GEOLOGY

Deep Origin of Hotspots— The Mantle Plume Model

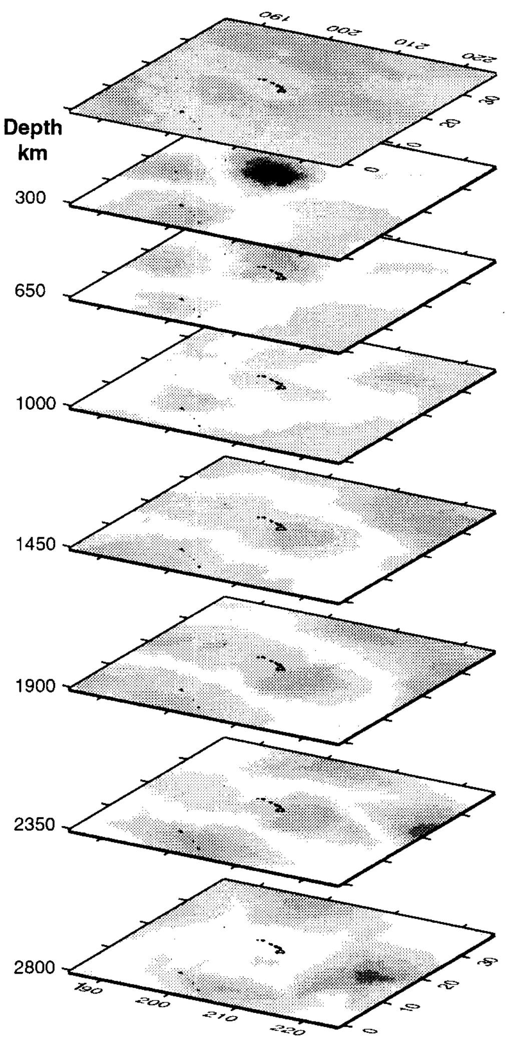
Donald J. DePaolo and Michael Manga

The workings of the hot interiors of the rocky planets of the solar system are most dramatically expressed by the size and arrangement of their volcanoes. Most volcanoes on Earth are a result of plate tectonics. At mid-ocean ridges, the spreading of the ocean floor generates upward flow of hot mantle rock beneath the ridge. This flow generates magma as a result of adiabatic decompression (*1*). At subduction zones, plates returning to the depths of the mantle carry water down in hydrous minerals. The water, when released by metamorphism, causes already hot rock material beneath island arcs to melt (*2*).

But not all volcanoes on Earth are located at mid-ocean ridges or subduction zones. "Hotspots"—regions with particularly high rates of volcanism—are not necessarily associated with plate boundaries. Hawaii, the premier example, is thousands of kilometers from the nearest plate boundary yet exudes lava at a higher rate per unit area than at any other place on Earth. The Hawaiian volcanic anomaly has remained mostly stationary for tens of millions of years and produced a 6000-km-long chain of islands and seamounts. This phenomenon is not explained by plate tectonics. It requires a separate mantle process that can account for narrow, long-lived upwellings of unusually hot mantle rock.

Shortly after the discovery of plate tectonics in the late 1960s, Morgan (*3*) proposed that hotspots represent narrow (100 km diameter) upwelling plumes that originate within the lower mantle. Since that time, evidence from geophysics, fluid dynamics, petrology, and geochemistry has supported if not required the existence of mantle plumes. For many geoscientists, the mantle plume model is as well established as plate tectonics.

Nonetheless, it is reasonable that we should want to verify the model by direct observation. The only way we can "see" into the deep Earth is with seismology. This endeavor has so far not produced the rubber stamp that most thought it would. Seismological studies of the Yellowstone hotspot found no clear evidence for a lower mantle source (*4*), while evidence of a deep plume beneath the Iceland hotspot remains equivocal (*5*). Does the model need rethinking, or are the seismological tools still not quite up to the task, or perhaps both?



Mapping deep plumes. Maps of P wave velocity anomalies (red, slow; blue, fast) under the Hawaiian Islands obtained with finite-frequency tomography, which corrects for the effects of wavefront healing (*16*). The red and yellow areas are interpreted as regions of anomalously high temperature in the mantle. These images suggest that the Hawaiian mantle plume can be traced with seismological techniques all the way down to the core-mantle boundary, at a depth of about 2900 km.

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The apparent controversy can be broken down into two questions. Is there evidence that deep mantle plumes exist? And do all volcanoes not associated with plate boundaries require a deep mantle plume? The answers seem most likely to be "yes" and "no," respectively.

Several observations support a deep (that is, plume) origin for some hotspots. Mid-ocean ridges are able to migrate over hotspots without changing the hotspot track, which implies that the hotspot source is deeper than about 200 km. At Hawaii, the high magma production rate in a small area requires an upwelling velocity of ~50 cm/year (*6*), about 10 times the average velocity of plates. The Hawaiian upwelling must therefore be distinct from flow associated with plate motions.

