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INSIDE

Ocean Drilling and the Volcanic Record of Hotspots

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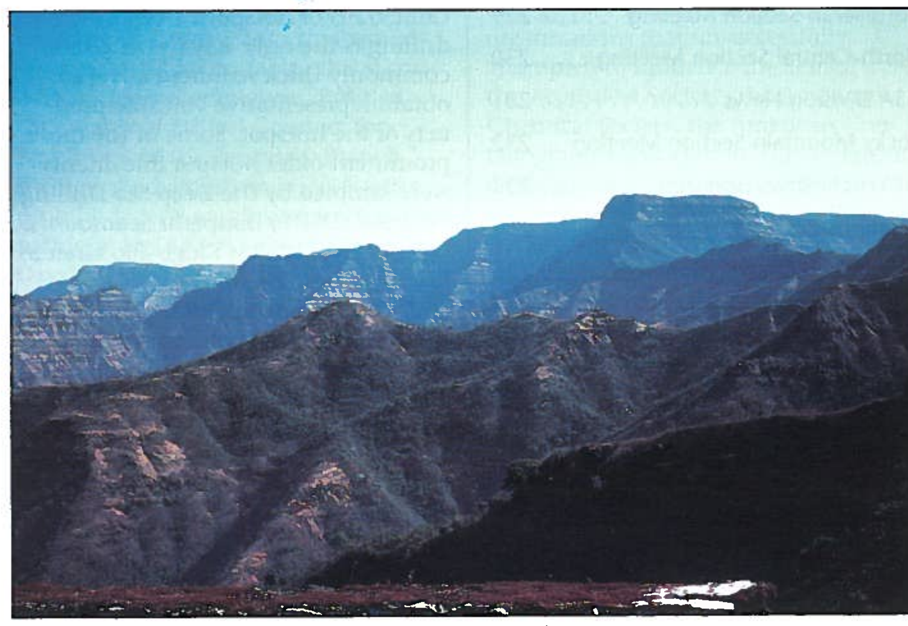
Editor's Note: The Ocean Drilling Program (ODP) is one of the largest and most ambitious international research projects in geology. Since 1969, it and its predecessors, the Deep Sea Drilling Project (DSDP) and the International Project of Ocean Drilling (IPOD), have addressed fundamental problems of ocean history and evolution by drilling almost 900 holes in the ocean bottom with the *GLOMAR Challenger* and, more recently, the JOIDES *Resolution.* This article is one of several that will summarize some of the more exciting recent discoveries of this important international project. The two photos symbolize the fact that in order to look at the along-strike nature of the exposure of basalts of the Deccan Traps, it is necessary to resort to drilling, as by the JOIDES *Resolution.*
—*Eldridge M. Moores*



Deccan flood basalt, western India. *Photo by J. Mahoney*

ABSTRACT

Hotspots are stationary, upper mantle thermal anomalies that are maintained over tens to hundreds of million years by convective upwelling in the form of mantle plumes. Lithospheric plate motions over hotspots have produced linear, age-progressive volcanic trails, such as most island and seamount chains in the ocean basins. Ocean drilling along several major hotspot tracks has documented a direct and simple frame of reference for plate reconstructions. Comparison of the hotspot and paleomagnetic reference frames reveals several episodes of true polar wander; that is, motion of the entire Earth with respect to its spin axis. Many of the longer lived hotspot tracks began with rapid eruption of flood basalts, including continental provinces but also many of the huge oceanic plateaus. Several of these catastrophic volcanic events have been linked with mass extinctions observed in the fossil record. The long-term, fixed nature of hotspots and the initial large-volume flood-basalt events reflect two modes of whole-mantle convection.

JOIDES *Resolution*, an ODP drilling ship. *Photo provided by the Ocean Drilling Program*

INTRODUCTION

The location, flux, and compositional variability of basaltic volcanism on our planet can be largely explained by the plate-tectonic model. Mid-ocean-ridge basalts are produced by decompression melting of passively upwelling upper mantle (asthenosphere) at the edges of separating plates, while subduction of oceanic lithosphere delivers water and other volatiles into the mantle to stimulate melting, yielding volcanic arc basalts along collisional plate boundaries. Such plate-margin environments account for the vast majority of all basaltic magma production. A significant but volumetrically minor class of basaltic volcanism occurs within plates or crosses plate boundaries and is characterized by linear chains of volcanoes that grow older in the directions of plate motion. Familiar examples of this volcanic phenomenon are the young, parallel island chains of the Pacific basin (such as the Hawaiian Islands), the Yellowstone–Snake River Plain province, and the volcanic platform and ridge system centered on Iceland. The linear geometry and progressive age of volcanism within these provinces are thought to result from focused upper mantle zones of melting called hotspots (Wilson, 1963, 1965) that remain stationary as Earth's outer shell of lithospheric plates moves across them. The proposed locations of present hotspot volcanism are shown in Figure 1.

Morgan (1971, 1972) proposed that hotspots are maintained by unusually warm material rising from the lower mantle through upwardly convecting mantle plumes. These plumes, he speculated, constitute part of a long-lived, stable pattern of whole mantle convection. Once established, these conduits for heat and material transport from the lower mantle do not, Morgan suggested, move relative to one another. Because plumes arise from convection, it is popular to consider that they begin in the seismically defined thermal layer at the boundary between the core and mantle. Figure 1 shows that hotspots are not randomly distributed over the globe but are primarily a feature of the ocean basins and occur in two large clusters, one centered over the equatorial Pacific and the second running from the North Atlantic to the South Atlantic and western Indian oceans. Furthermore, hotspot locations correlate closely with positive departures from the average geoid (Crough and Jurdy, 1980) and with regions of slow seismic velocities (V_p) in the lower mantle (Morelli and Dziewonski, 1987). These observations support Morgan's (1971, 1972) claim that hotspots are connected with mantle-wide upward convection. An important question is whether or not plumes are, in fact, fixed with respect to one another over geologically significant time scales.

