

LAVA erupting from an active volcano in Hawaii comes from a hotspot, akin to a flame burning through the earth's crust.

HOT

○○○ By John A. Tarduno

Where was the cone? We had just pulled up our drill pipe, replaced its worn drill bit, and lowered it back down to the seafloor, a mile under our ship. Crowding into the control room, we watched images from a camera attached to the end of the pipe, looking for a cone we had left as a marker to guide the pipe back to the hole we were drilling. The team had gone through this exercise many times before. Usually we would see a fish swim by or a squid momentarily grab the pipe, and then the cone would appear. This time we saw only fish and squid. What had gone wrong?

We had come to the northwestern Pacific Ocean to extract core samples from the submerged extinct volcanoes, known as the Emperor seamounts, that form the northernmost leg of the Hawaiian-Emperor volcanic chain. The neat pattern formed by the chain is apparent on any world map and, along with the jigsaw-puzzle shape of South America and Africa, has long stood as a testament to plate tectonics—the principle that our planet's surface is an ever shifting mosaic of rocky puzzle pieces. Not only do the islands and seamounts form an uncannily straight line for 3,500 kilometers across the Pacific, their rocks get steadily older as you move northwest up the chain: from the Big Island (which is still growing) through Maui, Oahu, Kauai and on up to the Midway atoll, whose long-extinct volcano has subsided so much that it barely sticks up above the sea surface. Past Midway, the line makes a sharp bend, continuing northward along the Emperor seamounts and stretching

RENE FREDERICK/Getty Images

SPOTS

Long considered fixed founts of molten material from deep within the planet, hotspots now join the list of moving parts

Unplugged

nearly as far as the tip of the Aleutian Islands.

The standard explanation for this pattern, based on ideas put forward by geophysicist J. Tuzo Wilson in 1963, is that the islands record motion of the Pacific plate over a volcanic hotspot [see “Hot Spots on the Earth’s Surface,” by Kevin C. Burke and J. Tuzo Wilson; *SCIENTIFIC AMERICAN*, August 1976]. The hotspot can be thought of as a candle within the earth whose flame burns through the crust, pumping lava to the surface and building an island. The ever moving plate pulls the island off the hotspot, the hotspot generates a new island, and the cycle continues. Together the hotspot and plate tectonics produce islands like an assembly line.

In 1971 Jason Morgan of Princeton University went a step further. He proposed that the “candle” was the molten tip of a plume of hot rock rising from deep within the earth’s mantle. Pinned down in the planet’s interior, the hotspot itself did not move; only the plate did. In this view, the Hawaiian hotspot has remained at a latitude of about 19 degrees north, while the Pacific plate has moved northwest at about 10 centimeters a year. The great bend in the hotspot’s track suggests that the direction of plate motion suddenly changed some 47 million years ago.

Beyond accounting for the evolution of Hawaii and other island chains, the fixed position of hotspots has given earth scientists a very powerful set of landmarks. These landmarks have allowed geologists to reconstruct plate motions and determine the original location of geologic samples, such as sediment cores used to

measure past climate and rocks used to gauge the motion of the solid earth relative to the planet’s spin axis. So it has come as a shock to geologists that hotspots may not be all they appear to be.

My colleagues and I have recently demonstrated that they are not, in fact, fixed. In a sense, they are like the cone we left at the bottom of the Pacific as a reference marker. When we failed to find it in place, we realized that ocean currents must have swept it away. The team repositioned the ship, located the drilling hole, and entered it without a cone to guide us. Similarly, geophysicists now have to figure out why hotspots drift and have to develop a new way to get our bearings.

Magnetic Filings

The evidence that clinched the case for plate tectonics in the 1960s, and that has since refined our understanding of hotspots, is the record of plate movement provided by rock magnetization. When lava cools, magnetic minerals within it, principally magnetite and titanomagnetite, crystallize. These miniature bar magnets lock in the direction of the earth’s magnetic field at that moment in time and that location on the surface.

