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The link between Hawaiian mantle plume composition, magmatic flux, and deep mantle geodynamics

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A B S T R A C T

Oceanic island basalts sample mantle reservoirs that are isotopically and compositionally heterogeneous. The Hawaiian–Emperor chain represents ∼85 Myr of volcanism supplied by a deep mantle plume. Two geographically and geochemically delineated trends, Kea and Loa, are well documented within the Hawaiian Islands. Enriched Loa compositions originate from subduction recycled or primordial material stored in deep mantle reservoirs such as the large low shear velocity province (LLSVP) below Hawai'i. Loa compositions have not been observed along the Emperor Seamounts (>50 Ma), whereas lavas on the Hawaiian Islands (<6.5 Ma) sample both Kea and Loa sources. Lead isotopes in shield lavas along the Northwest Hawaiian Ridge (NWHR) spanning ∼42 Myr between the bend in the chain and the Hawaiian Islands record the geochemical evolution of the Hawaiian mantle plume over a time period when many geophysical parameters (volcanic propagation rate, magmatic flux, mantle potential temperature) increased significantly. Along the NWHR, the Loa geochemical component appears ephemerally, which we link to the sampling of different lower mantle compositional domains by the Hawaiian mantle plume. The plume initially sampled only the deep Pacific mantle (Kea component) from outside the LLSVP during the formation of the Emperor Seamounts. Southward migration and anchoring of the plume on the LLSVP led to entrainment of increasing amounts of LLSVP material (Loa component) along the NWHR as documented by an increase in $^{208}Pb^*/^{206}Pb^*$ with decreasing age. The correlation between $^{208}Pb^*/^{206}Pb^*$ and magmatic flux suggests source composition affects the magmatic flux, and explains why the Hawaiian mantle plume has dramatically strengthened through time.

1. Introduction

Long-lived intraplate oceanic islands and chains such as Iceland, Kerguelen, and Hawai'i are typically explained as the products of mantle plumes (Morgan, 1972; Boschi et al., 2007). Hawai'i is one of the most studied examples of such volcanism because it has a well-documented age progression along the chain (O'Connor et al., 2013; Garcia et al., 2015), is far from continent and mid-ocean ridge sources of contamination, has a deep mantle source (French and Romanowicz, 2015), and, on the main islands, exhibits two geographical trends, Kea and Loa, with distinct geochemical signatures (Abouchami et al., 2005; Tanaka et al., 2008; Weis et al., 2011). Although Hawai'i is the archetypal mantle plume, it is anomalous in many of its dynamic and geochemical features. For example, intraplate lavas worldwide are dominantly alkalic in composition, reflecting lower degrees of partial melting, in comparison to Hawai'i where ∼98% of eruptive products are of tholeiitic composition (Garcia et al., 2015). In addition, mantle plumes typically exhibit higher magmatic production at their initial arrival at the base of the lithosphere that dramatically diminishes with time, i.e. from melting the plume head to the plume tail (White, 1993; Jellinek and Manga, 2004; Kumagai et al., 2008). The volume flux of Hawaiian eruptive products, conversely, has increased ∼650% along the Northwest Hawaiian Ridge (NWHR) and an additional ∼375% during the formation of the Hawaiian Islands to an all-time high at the current locus of volcanism centered on Kilauea and Lō'ihi volcanoes (Wessel, 2016). At the same time, mantle potential temperature has increased (Tree, 2016), along with the volcano propagation rate (i.e. the frequency that a new volcano is created as the Pacific Plate moves over the Hawaiian mantle plume; O'Connor et al., 2013). Thus, on the basis of most major physical parameters, the Hawaiian mantle plume has strengthened, an unexplained observation that is a very unusual feature among mantle plumes worldwide (Tree, 2016). No modern geochemical study has

