of peridotite, eclogite, and pyroxenite (Sobolev et al., 2005). For simplicity, the recycled oceanic crust was limited to a combination of two components (Fig. 3C), altered MORB and fresh lower crustal gabbro. The effect of marine sediment was considered only for the Koolau parental magma. The composition of the altered MORB was assumed to be modified by the process of subduction, according to the mobility of the elements in fluids as the slab is dehydrated (based on experiments; Kogiso et al., 1997; Kessel et al., 2005). This approach is similar to Stracke et al. (2003), except that we allowed the extent of dehydration to vary. Scenario #1 represents the simplest case in which the recycled oceanic crust and peridotite matrix have homogenized through mixing and diffusion to create a fertile peridotite (e.g., Putirka et al., 2011). Scenario #2 is a two-stage melting model based on Sobolev et al. (2005). First, deep melting of eclogite produces a high-degree melt that incompletely reacts with the surrounding peridotite matrix to produce a secondary pyroxenite, an eclogite residue that is too refractory to melt further, and unreacted peridotite. Second, as upwelling continues,

Table 1
Summary of the model results for Hawaiian parental magmas.

	Loihi	Kilauea		Mauna Loa	Koolau	
		Early 20th c.	Puu Oo			Mauna Loa-like
<i>Lithologically homogeneous source</i>						
Altered MORB (%)	10.7	10.7	13.0	11.9	13.8	7.9
Lower crustal gabbro (%)	0.0	0.0	0.0	2.6	2.7	6.9
Total oceanic crust (%)	10.7	10.7	13.0	14.4	16.6	14.8
Gabbro/MORB	0.00	0.00	0.00	0.22	0.20	0.88
X_f (%)	11.1	6.1	4.0	2.6	2.0	0.2
F_{pd} (%)	4.6	4.0	6.4	8.4	9.8	8.6
<i>Lithologically heterogeneous source</i>						
Altered MORB (%)	8.4	8.5	12.4	13.1	17.9	10.2
Lower crustal gabbro (%)	0.0	0.0	0.0	2.8	3.2	8.2
Total oceanic crust (%)	8.4	8.5	12.4	15.9	21.1	18.4
Gabbro/MORB	0.00	0.00	0.00	0.21	0.18	0.80
X_f (%)	12.6	6.3	3.1	1.9	1.3	0.0
F_{pd} (%)	3.1	2.6	4.0	5.0	5.6	5.1
F_{px} (%)	18.4	15.8	23.7	30.2	33.5	30.3

X_f is the extent of dehydration for the altered MORB; F_{pd} is the melt fraction for the peridotite source; F_{px} is the melt fraction for the pyroxenite source. The full model results are presented in Appendix A.

