GEOSCIENCE

Heating Up the Hotspot Debates

Paul Tackley

The theory of plate tectonics has been extraordinarily successful in explaining the first-order behavior of our planet's rocky outer layer and the location of most volcanoes and earthquakes—they occur at plate boundaries. Many volcanoes do not, however, fit this framework. Some of these are characterized as "hotspots" and commonly thought to be caused by hot, columnar plumes upwelling from deep within Earth's 2900-km-thick rocky mantle, perhaps from its base where the mantle meets the liquid iron outer core. A plume impinging on a rapidly moving plate might explain long chains of volcanoes such as the Hawaiian-Emperor chain, a 4000-km-long procession of seamounts and volcanoes that extends west and north from the Hawaiian Islands to the Aleutian Islands at the edge of the Pacific plate. Plumes that initially develop with a large, rounded head might explain flood basalts—immense, rapid outpourings of magma that have covered large areas of continent or ocean floor and often exist at the start of hotspot tracks. The observed geochemical differences between magmas erupted at hotspots and those erupted at mid-ocean ridges could be explained by plumes sampling the deep mantle while midocean ridges sample the shallow mantle.

Plates, Plumes, and Paradigms

Gillian R. Foulger, James H. Natland, Dean C. Presnall, and Don L. Anderson, Eds.

Geological Society of America, Boulder, CO, 2005. 893 pp. Paper, $180. ISBN 0-8137-2388-4. Special Paper 388.

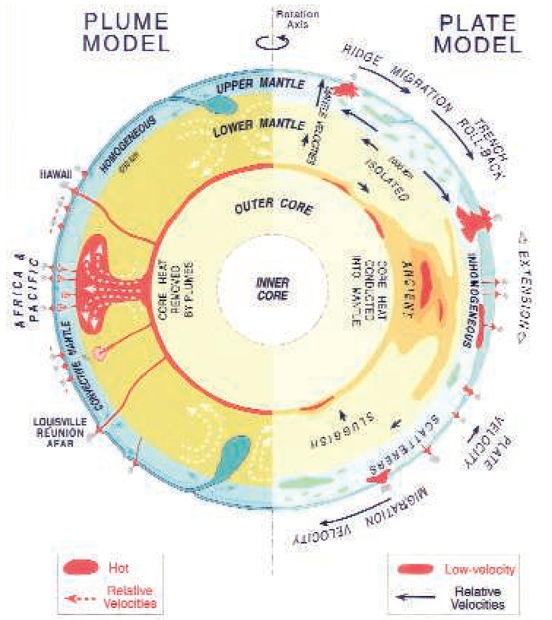
Despite these apparent successes of plume theory, some are skeptical. *Plates, Plumes, and Paradigms* has been compiled and edited by geoscientists who believe that hotspots and flood basalts are not caused by plumes but have other, shallow causes. Although this view is at one end of the spectrum, there has always been a debate even among plume advocates about which hotspots are caused by deep-seated plumes—for example, one recent survey identified only seven hotspots that originate from the deepest part of the mantle (*1*). The volume contains an interesting mixture of 47 peer-reviewed chapters, which range from reviews and historical perspectives to presentations of new scientific findings and cover a wide range of scientific subdisciplines including geology, petrology, geochemistry, seismology, tectonics, geomagnetism, and planetary science. Even though this compendium is not intended to present a balanced debate on the merits of plume theory—there are no contributions from major plume proponents, and the majority of chapters focus on problems with the theory and favor alternative explanations—it includes several chapters that offer useful neutral surveys of findings from seismology and other fields and a few that argue in support of plumes.

What is wrong with the idea that plumes cause hotspots and flood basalts? Several authors document ways in which, for some such features, inferences they make from observations are in conflict with a plume cause. Various chapters argue, for example, that the sources of some hotspot magmas were not hot (inferred from petrology or subsidence rates), the 1- to 4-km uplift expected should a buoyant plume head reach a plate is not observed for many flood basalts, there is a lack of a clear signal indicating enhanced heat flux, some hotspot chains show inconsistencies in the progression of their ages, and there are some problems with spatial relations between hotspot chains and supposedly related flood basalts.