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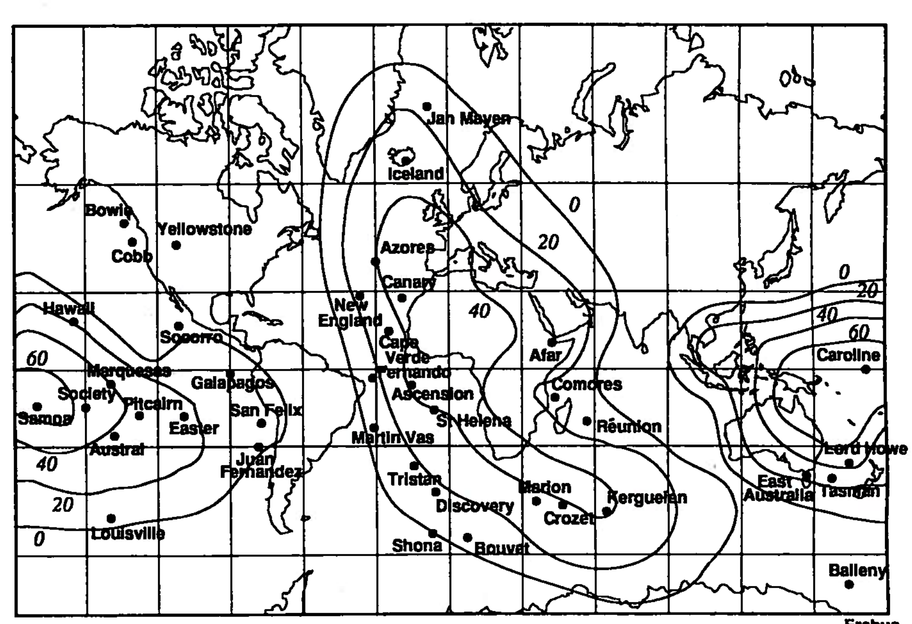

Figure 1. The global constellation of hotspots, which are upper mantle thermal anomalies that remain stationary and leave volcanic trails on the lithospheric plates. Hotspots are not randomly distributed but are concentrated in zones of high geoid residuals (contours, in metres, are from Crough and Jurdy, 1980). The pattern of hotspots also correlates with regions of slow V_p in the lower mantle (Morelli and Dziewonski, 1987), suggesting that hotspots are connected with mantle-wide upward convection.

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The answer to this has implications for the viscosity structure of the mantle and the scale and pattern of convection, as well as the idea that hotspot volcanism provides a useful reference frame for plate motions.

This paper reviews the contributions of the Ocean Drilling Program (ODP) to understanding of the dynamics and the compositional and thermal histories of mantle plumes, through sampling the volcanic record of long-lived hotspots. The products and effects of current hotspot activity can be studied in numerous young island chains, but long-term aspects of hotspot behavior can be investigated only by sampling the older, submerged volcanic trails of hotspots. Deep ocean drilling is the only way to penetrate commonly thick sediment cover to obtain representative volcanic products of the hotspot. Some of the more prominent older hotspot lineaments were sampled by the Deep Sea Drilling Program (DSDP) (Emperor Seamounts, Line Islands, Walvis Ridge–Rio Grande Rise, and New England Seamounts), and an early focus of ODP has been the complete volcanic history of two major Indian Ocean hotspots, Réunion and Kerguelen. Such extensive coverage has established the genetic connection between now active hotspots, island chains, seamount lineaments, and, in many instances, flood-basalt provinces. This density of sampling, coupled with biostratigraphic and radiometric age determinations, has strengthened the case for stationary mantle plumes over periods as long as 100 m.y. Compositional studies have traced the chemical variability in hotspot products with time, reflecting mixing of plume and upper mantle material.

LIFE CYCLE OF HOTSPOTS

Much of what we know about hotspot volcanic chains has been learned at young island chains, Hawaii in particular. Yet these occurrences tell us only about the present activity of these thermal anomalies. How do mantle plumes start? What is the average life span of a hotspot? How do the composition and flux of volcanic material at a given hotspot change with time? To answer these questions requires sampling of volcanic lineaments that record the entire life cycle of hotspots. Two of these are in the Indian Ocean, those produced by the Réunion and the Kerguelen hotspots (Fig. 2), and they were the focus of four ODP drilling legs during 1987–1989.

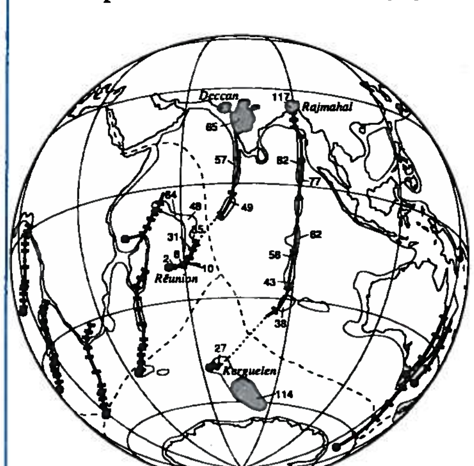

Figure 2. Computer-modeled hotspot tracks for the Indian Ocean basin, superimposed on the Réunion and Kerguelen volcanic lineaments. Black circles are current hotspot positions; heavy lines are predicted tracks (age of volcanism shown by ticks at 10-m.y. increments). Numbers are radiometric ages determined on basaltic rocks from island, submarine, and continental locations along the trends. The close correspondence between observed and modeled tracks supports the notion that hotspots are fixed and are maintained by deeply rooted mantle plumes. Flood basalts (stippled) mark the beginning of the two Indian Ocean hotspots investigated by ocean drilling.

The western (Réunion) province trends northeastward from the islands of Réunion and Mauritius, along the eastern limb of the Mascarene Plateau, then north along the Chagos-Maldive-Laccadive ridges to the Deccan continental flood basalts of central-western India. The eastern (Kerguelen) province includes the Kerguelen Archipelago, the Kerguelen Plateau, the Broken and Ninetyeast ridges, and the Rajmahal flood basalts. (Older and younger parts of both tracks have been separated by recent sea-floor spreading in the central Indian basin.) In addition to the subaerial exposures at islands and in India, deep drilling has recovered basalts beneath thick pelagic and shallow-water (carbonate and volcaniclastic) sedimentary deposits at six locations along the Réunion hotspot track and at six sites along the Kerguelen hotspot track; at an additional four sites on the Kerguelen Plateau, drilling reached basaltic basement.

Radiometric ages (^{40}Ar-^{39}Ar incremental heating experiments; Duncan and Hargraves, 1990; Duncan, 1991) define clear southward progressions in the age of volcanic activity along the two trends (Fig. 2). The contiguous, linear and parallel geometry of these lineaments, together with the age distribution of the volcanism, link each hotspot with the older elements of its trace. Both of these hotspots appear to have begun with massive outpourings of basaltic magmas over broad regions of the Indian subcontinent, but at different times. The earliest manifestation of the Réunion hotspot is the Deccan flood basalt province, with an estimated original volume of about 1.5×10^6 km^3. On the basis of direct radiometric dating and magnetostratigraphic data, this entire sequence of lava flows is believed to have erupted extremely rapidly, within 1 m.y., at about 65 Ma (Duncan and Pyle, 1988; Courtillot et al., 1988; Baksi and Farrar, 1991). This catastrophic volcanic activity coincided with the Cretaceous/Tertiary boundary and probably contributed to climate change at that time through magma degassing (SO_2, HCl, HF, CO_2). The Kerguelen hotspot began similarly but earlier, with a flood basalt phase of activity at about 117 Ma. Plate reconstruction of the eastern Indian Ocean for this time places the contemporaneous southern Kerguelen Plateau adjacent to the Rajmahal basalts (Royer and Sandwell, 1989), indicating a volume several times larger than the Deccan province.