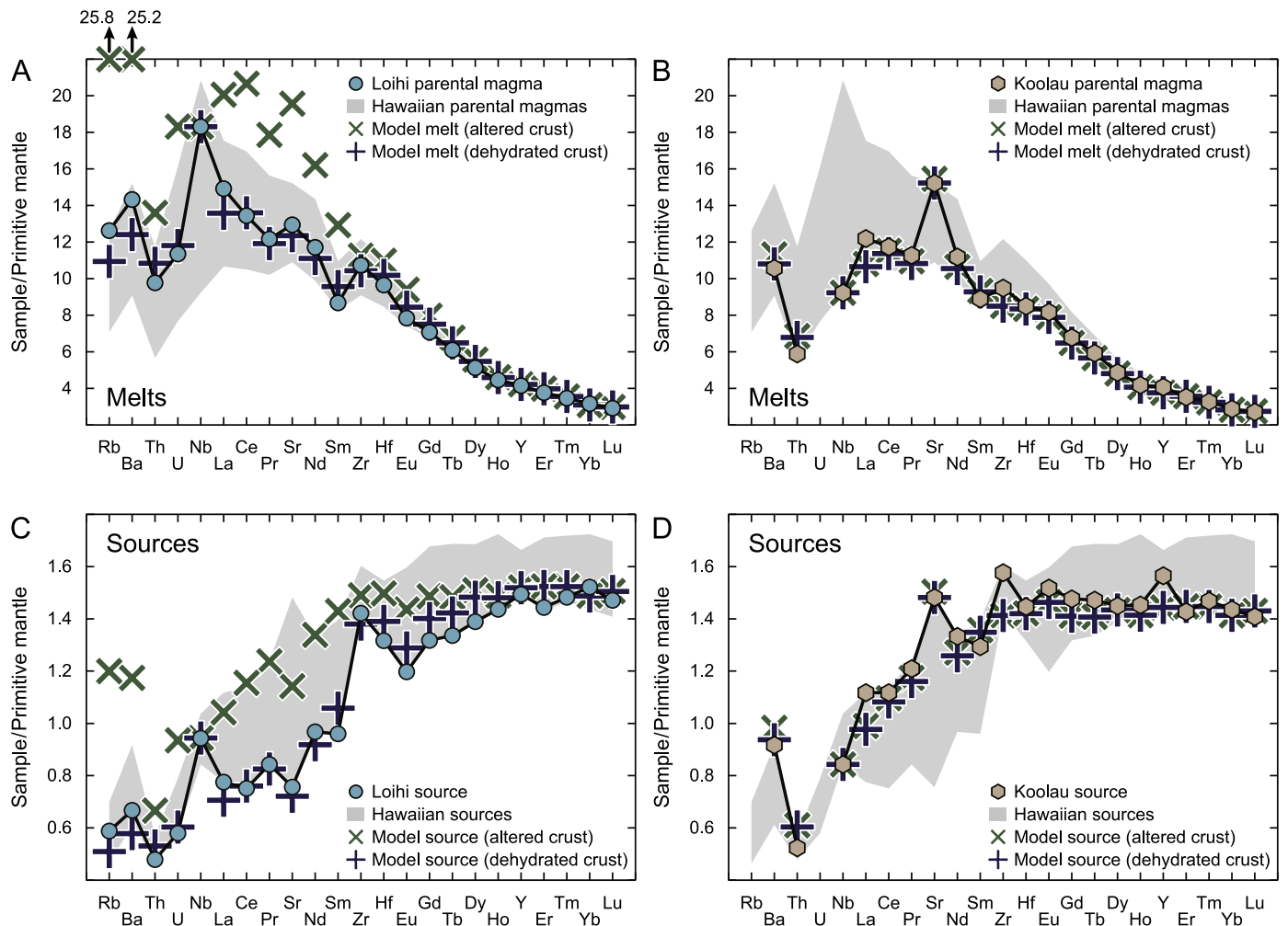


Fig. 4. Mantle source and melting model for Hawaiian parental magmas, assuming a lithologically homogeneous source. All of the trace element abundances were normalized to the primitive mantle values of Sun and McDonough (1989). The parental magma compositions for Loihi (A) and Koolau (B) were estimated as described in Appendix A. The equivalent mantle sources for Loihi (C) and Koolau (D) were calculated by “unmelting” each parental magma using the model parameters in Table 1 (as described in Appendix A). These parental magmas and sources represent the target compositions for the model. For comparison, the fields show the range for all of the Hawaiian parental magmas (A and B) and mantle sources (C and D). Model sources, shown as crosses and pluses in (C) and (D), were estimated from a combination of the recycled oceanic crust (altered MORB and fresh lower crustal gabbro) and ambient Hawaiian mantle shown in Fig. 3 (see Table 1 and Appendix A for the full model parameters). Partial melting of these sources (to the same degree used to calculate the mantle source from the “unmelted” parental magma of each volcano) results in the model melts, shown as crosses and pluses in (A) and (B). The symbols used for these model results represent the compositions of the melts and sources either with (pluses) or without (crosses) dehydration of the altered MORB during subduction. Similar plots of the model results for parental magmas from Kilauea and Mauna Loa are shown in Appendix A.

the unreacted peridotite and secondary pyroxenite undergo partial melting, and these melts mix to form the parental magma. These scenarios (and related assumptions) are detailed in Appendix A.