Because the earth’s magnetic field varies in both time and space, rock magnetization provides two ways to determine how plates have moved. First, geologists can study the time variation. At irregular time intervals, the planet’s field reverses polarity: the North and South magnetic poles switch places. Consider what that means for lava erupting at mid-ocean ridges. When the rock emerges and cools, the magnetization of its

KEY CONCEPTS

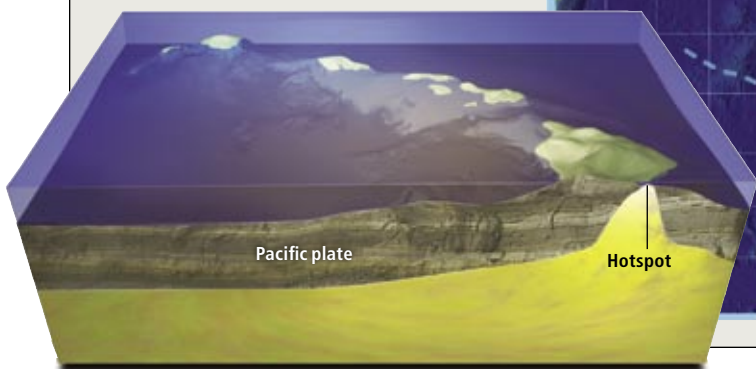
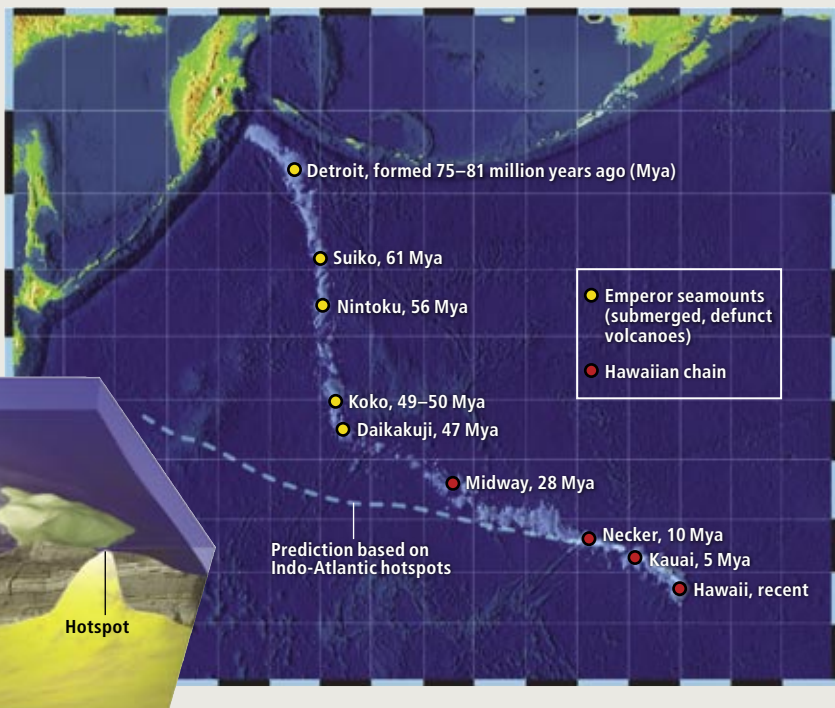
- Volcanic hotspots, such as the one creating the Hawaiian Islands today, have long been considered fixed points in the scheme of slowly moving tectonic plates that form the earth’s outer surface.
- New evidence that hotspots can instead be mobile comes from study of Hawaii’s chain of islands and submerged defunct volcanoes. The chain’s elbowlike geometry has traditionally been attributed only to a change in the motion of the Pacific plate. Now it is in part credited to hotspot migration, itself an expression of movement in the earth’s mantle deep below the surface.
- Implications include textbook rewrites, as well as new views on paleoclimate records and the stability of the entire earth on its spin axis.