Other prominent hotspot tracks appear to have begun with flood-basalt events. The association of Mesozoic and younger flood basalts and hotspots (Morgan, 1972, 1981; Richards et al., 1989) is shown in Figure 3; the spatial and temporal relations are often more speculative than for the well-defined Réunion-Deccan and Kerguelen-Rajmahal pairs. One of the largest occurrences, the Siberian Traps, coincided with the largest known mass extinction event, that defining the Permian/Triassic boundary (Renne and Basu, 1991). This 250 Ma province, however, is not clearly connected to a now-active hotspot. Flood-basalt provinces are present along continental margins where they are associated with the early stages of continental rifting (White and McKenzie, 1989), but also interior to continents and in wholly oceanic settings. Table 1 compares the mantle plume volcanic production rates for flood-basalt and ocean-island phases of the hotspot life cycle. Initial eruption rates are between one and two orders of magnitude greater than for the subsequent "steady-state" mode.

These dynamic changes in the behavior of hotspots have been explained by the structure of diapirs produced in laboratory experiments, which are thought to mimic mantle plumes arising from deep mantle gravitational instabilities (Richards et al., 1989; Campbell and Griffiths, 1990). These experiments and theory show

Table 1. Comparison of Hotspot and Associated Flood Basalt Production Rates

Province and age (Ma) or hotspot	Original volume (km^3)	Duration (m.y.)	Rate (km^3 per year)
Deccan (66±1)	>1,500,000	<1.0	>1.5
*Reunion	75,000	2.0	0.04
North Atlantic Tertiary (60±1)	>2,000,000	2.0	>1.0
*Iceland	3,500,000	15.	0.02
Parana-Etendeka (125±5)	1,500,000	2.0?	~0.75
*Tristan da Cunha	6,000	0.2	0.03
Karoo (early phase) (195±5)	2,000,000	2.0?	~1.0
*Marion-Prince Edward	10,000	0.5	0.02

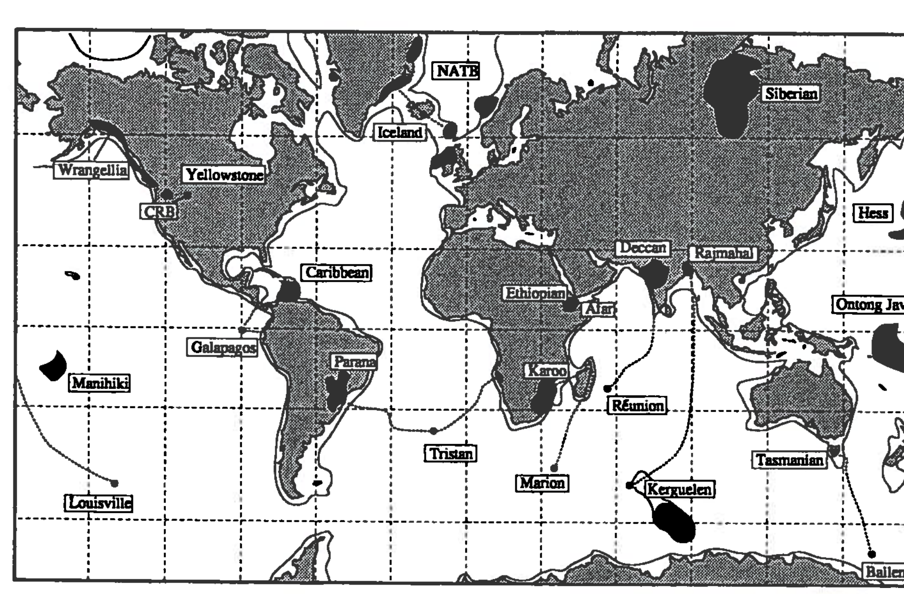

Figure 3. Global distribution of flood basalt provinces erupted in the past 250 m.y. and associated hotspots (where known or guessed). These occur along continental margins, in continental interiors and in ocean basins; some, like Wrangellia, may be accreted oceanic plateaus. CRB are Columbia River basalts, and NATB are North Atlantic Tertiary basalts.

that plumes may start as lower viscosity (warmer) diapirs that grow from their supply through a trailing conduit as they rise through higher viscosity (cooler) mantle. The plume thus develops a large, spherical head and a long, narrow tail. On arrival at the base of the lithosphere, the plume head flattens and melts by decompression, producing enormous quantities of magma in a short period. These are the flood basalt events that have occurred on continents and in ocean basins and that signal the beginning of major hotspot tracks. Subsequent volcanism over the plume conduits (or "tails"), established by the initial plume upwelling, are the familiar tracks that connect flood basalts to currently active hotspots. Thus, an important prediction of this model is that oceanic plateaus, such as Ontong-Java, Kerguelen, and Manihiki, are flood basalt provinces equivalent to the continental examples. Only deep-sea drilling can sample these vast submarine features, although Richards et al. (1991) believe that some ancient oceanic plateaus have been accreted to continents, such as Wrangellia, southeast Alaska. (Is the ultimate fate of the flood basalt that began the Hawaiian hotspot an accreted terrane in Siberia?) Ocean drilling on the Ontong-Java plateau has recently been completed (ODP Leg 130) where flood-type basalt flows about 120 m.y. old are present at sites separated by more than 1500 km.

Following the formation of hotspots in flood-basalt volcanism, mantle plume flux along the Réunion and Kerguelen traces has been more or less constant, with no sign of waning activity. Some hotspots, notably the one that began with the Ontong-Java plateau and later formed the Louisville seamount chain, have disappeared, while others such as the Marquesas produce intermittent volcanic chains. On the basis of deep ocean drilling evidence for continuity of major hotspot tracks, it is clear that mantle plumes have lifetimes on the order of 120 m.y. or more.