Similar results were obtained for both scenarios (Table 1). For simplicity, the general behavior of the trace element model is illustrated for the case of a lithologically homogeneous source with results for the Loihi (Fig. 4A) and Koolau (Fig. 4B) parental magmas. The full model results for both scenarios and all of the parental magmas are presented in Appendix A. For each parental magma, we performed a forward model (to match its trace element abundances; Fig. 4A and B) and an inverse model (to infer its mantle source composition; Fig. 4C and D). The enrichment of Rb, Ba, and U in the altered MORB was allowed to vary within the limits shown on Fig. 3C (Sr enrichment is expected to be relatively minor, and thus, was ignored). The remaining free parameters of the forward model (the amounts of MORB and gabbro, the extent of dehydration of the altered MORB during subduction, and the degree of partial melting) were changed iteratively to minimize the % difference between the calculated and observed trace element abundances of each parental magma

(identical parameters were used for the corresponding inverse model). A similar approach was followed for the case of a lithologically heterogeneous source. In both scenarios, the trace element abundances of the parental magmas were matched to ~4% (on average) with maximum residuals of 15% for the case of a lithologically homogeneous source and 25% for the case of a lithologically heterogeneous source.

For the Loihi parental magma, the model predicts a gabbro-free source with ~8–11% altered MORB (Table 1). The model fit is optimized if the composition of the altered MORB is assumed to be modified by dehydration with ~11–13% fluid loss (the highest value inferred for the Hawaiian parental magmas in Table 1). Without dehydration of the altered MORB, the model results give Rb, Ba, Th, U, LREE (from La to Sm), and Sr concentrations that are ~24–104% too high in both the model melt (Fig. 4A) and source (Fig. 4C). These results highlight our interpretation (based on Nb/La ratios) that the recycled oceanic crust in the source of Loihi lavas must have experienced the greatest amount of dehydration during subduction.

For the Koolau parental magma, a mixture ~8–10% altered MORB and ~7–8% gabbro with little or no dehydration of the altered MORB

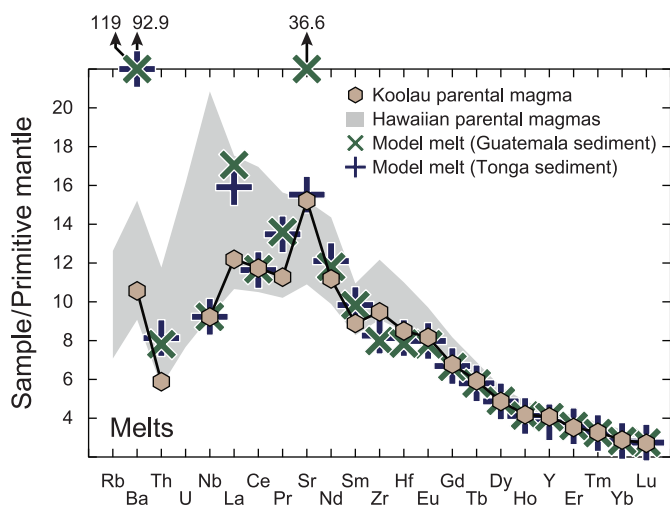


Fig. 5. Modification of the melting model for the Koolau parental magma, assuming the presence of recycled marine sediment in the mantle source. All of the trace element abundances were normalized to the primitive mantle values of Sun and McDonough (1989). Model results are shown for the bulk addition of 3% Guatemala carbonate (crosses) and 0.25% Tonga hydrothermal clay (pluses), the two types of sediment proposed to be present in the mantle source of Koolau lavas by Huang and Frey (2005). The compositions of these sediments from Plank and Langmuir (1998) are shown in Fig. 3D. The parental magma compositions for Koolau and the other Hawaiian volcanoes (field) were estimated as described in Appendix A. The extent of dehydration for the altered MORB (0.2% fluid loss) and the ratio of gabbro to altered MORB (0.88) in the Koolau source were assumed to be the same as the sediment-free case (Fig. 4B and D). The two types of sediment were added in bulk (i.e., no dehydration during subduction). The other model parameters for partial melting of this sediment-bearing source are discussed in the text.

