

Melt generation and migration beneath Kilauea: Constraints from Os isotopes and phase equilibria

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Introduction. Understanding the nature of the processes which govern the generation and segregation of melt is of prime importance for studying mantle heterogeneity through the chemistry of basaltic magmas. This is particularly true for hotspots, where the geochemical variety of the Earth's deep interior is most evident. Although the sources of hotspot magmas are clearly distinct from the upper mantle sources of MORB, all hotspot magmas must pass through the oceanic lithosphere prior to eruption. However, the degree to which the oceanic lithosphere contributes to the diverse chemistry of hotspot magmas remains a subject of considerable uncertainty.

Previous studies concerned with Hawaiian melt generation have focused on the geochemical and isotopic systematics of incompatible elements [e.g. Hofmann *et al.*, CMP 88 1984; Budahn and Schmitt, GCA 49 1985; Watson, J.Petrol. 34 1993]. These studies have demonstrated that the incompatible element signatures of Hawaiian shield lavas are the result of melting garnet lherzolite. However, these studies are insensitive to interaction of the melts with the oceanic lithosphere. This is because the lithosphere, due to extraction of MORB, is strongly depleted in clinopyroxene, the dominant host for incompatible elements in an anhydrous lithosphere. Since mineral/melt partition coefficients of incompatible elements are extremely low for olivine and orthopyroxene (Ti is a possible exception), these elements will not reflect interaction with harzburgite, and shield basalts will preserve the trace element and He, Sr, Nd and Pb isotopic signatures of their garnet-bearing source regions.

Equilibration depths of Hawaiian primary magmas.

In contrast, the major element characteristics of basaltic magmas may be significantly affected by interaction with harzburgite [Kelemen *et al.*, 1992]. The discovery of picritic glass fragments from Hawaii [Clague *et al.*, Nature 353 1991], with up to 15% MgO and Fo_{90.7} olivine phenocrysts, places severe constraints on Kilauea primary magma compositions. In a high pressure experimental

study, Wagner and Grove [1992] have recently shown that a primary magma composition derived from these picritic glasses, and in equilibrium with Fo_{90.7} olivine, is multiply saturated with a harzburgite mineral assemblage at 1.5 GPa and 1400°C. Down temperature crystallization (100°C) did not produce multiple saturation with either spinel or garnet lherzolite. Despite this harzburgite signature, ion microprobe trace element data for the picritic glasses [Wagner and Hauri, unpub. data] are similar to other Kilauea magmas [Hofmann *et al.*, 1984] which show a signature of equilibration with garnet lherzolite. This result is clear evidence of the insensitivity of incompatible trace elements to equilibration with harzburgite.

Compared to experimentally determined melts saturated with garnet lherzolite [Takahashi, JGR 91 1986; Kinzler, EOS 73 1992], the Hawaiian picritic glasses require assimilation of 40 wt% orthopyroxene and crystallization of 13 wt% olivine to reach their observed bulk compositions. The experimentally determined depths of this harzburgite interaction are within the oceanic lithosphere beneath Hawaii, the base of which is estimated at 80-90 km. However, fluid dynamic studies by Yuen and Fleitout [1985] and Ribe and Christensen [1994] have shown that the lithosphere can be significantly eroded and replaced with plume mantle. Thus, an important question arises: Is the chemical signature of harzburgite saturation in Hawaiian primary magmas derived from the oceanic lithosphere, or the Hawaiian plume?

Tracing compatible elements with Os isotopes.

Since the isotopes of the incompatible elements He, Sr, Nd and Pb are insensitive to harzburgite interaction, we must look to a different geochemical tracer. Several studies have shown that the concentrations of Os are roughly one to two orders of magnitude higher in mantle peridotites compared to mantle-derived basalts; an Os mantle/melt partition coefficient of 10-20 is suggested by the data. Thus Os occupies a unique role in observational studies of melt