HOTSPOT REFERENCE FRAME

If the global constellation of mantle plumes forms a long-lived, stable pattern of convection of heat and material from the lower to the upper mantle, then the geographic orientations and age distributions of volcanic chains related to hotspots offer a very simple and direct record of the motion of lithospheric plates during the history of opening of most of the present ocean basins. Rates and directions of plate separation derived from the alternating normal and reversely magnetized stripes of seafloor parallel to spreading ridges measure past large-scale horizontal movements of pieces of Earth's surface relative to their neighbors. This is called a relative motion reference frame because the spreading ridges from which motion is measured are themselves moving over the mantle, albeit more slowly than plates. A third reference frame for plate motions is provided by Earth's magnetic field, which is assumed to have the shape (on average) of a dipole field aligned along the spin axis. Rocks that are magnetized in this field acquire a magnetic inclination (angle of the rock magnetic vector from horizontal) unique to their latitude. Thus, any trans-latitudinal (north-south) motion of lithospheric plates can be determined from the paleomagnetic reference frame; east-west motions cannot be measured by this method.

An essential question concerning hotspot volcanism, then, is whether or not mantle plumes are, in fact, fixed relative to one another and thus define an irregular, but rigid reference frame. Some amount of interplume (hotspot) motion might be expected because of viscous coupling between the base of the moving lithospheric plates and the upper mantle due to horizontal flow of the upper mantle away from spreading centers and toward subduction zones. If these perturbations are small or constant over long periods, then interplume drift may be significantly less than plate velocities, and hotspots with associated volcanic traces constitute a convenient and direct reference frame for reconstructing plate motions, independent of the paleomagnetic reference frame.

The magnitude of interplume motion can be assessed by comparing the geometry and age distribution of volcanism along hotspot tracks with reconstructions of past plate movements based on relative-motion data. If the motion of one plate over hotspots underlying it is determined from the orientation and age of volcanism along trails of islands, seamounts, and linear ridges, reconstructions of the past positions of neighboring plates relative to those hotspots can be calculated from sea-floor–spreading data. If hotspots underlying all plates are stationary, then the calculated motions of the neighboring plates should follow hotspot tracks observed on them. Any deviations of these predicted plate movements from actual hotspot tracks would then indicate the magnitude and direction of interplume drift. Figure 2 shows such computer-modeled hotspot tracks. In this example, the motion of the African plate has been described by a sequence of rotations over fixed hotspots that best fits the geometry and ages along sampled tracks, most notably the Walvis Ridge (O'Connor and Duncan, 1990). Modeled ages, shown in 10-m.y. increments, increase northeastward from 0 to 120 Ma, the approximate age of opening of the South Atlantic.

Addition of the relative plate motion between India and Africa and between Antarctica and Africa predicts the tracks that should be left by the Réunion and Kerguelen hotspots if these have remained fixed relative to the South Atlantic hotspots. As can be seen in Figure 2, there is a close match between predicted and observed volcanic trends, both in geometry and in age distribution. Hotspot tracks in eastern Australia and the Tasman Sea are similarly well matched (McDougall and Duncan, 1988). The success of this modeling, then, is strong support for the notion that hotspots maintain a fixed geometry over periods as long as 120 m.y. Molnar and Stock (1987), on the other hand, have found significant differences between observed and calculated tracks when comparing Atlantic and Pacific hotspots. Their analysis, however, assumes a single Antarctic plate from Late Cretaceous through Tertiary time, but all hotspots can be stationary if some relative motion between East and West Antarctica occurred during 80–40 Ma (Duncan, 1981).

The mantle reference frame for plate motions defined by hotspot tracks is independent of the paleomagnetic reference frame and has certain distinct advantages: It does not depend on the assumption of the geocentric axial dipole field (for which there is good evidence except during polarity reversals of the field), and it resolves

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WASHINGTON REPORT

Bruce F. Molnia

Washington Report provides GSA membership with a monthly window on the activities of the federal agencies, Congress and the legislative process, and international interactions that could impact the geoscience community. In future issues, Washington Report will present summaries of agency and interagency programs, track legislation, and present insights into Washington, D.C., geopolitics as they pertain to the geosciences.

Potpourri

Government Ethics and Scientific Societies. On September 20, the comment period closed on a series of proposed guideline revisions that would change what is acceptable ethical conduct for federal employees. Entitled "Standards of Ethical Conduct for Employees of the Executive Branch," the new guidelines would, in essence prohibit federal employees from participating in the operational affairs of professional societies such as GSA. The Outside Activities section of the new guidelines would prohibit federal employees from using official on-the-job time to administer the internal affairs of professional societies or to conduct business affairs of the professional societies. In essence, this would eliminate federal employees serving as, for example, officers of GSA or editors of *GSA Today*. According to GSA President E-an Zen, the revised guidelines "could cause real problems for government scientists and could give young researchers one more reason not to work for the federal government." [See September *GSA Today*, p. 191, for Zen's notice about this.]

Wetlands. Last year's wetland is no longer this year's wetland. As much as 10% of the 100,000,000 acres in the U.S. previously defined as wetlands no longer meet the newest criteria of what constitutes a wetland. In 1988, George Bush, while campaigning for the Presidency, pledged a wetland protection policy of "no net loss." This position was strongly supported by the environmental and conservation communities. In early August, the administration's definition of what constitutes a wetland was changed to exclude several environments that had been previously included, and consequently previously protected from various types of development. Environmental Protection Agency Administrator William Reilly had attempted to maintain a broad interpretation of what constituted a wetland but was perceived by some members of the President's staff, some members of Congress, and several other Cabinet members as holding to an "anti-growth" position. The result of this new administration position is to remove certain environments, such as prairie potholes, from meeting the criteria for definition of wetlands.

