The Yellowstone Hotspot: Plume or Not?
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Intraplate hotspots, frequently expressing themselves as age-progressive eruptive centers, have long been attributed to cylindrical plumes of hot, buoyant mantle rising from great depths, perhaps as deep as the core-mantle boundary (e.g., Morgan, 1971). A deep mantle plume-derived source for hotspot tracks along oceanic lithosphere is straightforward from the standpoint of mantle dynamics, since convective instabilities arise from boundary layers (i.e., the core-mantle boundary), oceanic lithosphere is thinner and easier to penetrate than continental lithosphere, and upper mantle flow beneath the interior of large tectonic plates should be simpler than at plate boundaries. The mantle plume model therefore works well for oceanic hotspot tracks, such as the Hawai`ian-Emperor, Marquesas, and Cape Verde systems, particularly given their seismic signatures of hot mantle extending to great depths (e.g., Wolfe et al., 2009).

A simple deep mantle plume model as the source for continental hotspots presents significantly greater challenges, however. A striking example is the Yellowstone–Snake River Plain (YSRP) system, where some observations have led to the conclusion that the YSRP originated from the ascending tail of a deep mantle plume (e.g., Armstrong et al., 1975; Smith and Braile, 1994; Camp, 1995; Pierce and Morgan, 2009). The YSRP is an age-progressive rhyolitic volcanic track dating back to at least 12 Ma (Shervais and Hanan, 2008), and its migration matches the inherent strength of slabs and the expected strong overall downwelling and Farallon slab breakup. These models are difficult to reconcile with the inherent strength of slabs and the expected strong overall downwelling mantle flow field due to subduction.

Vigorous debate regarding the source of the YSRP system has continued for decades, however, given the broad range of data that do not require a deep mantle plume source, and in some instances, argue against it. Petrologic constraints suggest an uppermost mantle source (e.g., Carlson and Hart, 1987; Leeman et al., 2009). Structural and dynamic models include convective roll (Humphreys et al., 2000), a propagating rift (e.g., Christiansen et al., 2002), edge-driven convection (e.g., King, 2007), lithospheric control (Tikoff et al., 2008), and subducted slab-controlled upwelling (e.g., Facenna et al., 2010). While each model explains facets of the YSRP system, it remains a key challenge to develop a holistic conceptual model for the region. Kelbert et al. (2012, p. 447 in this issue of Geology) present important and intriguing results that provide key new constraints on the deep magmatic plumbing system beneath the YSRP system.

Kelbert et al.’s three-dimensional (3-D) conductivity model was developed using magnetotelluric (MT) data collected by EarthScope’s USArray Transportable Array (TA) (http://www.usarray.org). Their images show focused zones of highly conductive crust and upper mantle, with the highest conductivities in the uppermost mantle beneath the central Snake River Plain and extending to ~100 km depth. Beneath Yellowstone, however, Kelbert and colleagues find lower conductivity values, and propose that there may be substantially reduced levels of partial melt in the lower crust and uppermost mantle directly beneath the Yellowstone caldera relative to the Snake River Plain region.

The aperture of the seismic component of the USArray TA provides important new constraints regarding the plumbing system of intraplate hotspots. One conceptual model that does not require a deep mantle plume involves flow around a subhorizontal, partially stranded fragment of the Juan de Fuca plate with an eastern edge beneath Yellowstone, consistent with the tomographic models. Flow of deep mantle around this sinking slab remnant would produce upwelling mantle beneath the entire YSRP, and could also explain the significant tectonomagmatism of the Columbia River flood basalts and continuing volcanic activity on the High Lava Plains, perhaps even the regional geoid high, if it is generated by dynamic topography (e.g., Moucha et al., 2009) rather than a deep positive buoyancy source. Portions of this conceptual model are direct outcomes of numerical modeling (e.g., Facenna et al., 2010).

At shallower depths, Kelbert et al.’s results provide important new constraints regarding the plumbing system of intraplate hotspots. One possibility is the model proposed by Eagar et al. (2011) for the High Lava Plains/central Cascades region. This area exhibits high conductivity lobes in the lower crust and uppermost mantle east of the Cascades, with the exception of a reduced conductivity zone near the Newberry hotspot, the westernmost expression of the High Lava Plains (Patro and Egbert, 2008). The areas of high conductivity also exhibit high P- to S-wave speed ratios (Vp/Vs), while the region of lower conductivity beneath Newberry also possesses lower crustal Vp/Vs values (Eagar et al., 2011). Combined, these

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geophysical constraints are consistent with a zone of intracrustal partial melt away from relatively active volcanism, suggesting that present-day hotspot volcanism represents a zone of crustal melt drainage. Kelbert et al.’s results also suggest that significant lateral transport of melts in the crust and uppermost mantle may be an important part of the evolution of hotspot-related magmatic plumbing systems in continental lithosphere.

In conclusion, the massive and widespread tectonomagmatic system expressed at the surface by the Columbia River flood basalts, the High Lava Plains, and the Yellowstone/Snake River Plain system requires a holistic framework of mantle dynamics not well explained by a simple deep mantle plume. Efforts on several fronts can help us develop an improved conceptual framework for the region.

(1) Provide improved constraints regarding the origin depth of basalts exhibiting high 4He/He ratios.

(2) Generate regional-scale crustal Vp/Vs and conductivity models, placing the High Lava Plains/Cascadia results in context.

(3) Form an improved understanding of the source of the regional geoid high. The new tomographic models enabled by USArray should figure prominently in this effort.

(4) Develop better constraints on the regional mantle flow field. A portion of the mantle flow pattern can be examined using continental-scale seismic anisotropy constraints (e.g., Lin et al., 2010; Zandt and Humphreys, 2008), but these provide only a coarse proxy for flow in the upper ~400 km of the mantle.

(5) Generate integrated imaging techniques that use seismic, gravity, and magnetotelluric data sets, either through direct joint interpretation, or via formalized forward and/or inverse modeling approaches. A major challenge is how physical parameters (e.g., density, conductivity, seismic wave speed) translate from one data set to another.

(6) Continue development of next-generation geodynamic numerical models that incorporate new results derived from EarthScope data with regional tectonic and volcanic history. Important forward steps in this effort are already in progress (e.g., Liu and Stegman, 2011).

With these comprehensive syntheses of new geophysical, geological, and geochemical data, we can improve our understanding of both the Yellowstone hotspot and its relationship to the regional tectonomagmatic system, as well as the formation and evolution of continental hotspots worldwide.

REFERENCES CITED


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