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 $^3He/^4He$ 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).

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GEOLOGY

Is "Hotspot" Volcanism a Consequence of Plate Tectonics?

G. R. Foulger and J. H. Natland

The plate tectonic model, first proposed in the mid-1960s, elegantly accounted for the distribution of most volcanism on Earth's surface—that which occurs at plate boundaries. However, it did not appear to explain areas of unusually profuse volcanism within plates and near mid-ocean ridges, for example, at Yellowstone, Hawaii, and Iceland. In 1971, Morgan proposed a second, independent mode of convection to account for this type of volcanism: mantle plumes (*1*). More recently, explanations for "anomalous" volcanism based on plate tectonics have come to rival the plume model.

According to the plume model, columns of hot material ascending from great depths deliver large amounts of melt to the surface. The volcanic chains associated with many of these melt anomalies (or "hotspots") appeared to all trend in the same direction and to age regularly along the chains, suggesting that the "hotspots" are fixed relative to one another. Morgan suggested that this indicated that the plumes are rooted in the lower mantle, below the level of vigorous convection associated with plate tectonics.

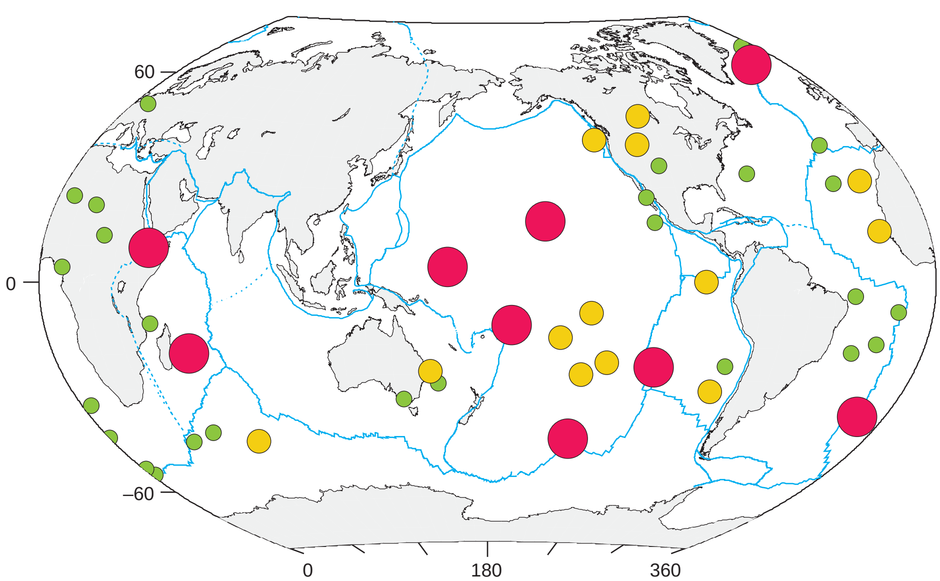
Despite some early skepticism about the fluid dynamics of the proposed plumes, the hypothesis was subsequently used to account for almost all anomalous volcanism. However, the original predictions of the hypothesis—including seismic-wave anomalies in the lower mantle, relative fixity, and high temperatures—have not been confirmed.

First, seismologists have generally not detected the vertical structures with low wave speeds predicted to underlie the "hotspots" and extend into the deep mantle, for example, at Yellowstone (*2*). Where such structures have been reported, the results are often not confirmed by more detailed experiments. Second, "hotspots" are not fixed relative to one another (*3*). Hawaii has not remained stationary; it changed direction radically at the time of the bend in the Hawaiian-Emperor chain ~50 million years ago, when the Pacific plate did not change direction. Third, heat-flow measurements and petrological observations provide little evidence of the high eruptive temperatures required by deep plumes (*4*, *5*).

The plume hypothesis survived largely as a belief system and had to be extensively modified to account for unexpected observations. From Morgan's initial estimate of ~20 plumes in Earth's mantle, the proposed number peaked at 5200 in 1999, but most lists now contain ~50 plumes. Subdivision into deep, intermediate, and shallow "hotspots" has been proposed, and the most recent estimate for the number of plumes ascending from the core-mantle boundary has dropped below 10 (*6*) (see the figure). Most scientists actively working on the subject now accept that not all "hotspots" are underlain by deep mantle plumes.

What, then, causes those melt anomalies and enriched geochemical signatures that do not arise from deep mantle plumes, and are there any true deep mantle plumes anywhere within Earth? The answers to

G. R. Foulger is in the Department of Geological Sciences, University of Durham, Durham DH1 3LE, UK. She is currently on leave at the U.S. Geological Survey, Menlo Park, CA 94025, USA. E-mail: g.r.foulger@durham.ac.uk J. H. Natland is at the Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149, USA.



