



The aluminum conundrum in Hawaiian shield-building lavas: An argument for a deep, garnet-bearing, mantle source

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Abstract

In contrast with other major elements (e.g. SiO_2 , CaO , TiO_2), isotopic ratios (e.g. Sr, Nd, Pb), and some trace element ratios (e.g. Zr/Nb, Zr/Y, La/Nb), the Al_2O_3 content of Hawaiian shield lavas, at a given MgO content, is remarkably uniform within and between volcanoes. The overall range at 10% MgO is about 0.8% from Loihi (12.1%) to Koolau (12.9%). There is substantial overlap between the “Loa” and “Kea” trend volcanoes, but the regression data for “Loa” trend volcanoes are slightly higher (0.2%) in Al_2O_3 than “Kea” trend volcanoes. Post-shield lavas, from both “Kea” and “Loa” trends are higher in Al_2O_3 at a given MgO content than corresponding shield lavas. These observations are completely at odds with what we think we know about melt production in a heterogeneous, thermally zoned, mantle plume. Peridotite melting models and experiments, at varying pressures and temperatures, result in melts with significantly different Al_2O_3 contents at a given MgO content. The almost constant Al_2O_3 at a given MgO content is analogous to the almost constant normalized Yb abundances in Hawaiian tholeiites. Both require melting in the presence of a garnet residue. The aluminum conundrum can be explained if Hawaiian shield lavas result from melting garnet peridotite at depths corresponding to around 120 km. However, this explanation is at odds with the variable, but relatively high SiO_2 contents of most of these lavas, which imply melt production at relatively shallow depths corresponding to less than 90 km. This paradox can be resolved if low SiO_2 parental magmas derived from garnet peridotite react with a depleted harzburgite residue from prior melting as the magma ascends through the upper regions of the plume.

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1. INTRODUCTION

The compositions of basaltic magmas erupted from Hawaiian volcanoes are widely interpreted to be a consequence of melting and magma production as individual volcanoes are transported by the northwest-moving Pacific plate over a stationary, thermally-zoned and compositionally-heterogeneous mantle plume (e.g. [Watson and McKenzie, 1991](#); [Frey and Rhodes, 1993](#); [Ribe and Christenson, 1999](#); [Farnetani and Hofmann, 2010](#)). The most compelling evidence for this inference is found in the compositional differences between shield-stage and post- and pre-shield

stage volcanism ([Stearns and Macdonald, 1946](#); [Macdonald, 1972](#); [Moore and Clague, 1992](#)). Shield-stage lavas are tholeiitic, whereas post- and pre-shield stage lavas are often alkalic, or characterized by transitional tholeiites with lower SiO_2 and higher alkali and incompatible element content than shield-stage lavas. These differences are thought to be indicative of lower degrees of magma production at the cooler margins of the plume, an inference supported not only by the presence of alkalic and low SiO_2 lavas with high incompatible element abundances, but also by a greater preponderance of evolved lavas in the post-shield stage (e.g. [Frey et al., 1991](#); [Feigenson et al., 1983](#)), accompanied by almost an order of magnitude reduction in lava accumulation rates ([Sharp and Renne, 2005](#)).

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Therefore, as a volcano traverses the thermally-zoned and compositionally-heterogeneous mantle plume, we should expect to find significant differences in: melt production between volcanoes; melt production over time at individual volcanoes; the depth of melt segregation, within and between volcanoes; and the proportion of source components, within and between volcanoes. To a large extent these expectations are realized, given the difficulties in sampling the ~100 ka magmatic histories of young Hawaiian volcanoes (e.g. DePaolo and Stolper, 1996; Quane et al., 2000; Stolper et al., 2009; Rhodes, 2015). There are significant differences between volcanoes and, sometimes, during the growth of an individual volcano, in major elements, trace elements and isotopic ratios (e.g. Wright, 1971; Staudigal et al., 1984; Garcia et al., 1989; Rhodes et al., 1989; Lassiter et al., 1996; Frey et al., 1991; Frey and Rhodes, 1993; Rhodes and Vollinger, 2004; Stolper et al., 2004; Abouchami et al., 2005; Weis et al., 2011; Jackson et al., 2012). The differences in major element composition of lavas erupted during the shield-building stage of individual Hawaiian volcanoes has long been recognized (e.g. Powers, 1955; Wright, 1971; Rhodes et al., 1989; Garcia et al., 1989; Moore and Clague, 1992; Frey and Rhodes, 1993). In particular, volcanoes along the westerly “Loa” and easterly “Kea” trends of Jackson et al. (1972) differ significantly from one another. For example, at a given MgO content, “Kea” trend lavas tend to be lower in SiO₂, and higher in CaO, TiO₂, Na₂O and K₂O than “Loa” trend lavas. They also tend to be higher in highly incompatible trace element abundances. See Figs. 3–6 in Jackson et al. (2012) for a detailed summary of major element and isotopic differences between Hawaiian volcanoes along the “Loa” and “Kea” trends. Lower abundances of MgO-normalized TiO₂ and other incompatible major and trace elements are generally attributed to a greater extent of melting needed to produce the “Loa” trend magmas compared to the Kea trend magmas (e.g. Hofmann and Farnetani, 2013). In contrast, normalized SiO₂ is pressure-dependant, relating to the depth of melt segregation from a peridotite source (e.g. Carmichael et al., 1970; Albarède, 1992; Lee et al., 2009), and also to the extent of peridotite melting (e.g. Kushiro, 1996; Walter, 1998; Longhi, 2002). On the other hand, the apparent correlation of normalized SiO₂ abundances with isotopic ratios has been used as an argument for varying amounts of a subducted oceanic crustal eclogite/pyroxenite component, mixed with a peridotite component, in the plume source of Hawaiian volcanoes (e.g. Hauri, 1996; Takahashi and Nakajima, 2002; Sobolev et al., 2005; Jackson et al., 2012). Herzberg (2006) takes this even further, arguing that only high CaO – low SiO₂ lavas from Loihi and Mauna Kea are derived from peridotite melting, all others are produced by melting of an olivine-free eclogite/pyroxenite source.