—The Editors

[CASE STUDY]

THE OLD VIEW OF HAWAII'S ORIGIN

Textbooks say that the chain composed of Hawaii's islands and the Emperor seamounts (*right*) formed as the Pacific tectonic plate passed over a fixed hotspot. Venting lava built an island; then the plate carried the island to the northwest, to be replaced by another (*below*). The chain's sharp bend was ascribed to a shift in plate motion. But varied findings indicate the scenario is incomplete. If it were correct, for instance, the chain geometry would match that predicted by the study of hotspots in the Indian and Atlantic basins (*dashed line*).



[THE AUTHOR]

John A. Tarduno is thankful that only a single sandstorm struck his expedition to northeastern Mauritania last year. He had gone to the Sahara to recover 200-million-year-old rocks, whose ancient magnetic signatures reveal how the earth's plates have moved over the eons. Then he hauled his drilling equipment up 800-foot cliffs on Chatham Island off New Zealand, this time to obtain 85-million-year-old rocks. The North Pole and South Africa have also been on his recent itinerary. Tarduno is a professor in the departments of earth and environmental sciences and of physics and astronomy at the University of Rochester and is founder of its paleomagnetism laboratory.



minerals lines up like magnetic filings pointing, say, to the north. Plate tectonics then carries the rocks away from the ridge. After several hundred thousand years or so, the polarity flips, and from that moment newly formed rocks are magnetized the opposite way. These, too, are carried away from the ridge. The polarity eventually flips back, and the cycle continues. The result is a series of horizontal stripes recorded in the oceanic crust, alternating between north-pointing and south-pointing magnetic minerals—a geologic version of tree rings. Geologists date the stripes by matching them against the timeline of polarity reversals. They then use time and distance data to calculate a plate's direction and speed relative to an adjoining plate.

The second technique exploits the fact that the direction of the earth's magnetic field has two components: horizontal (declination) and vertical (inclination). When you rely on a compass to find the direction of north, you use the declination, but if you look closely at the compass needle, you will see that it is also tilted slightly with respect to the horizontal. As Neil Opdyke of the University of Florida demonstrated in a classic study in the late 1960s, the inclination is directly related to latitude. Measuring inclination reveals the latitude where the rock originally formed and hence the minimum

distance that the plate must have moved since then. (It does not reveal the longitude.)

Using these approaches is not entirely straightforward. The earth's magnetic field does not point purely north-south. It has a more complex shape that geophysicists think reflects the flow of liquid iron in the planet's core. When averaged over several millennia, however, these deviations cancel out. Thus, researchers can compensate for the complexity of the field by sampling a large number of rocks representing a long enough span of time. Few islands still have old rocks that date back far enough, so geologists have to drill into the ocean floor.

That process presents its own complications. Oceanic crust can be tilted, which can be mistaken for magnetic inclination. The best rock samples come from areas that seismic data confirm lie flat. Geologists have drilled deeply into only a few of these areas. Another approach is to tow a magnetometer behind a ship and measure the magnetization of the seafloor rock remotely. Unfortunately, such measurements reflect not only the magnetization imprinted when the rock formed but also the induced magnetizations imparted by the earth's present-day field, as well as the magnetization acquired over geologic time as some of the magnetic domains within the crystals spontaneously reoriented themselves.

COURTESY OF JOHN A. TARDUNO (Tarduno); KEVIN HAND (Illustration)



Magnetometer readings therefore still need to be calibrated against directly sampled rocks.

Wide Latitude

The first hint that the Hawaiian hotspot might not be fixed came in the early 1970s from studies conducted by Tanya Atwater and Peter Molnar, both then at the Massachusetts Institute of Technology. They looked at two phenomena to deduce plate motion: seafloor stripes and island chains. When two plates meet at a mid-ocean ridge, their motions create a series of seafloor stripes and, if each plate is underlain by a hotspot, a pair of island chains. Researchers can predict what the hotspot track of an island chain should look like on one plate by examining the track of the corresponding chain on the other plate.

Atwater and Molnar reported that the predictions for several hotspot tracks failed to match the location of the actual volcanoes, suggesting that the hotspots had moved. The technique has since been refined and extended by Joann Stock of the California Institute of Technology and her colleagues, with essentially the same results. Predictions for the Hawaiian-Emperor chain made using hotspots in the Atlantic Ocean are in rough agreement with the portion of the chain formed over the past 30 million years, but they deviate further back in time. At 60 million years ago the offsets are very large.