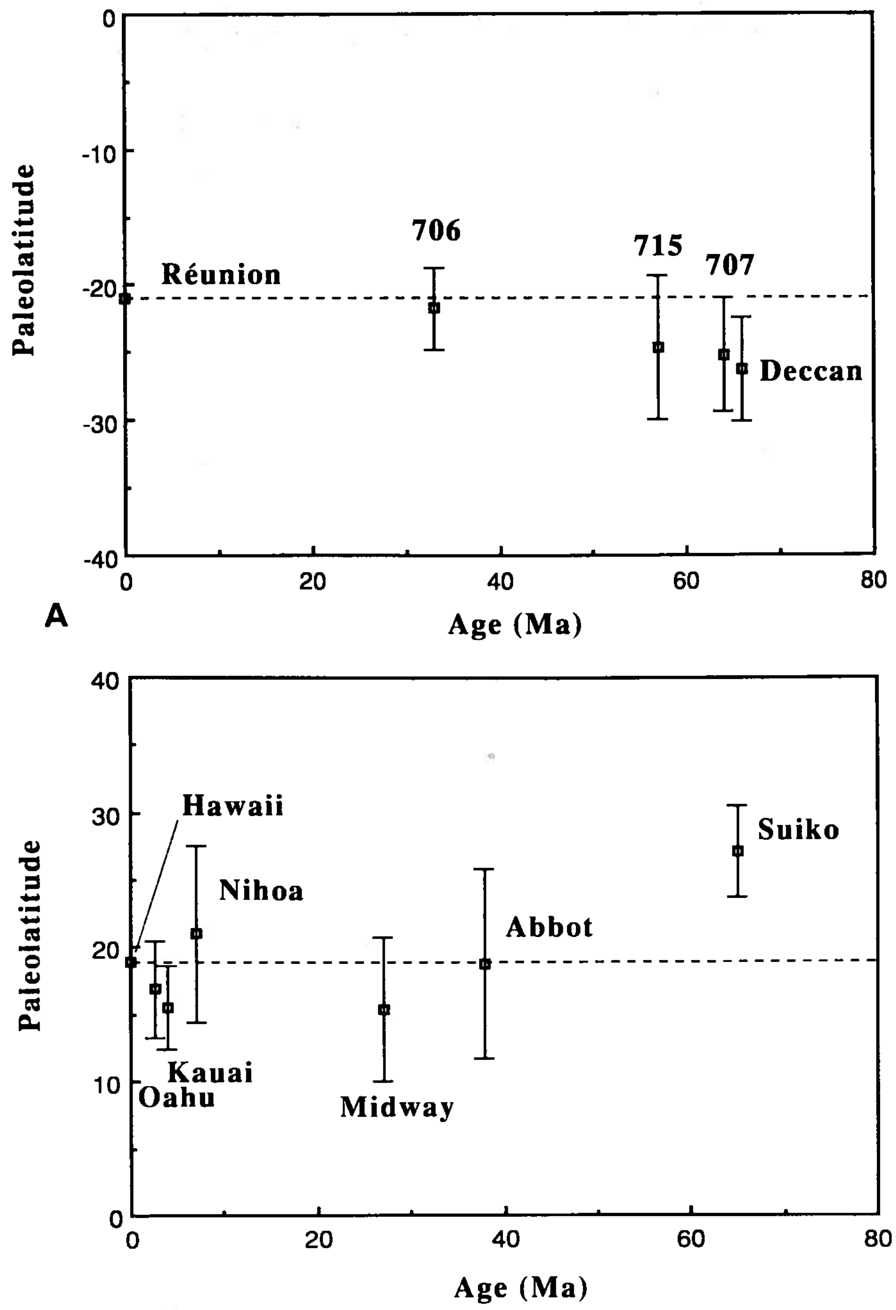
Space Station Freedom. In mid-July, the Senate Appropriations Committee voted to approve full funding for the National Aeronautics and Space Administration's (NASA) Space Station Freedom project. What made this more than just a routine action on the part of the committee was that prior to the committee's vote, 14 scientific organizations and societies sent letters to members of the Senate opposing funding of Space Station Freedom. The letters stated that the excessive cost of the space station project (NASA stated a cost of $30 billion) would drain substantial amounts of funding from the support of science. The letters also asserted that the space station project would threaten "the vitality" of essential research programs and would jeopardize U.S. leadership in the world technology community. Among the 14 organizations that unsuccessfully attempted to influence the Senate were the Acoustical Society, the American Chemical Society, the American Crystallographic Association, the American Geophysical Union, the American Mathematical Society, the American Physical Society, the Optical Society of America, and Sigma Xi. (GSA was not one of the 14 organizations.) Committee chairwoman Barbara Mikulski's response to the plea from the scientific community was to suggest that they, the scientists, were misinformed and arguing from a position of vested interest.

Among the budgetary manipulations necessary to fully fund the space station, the committee recommended a cut in NSF's Antarctic program, a cut in the budget for housing for the elderly, and a $50 million cut in NASA's Earth Observing System (EOS) project. For FY 1993, the Committee recommended a ceiling of $2.25 billion for the space station project.

In May, the House Appropriations Subcommittee had voted to virtually eliminate the space station project from the FY 1992 budget. Lobbying by a vocal administration group, including Vice President Quayle, resulted in the resurrection of the project. Critics of Space Station Freedom have pointed out that the stated $30 billion cost for the project is a gross understatement. Critics estimate that the full cost for the 30-year life of the project may run as high as $180 billion.

Global Warming Halted (at least for the short term). A report in the *Washington Post* by William Booth quotes National Oceanic and Atmospheric Administration (NOAA) scientists as stating that the June 15 and 16 eruption of Mount Pinatubo introduced enough volcanic ash, dust, and gasses into the atmosphere to overcome the warming effects of greenhouse gas buildup, and to result in a cooling of Earth, at least for a few years. Described as the largest volcanic eruption of the century, Pinatubo's volcanic emissions may be two or three times more voluminous than those of the 1982 eruption of El Chichon. Based on analysis of polar-orbiting weather-satellite data, the NOAA scientists predict as much as a 4°F lowering of average temperatures in the tropics.

A concern raised by the environmental community is that any cooling, even a very temporary cooling related to atmospheric ash buildup, will be used to support the Bush Administration's lack of full acceptance of global warming and its potential consequences. The *Post* article quotes Michael Oppenheimer of the Environmental Defense Fund as stating, "The cooling is only temporary. It would be most foolish to use this hiatus in the warming trend as an excuse for inaction." ■



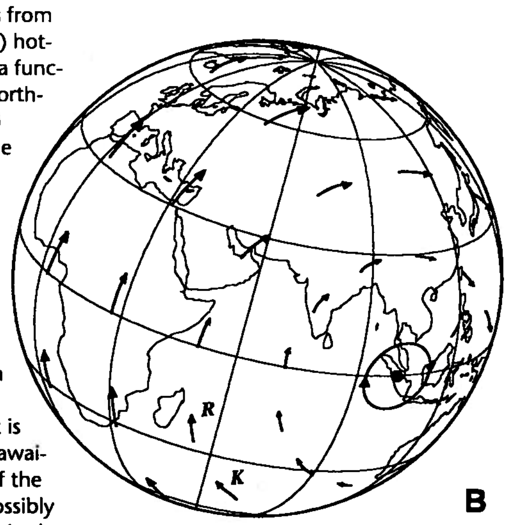


Figure 4. A: Paleolatitudes of sample sites from the Réunion (above) and Hawaiian (below) hotspot tracks, with α_{95} confidence limits, as a function of time. These data indicate a small northward motion of the Réunion hotspot (~7°) concurrent with a southward motion of the Hawaiian hotspot (~8°). The results are consistent with an episode of true polar wander; that is, motion of the entire Earth relative to its spin axis, as shown in B.