during subduction (< 0.2% fluid loss) provides a good fit to both the model melt (Fig. 4B) and source (Fig. 4D). The relatively large amount of recycled gabbro inferred for the source of Koolau lavas (compared to the other Hawaiian parental magmas in Table 1) results from (1) the larger positive anomaly of Sr observed in the Koolau parental magma (Fig. 3B) and (2) the fact that lower crustal gabbro is the only Sr-enriched source component in the model (Fig. 3C). This result is consistent with the idea (based on rare Sr-rich melt inclusions in Mauna Loa olivines) that recycled oceanic gabbro with (former) accumulated plagioclase is present in the mantle source of Hawaiian lavas with positive Sr anomalies (Sobolev et al., 2000). However, the model results for Loihi (and the other gabbro-free parental magmas) confirm that recycled plagioclase-rich gabbro is not required to explain the low Th/La (or Th/Ce) and high Ba/Th ratios of Hawaiian lavas (relative to the primitive mantle).

The effects of recycled sediment on the model results for the Koolau parental magma were evaluated using a lithologically homogeneous source (Fig. 5). Bulk addition of either 3% Guatemala carbonate or 0.25% Tonga hydrothermal clay (Fig. 3D) has only a small effect (cf., the model results for the sediment-free case in Table 1) on the total amount of recycled oceanic crust (7% altered MORB and 6% gabbro for both types of sediment) and melt fraction (8–9%). However, bulk sediment addition (Fig. 5) leads to a melt with an over-enrichment of Ba and (to a lesser extent) the LREE, negative anomalies of Nb (~23–26% relative to Th and La) and Ce (~21–24% relative to La and Pr), and for the case of Guatemala carbonate, a large positive anomaly of Sr (~190% relative to Pr and Nd). None of these signatures are observed in Koolau or other Hawaiian lavas (Fig. 3A and B).

The abundances of Ba, the LREE, and Sr (when the Sr-rich Guatemala carbonate is considered) in the Koolau parental magma cannot be matched unless the sediment is assumed to be strongly dehydrated during subduction (> 60% fluid loss). However, this would strip > 96% these elements (along with Rb,

Th, and U) from the sediment, and effectively remove many of the chemical signatures (such as low Th/La, Nb/La, and Nb/Sr ratios) that made sediment a potentially important source component for Koolau lavas. Thus, any recycled sediment in the mantle source of Hawaiian lavas must be either (1) chemically modified (possibly due to extensive dehydration during subduction) or, if added in bulk, (2) extremely minor in abundance and/or (3) different in composition from the sediments proposed by Huang and Frey (2005). Huang et al. (2009) argued that the high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Koolau and other Loa-type lavas are difficult to explain without the presence of recycled marine sediment (with a seawater-like Sr isotopic composition) in the mantle source of these volcanoes. Alternately, the elevated Sr isotope ratios of these lavas could result from (1) seawater alteration of the recycled oceanic crust to increase its $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (Sobolev et al., 2011) and (2) preservation of this seawater-derived Sr during subduction, if the recycled oceanic crust was only weakly dehydrated (as expected for Koolau). This possibility is evaluated further in Appendix A. In any case, the trace element model results confirm that recycled marine sediment is not required to explain the chemical signatures of Hawaiian lavas.