These conclusions did not convince many geologists, however. Other effects could explain the disagreement between the two data sets. The Pacific and Atlantic basins consist of plates that abut the continent of Antarctica, which itself is made of at least two plates. These plates can ro-

tate like interlocking gears, potentially changing the way that geographic features in the Atlantic relate to those in the Pacific. Unfortunately, much of the geologic history of Antarctica remains a mystery, buried under thick ice caps. This uncertainty prevented geologists from reconstructing the plate motions fully.

The only way to settle the matter was to go back to the rock samples. My University of Rochester colleague Rory Cottrell and I took up this challenge in 1995. We visited the Ocean Drilling Program (ODP) at Texas A&M University and examined archived cores of sediment and rock collected over several decades. The most promising had been collected in 1992 from one of the Emperor seamounts, known as Detroit, which formed between 75 million and 81 million years ago. The rock type was basalt—similar to that erupting on Hawaii's Big Island today—which carries the best-understood type of magnetic signal. The core had drawn little attention because researchers thought it was too short in length to provide enough accurate readings of magnetic inclination.

A new analysis proved otherwise. To remove the effects of induced magnetization and spontaneous reorientation of large magnetic mineral domains so that we could identify the minerals' original magnetization, we measured the samples in a shielded superconducting quantum interference device (SQUID) magnetometer and went through an exhaustive demagnetizing procedure. It turned out that the core was just long enough to provide precise readings of magnetic inclination and hence the latitude at which the minerals formed: 36 degrees north.

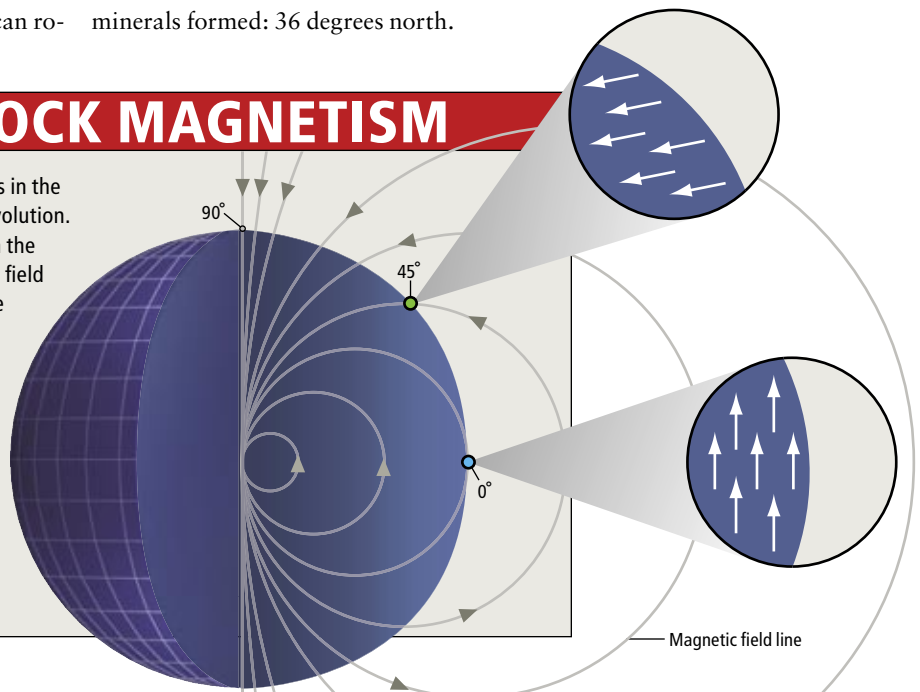


▲ DRILL RIG towering over the deck of the *JOIDES Resolution* lowered and raised the long drill pipe (*foreground*) that the author and his team sent to the seafloor to extract rock cores from seamounts.