B: The early Tertiary true polar wander episode can be described by clockwise rotation (~9°) of the Earth about a pole on the equator at about 100°E. The resulting northward motion of the Réunion hotspot is about 7°, and southward motion of the Hawaiian hotspot is about 8°. This adjustment of the Earth's principal moment of inertia was possibly caused by reorganization of plate motions in the early Tertiary.

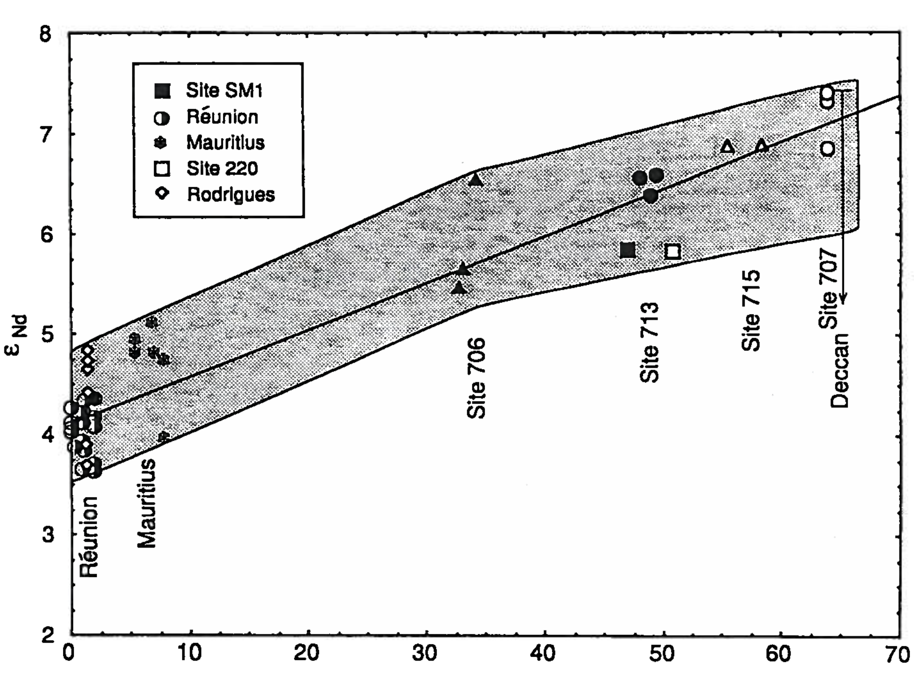


Figure 5. Variation of $^{143}Nd/^{144}Nd$ (shown as ε_{Nd}) of Réunion hotspot magmas as a function of time. The trend is from compositions similar to ocean-floor basalts in the early stages of hotspot activity (including the Deccan flood basalts) toward more plumelike ocean-island compositions.

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east-west plate motion, which is not detected in paleomagnetic studies. Several groups have used the mantle reference frame to determine the history of plate convergence across subduction zones, where the record of relative plate motion is largely destroyed (e.g., Engebretson et al., 1984). Continental tectonic and volcanic events in western North America are particularly well correlated with changes in the magnitude and direction of plate convergence predicted from the hotspot reference frame. This method eliminates the need to construct global circuits of plate motions that cross only spreading ridges and reduces the large uncertainties accumulated in combining sequences of rotation poles.

Also, differential motion between the mantle and the spin axis can in principle be determined by comparing plate motions recorded by the hotspot and paleomagnetic reference frames. Such motion has been termed *true polar wander* (distinguished from apparent polar wander of the magnetic [= spin] axis inferred from time sequences of paleomagnetic field directions for given plates). It is possible that redistribution of mass within Earth through processes such as mantle convection and plate motions may change the planet's moments of inertia sufficiently to cause a shift of the entire body relative to its spin axis (Goldreich and Toomre, 1969). This is, in fact, an old idea, suggested as an alternative to continental drift to explain paleoclimatic evidence for translatitudinal motion of Earth's surface (Irving, 1964). True polar wander, however, was largely ignored after it was demonstrated that separate continents had distinct apparent polar wander paths and that continental drift (plate motion) must have occurred. Could both motions occur simultaneously?

In the absence of true polar wander, mantle plumes do not move relative to the spin axis. Hence, every volcano generated along a given hotspot track would record the magnetic inclination, usually expressed as the paleolatitude, of the site of present hotspot activity. If measured paleolatitudes are constant along a hotspot track, then that hotspot has not moved with respect to the spin axis. On the contrary, a change in hotspot paleolatitude with time would indicate motion of the mantle (because plumes are stationary within the mantle) relative to the spin axis, which is true polar wander. (Note that the low viscosity of the fluid outer core allows the geomagnetic field to remain coupled with the spin axis.)

Paleolatitude data for core material recovered at three ODP Leg 115 sites, together with the paleolatitude of the Deccan flood basalts (–27.9° ± 2.4°, Vandamme et al., 1991), indicate an ~7° northward motion of the Réunion hotspot (Fig. 4A). This small amount of true polar wander is just barely significant at the α_{95} confidence level of the paleomagnetic data. However, the direction and magnitude of this inferred mantle motion are consistent with other comparisons of the hotspot and paleomagnetic reference frames. Of particular interest are magnetic data from basalts recovered by DSDP drilling at Suiko seamount in the northern Hawaiian-Emperor chain that yielded a paleolatitude for the Hawaiian hotspot of 27.1° ± 3.4° (Kono, 1980), requiring ~8° southward motion of this hotspot since 65 Ma. Paleolatitudes of younger sites along the Réunion and Hawaiian hotspot tracks are not significantly different from the present hotspot positions (Fig. 4A), indicating that the true polar wander occurred in early Tertiary time.