If plumes are not the answer, what is? Here the arguments presented by the contributors sometimes get awkward. Often a different detailed explanation seems to be required for each case. Most proposals, however, fall under one or both of two themes: shallow processes related to plates and a shallow mantle that is laterally heterogeneous in both composition and temperature. One frequent topic is the relationship of flood basalts or hotspots to preexisting plate structures such as cratons (the old, strong parts of continents) and oceanic fracture zones and to changes in plate motions (including extension, continental breakups or collisions, and movements of triple junctions) or changes in plate stress. The volume contains arguments that, for example, hotspot chains may be caused by propagating cracks and flood basalts may be caused by tectonic events that trigger delamination of the lower part of the plate or by local convection driven by lateral variations in plate thickness. Lateral variations in composition, such as enrichment in volatiles or subducted crust, could also lead to high melt production in localized areas. Some chapters invoke asteroid impacts.

Such alternative explanations raise many issues that will need to be resolved before they become widely accepted. For example, the Pacific hotspots exhibit little relative motion as the plate moves over them. If they are caused by propagating cracks, why do all the cracks propagate at the same rate? Plate boundaries tend to be linear. Why then are flood basalts, and hotspots that occur at spreading centers, not linear, following the plate boundary? With some notable exceptions (delamination, "edge-driven" convection, impact volcanism), we currently lack quantitative modeling that demonstrates the feasibility of alternative mechanisms.

In conclusion, despite its strong emphasis on the skeptic side of the plume debate, *Plates, Plumes, and Paradigms* is a stimulating and useful reference for observations and arguments. The volume contains several



Schematic summary. Anderson contrasts plume and "plate" (or "shallow") models.

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valuable contributions that plume proponents will need to pay attention to. Most geoscientists agree that plate structure does exert a major influence on volcanism (for example, all continental flood basalts occur at the edge of cratons). Determining the relative importance of deep plumes versus plate dynamics in causing flood basalts and hotspots will not be straightforward. Resolving the issue will require much interdisciplinary research, integrating observational and theoretical constraints from geology, geophysics, geochemistry, petrology, and several other fields. Such future work may well demonstrate that the formation of hotspots requires a combination of both deep plumes and plate dynamics.

Reference

1. V. Courtillot, A. Davaille, J. Besse, J. Stoack, *Earth Planet. Sci. Lett.* **205**, 295 (2003).

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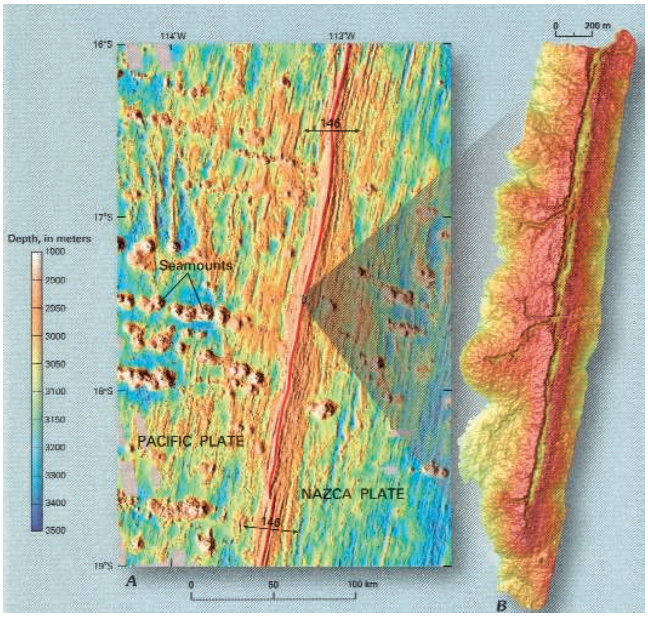
Charting Earth's Activities

Peter Crowley

Maps have been a mainstay of geologists since at least the publication of William Smith's geological map of England in 1815. Unfortunately, in recent years the paper map has almost disappeared; currently, most new maps are released instead as electronic databases. Although this development has produced a wealth of information for the specialist, it has made it harder to disseminate that information to the interested nonspecialist.