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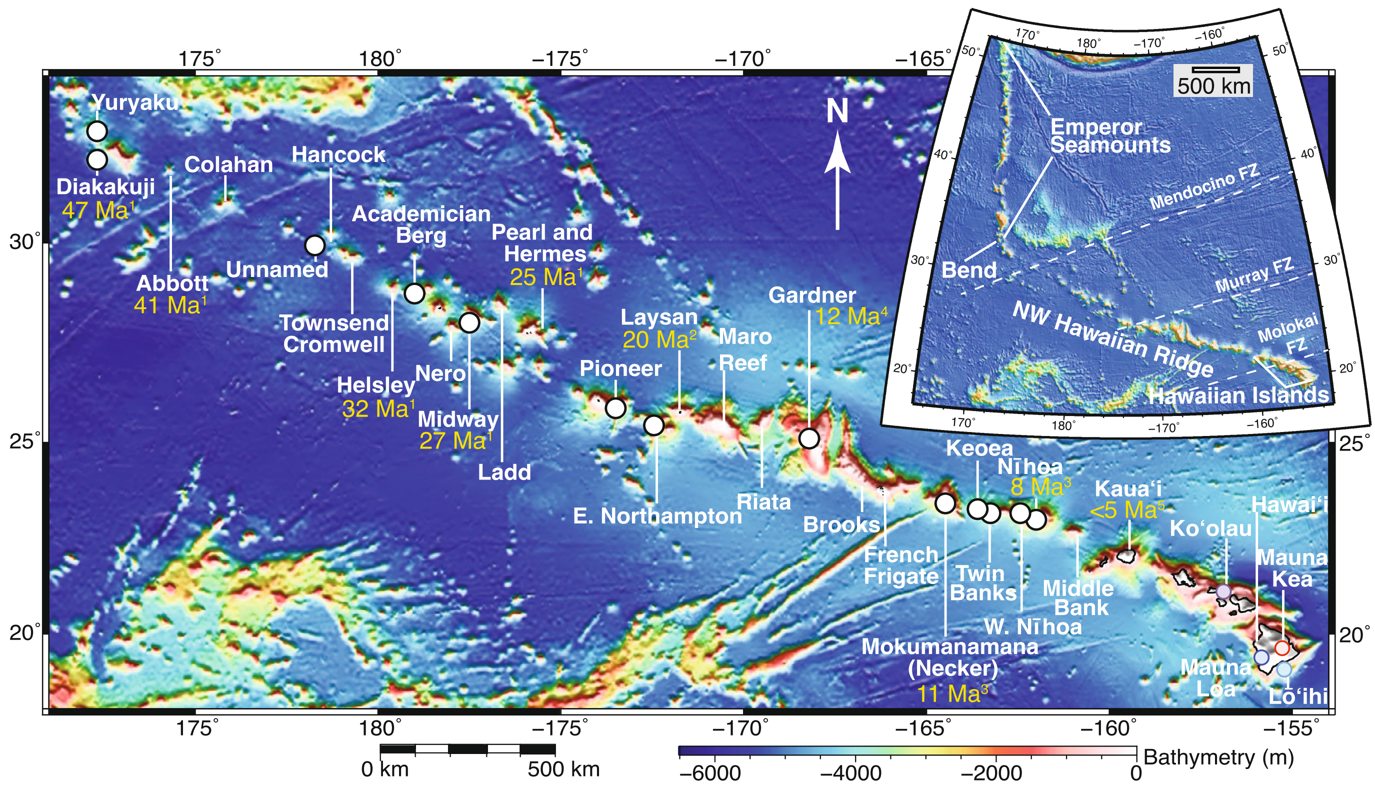

Fig. 1. Bathymetric map of the ∼51 seamounts and islands of the Northwest Hawaiian Ridge and sample locations. Bathymetry is 2-minute Gridded Global Relief Data ETOPO2v2 satellite altimetry dataset (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center, 2006) and new multibeam bathymetry (Smith et al., 2014). White circles show sample locations. References for ages are in yellow superscript and are as follows: 1 – O'Connor et al., 2013; 2 – Dalrymple et al., 1974; 3 – Dalrymple et al., 1981; 4 – Garcia et al., 1987; 5 – Garcia et al., 2010. Inset figure is a traverse Mercator projection of the Hawaiian–Emperor chain modified from Garcia et al., 2015. Dashed lines in this figure indicate major Pacific fracture zones (FZ). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

addressed this issue or determined the isotopic variation along the NWHR, to evaluate whether source changes have played a role.