6. Crustal recycling and the distribution of heterogeneities in the Hawaiian plume

The mantle sources of Hawaiian volcanoes appear to contain a significant amount of recycled oceanic crust (Table 1) with a factor of ~2 increase from Loihi (~8–11%) and Kilauea (a wide range of ~9–16% for the three parental magmas from this volcano) to Mauna Loa and Koolau (~15–21%). Thus, “enriched” (i.e., recycled oceanic crust) and “depleted” (i.e., ambient Hawaiian mantle) materials are likely to be present in the sources of both Kea- and Loa-trend volcanoes. For comparison, Sobolev et al. (2005) obtained similar estimates (based on trace element abundances) for the amount of recycled oceanic crust in the source of lavas from Kilauea (12%) and Mauna Loa (26%). These results are broadly consistent with other calculations (based on TiO_2 contents and trace element abundances) for up to ~10% recycled oceanic crust in the source of Hawaiian lavas (Prytulak and Elliott, 2007; Putirka et al., 2011). The calculated amount of recycled lower crustal gabbro (and the gabbro/MORB ratio) in the sources of the volcanoes increases (as the total amount of recycled oceanic crust increases) from zero at Loihi and Kilauea (except for the Mauna Loa-like Kilauea lavas with ~3% gabbro) to intermediate values at Mauna Loa (~3%) to the largest value at Koolau (~7–8%). In contrast, the calculated extent of dehydration for the altered MORB decreases strongly from Loihi (~11–13%) to Kilauea (a wide range of ~2–6%) to Mauna Loa (~1%) to Koolau (< 0.2%). These model trends suggest that chemical heterogeneity in the Hawaiian plume was created by a continuum of processes related to the recycling of oceanic crust (rather than simply its presence or absence in the mantle source).

We propose that (1) the Hawaiian plume contains a package of altered oceanic crust (basalt and gabbro, with little or no marine sediment) that was variably dehydrated during subduction to create a residual slab and (2) individual Hawaiian volcanoes have sampled portions of this residual slab that correspond to different depths within the original oceanic crust (cf., Gaffney et al., 2005; Lassiter and Hauri, 1998). The uppermost part of the residual slab is expected to be dominated by MORB (with a low ratio of gabbro/MORB) and might have experienced the greatest extent of dehydration during subduction because it would be the most altered and hydrated portion of the oceanic crust. In contrast, the lowermost gabbro-rich part of the residual slab would potentially be less altered, and thus, might have been less susceptible to

dehydration during subduction (consistent with the paucity of high-temperature alteration in the deepest gabbros drilled from the oceanic crust and their MORB-like $\delta^{18}\text{O}$ values; Bach et al., 2001; Gao et al., 2006). In this scenario, the recycled oceanic crust in the mantle source of Loihi and Kilauea lavas would be dominated by the uppermost portion of the residual slab (gabbro-free and strongly dehydrated), whereas the recycled oceanic crust in the mantle source of Mauna Loa and Koolau lavas would be dominated by the lowermost portion of the residual slab (gabbro-rich and weakly dehydrated).

This interpretation is opposite to the analogous model of Lassiter and Hauri (1998) and Gaffney et al. (2005). In their view,

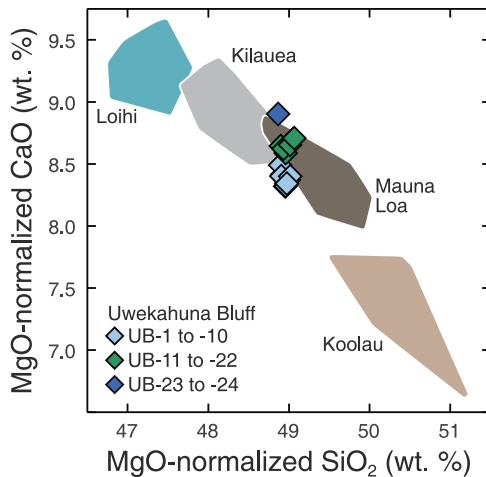


Fig. 6. Plot of the MgO-normalized CaO and SiO₂ abundances of Hawaiian lavas. The CaO and SiO₂ contents of the lavas were normalized to 16 wt% MgO by addition or subtraction of equilibrium olivine in small steps as described in Appendix A. Thus, the variations in the MgO-normalized CaO and SiO₂ abundances of the lavas are thought to track changes in the mantle source and melting processes. The data sources are listed in the caption to Fig. 2 with additional tholeiitic basalt glasses from Loihi Seamount (Pietruszka et al., 2011). The data were filtered to remove (1) any samples that have differentiated significantly beyond olivine control and (2) olivine-rich samples with > 20 wt% MgO. The 2 σ error bar is smaller than the size of the symbols.