migration, being the only isotopic tracer of compatible elements [Hauri and Hart, 1993; Hauri *et al.*, Nature 365 1993]. Specifically, in reference to models for melt migration in which magma moves by porous flow [e.g. Navon and Stolper, J. Geol. 95 1987; McKenzie and O'Nions, J. Petrol. 32 1991; Watson, 1993], it can be shown that, at magma-mantle equilibrium, Os will travel at a very small fraction of the melt velocity, and as a result, Os from the magma source will be almost entirely separated, in a chromatographic sense, from source He, Sr, Nd and Pb. Instead, the Os isotope signature of a percolating melt will reflect the mantle through which the magma is moving, and thus will track the major element characteristics of the melt until it loses chemical equilibrium with the surrounding mantle. The same cannot be said of Sr, Nd and Pb if the surrounding mantle is clinopyroxene-poor harzburgite.

We have concentrated on a stratigraphically-controlled suite of young tholeiites and picrites from Kilauea. The ages of the samples are well determined, either through historical records or radiocarbon dating of tree-derived charcoal inclusions, and range from 14 to > 30,000 years. The isotopic signatures of Sr and Nd in these samples are constant within analytical errors, but Pb and He isotopes (13–22 R_a) show significant variations which are non-systematic with age [Kurz, unpub. data].

Samples (2–3 grams) were attacked with aqua regia in sealed glass Carius tubes at 210°C for 2–6 days [Shirey and Walker, EOS 75 1994]. Os was separated by distillation and measured by NTIMS at DTM. Seven samples have been studied thus far. Os concentrations are high, and range from 140–1940 ppt (parts per trillion); blank corrections (4 pg) were within analytical errors. The standard deviation of ¹⁸⁷Os/¹⁸⁶Os is 0.5% (1σ) around a mean value of 1.103; no correlations with Os concentration, age, or He isotopes are apparent. Our Kilauea data are in good agreement with the data of Martin [1991] for Kilauea tholeiites with lower Os concentrations. The Kilauea Os isotope data are well outside the range of ¹⁸⁷Os/¹⁸⁶Os for abyssal peridotites (1.003–1.083), and are substantially higher than Os isotope ratios (0.966–1.064) from peridotites which have Sr, Nd and Pb isotopic signatures of MORB. The end result is that the Os isotope signature of Kilauea tholeiites and picrites is substantially higher than, and does not overlap, the range of ¹⁸⁷Os/¹⁸⁶Os which characterizes the depleted mantle source of MORB.

Based on our knowledge of the composition of the oceanic lithosphere, the Os isotope data for Kilauea tholeiites and picrites requires that these

magmas did not substantially interact with the depleted upper mantle, either lithosphere or asthenosphere. In order to preserve the Os isotope signature of the Hawaiian plume, Kilauea magmas must ascend to the surface under conditions of strong chemical disequilibrium with the lithospheric mantle, most likely through cracks or buffered channels. Reaction with the lithospheric mantle, to the extent necessary to reach harzburgite saturation, would not only lower ¹⁸⁷Os/¹⁸⁶Os to lithospheric values, but would also destroy the relative homogeneity of the suite if the process were variable or heterogeneous. The same conclusion was reached by Hauri and Hart [1993] for basalts from Tubuai and Mangaia, two islands in the Macdonald hotspot chain.

The implication for plume dynamics is clear. If the harzburgite saturation signature cannot be attributed to the lithosphere, it must come from the plume. Harzburgite is a plausible mineral assemblage for the uppermost part of an upwelling plume which has undergone extensive melt extraction. Therefore, the Hawaiian plume must be able to erode the lithosphere up to a depth of 45–60 km beneath Kilauea. Such extensive lithospheric erosion is favored by numerical simulations of plume–lithosphere interaction [Yuen and Fleitout, 1985], as well as the geoid/topography ratio and sharp rise of the leading edge of the Hawaiian swell [Ribe and Christensen, 1994]. The combined results from the trace element, phase equilibria and Os isotope data strongly support a coherent model in which Kilauea primary magmas are generated at depth in equilibrium with garnet lherzolite, subsequently assimilate orthopyroxene and crystallize olivine in the upper part of the Hawaiian plume at depths of 45–60 kilometers, then ascend through the lithosphere via channelized magma pathways from these depths.

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