The source of the Loa component in Hawaiian lavas is more enriched (higher Th/U, $^{208}Pb^*/^{206}Pb^*$, and Sr isotopic ratios; lower Nd and Hf isotopic ratios) than that of the Kea component. This signature is predominately explained by the presence of subduction recycled material (Weis et al., 2011) or primordial material in the deep source (Li et al., 2015). Lead isotopes provide the most robust tool for delineating the Loa and Kea components in Hawaiian basalts: at a given $^{208}Pb/^{204}Pb$, Loa-trend volcanoes will have a lower $^{206}Pb/^{204}Pb$ than Kea trend volcanoes (Abouchami et al., 2005; Weis et al., 2011). Emperor Seamount lavas (85–51 Ma) are Kea-like in geochemical affinity, whereas both Kea and Loa compositions are present in lavas from the Hawaiian Islands, and furthermore are clearly distributed along two geographical trends of volcanoes (Fig. 1; Keller et al., 2000; Regelous et al., 2003; Abouchami et al., 2005; Tanaka et al., 2008; Weis et al., 2011). On the basis of only three Pb isotope analyses previously available for the NWHR, Loa geochemical compositions have been observed at only one seamount, Daikakuji, near the bend in the Hawaiian–Emperor chain (Regelous et al., 2003). It was unknown whether this is an isolated case or represents the first arrival of the Loa geochemical component (Garcia et al., 2015). Furthermore, because the Loa composition typically is associated with a more fusible source component, its presence may be linked to the dramatic increase in volcano volume (lowest at Daikakuji with 30 km^3 to highest at Gardner with 540 km^3; Bargar and Jackson, 1974), magmatic flux (0.4 m^3/s at Daikakuji to a maximum of 4 m^3/s at Gardner; Wessel, 2016), and volcanic propagation rate (Detroit to Midway 57 ± 2 km/Myr, from which increases to 80–100 km/Myr afterwards; O'Connor et al., 2013) observed along the ∼2800 km long ridge (Pertermann and Hirschmann, 2003; Garcia et al., 2015).

Lead isotopic compositions were measured on 22 shield-stage samples from 13 NWHR volcanoes spanning from ∼47 Ma at the bend to ∼7 Ma at Nīhoa (Fig. 1; Dalrymple et al., 1974; O'Connor et al., 2013). There were no Pb isotopic measurements for NWHR volcanoes younger than Daikakuji Seamount; this study fills this critical 40 million year gap. The Pb isotopic evolution of the entire Hawaiian–Emperor Seamount chain was examined to identify when the enriched Loa component appears and to assess its involvement in magmatic flux variations. Finally, we discuss the implications of these results for the Hawaiian deep mantle source and the potential contribution of material from the Pacific LLSVP to account for flux variations.

2. Geological setting and sampling

Fifty-one volcanoes erupted over ∼42 million years between the bend in the Hawaiian–Emperor chain and the Hawaiian Islands constitute the Northwest Hawaiian Ridge (NWHR; Garcia et al., 2015). We focus on shield stage tholeiitic lavas because they are most likely to record the plume source compositional variation (i.e. Loa and Kea geochemical variation), whereas the later post-shield and rejuvenated Hawaiian lavas present a uniform depleted isotopic composition regardless of the geochemical affinity of shield stage lavas at the same volcano (Frey et al., 2005; Hanano et al., 2010). Study of the Hawaiian Islands shows that single islands are composed of several volcanic centers which may erupt different geochemical signatures from as close as ∼50 km apart (e.g. Mauna Loa and Mauna Kea on Hawai'i; Abouchami et al., 2005). One to four samples from selected volcanoes were available

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