"Hotspots" around the world. Courtillot *et al.* (*6*) divided "hotspots" into three categories, corresponding to proposed origins at the core-mantle boundary (red), at the base of the upper mantle (yellow), and in the lithosphere (green). Many of these assignations, particularly the deeper ones, are contested on geological and geophysical grounds (*15*).

these questions are probably "the by-products of plate tectonics itself" and "no."

The acquisition of progressively better seismic, geological, and geochemical data is resulting in rapid progress in this field. At Iceland and Yellowstone—the type examples of ridge-centered and mid-continental "hotspots", respectively—seismic tomography suggests that composition or phase anomalies are confined to the shallow mantle (*2*, *7*), and heat flow and petrology suggest modest or no temperature anomalies (*5*). However, Yellowstone is associated with a time-progressive volcanic trail parallel to other volcanic chains, showing that this characteristic (considered by many to be compelling evidence for a deep mantle plume) can accompany shallow melting processes. Ocean-island basalts (which have been empirically associated with "hotspots") have been found throughout the Pacific, and are more voluminous on thousands of seamounts dispersed over the ocean floor than at proposed "hotspots". Such results are more compatible with a shallow, cool, distributed source controlled by the lithosphere than with a deep, hot, localized one controlled by Earth's core.

The primary observations at "hotspots" are usually excess magmatism at relatively normal temperatures and unusual geochemistry. The locus may be stationary, migrate linearly, wander irregularly, and be either localized or widespread. In many cases, there is evidence for a tectonic discontinuity or an old suture where ocean crust was trapped in the upper mantle in the past. For example, the Yellowstone "track" lies along the northern boundary of the Great Basin (which includes most of Nevada and parts of California and Utah); Iceland lies at the intersection between the mid-Atlantic ridge and the ~440-million-year-old Caledonian suture (*8*). These observations provide further support for shallow lithospheric control.

As an alternative to the plume model, a growing number of models treat anomalous volcanism as a by-product of plate tectonics (*9*). There are two requirements for producing a surface melt anomaly: a source of melt, and stretching and cracking of Earth's crust. In Yellowstone, there is no evidence for an exceptionally large volume of magma, because the crust there is no thicker than the regional average. The primary process appears to be the remelting of existing continental lithosphere. Yellowstone lies at the junction of two contrasting tectonic provinces—the Great Basin and the ancient, thick lithosphere to the north—and a small component of differential motion between them may be causing a propagating continental rift (*2*). Propagating cracks or leakage through fracture zones have been proposed elsewhere, for example, for volcanic chains in the Pacific (*10*, *11*).

In the oceanic crust, large-volume melt anomalies are usually associated with relatively normal mantle temperatures (*12*). Thus, the excess melt can only be explained by variations in source composition. At Iceland, where the crust is typically 30 km thick, melting of recycled oceanic crust in the upper mantle at the Caledonian suture can explain both the volume (*13*) and the geochemistry (*5*) of lavas. Superpositions of melting anomalies on old sutures are rather common, for example, at the Tristan da Cunha hotspot and the Damara belt in southern Africa (*8*). There is also isotopic and trace-element evidence that recycled ocean crust contributes to the melt source at Hawaii. The widespread remelting of subducted crust at shallow depth can thus explain the high magmatic productivity at low temperatures of primitive lavas at "hotspots" in general. It is not necessary to transport oceanic crust to the core-mantle boundary and back again in order to explain hotspot geochemistry.

Models for flood basalts at continental margins include edge-driven convection in the shallow mantle, which occurs where thick, cold lithosphere is adjacent to warmer oceanic mantle (*14*). Ancient subducted crust and recycled continental mantle lithosphere can both enhance the melt volume and explain the observed geochemistry (*8*). These models may seem at first glance to be more diverse than the simple plume model. However, they are related through their common association with intraplate deformation, its culmination in continental breakup, and the heterogeneity imparted to the shallow mantle by the flow of material into Earth at subduction zones. These are all plate tectonic processes.

When the plume hypothesis was first proposed, a flurry of alternative hypotheses for volcanic anomalies, based on shallow interactions between lithospheric plates and the upper mantle, were suggested but not pursued. With superior data sets from many volcanic regions, scientists are now revisiting these ideas and developing others that are essentially by-products of plate tectonics (*15*). This model can radically simplify our view of convection within Earth (*9*): Instead of two independent modes of convection, only one is required. Plate tectonics may turn out to be even more powerful for explaining global volcanism than was at first realized.

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