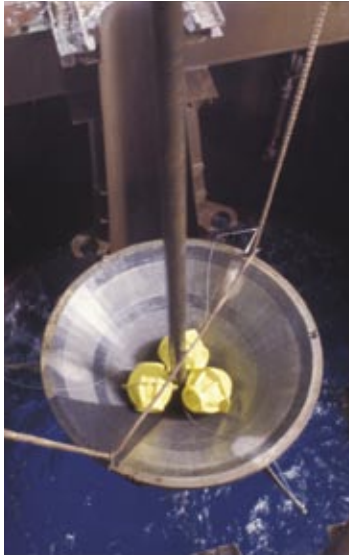
[RESEARCH TOOL]

CLUES FROM ROCK MAGNETISM

Magnetic studies were key to revealing flaws in the old view of the Hawaiian-Emperor chain's evolution. When lava solidifies, certain minerals lock in the inclination, or angle, of the earth's magnetic field at that latitude (*white arrows in details*). The minerals line up parallel to the planet's surface at the equator (*bottom*), perpendicular to it at the magnetic poles, and at intermediate angles at mid-latitudes (*top*). Should a rock move, it will retain its original magnetic inclination. If the chain developed as a plate moved over a fixed hotspot, magnetic inclinations in seamount rocks would have matched those in rocks from Hawaii, but they did not.



COURTESY OF JOHN A. TARDUINO (artist); KEVIN HAND (illustration)



▲ CONE is being dispatched to the seafloor through an opening, called a moon pool, in the center of the *JOIDES Resolution*. Such cones helped to position the drill pipe that brought up rock cores for magnetic analysis.



We compared our new result with a study done in 1980 by Masaru Kono, then at the Tokyo Institute of Technology, using ODP's predecessor, the Deep Sea Drilling Project. He had taken samples of the 61-million-year-old Suiko seamount of the Emperor chain and found that it had formed at 27 degrees north. These were startling results. If the Hawaiian hotspot, now located at a latitude of 19 degrees north, were fixed, the Detroit and Suiko seamounts would have formed at the same latitude. The three latitude values differed, suggesting that the Emperor seamounts marked the trace of a moving plume. Among our colleagues, though, the results met with a reception notable for its air of indifference. All our thousands of laboratory measurements condensed down to a mere two points on a graph. Skeptics required more before they would reconsider the textbook plate-motion explanation of the Hawaiian chain.

A Leg Up

In late 1997 Cottrell and I began thinking about a new ocean drilling expedition. We chose drilling sites with the help of David Scholl of Stanford University and also invited Bernhard Steinberger, who had been modeling mantle flow for his Ph.D. dissertation at Harvard University, to join the effort. We sailed off onboard the Ocean Drilling Program's *JOIDES Resolution* in the summer of 2001 on a two-month expedition—called Leg 197—that took us to three of the Emperor seamounts: Detroit, Nintoku and Koko.

Before drilling, we conducted short seismic surveys to ensure we would recover flat-lying

lava layers, eliminating one source of potential error. Once we got the samples on deck, a cadre of experts helped us analyze them, including Robert Duncan of Oregon State University, Thorvaldur Thordarson, then at the University of Hawaii at Manoa, Frederick Frey of M.I.T. and Clive Neal of the University of Notre Dame. To estimate the rock's ages, we examined microfossils in sediments lying on top of or intermixed with the lavas. The ship had a magnetism lab where we gauged the rock's magnetization. It would take many months of follow-up work in shore-based laboratories, including critical isotope geochronological work, to confirm our findings. But the overall picture was apparent by the time we returned to port in Yokohama.

The hotspot had clearly moved rapidly south. Its inferred velocity during the period from 81 million to 47 million years ago was more than four centimeters a year, comparable to that of tectonic plates. Corroborating this finding, we found no coral debris at the Detroit or Nintoku seamounts and only a smattering at the Koko seamount. If these islands had formed at Hawaii's tropical latitude, we would have expected coral reefs to have taken shape around them.