The upwelling mantle under Hawaii must also be 200 to 300 K hotter than the surrounding mantle to achieve the required large melt fractions at depths below the 80-km-thick lithosphere (*6*). Such hot rock material must come from a thermal boundary layer. The core-mantle boundary is the most likely source, unless there is another interface within the mantle between compositionally distinct layers. The chemistry and isotopic composition of many hotspot lavas, especially the high ^{3}He/^{4}He ratios, indicate that the hotspots sample a part of the mantle distinct from that sampled by mid-ocean ridge basalts (*7*). Numerical simulations of plumes reproduce many of the geophysical observations (*6*), such as the rate of magma production and the topography and gravity anomalies produced by plume material as it spreads beneath the lithosphere.

Theoretical and laboratory studies of fluids also predict that plumes should form in the deep Earth. Because the core is much hotter than the mantle, heat conducted from the core warms the base of the mantle, forming a thermal boundary layer. As this layer thickens, it can become gravitationally unstable. The hot buoyant boundary layer should then rise, forming a large mushroom-shaped plume "head" followed by a narrow plume "tail" (*8*). The head is thought to form large flood basalt provinces once it reaches Earth's surface, whereas the tail provides a conduit through which hot mantle continues to flow to the hotspot (*9*).

The persistence of flow through the tail for 100 million years or more (several times the number of years required for

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The authors are in the Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA. D. J. DePaolo is also in the Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA. E-mail: depaolo@eps.berkeley.edu

plume heads to rise through the mantle) implies that the plume is much less viscous than the surrounding mantle (*10*). In a planet with plate tectonics such as Earth, cooling of the mantle by the subduction of tectonic plates allows large variations of viscosity to exist at the base of the mantle, and hence between the plume and its surroundings (*11*).

Deep mantle plumes may not be the cause of all hotspots. Courtillot *et al.* (*12*) argue that the main features predicted by the plume model are clearly evident in only seven hotspots—including Hawaii and Iceland, but not Yellowstone. Criteria used to recognize plumes include the presence of a hotspot track and an associated flood basalt province, a large buoyancy flux (the product of the volume flux through the plume and the density difference between the plume and its surroundings), a high ^{3}He/^{4}He ratio, and a monotonic age progression in the chain of volcanoes. Superswells—regions of the lower mantle beneath Africa and the Pacific that are characterized by low seismic wave velocity (*13*)—are inferred to be broad, hot upwellings. Secondary, weaker plumes are proposed to form in the mantle from these large superswells. Still other hotspots are not obviously associated with either deep plumes or superswells. They require other models that are not yet generally agreed upon.

The mantle plume model has implications beyond accounting for the spatial distribution of volcanism. If plumes come from the base of the mantle, then the erupted lavas from hotspot volcanoes may carry clues about the workings of the deepest mantle and even the core. Plumes provide a connection between geochemical and isotopic reservoirs (inferred from studies of lavas) and seismological structures imaged within the mantle. The origin of hotspots is therefore linked with our ability to integrate geochemical and seismological observations with geodynamic models. Moreover, plumes potentially provide a constraint on the heat flux from the core (*14*) and hence insight into the energy budget for the core dynamo that generates Earth's magnetic field (*15*).

Many natural phenomena were deduced correctly from indirect effects before instruments were developed with sufficient sensitivity to verify their existence directly. Direct evidence for mantle plumes will require seismic imaging at resolution sufficiently high to detect narrow conduit-like structures in the lower mantle. The present lateral resolution of 1000 km that is achieved with standard techniques is too poor for this task. However, preliminary results (*16*) suggest that image resolution can be improved using alternative data reduction approaches, and that the deep roots of mantle plumes can already be resolved with available data (see the figure).

References

1. D. J. McKenzie, *J. Petrol.* **25**, 713 (1984).
2. Y. Tatsumi, S. Eggins, *Subduction Zone Magmatism* (Blackwell Science, Boston, 1995).
3. W. J. Morgan, *Geol. Soc. Am. Mem.* **132**, 7 (1972).
4. E. D. Humphreys, K. G. Dueker, D. L. Schutt, R. B. Smith, *GSA Today* **10**, 1 (2000).
5. R. M. Allen *et al.*, *J. Geophys. Res.* **107**(B12), 2325 (2002).
6. N. M. Ribe, U. R. Christensen, *Earth Planet. Sci. Lett.* **171**, 517 (1999).
7. P. E. Van Keken, E. H. Hauri, C. J. Ballentine, *Annu. Rev. Earth Planet. Sci.* **30**, 493 (2002).
8. R. W. Griffiths, *Phys. Earth Planet. Inter.* **43**, 261 (1986).
9. M. A. Richards, R. A. Duncan, V. Courtillot, *Science* **246**, 103 (1989).
10. N. H. Sleep, M. A. Richards, B. H. Hager, *J. Geophys. Res.* **93**, 7672 (1988).
11. H.-C. Nataf, *Tectonophysics* **187**, 261 (1991).
12. V. Courtillot, A. Davaille, J. Besse, J. Stock, *Earth Planet. Sci. Lett.* **205**, 295 (2003).
13. B. Romanowicz, Y. C. Gung, *Science* **296**, 513 (2002).
14. G. F. Davies, *Geophys. J. Int.* **115**, 132 (1993).
15. B. A. Buffett, *Geophys. Res. Lett.* **29**(12), 1566 (2002).
16. R. Montelli, G. Nolet, G. Masters, F. A. Dahlen and S.-H. Hung, EGS-AGU-EUG Joint Assembly, Nice, France, 6 to 11 April 2003, abstract EAE03-A03002.