The Yellowstone Hotspot: Plume or Not?

Matthew J. Fouch*
Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, DC 20015

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 present-day velocity of the North American plate (e.g., Pierce and Morgan, 1992). Further, high $^{3}He/^{4}He$ ratios in the associated continuing basaltic volcanism (e.g., Graham et al., 2009) and the regional geoid high (e.g., Smith and Braile, 1994) are frequently attributed to a deep mantle source.

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., Faccenna 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 the resolution necessary to complement Kelbert et al.'s new 3-D MT model, while also probing the mantle at significantly greater depths (e.g., Lin et al., 2010; Obrebski et al., 2010; Schmandt and Humphreys, 2010; Wagner et al., 2010; James et al., 2011; Sigloch, 2011; Burdick et al., 2012). These models show a distinct swath of strongly reduced seismic wave speeds beneath the entire YSRP, consistent with the presence of partial melt zones in the YSRP crust and uppermost mantle extending to depths of ~125 km, and perhaps deeper, and co-located with widespread regional Quaternary basaltic volcanism. However, contrary to the low conductivities in the deep crust and uppermost mantle beneath Yellowstone imaged by Kelbert et al., seismic wave speeds are lowest beneath Yellowstone, suggesting high degrees of partial melt. Significantly, none of the deep-sampling body wave tomographic models show compelling evidence for a continuous conduit of mantle plume–generated reduced seismic wave speeds extending into the deeper lower mantle beneath Yellowstone.

A significant challenge faced by the deep mantle plume model is that the YSRP hotspot track resides squarely within a long-lived subduction system. How might a plume remain present in a region with significant dynamic complexity? Some conceptual models propose direct slab-plume interaction, where a deep mantle plume slips through a gap in subducted slab material, exploits a zone of weakness in the slab, or breaks through the slab (e.g., Obrebski et al., 2010). Alternatively, an upwelling plume might slip around the exposed southern edge of the subducting Juan de Fuca slab, or be drawn in from the east during westward trench retreat 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.

Alternatively, complex subduction-driven mantle dynamics could play an important role in generating hotspot and other regional volcanism. 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 coeval with YSRP volcanism (e.g., James et al., 2011; Sigloch, 2011). Continued slab-driven upwelling could sweep up lower mantle rock containing the sources of high $^{3}He/^{4}He$ in Yellowstone basalts, as well as generate deeper strong thermal gradients that could explain the low seismic wave speeds at depths of ~900 km, and perhaps deeper. This model might also explain 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., Faccenna 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 (V_p/V_s), while the region of lower conductivity beneath Newberry also possesses lower crustal V_p/V_s values (Eagar et al., 2011). Combined, these

*E-mail: fouch@dtm.ciw.edu.

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 $^3He/^4He$ ratios.

(2) Generate regional-scale crustal V_p/V_s 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

Armstrong, R. L., Leeman, W. P., and Malde, H. E., 1975, K–Ar dating Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho: American Journal of Science, v. 275:3, p. 225–251.

Burdick, S., Van Der Hilst, R.D., Vernon, F.L., Martynov, V., Cox, T., Eakins, J., Karasu, G.H., Tylell, J., Astiz, L., and Pavlis, G.L., 2012, Model update March 2011: Upper mantle heterogeneity beneath North America from traveltime tomography with global and USArray Transportable Array data: Seismological Research Letters, v. 83, p. 23-28, doi:10.1785/gssrl.83.1.23.

Camp, V.E., 1995, Mid-Miocene propagation of the Yellowstone mantle plume head beneath the Columbia River Basalt source region: Geology, v. 23, p. 435–438, doi:10.1130/0091-7613(1995)023<0435:MMPOTY>2.3.CO;2.

Carlson, R.W., and Hart, W.K., 1987, Crustal genesis on the Oregon Plateau: Journal of Geophysical Research, v. 92, p. 6191–6206, doi:10.1029/JB092iB07p06191.

Christiansen, R., Foulger, G., and Evans, J., 2002, Upper-mantle origin of the Yellowstone hotspot: Geological Society Of America Bulletin, v. 114, p. 1245–1256, doi:10.1130/0016-7606.

Eagar, K.C., Fouch, M.J., James, D.E., and Carlson, R.W., 2011, Crustal structure beneath the High Lava Plains of eastern Oregon and surrounding regions from receiver function analysis: Journal of Geophysical Research, v. 116, doi:10.1029/2010JB007795.

Faccenna, C., Becker, T.W., Lallemand, S., Lagabrielle, Y., Funiciello, F., and Piromallo, C., 2010, Subduction-triggered magmatic pulses: A new class of plumes?: Earth and Planetary Science Letters, v. 299, p. 54–68, doi:10.1016/j.epsl.2010.08.012.

Graham, D.W., Reid, M.R., Jordan, B.T., Grunder, A.L., Leeman, W.P., and Lupton, J.E., 2009, Mantle source provinces beneath the northwestern USA delimited by helium isotopes in young basalts: Journal of Volcanology and Geothermal Research, v. 188, p. 128–140, doi:10.1016/j.jvolgeores.2008.12.004.

Humphreys, E., Dueker, K., Schutt, D., and Smith, R., 2000, Beneath Yellowstone: Evaluating plume and nonplume models using teleseismic images of the upper mantle: GSA Today, v. 10, p. 1–7.