Hargraves and Duncan (1973) first noted the systematic northward motion of hotspots in the Atlantic region and simultaneous southward motion of hotspots in the Pacific region, relative to the geomagnetic pole, over the past ~50 m.y. This observation was explained by a 12° clockwise rotation of the mantle about an equatorial axis emerging in the western Indian Ocean (Fig. 4B). Subsequent studies (summarized in Courtillot and Besse, 1987) have confirmed this surprising conclusion and have extended the history of true polar wander to 200 Ma. Intriguingly, the early Tertiary true polar wander event occurred within a period of global plate-motion reorganization, resulting in significantly more east-west collisional plate boundaries (Rona and Richardson, 1978). The abrupt change in direction of the Pacific plate, reflected in the Hawaiian-Emperor bend (43 Ma), and the "hard" collision of India and Africa-Arabia against Eurasia (45–50 Ma) occurred at this time. Courtillot and Besse (1987) concluded that these changes in subduction-zone location and activity perturbed the torque balance of the coupled upper mantle–lithosphere system, which produced the true polar wander.

HOTSPOTS AS WINDOWS INTO MANTLE STRUCTURE

Because hotspots appear to be maintained by deep-seated mantle plumes, the composition of their volcanic products offers glimpses into the chemical structure of the mantle below the source region for ocean spreading ridge volcanism. It has been recognized since Gast's (1968) work that ocean island and sea-floor basalts are melted from distinct mantle reservoirs that have been separate for billions of years. Plumes deliver material from the lower mantle that is primordial or has been accumulating over billions of years of plate subduction (Zindler and Hart, 1986). A major objective of ODP Leg 115 basement drilling was to sample a time sequence of the volcanic products of Réunion hotspot activity to examine compositional changes from flood basalts to ocean-island volcanism. The seamount and island basalts of other similarly long-lived hotspots are characterized by a remarkable uniformity in composition (e.g., the Hawaiian-Emperor chain and the Louisville Ridge), but certain isotopic and trace element ratios indicate that subtle changes in the mantle source for melt production may occur with time. Compositions of basalts from the endpoints of the Deccan-Réunion chain (Cox and Hawkesworth, 1985; Fisk et al., 1989) show that there was a change in the mantle material supplied to the hotspot through Tertiary time.

Major element contents show that volcanic rocks all along the Réunion hotspot track are predominantly ocean-island tholeiites with variabilities controlled principally by low-pressure olivine and plagioclase fractionation. The abundance of incompatible elements (e.g., K, Ti, and Zr) in parental magmas, however, appears to increase with time, from Deccan to Réunion sites. Moreover, trace element abundance ratios that are generally insensitive to variations in partial melting and fractional crystallization (e.g., Ba/Ti, Nb/Y, and Zr/Nb) show systematic

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decreases from north to south, indicating increasing influence of plume material. White et al. (1990) have determined the isotopic compositions (Sr, Nd, and Pb) of the drilled basalts, which are distinct from both Réunion and Deccan basalts. There is a clear trend toward higher $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ and lower ε_{Nd} with time (e.g., Fig. 5). This pattern is correlated with both a change from near-ridge to intraplate hotspot setting and a dramatic drop in magma production rate (from flood basalts to discrete volcanic centers).

There may be several causes for the temporal variations in basalt compositions produced from the Réunion hotspot: (1) the plate-tectonic environment in which the magmas erupted; (2) the effects of decreasing degrees of partial melting of plume material, which is heterogeneous on a small scale; and (3) changes in the composition of the plume itself. White et al. (1990) concluded that although decreasing degrees of partial melting may increase the proportions of incompatible elements and "enriched" isotopic ratios in hotspot magmas derived from compositionally heterogeneous plume material, the most plausible explanation for the observed geochemical variations is decreasing entrainment of asthenosphere by the rising plume. In the diapir model for plume initiation and flood basalt volcanism (Richards et al., 1989), the hot, low-viscosity, deeper mantle plume material will warm and entrain the upper mantle material through which it rises (Griffiths, 1986). Extensive examination of the Deccan basalts has shown that these magmas were a blend of plume (represented by Réunion basalt compositions) and Indian Ocean upper mantle (source for spreading ridge magmas), variably contaminated with continental lithosphere (e.g., Mahoney, 1988). The sheer size of the Deccan flood basalt event argues that a substantial region of the upper mantle beneath western India was involved in melting. Once the plume head had melted, the established plume conduit (tail) did not foster the same degree of entrainment of surrounding mantle, and the hotspot trail then formed from a much smaller scale of melting that involved progressively less upper mantle influence.

FUTURE DRILLING TARGETS

Deep ocean drilling along older, submerged parts of long-lived hotspot tracks has provided evidence that the array of hotspots is stable within useful time scales and provides a direct reference frame for plate motions. A small but apparently significant early Tertiary episode of true polar wander can be resolved through comparison of hotspot and paleomagnetic reference frames. Several major hotspots have burst into life with flood-basalt volcanism, most likely the initiation of mantle plumes. Compositional changes in the volcanic products of hotspots reflect the variable mixing of deep and shallow mantle and, occasionally, lithosphere contributions to melting. It is clear that hotspot traces provide a rich source of constraints on the dynamical, compositional, and thermal histories of the mantle; deep ocean drilling is an important aspect of investigating the temporal variations in hotspot activity.

Further study of hotspot–mantle plume phenomena is underway and planned for ODP drilling in the near future. The Kerguelen and Ontong-Java ocean plateaus were the focus of separate recent drilling legs. While analytical work is ongoing, it appears that these are oceanic equivalents of the continental flood-basalt provinces. Only a few hundred metres of the flow sequence has been sampled, so the full time and compositional range of volcanism will not be known soon. Future drilling in the North Atlantic will investigate the timing of continental rifting and volcanism surrounding the birth of the Iceland hotspot. A remarkable peak in mantle plume activity in Early to middle Cretaceous time will be examined by drilling into seamount chains in the western Pacific. This volcanism coincides with faster rates of sea-floor spreading, higher sea level, and higher atmospheric CO_2 than today, and a long period of uniform geomagnetic field polarity. Drilling will aim at establishing a precise time scale for the volcanism and its relation to the extreme Cretaceous climatic conditions. Drilling is also planned for one of the northernmost (and oldest) of the Emperor seamounts, to extend our picture of the compositional variability of the Hawaiian hotspot. A better constraint on the timing of true polar wander is also expected.

REFERENCES CITED

Baksi, A.K., and Farrar, E., 1991, $^{40}Ar/^{39}Ar$ dating of the Siberian Traps, USSR: Evaluation of the ages of the two major extinction events relative to episodes of flood-basalt volcanism in the USSR and the Deccan Traps, India: Geology, v. 19, p. 461–464.

Campbell, I.H., and Griffiths, R.W., 1990, Implications of mantle plume structure for the evolution of flood basalts: Earth and Planetary Science Letters, v. 99, p. 79–93.

Courtillot, V., and Besse, J., 1987, Magnetic field reversals, polar wander, and core-mantle coupling: Science, v. 237, p. 1140–1147.