the high $\delta^{18}\text{O}$ values of Koolau lavas (relative to MORB) result from the melting of recycled seawater-altered upper oceanic crust (and sediment), whereas the low $\delta^{18}\text{O}$ values of Kea-type lavas (relative to MORB) result from the melting of recycled hydrothermally altered lower oceanic crust and lithospheric mantle. However, the unusually low $\delta^{18}\text{O}$ values of some glasses and olivines from Kilauea and Mauna Kea are now thought to be caused mostly by crustal contamination within the magmatic plumbing systems of these volcanoes (e.g., Garcia et al., 1998b; Wang and Eiler, 2008). Nevertheless, the average $\delta^{18}\text{O}$ values of “melts” (inferred from olivine, assuming a constant fractionation factor between melt and olivine of 0.5‰; Eiler et al., 1997) from Loihi (a MORB-like value of 5.7‰; Eiler et al., 1996) and Koolau (6.4‰; Eiler et al., 1996; Wang et al., 2010) are distinct. These (presumably) mantle-derived differences in $\delta^{18}\text{O}$ can potentially be explained using the trace element model parameters (Table 1) as described in Appendix A. Briefly, the MORB-like $\delta^{18}\text{O}$ values of Loihi melts could result from extensive dehydration of the altered MORB in the source of this volcano. This process might preferentially release ¹⁸O-enriched fluids to the overlying mantle wedge from hydrous phases associated with the low-temperature seawater alteration of MORB, leaving behind a residual slab with nearly MORB-like $\delta^{18}\text{O}$ values. This view is consistent with the relatively high $\delta^{18}\text{O}$ values (relative to MORB) of some olivines (up to ~5.8‰) and unusual olivine-hosted melt inclusions (up to ~11‰) in island arc lavas (Eiler et al., 1998, 2000). In this context, the relatively high $\delta^{18}\text{O}$ values of Koolau melts might be explained if the recycled MORB in the source of this volcano was only weakly dehydrated during subduction, preserving its ¹⁸O-enriched signature of low-temperature seawater alteration.

The trace element model results (Table 1) suggest that both Loihi and Kilauea lavas are derived from the melting of significant amounts of recycled oceanic crust (~8–16%) that was strongly dehydrated (more so for Loihi) in an ancient subduction zone (rather than a source composed solely of entrained ambient lower to upper Pacific mantle). Thus, we propose that Loihi lavas are simply a more extreme variant of historical Kilauea (i.e., Kea-type) lavas despite (1) the location of Loihi on the Loa trend (Fig. 1) and (2) the elevated ²⁰⁸Pb/²⁰⁴Pb at a given ²⁰⁶Pb/²⁰⁴Pb in Loihi lavas (Fig. 2A), which is commonly interpreted as a Loa-type