James, D.E., Fouch, M.J., Carlson, R.W., and Roth, J.B., 2011, Slab fragmentation, edge flow and the origin of the Yellowstone hotspot track: Earth and Planetary Science Letters, v. 311, p. 124–135, doi:10.1016/j.epsl.2011.09.007.

Kelbert, A., Egbert, G.D., and deGroot-Hedlin, C., 2012, Crust and upper mantle electrical conductivity beneath the Yellowstone Hotspot Track: Geology, v. 40, p. 447–450, doi:10.1130/G32655.1.

King, S.D., 2007, Hotspots and edge-driven convection: Geology, v. 35, p. 223–226, doi:10.1130/G23291A.1.

Leeman, W.P., Schutt, D.L., and Hughes, S.S., 2009, Thermal structure beneath the Snake River Plain: Implications for the Yellowstone hotspot: Journal of Volcanology and Geothermal Research, v. 188, p. 57–67, doi:10.1016/j.jvolgeores.2009.01.034.

Lin, F.-C., Ritzwoller, M.H., Yang, Y., Moschetti, M.P., and Fouch, M.J., 2010, Complex and variable crustal and uppermost mantle seismic anisotropy in the western United States: Nature Geoscience, v. 4, p. 55–61, doi:10.1038/ngeo1036.

Liu, L., and Stegman, D.R., 2011, Segmentation of the Farallon slab: Earth and Planetary Science Letters, v. 311, p. 1–10, doi:10.1016/j.epsl.2011.09.027.

Morgan, W.J., 1971, Convection plumes in the lower mantle: Nature, v. 230, p. 42–43, doi:10.1038/230042a0.

Moucha, R., Forte, A.M., Rowley, D.B., Mitrovica, J.X., Simmons, N.A., and Grand, S.P., 2009, Deep mantle forces and the uplift of the Colorado Plateau: Geophysical Research Letters, v. 36, L19310, doi:10.1029/2009GL039778.

Obrebski, M., Allen, R.M., Xue, M., and Hung, S., 2010, Slab-plume interaction beneath the Pacific Northwest: Geophysical Research Letters, v. 37, L14305, doi:10.1029/2010GL043489.

Patro, P.K., and Egbert, G.D., 2008, Regional conductivity structure of Cascadia: Preliminary results from 3D inversion of USArray Transportable Array magnetotelluric data: Geophysical Research Letters, v. 35, L20311, doi:10.1029/2008GL035326.

Pierce, K.L., and Morgan, L.A., 2009, Is the track of the Yellowstone hotspot driven by a deep mantle plume? Review of volcanism, faulting, and uplift in light of new data: Journal of Volcanology and Geothermal Research, v. 188, p. 1–25, doi:10.1016/j.jvolgeores.2009.07.009.

Schmandt, B., and Humphreys, E., 2010, Complex subduction and small-scale convection revealed by body-wave tomography of the western United States upper mantle: Earth and Planetary Science Letters, v. 297, p. 435–445, doi:10.1016/j.epsl.2010.06.047.

Shervais, J.W., and Hanan, B.B., 2008, Lithospheric topography, tilted plumes, and the track of the Snake River-Yellowstone hot spot: Tectonics, v. 27, TC5004, doi:10.1029/2007TC002181.

Sigloch, K., 2011, Mantle provinces under North America from multi-frequency P-wave tomography: Geochemistry Geophysics Geosystems, v. 12, p. 1–27, doi:10.1029/2010GC003421,.

Smith, R.B., and Braile, L.W., 1994, The Yellowstone Hotspot: Journal of Volcanology and Geothermal Research, v. 61, p. 121–187, doi:10.1016/0377-0273(94)90002-7.

Smith, R. B., Jordan, M., Steinberger, B., Puskas, C. M., Farrell, J., Waite, G. P., Husen, S., Chang, W.-L., and O, C. R. J., 2009, Geodynamics of the Yellowstone hotspot and mantle plume: Seismic and GPS imaging, kinematics, and mantle flow: Journal of Volcanology and Geothermal Research, v. 188, p. 26–56, doi:10.1016/j.jvolgeores.2009.08.020.

Tikoff, B., Benford, B., and Giorgis, S., 2008, Lithospheric control on the initiation of the Yellowstone hotspot: Chronic reactivation of lithospheric scars: International Geology Review, v. 50, p. 305–324, doi:10.2747/0020-6814.50.3.305.

Wagner, L.S., Forsyth, D.W., Fouch, M.J., and James, D.E., 2010, Detailed three-dimensional shear wave velocity structure of the northwestern United States from Rayleigh wave tomography: Earth and Planetary Science Letters, v. 299, p. 273–284, doi:10.1016/j.epsl.2010.09.005.

Wolfe, C.J., Solomon, S.C., Laske, G., Collins, J.A., Detrick, R.S., Orcutt, J.A., Bercovici, D., and Hauri, E.H., 2009, Mantle shear-wave velocity structure beneath the Hawaiian hot spot: Science, v. 326, p. 1388–1390, doi:10.1126/science.1180165.

Zandt, G., and Humphreys, E., 2008, Toroidal mantle flow through the western U.S. slab window: Geology, v. 36, p. 295–298, doi:10.1130/G24611A.1.

Printed in USA