

Mantle reservoirs and mantle convection: Lessons from the Hawaiian plume

E. H. Hauri

DTM, Carnegie Institution of Washington, Washington, DC
20015, USA

The Hawaiian plume has long played a central role in conceptual, theoretical, geophysical and geochemical studies of mantle convection. Over the past 80 million years, the Hawaiian hotspot has been the site of the most voluminous intraplate basaltic volcanism on the Earth's surface, and still provides the strongest evidence to date for the presence of active upwelling in the upper mantle.

There are several fundamental observations about Hawaiian volcanism which pertain to mantle convection on regional and global scales. Though geophysical studies are increasingly focused on looking for relative hotspot motions, the Hawaiian plume has remained essentially stationary (± 100 km) over the past 80 Ma. Distinct structural lineaments ('Loa' and 'Kea' trends) along the youngest Hawaiian islands erupt compositionally distinct lavas, though there is a certain amount of overlap. Adjacent active Hawaiian volcanoes, separated by as little as 25 km, erupt compositionally distinct shield lavas, which places some limits on the lateral scale of source heterogeneity (Frey and Rhodes, 1993). Finally, there exist at least three (and possibly four) compositionally distinct components in Hawaiian lavas, all of which are different in composition from the upper mantle source of MORB. Any model of mantle convection must be able to reproduce the thermal and chemical perturbations which are exemplified by the Hawaiian plume and its volcanic expression.

Hawaiian components

Geochemical studies utilizing He, Sr, Nd and Pb isotopes have delineated three components present in Hawaiian shield-stage lavas. These may be termed 'Loihi' (high $^3\text{He}/^4\text{He}$ ratios), 'Kea' (depleted Sr-Nd isotopes), and 'Loa' (enriched Sr-Nd isotopes). Additional studies utilizing major elements (Hauri, 1996) and the isotopes of Os (Lassiter and Hauri, 1998), and oxygen (Eiler *et al.*, 1997) have also identified these same components, and have placed additional constraints on their origin. All of these

components are distinct from MORB, and are thus thought to be common to the Hawaiian plume; there is not a single 'Hawaiian plume component'. Within Hawaiian shield lavas, all isotope systems show good correlations with each other, but each isotopic system places its own unique constraints on the origin of the sub-Hawaiian mantle.

Osmium isotope constraints

The good correlations of Os isotopes (compatible element) with other isotope tracers (incompatible elements) requires that Hawaiian tholeiites have not reacted or exchanged with the lithospheric mantle to any significant degree. Os isotope ratios in all Hawaiian lavas are higher than the upper mantle, and are higher than nearly all peridotite xenoliths on a world-wide basis. A high Re/Os Hawaiian source might originate in three ways, (1) heterogeneous accretion without subsequent whole-mantle mixing, (2) core-mantle interaction, or (3) subduction and recycling of oceanic lithosphere.

Heterogeneous accretion is not likely a viable hypothesis, given the observation that different high- ^{187}Os plume sources have different Sr, Nd, Pb and Hf isotopic compositions. A single mantle source with uniquely high ^{187}Os does not appear to exist.

Different mantle sources, through core-mantle interaction, could acquire elevated $^{187}\text{Os}/^{188}\text{Os}$ ratios if the outer core had an elevated Re/Os ratio. Data for a different Os isotope in Hawaiian lavas, ^{186}Os from decay of ^{190}Pt , has been used to argue for core-mantle interaction at the 1 wt.% level (Brandon *et al.*, this meeting). Pt-Re-Os fractionations in iron meteorites are in the required directions to produce radiogenic ^{186}Os and ^{187}Os (denoted $^{186}\text{Os}^*$ and $^{187}\text{Os}^*$) in liquid iron metal, and would appear to support a core-mantle interaction hypothesis.

However, addition of 1 wt.% core to a mantle source has substantial effects on Fe, Ni, Re and Os abundances. Addition of 1 wt.% core material would increase the Re and Os abundances in a mixed source by 4–5 \times , resulting in similarly elevated Re and Os

abundances in melts derived from such a source. At 8 wt.% MgO, Hawaiian lavas actually have lower Re and similar Os concentrations when compared to primitive MORB, and there is no correlation of Os isotopes with fractionation-corrected Re and Os abundances as would be required in the core-mantle interaction model. Furthermore, addition of 0.8–1 wt.% Fe metal would produce magmas which have f_{O_2} fixed by the Fe-FeO buffer, far more reduced than any Hawaiian lava (by about 3–4 log units). In fact, at a given Mg#, lavas from Koolau volcano (with the highest $^{186}Os^*$ and $^{187}Os^*$) have the lowest Fe and highest f_{O_2} of all Hawaiian lavas; this is certainly not a predicted result of core-mantle interaction.

