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Rapid passage of a small-scale mantle heterogeneity through the melting regions of Kilauea and Mauna Loa Volcanoes

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Abstract

Recent Kilauea and Mauna Loa lavas provide a snapshot of the size, shape, and distribution of compositional heterogeneities within the Hawaiian mantle plume. Here we present a study of the Pb, Sr, and Nd isotope ratios of two suites of young prehistoric lavas from these volcanoes: (1) Kilauea summit lavas erupted from AD 900 to 1400, and (2) ^{14}C-dated Mauna Loa flows erupted from ~2580–140 yr before present (relative to AD 1950). These lavas display systematic isotopic fluctuations, and the Kilauea lavas span the Pb isotopic divide that was previously thought to exist between these two volcanoes. For a brief period from AD 250 to 1400, the ^{206}Pb/^{204}Pb and ^{87}Sr/^{86}Sr isotope ratios and ε_{Nd} values of Kilauea and Mauna Loa lavas departed from values typical for each volcano (based on historical and other young prehistoric lavas), moved towards an intermediate composition, and subsequently returned to typical values. This is the only known period in the eruptive history of these volcanoes when such a simultaneous convergence of Pb, Sr, and Nd isotope ratios has occurred. The common isotopic composition of lavas erupted from both Kilauea and Mauna Loa during this transient magmatic event was probably caused by the rapid passage of a small-scale compositional heterogeneity through the melting regions of both volcanoes. This heterogeneity is thought to have been either a single body (~35 km long based on the distance between the summits of these volcanoes) or the plume matrix itself (which would be expected to be present beneath both volcanoes). The time scale of this event (centuries) is much shorter than previously noted for variations in the isotopic composition of Hawaiian lavas due to the upwelling of heterogeneities within the plume (thousands to tens of thousands of years). Calculations based on the timing of the isotopic convergence suggest a maximum thickness for the melting region (and thus, the heterogeneity) of ~5–10 km. The small size of the heterogeneity indicates that melt can be extracted from small regions within the Hawaiian plume with minimal subsequent chemical modification (beyond the effects of crystal

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fractionation). This would be most effective if melt transport in the mantle beneath Hawaiian shield volcanoes occurs mostly in chemically isolated channels.

Keywords: Hawaii; volcanoes; Kilauea; Mauna Loa; mantle plumes; isotopes; geochemistry

1. Introduction

The temporal and spatial variations in the chemistry of basaltic lavas from volcanic "hotspots" like the Hawaiian Islands provide a distinctive fingerprint for the physical and chemical structure of mantle plumes (Frey and Rhodes, 1993; Kurz et al., 1995; Rhodes and Hart, 1995; Lassiter et al., 1996; DePaolo et al., 2001; Blichert-Toft et al., 2003; Eisele et al., 2003; Kurz et al., 2004; Abouchami et al., 2005; Bryce et al., 2005). Hawaii is one of the best locations to investigate the internal dynamics of an upwelling plume because the Hawaiian plume probably does not entrain a significant amount of the ambient upper mantle (Pietruszka and Garcia, 1999; Abouchami et al., 2005; Bryce et al., 2005) as it rises quickly towards the surface (>30 cm/yr near its central axis; Watson and McKenzie, 1991; Hauri et al., 1994; Sims et al., 1999; Pietruszka et al., 2001). This high rate of mantle upwelling is thought to bring a range of deep-mantle compositional heterogeneities into the shallow melting regions of Hawaiian volcanoes on a time scale of thousands to tens of thousands of years (Blichert-Toft et al., 2003; Kurz et al., 2004).

Previous studies have proposed two different length scales for the compositional heterogeneities within the Hawaiian plume. Large-scale heterogeneity (Frey and Rhodes, 1993; Kurz et al., 1995; Lassiter et al., 1996; DePaolo et al., 2001; Kurz et al., 2004; Abouchami et al., 2005; Bryce et al., 2005) has been inferred from intershield geochemical differences (e.g., Frey and Rhodes, 1993) and the long-term geochemical evolution of individual shield volcanoes (Kurz et al., 1995; Lassiter et al., 1996; DePaolo et al., 2001; Tanaka et al., 2002; Blichert-Toft et al., 2003; Eisele et al., 2003; Kurz et al., 2004; Abouchami et al., 2005; Bryce et al., 2005). The distinctive compositional and isotopic (e.g., $^{206}Pb/^{204}Pb$) signatures of adjacent Hawaiian volcanoes, such as Kilauea and Mauna Loa (Fig. 1), suggest that the source regions of these volcanoes have been physically and chemically distinct over most of their known eruptive history on the ~35 km scale of the distance between their summits (Frey and Rhodes, 1993). On a similar length scale, modern and ancient Hawaiian volcanoes appear to lie along two distinct loci of volcanism (Jackson et al., 1972): the northeastern "Kea" trend (including Kilauea) and the southwestern "Loa" trend (including Mauna Loa). Many studies (Tatsumoto, 1978; Stille et al., 1986; Frey and Rhodes, 1993; Lassiter et al., 1996; Abouchami et al., 2005) have noted that lavas from Kea- and Loa-trend volcanoes tend to be compositionally and isotopically distinct. In addition to these intershield geochemical differences, lavas from some Hawaiian volcanoes, such as Mauna Loa (Kurz et al., 1995; DePaolo et al., 2001), Mauna Kea (Lassiter et al., 1996; Blichert-Toft et al., 2003; Eisele et al., 2003; Kurz et al., 2004; Abouchami et al., 2005; Bryce et al., 2005), and Koolau (Tanaka et al., 2002), display a long-term evolution in their radiogenic isotope ratios. These observations are typically explained by the gradual passage of each volcano (as a consequence of the motion of the Pacific plate) over large-scale plume heterogeneities with a radial (Lassiter et al., 1996; DePaolo et al., 2001; Bryce et al., 2005), bilaterally asymmetric (Abouchami et al., 2005), or irregular (Kurz et al., 2004) distribution.

Hawaiian lavas also display variations of radiogenic isotope ratios that are thought to result from the partial melting of small-scale compositional heterogeneities within the Hawaiian plume (Frey and Rhodes, 1993; Rhodes and Hart, 1995; Kurz et al., 1995; Pietruszka and Garcia, 1999; Blichert-Toft et al., 2003; Eisele et al., 2003; Kurz et al., 2004; Abouchami et al., 2005; Bryce et al., 2005). The strongest evidence for the presence of such small-scale heterogeneity comes from the short-term fluctuations of Pb, Sr, and Nd isotope ratios on a time scale of years to centuries at Kilauea (Garcia et al., 1996; Pietruszka and Garcia, 1999; Garcia et al., 2000; Pietruszka et al., 2006) and Mauna Loa (Kurz et al., 1995; Rhodes and Hart, 1995), and fine-scale Pb isotopic variations at individual Hawaiian volcanoes (Eisele et al., 2003; Abouchami et al., 2005). The fastest isotopic variations at these volcanoes probably result from rapid changes in the pathway that melt follows from the volcano's source region (which is heterogeneous on a small scale) to the surface (Pietruszka et al., 2001, 2006).