The implications are now rippling through the earth sciences, answering old questions and raising new ones. For example, one other geologic indicator of latitude is the type of sediments deposited in the deep oceans. Near the equator, sediments are rich in the calcium carbonate shells of plankton, which accumulate because of the high biological productivity of this region. Outside the equatorial zone, the sediments are carbonate-

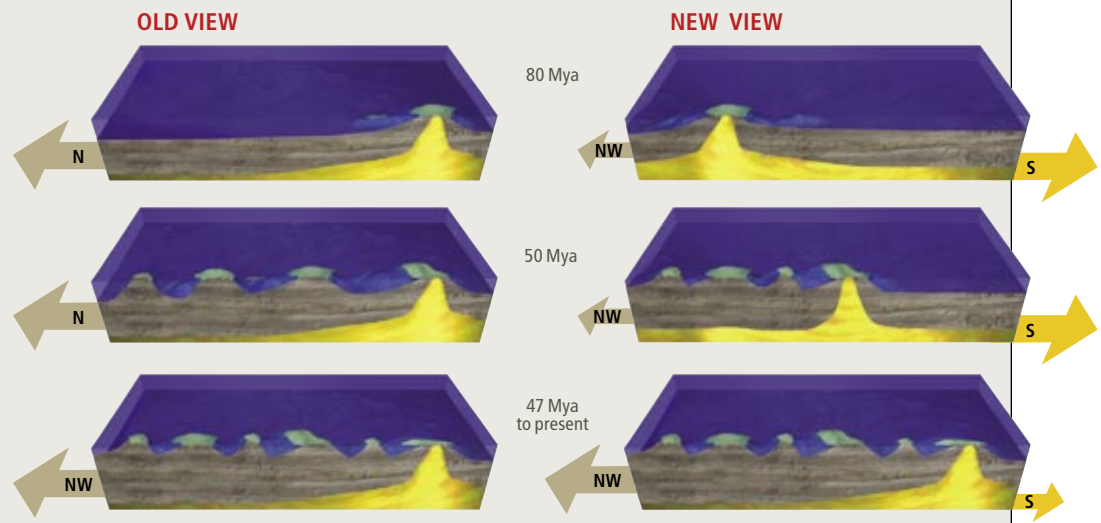
COURTESY OF JOHN A. TARDUINO (cone), KEVIN HAND (illustration)

[CASE STUDY REVISITED]

WHAT REALLY HAPPENED

The magnetic work showed that the seamounts arose at progressively lower latitudes, with Detroit forming at about 36 degrees north and Koko at about 22 degrees north. So, although the old view of the Hawaiian-Emperor chain's evolution held that the hotspot stood still while the Pacific plate crossed over it (*left*), it is now clear that the hotspot migrated, too (*right*), heading south. (Arrow sizes represent relative speed.)

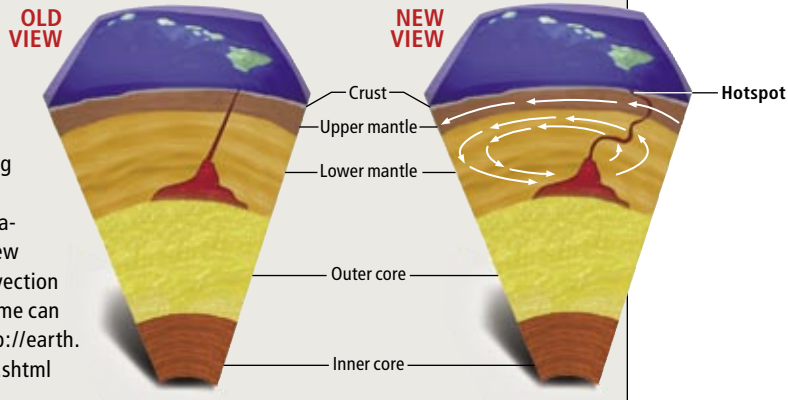
← Plate motion
→ Hotspot motion



[NEW UNDERSTANDING]

BLOWING IN THE (MANTLE) WIND

Discovery that hotspots can travel has revised understanding of what they are. They are still defined as the tip-tops of mantle plumes that originate near the boundary between the earth's liquid core and the overlying viscous mantle. In the old view (*left*), though, the plumes remained fixed relative to the deep interior. In the new view (*right*), the plumes are swayed by convection within the mantle. The base of the plume can also move, as shown in a movie at <http://earth.uni-muenster.de/dyn/plumedynamics.shtml>



poor. Sediments in cores from the Pacific Ocean up to 50 million years old do not fit the carbonate-rich pattern that one would expect if hotspots were fixed. Josep M. Pares and Ted C. Moore of the University of Michigan at Ann Arbor recently found that this paradox would be resolved if the Hawaiian hotspot was drifting southward.