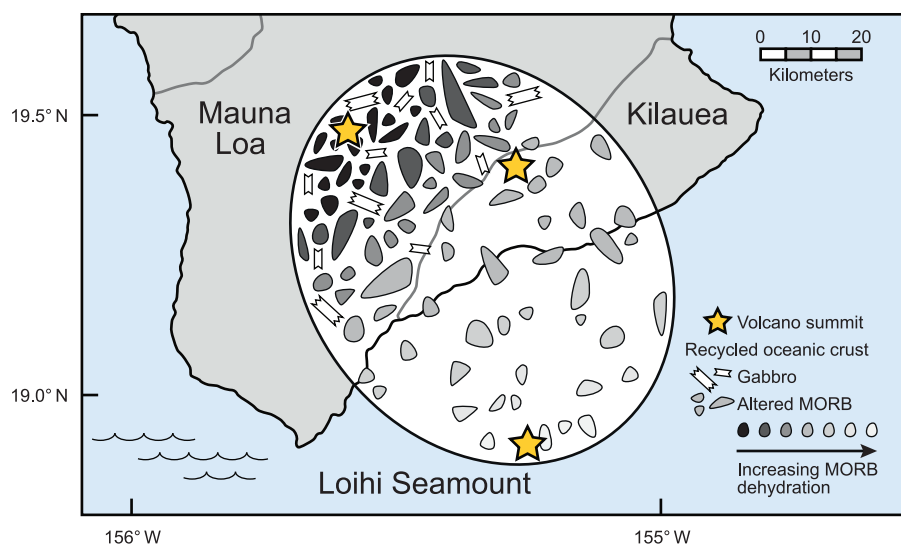


Fig. 7. Model for the present-day distribution of small-scale compositional heterogeneities in the Hawaiian plume. The trace element model results suggest that the Hawaiian plume contains recycled oceanic crust (schematically illustrated as blobs of altered MORB and angular fragments of gabbro) in a matrix of ambient mantle (white areas between the blobs and fragments). The amount of recycled oceanic crust (and the gabbro/MORB ratio) increases from Loihi to Kilauea to Mauna Loa. In contrast, the extent of subduction-related dehydration of the altered MORB decreases from Loihi to Kilauea to Mauna Loa. Lavas from Kilauea Volcano sample a wide range of heterogeneities due to a spatial gradient in the amount, type (i.e., MORB vs. gabbro), and extent of dehydration of the recycled oceanic crust beneath this volcano. The relative amounts of recycled MORB and gabbro are based on the model results (Table 1), but are exaggerated for clarity.

signature (Abouchami et al., 2005; Weis et al., 2011). A Kea-type signature for Loihi lavas is also consistent with (1) their generally Kilauea-like Pb (Fig. 2A), Sr, and Nd isotope ratios (Garcia et al., 1998a) and (2) their end-member MgO-normalized CaO and SiO₂ abundances that are similar to Kilauea lavas (Fig. 6). An analogous link (between a Kea-trend volcano and Loihi-like lavas) is demonstrated by the “Kea hi-8” lavas drilled from Mauna Kea, which have Loihi-like high ²⁰⁸Pb/²⁰⁴Pb at a given ²⁰⁶Pb/²⁰⁴Pb (Eisele et al., 2003) and low MgO-normalized SiO₂ contents (Rhodes and Vollinger, 2004). The origin of the MgO-normalized major element variations of Hawaiian lavas is controversial (e.g., Putirka et al., 2011). However, Jackson et al. (2012) suggested that the relatively low MgO-normalized SiO₂ abundances of Loihi lavas might result from the preferential loss of silica during subduction of the recycled oceanic crust in the source of this volcano (with little or no silica loss from the recycled oceanic crust in the source of the Koolau lavas).

If our inferences are correct, the present-day distribution of compositional heterogeneities in the Hawaiian plume cannot be described by either a large-scale bilateral asymmetry (which requires Loihi to erupt Loa-type lavas) or a radial zonation (which requires an ambient depleted mantle source for Loihi and Kilauea lavas). Instead, the mantle source of the active Hawaiian volcanoes is probably heterogeneous on a small scale with a NW–SE oriented spatial gradient in the amount, type (i.e., basalt vs. gabbro), and extent of dehydration of the recycled oceanic crust (Fig. 7). The source-related trace element (Fig. 2C) and Pb, Sr, and Nd isotope (Marske et al., 2007) ratios of the prehistoric Kilauea lavas from the Uwekahuna Bluff (which trend from Kilauea-like to Mauna Loa-like and back) indicate that both Kea- and Loa-type lavas can erupt from a single Hawaiian volcano over a short period of time (< 500 yr). This observation can be explained if the mantle source of Kilauea lavas (Fig. 7) contains small-scale Loa-like heterogeneities (in addition to more typical Kea-like heterogeneities). This interpretation is consistent with the Mauna Loa-like affinities of the Ba/Th, ²⁰⁶Pb/²⁰⁴Pb, and ⁸⁷Sr/⁸⁶Sr ratios of some lavas from the Puu Oo eruption of Kilauea Volcano (Marske et al., 2008; Pietruszka et al., 2006), and the discovery of a range of Loa- to Kea-type compositions in olivine-hosted melt inclusions from lavas erupted at individual Hawaiian volcanoes (Ren et al., 2005).