Courtillot, V., Feraud, G., Maluski, H., Vandamme, D., Moreau, M.G., and Besse, J., 1988, Deccan flood basalts and the Cretaceous/Tertiary boundary: Nature, v. 333, p. 843–846.

Cox, K.G., and Hawkesworth, C.J., 1985, Geochemical stratigraphy of the Deccan Traps at Mahabaleshwar, Western Ghats, India, with implications for open-system magmatic processes: Journal of Petrology, v. 26, p. 355–377.

Crough, S.T., and Jurdy, D.M., 1980, Subducted lithosphere, hotspots, and the geoid: Earth and Planetary Science Letters, v. 48, p. 15–22.

Duncan, R.A., 1981, Hotspots in the southern oceans—An absolute frame of reference for motion of the Gondwana continents: Tectonophysics, v. 74, p. 29–42.

Duncan, R.A., 1991, The age distribution of volcanism along aseismic ridges in the eastern Indian Ocean, *in* Proceedings of the Ocean Drilling Program, scientific results, Leg 121: College Station, Texas, Ocean Drilling Program (in press).

Duncan, R.A., and Hargraves, R.B., 1990, ^{40}Ar-^{39}Ar geochronology of basement rocks from the Mascarene Plateau, Chagos Bank and the Maldive Ridge, *in* Duncan, R.A., et al., Proceedings of the Ocean Drilling Program, scientific results, Leg 115: College Station, Texas, Ocean Drilling Prgram, p. 43–51.

Duncan, R.A., and Pyle, D.G., 1988, Rapid eruption of the Deccan flood basalts at the Cretaceous/Tertiary boundary: Nature, v. 333, p. 841–843.

Engebretson, D.C., Cox, A., and Thompson, G., 1984, Correlation of plate motions with continental tectonics: Laramide to Basin-Range: Tectonics, v. 3, p. 115–119.

Fisk, M.R., Duncan, R.A., Baxter, A.N., Greenough, J.D., Hargraves, R.B., Tatsumi, Y., and Shipboard Scientific Party, 1989, Réunion hotspot magma chemistry over the past 65 m.y.: Results from Leg 115 of the Ocean Drilling Program: Geology, v. 17, p. 934–937.

Gast, P.W., 1968, Trace element fractionation and the origin of tholeiitic and alkalic magma types: Geochimica et Cosmochimica Acta, v. 32, p. 1057–1086.

Goldreich, P., and Toomre, A., 1969, Some remarks on polar wandering: Journal of Geophysical Research, v. 74, p. 2555–2567.

Griffiths, R.W., 1986, Thermals in extremely viscous fluids, including the effects of temperature-dependent viscosity: Journal of Fluid Mechanics, v. 166, p. 115–138.

Hargraves, R.B., and Duncan, R.A., 1973, Does the mantle roll?: Nature, v. 245, p. 361–363.

Irving, E., 1964, Paleomagnetism and its application to geological and geophysical problems: New York, John Wiley & Sons, 399 p.

Kono, M., 1980, Paleomagnetism of DSDP Leg 55 basalts and implications for the tectonics of the Pacific plate, *in* Jackson, E.D., et al., Initial reports of the Deep Sea Drilling Project, Volume 55: Washington, D.C., U.S. Government Printing Office, p. 737–752.

Mahoney, J.J., 1988, Deccan Traps, *in* Macdougall, J., ed., Continental flood basalts; Dordrecht, Netherlands, Kluwer, p. 151–194.

McDougall, I., and Duncan, R.A., 1988, Age progressive volcanism in the Tasmantid seamounts: Earth and Planetary Science Letters, v. 89, p. 207–220.

Molnar, P., and Stock, J., 1987, Relative motions of hotspots in the Pacific, Atlantic and Indian oceans since Late Cretaceous time: Nature, v. 327, p. 587–591.

Morelli, A., and Dziewonski, A.M., 1987, Topography of the core-mantle boundary and lateral homogeneity of the liquid core: Nature, v. 325, p. 678–683.

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

Morgan, W.J., 1972, Deep mantle convection plumes and plate motions: American Association of Petroleum Geologists Bulletin, v. 56, p. 203–213.

Morgan, W.J., 1981, Hotspot tracks and the opening of the Atlantic and Indian Oceans, *in* Emiliani, C., ed., The sea, Volume 7: New York, Wiley-Interscience, p. 443–475.

O'Connor, J.M., and Duncan, R.A., 1990, Evolution of the Walvis Ridge and Rio Grande Rise hotspot system: Implications for African and South American plate motions over plumes: Journal of Geophysical Research, v. 95, p. 17,475–17,502.

Renne, P.R., and Basu, A.R., 1991, Rapid eruption of the Siberian Traps flood basalts at the Permo-Triassic boundary: Science (in press).

Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hotspot tracks: Plume heads and tails: Science, v. 246, p. 103–107.

Richards, M.A., Jones, D.L., Duncan, R.A., and DePaolo, D.J., 1991, A mantle plume initiation model for the formation of Wrangellia and other oceanic flood basalt plateaus: Science (in press).

Rona, P.A., and Richardson, E.S., 1978, Early Cenozoic global plate reorganization: Earth and Planetary Science Letters, v. 40, p. 1–11.

Royer, J.-Y., and Sandwell, D.T., 1989, Evolution of the Eastern Indian Ocean since the Late Cretaceous: Constraints from Geosat altimetry: Journal of Geophysical Research, v. 94, p. 13,755–13,782.

Vandamme, D., Courtillot, V., and Besse, J., 1991, Paleomagnetism and age determinations of the Deccan Traps (India): Results of a Nagpur-Bombay traverse and review of earlier work: Reviews of Geophysics, v. 29, p. 159–190.

White, R., and McKenzie, D., 1989, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, p. 7685–7729.

White, W.M., Cheatham, M.M., and Duncan, R.A., 1990, Isotope geochemistry of Leg 115 basalts and inferences on the history of the Réunion mantle plume: Proceedings of the Ocean Drilling Program, scientific results, Leg 115: College Station, Texas, Ocean Drilling Program, p. 53–62.

Wilson, J.T., 1963, A possible origin of the Hawaiian Islands: Canadian Journal of Physics, v. 41, p. 863–868.

Wilson, J.T., 1965, Evidence from ocean islands suggesting movement in the earth: Royal Society of London Philosophical Transactions, v. 258, p. 145–165.

Zindler, A., and Hart, S., 1986, Chemical geodynamics: Annual Review of Earth and Planetary Sciences, v. 4, p. 493–571. ■