Geologists may need to rewrite their textbooks about North America, too. Experts have known for a long time that large tracts of the American West did not form where they are now. These landmasses were pushed into their present positions by the long-gone plates that once composed the Pacific Ocean basin. Interactions between oceanic and continental plates are also responsible for the formation of major geologic features such as the Rocky Mountains. But the plate interactions have been estimated assuming that Hawaii's hotspot was a fixed reference point. Because it is not, geologists must revisit how western North America was built.

Pole Position

On a still larger scale, hotspot motion affects how researchers think about polar wander—rotation of the entire solid earth relative to the planet's spin axis. Polar wander is a confusing term in geophysics, because the phrase implies that the pole itself moves around. In fact, both the spin and magnetic axes remain almost fixed in absolute space; it is the land and seafloor that wander. The sinking of tectonic plates might shift the earth's mass distribution and cause an imbalance of forces, like a washing machine with a lopsided load of clothes. To rebalance itself, the entire planet would rotate. In the extreme case, Florida might wind up at the North Pole or Greenland might become a tropical island. This process differs from plate tectonics because the rela-

tive positions of the plates would remain the same.

In the 1980s geologists used the assumption of hotspot fixity to reconstruct plate motions and pinpoint the past locations of the earth with respect to its spin axis. The data suggested the earth had migrated up to 20 degrees relative to the axis over the past 130 million years. Our findings refute that claim: the hotspots moved, not the entire earth. So hotspots can be a false beacon for plate motions and polar wander.

The deepest implication of hotspot mobility relates to the earth's mantle. The hotspot may still be rooted in the deep mantle, but its base may move around, and the rising plume may be bent by the mantle flow. More radically, the concept of plumes itself has come under scrutiny. Don Anderson of Caltech has argued that hotspot plumes may not, in fact, be rooted in the lower mantle. They may instead be shallow phenomena, emerging from the upper layers of the mantle or lower layers of the crust. Others think plumes come in all shapes and sizes and originate at various layers within the planet.

As dramatic as our discoveries on hotspot mobility have been, they do not mean that all of present geologic understanding must be overturned. Science seldom works like that. The remarkable age progression and the sheer volume of magma marked by the Hawaiian-Emperor chain show that the Hawaiian hotspot is still closest to the ideal envisioned by Wilson and Morgan. But rather than being fixed in the deep mantle, it has had an unexpected mobility. A simple picture has given way to a complicated one. Both plates and hotspots move, and the observed effects can reflect a combination of both—challenging scientists to determine the contribution of each. Underappreciated until now, turmoil in the mantle deserves new respect. ■

MORE TO EXPLORE

Fixed Hotspots Gone with the Wind. Ulrich Christensen in *Nature*, Vol. 391, pages 739–740; February 26, 1998.

The Emperor Seamounts: Southward Motion of the Hawaiian Hotspot Plume in Earth's Mantle. John Tarduno et al. in *Science*, Vol. 301, pages 1064–1069; August 22, 2003.

Geophysics—Hotspots Come Unstuck. Joann Stock in *Science*, *ibid.*, pages 1059–1060.

Animations of plate tectonics processes are available in the Chapter 8 section at the Web site "Exploring Earth Visualizations": www.classzone.com/books/earth_science/terc/navigation/visualization.cfm

Tarduno's University of Rochester Paleomagnetic Research Group Web site is at www.earth.rochester.edu/pmag, and more information on the Integrated Ocean Drilling Program is at www.iodp.org