Recycling of oceanic lithosphere is most consistent with the Os isotope data and their correlations with other isotopes. The enriched Koolau component has high $^{187}Os^*$, and the only identified terrestrial rocks with the required high Re/Os ratios are oceanic and continental crust. Recent high-precision work on oxygen isotopes in Hawaiian lavas (Eiler *et al.*, 1997) shows that $^{187}Os^*$ is well correlated with $\delta^{18}O$, providing strong evidence for recycled crustal material. The recycling hypothesis is strengthened by observed correlations between major elements and these isotopes, which together require a mafic component within the Hawaiian plume (Lassiter and Hauri, 1998). Hydrothermally altered crustal materials, with the proper Pt/Os and Pt/Re ratios to create correlated $^{186}Os^*$ and $^{187}Os^*$ and ^{18}O anomalies, exist on the seafloor and are available for subduction into the deep mantle.

Further work on Hawaiian melt inclusions and deeply erupted submarine glasses (Hauri, this meeting; Garcia *et al.*, 1989; Dixon *et al.*, 1997) show correlations among major elements, H₂O-S-Cl-F contents, D/H ratios, and isotope ratios of the host lavas. The δD values range from –50‰ to –120‰, and appear (at this stage) to be related to variations between distinct mantle sources. The H₂O and D/H data, while preliminary, suggest that the ‘enriched’ high- $^{187}Os^*$ component in Koolau lavas contains low [H₂O], low [Cl] and low D/H ratios, consistent with extensive dehydration during ancient subduction.

Lateral scale of mantle variability

The clear differences in the isotope geochemistry of adjacent active Hawaiian volcanoes requires that

variations in mantle source composition exist at the 25–50 km scale within the Hawaiian plume. Simple mixing during convection, or juxtaposition of mantle components by entrainment during plume flow (Hauri *et al.*, 1994) are both viable mechanisms to create this scale of heterogeneity, though several billion years may be required to mix down to the 50-km scale by convection alone. Combined major element, osmium and oxygen isotope data require the presence of a mafic source in the Hawaiian plume, and all geochemical indicators suggest that this mafic material is recycled oceanic lithosphere. In order to preserve H isotope heterogeneity against rapid H diffusion and homogenization in the mantle, this slab component must be very thick (order 10–20 km) or be relatively young (< 1 Ga) or both. Pb-Pb age constraints do suggest a ‘young’ age (< 1 Ga) for the crustal component beneath Hawaii, but the Pb data are complicated by large errors. If one could estimate the mass fraction of crust in the Koolau source, perhaps from major element systematics, it would be possible to place further age constraints using Re-Os. Further work is required in order to ‘date’ the crustal component in the Hawaiian plume.

Acknowledgements

Many thanks to John Lassiter, Mark Kurz, Fred Frey, Mike Garcia, John Eiler, Al Hofmann, and Don DePaolo, Ed Stolper, and the HSDP gang for collaborations.

References

- Dixon, J.E., Clague, D.A., Wallace, P. and Poreda, R. (1997) *J. Petrol.*, **38**, 911–39.
- Eiler, J.M., Farley, K.A., Valley, J.W., Hofmann, A.W. and Stolper, E.M. (1997) *Earth Planet. Sci. Lett.*, **144**, 453–68.
- Frey, F.A. and Rhodes, J.M., (1993) *Philos. Trans. R. Soc. Lond.* **342**, 121–36.
- Garcia, M.O., Muenow, D.W., Aggrey, K.E. and O’Neil, J.R. (1989) *J. Geophys. Res.*, **94**, 10,525–38.
- Hauri, E.H., Whitehead, J.A. and Hart, S.R. (1994) *J. Geophys. Res.*, **99**, 24,275–300.
- Hauri, E.H. (1996) *Nature*, **382**, 415–9.
- Lassiter, J.C. and Hauri, E.H. (1998) *Earth Planet. Sci. Lett.* (in review).