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# Earth and Planetary Science Letters

journal homepage: [www.elsevier.com/locate/epsl](http://www.elsevier.com/locate/epsl)

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

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### ARTICLE INFO

#### Article history:

Received 14 February 2012

Received in revised form

21 September 2012

Accepted 19 October 2012

Editor: T. Elliot

Available online 26 November 2012

#### Keywords:

Hawaii  
geochemistry  
trace elements  
source heterogeneity  
mantle plumes  
crustal recycling

### 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  $\sim 2$  increase from  $\sim 8$ – $16\%$  at Loihi and Kilauea to  $\sim 15$ – $21\%$  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.

Published by Elsevier B.V.

### 1. Introduction

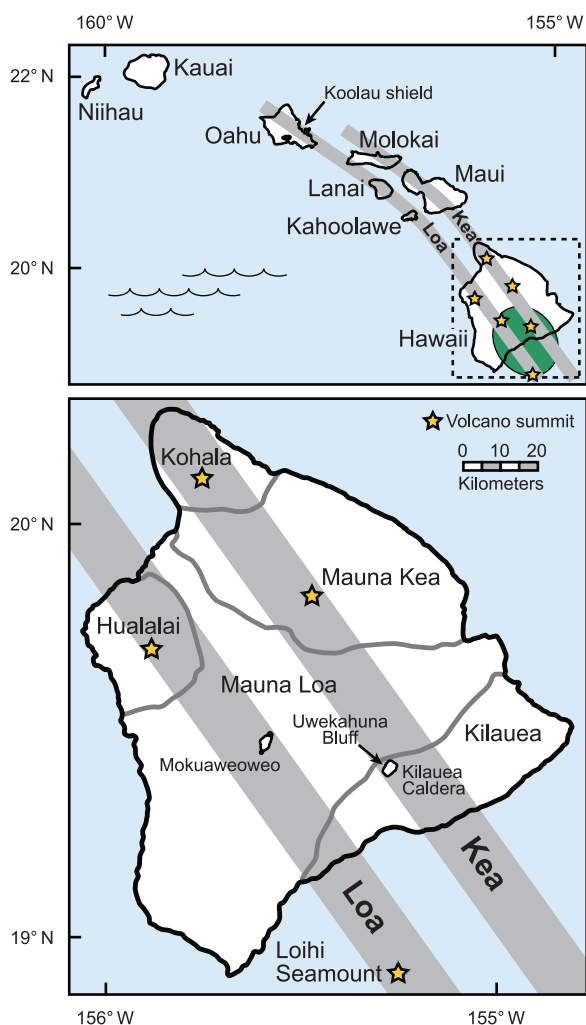
The deep recycling of oceanic crust at ancient subduction zones and its eventual return towards the surface by upwelling mantle plumes is thought to be one of the major controls on the compositional heterogeneity of the Earth's mantle (e.g., Chauvel et al., 1992; Hofmann and White, 1982; Stracke et al., 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  $\text{SiO}_2$  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  $\sim 2$ ) 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

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