The Kea isotopic end member of Hawaiian lavas, characterized by high ²⁰⁶Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb, is thought to derive from the melting of relatively young (< 1.5 Ga) source materials with high ²³⁸U/²⁰⁴Pb (μ) ratios (Eisele et al., 2003). Many studies have proposed that more extreme examples of this HIMU-type signature in OIB result from the melting of ancient recycled oceanic crust with high Th/Pb and U/Pb ratios (e.g., Chauvel et al., 1992; Hofmann and White, 1982; Stracke et al., 2003; Weaver, 1991). The high Th/Pb and U/Pb ratios of the recycled oceanic crust are thought to derive mostly from the preferential loss of Pb (e.g., Stracke et al., 2003), which is expected to be significantly more fluid mobile than either Th or U during dehydration of the subducted slab (e.g., Kessel et al., 2005; Kogiso et al., 1997). The relatively high Pb isotope ratios of Loihi and Kilauea lavas (Fig. 2A) can potentially be explained in this context by the presence of strongly dehydrated ancient MORB (with high Th/Pb and U/Pb ratios due to preferential Pb loss) in their mantle source, and vice versa for the relatively low Pb isotope ratios of Mauna Loa and Koolau lavas (i.e., a source containing weakly dehydrated ancient MORB). This interpretation is consistent with the trace element model results (Table 1). In this view, variations in the extent of dehydration of the ancient recycled MORB (rather than simply its presence or absence) is probably the dominant control on the Pb isotope ratios of Hawaiian lavas. Future quantitative studies are needed to (1) account for the Pb, Sr, and Nd isotope

ratios of Kea- and Loa-type lavas (including the subtle differences in ²⁰⁸Pb/²⁰⁴Pb at a given ²⁰⁶Pb/²⁰⁴Pb) in terms of the recycling hypothesis, and (2) link our model for the present-day distribution of compositional heterogeneities in the Hawaiian plume (Fig. 7) to the evidence for long-term Pb, Sr, and Nd isotopic differences between lavas from Kea- and Loa-trend volcanoes (Weis et al., 2011).

7. Conclusions

The mantle sources of Hawaiian volcanoes contain a significant amount of ancient recycled oceanic crust with a factor of ~2 increase from ~8–16% at Loihi and Kilauea to ~15–21% at Mauna Loa and Koolau. Chemical heterogeneity in the Hawaiian plume results from the melting of a package of recycled oceanic crust (basalt and gabbro, with little or no marine sediment) that was altered by interaction with seawater or hydrothermal fluids prior to being variably dehydrated during subduction. The recycled oceanic crust in the mantle source of Loihi and Kilauea lavas is dominated by the uppermost portion of the residual slab (gabbro-free and strongly dehydrated), whereas the recycled oceanic crust in the mantle source of Mauna Loa and Koolau lavas is dominated by the lowermost portion of the residual slab (gabbro-rich and weakly dehydrated). The present-day distribution of compositional heterogeneities in the Hawaiian plume cannot be described by either a large-scale bilateral asymmetry or radial zonation. Instead, the mantle source of the active Hawaiian volcanoes is probably heterogeneous on a small scale with a NW–SE oriented spatial gradient in the amount, type (i.e., basalt vs. gabbro), and extent of dehydration of the ancient recycled oceanic crust.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.epsl.2012.10.030>.

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