Maps, such as Bruce Heezen and Marie Tharp's shaded relief maps of the ocean floor (from the 1970s), have been instrumental in conveying complex geological ideas to broad audiences. By clearly showing the complicated topography of the ocean floor, the Heezen and Tharp maps made plate tectonics seem real and changed the way that many viewed our planet. In many ways, *This Dynamic Planet* (like its earlier, 1989 and 1994, versions) is an update of these now-classic maps. The front side of the sheet is dominated by the colored and shaded relief map of the world on which the locations of earthquakes, volcanoes, plate boundaries, and impact craters are plotted. The 1:30 million map uses a variety of symbols to depict earthquake magnitudes and focal depths, the size of impact craters, and the age of volcanic eruptions as well as absolute and relative plate motion vectors. The reverse side of the map provides a heavily illustrated explanation of plate tectonics.



Topography of a fast-spreading ridge. Here on the East Pacific Rise, the Pacific and Nazca plates are separating at 146 mm/year.

Although the topography of the ocean floor on *This Dynamic Planet* is much less exaggerated than it was on the Heezen and Tharp maps, important features of the deep ocean such as trenches, fracture zones, and seamounts are distinctly depicted, as are the large-scale features of the continents. The overlay of plate boundaries, volcanoes, and earthquakes on the topography very clearly demonstrates the importance of plate boundary processes. The explanation of plate tectonics given on the back of the map (which occupies the spatial equivalent of approximately 25 printed pages) is beautifully illustrated and extraordinarily detailed. That detail proves to be both the strength and the weakness of the map's reverse side. The quite complete but sometimes nuanced explanations make for good reference material, but they may prove a hard read for anyone who is not already familiar with the basics of plate tectonics.

This Dynamic Planet
World Map of Volcanoes, Earthquakes, Impact Craters, and Plate Tectonics

by Tom Simkin, Robert I. Tilling, Peter R. Vogt, Stephen H. Kirby, Paul Kimberly, and David B. Stewart

U.S. Geological Survey, Smithsonian Institution, and U.S. Naval Research Laboratory, Washington, DC, 2006. $14. U.S.G.S. Geologic Investigations Series Map I-2800.
www.minerals.si.edu/tdpmap/index.htm

For educators, the uses of this map are far from clear. Although the map is large (1.5 m by 1 m), it is nonetheless too small and detailed for use during lectures. The details that make the map so informative (e.g., plate boundaries and earthquake locations) become difficult to discern at distances greater than just a few meters. Thus educators may find the companion Web site (www.minerals.si.edu/tdpmap/index.htm) very helpful. The Web site offers an interactive version of the map that allows the viewer to examine any or all of 18 different layers of information as well as PDF versions of the map and its explanatory text and figures. Images from the Web site could be projected so that both the big picture and its details are evident to a class.

Overall, the map is extremely useful, and my complaints are fairly minor. Divergent and transform plate boundaries are shown on the main map, but convergent boundaries are, for some reason, omitted. This is an unfortunate oversight, particularly since they are depicted on the PDF version and are available as a layer on the interactive map. Even though the shallow ocean topography is more exaggerated than that of the deep ocean, details of continental margins such as submarine canyons remain hard to see. The Web site allows users to create a wide array of interesting and revealing maps and to save images of those maps. These images would be ideal for classroom projection if only the resolution was a bit higher.

In an era when new maps are commonly released as geographic information systems databases, it is refreshing that a hard-copy version of the U.S. Geological Survey's best-selling *This Dynamic Planet* has been updated and re-released. My copy is already up on the wall, where it will serve as a valuable reference tool.

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