What is surprising is that, despite the well-documented variations in MgO normalized SiO₂, CaO and TiO₂, the MgO normalized abundances of Al₂O₃ are remarkably uniform in Hawaiian shield-building lavas, with very little difference between individual volcanoes, or between “Kea” and “Loa” trend volcanoes. This presents a conundrum, because examination of the results of peridotite melting

experiments leads one to expect that the Al₂O₃ content of a melt will be sensitive to the extent of melting as well as to the depth at which the melt segregates from its residue (e.g. Kushiro, 1996; Walter, 1998; Longhi, 2002; Salters et al., 2002). Additionally, assuming much of the heterogeneity inferred for the Hawaiian plume results from mixtures of peridotite and subducted oceanic crustal components, one might anticipate considerable variation in Al₂O₃ content in Hawaiian shield-building lavas. Indeed, Sobolev et al., (2005, Fig. 4) use the Al₂O₃ content of inferred primary magmas to estimate the proportions of melt derived from a pyroxenitic component in the Hawaiian plume. In this paper, I will document the extraordinary uniformity of Al₂O₃ among Hawaiian shield-building lavas from volcanoes along both the “Loa” and “Kea” trends, arguing that the only plausible reason for this uniformity is the presence of substantial garnet in the source peridotite. This implies that these magmas were derived by melting of garnet peridotite in the Hawaiian plume at depths greater than 90 km and most probably closer to about 120 km.

2. ANALYTICAL METHODS

About 200–600 g of sample were crushed by hand in a high-carbon steel percussion mortar. The resulting gravel-sized fragments were washed in tap water, followed by washing in an ultrasonic bath with de-ionized water. About 100–200 g was further crushed to about 200 mesh size in a Spex tungsten carbide (WC) shatterbox. Aliquants of this powder were analyzed by X-ray fluorescence analysis (XRF). The major elements were measured on a fused La-bearing lithium borate glass disc using modifications of the method of Norrish and Hutton (1969), the principle difference being that the samples are first ignited at 1000–1040 °C for several hours in order to oxidize iron to Fe³⁺ and remove volatiles. They are then fused in an electric furnace at ~1020 °C and pressed into glass discs. All oxides were measured in duplicate on a Siemens MRS-400 simultaneous spectrometer. Analyses that did not give summations between 99.4% and 100.3% were discarded and repeated. Estimates of the precision and accuracy of these data are given by Rhodes (1996) and Rhodes and Vollinger (2004). Of specific relevance to this paper the precision for Al₂O₃ and MgO are 0.06 and 0.03 wt.% (2 sigma) respectively.

Because the differences in Al₂O₃ content of lavas from different Hawaiian volcanoes are small, I have restricted the study to data generated by X-ray Fluorescence Spectroscopy (XRF) in my laboratory at the University of Massachusetts, in order to minimize the possible effects of inter-laboratory bias. The data have been archived in the EarthChem Library and are available for download from www.earthchem.org/library/rhodes.

3. THE AL₂O₃ CONTENT OF HAWAIIAN SHIELD-STAGE LAVAS

Plots of major element compositions against MgO in Hawaiian shield-stage tholeiites show that at around 7% MgO there are two contrasting trends. In one trend,

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