Set Adrift by Wandering Hotspots

These sources of volcanic activity have long served as scientific benchmarks. But are they really that reliable?

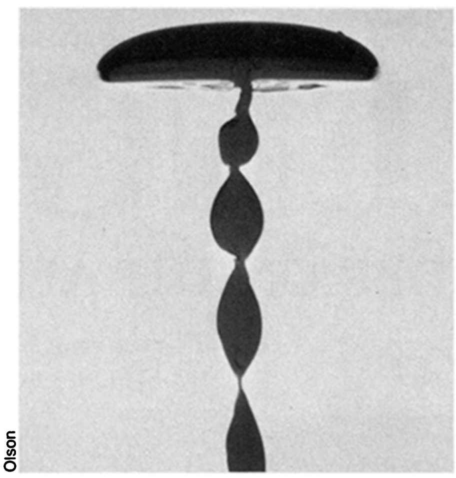
By RICHARD MONASTERSKY

Since cartographers began making accurate world maps, scientists and children have noticed that Africa and South America would fit together quite nicely. In fact, the shape of Brazil seems to match the west coast of Africa so well that the two might be neighboring pieces of a jigsaw puzzle.

With the acceptance of the theory of plate tectonics in the 1960s, it became clear that the jigsaw metaphor does indeed apply to the face of the earth. But this is a complicated puzzle, an ever-shifting pattern of continents and oceans. And in the wake of plate tectonics theory, some fundamental questions have bobbed to the surface.

In particular, scientists are wondering what is the driving force that pushes around the dozen plates that fit together to form the surface of this planet. Others are interested in how the plates have evolved through time.

In pursuit of answers, earth scientists must first trace a history of the earth's plates, which means determining the previous positions and speeds of these giant sections of the earth's crust. For more than a decade, one favored method of accomplishing this task has relied on "hotspots" — those areas of the earth that seem to remain hot for periods as long as 100 million years.



Olson

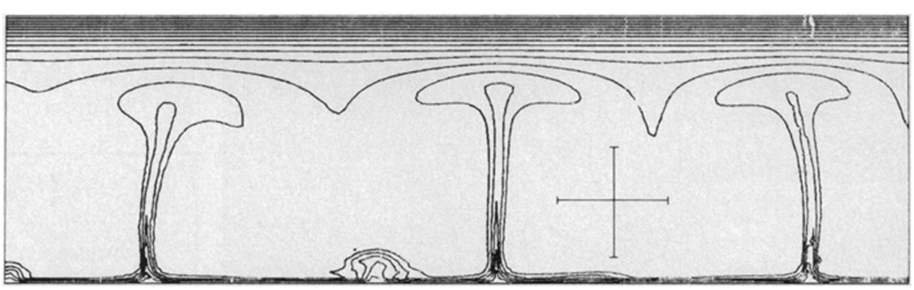
Physical model simulating buoyant plume material rising through a high-viscosity mantle. The top layer has been cooled from above to represent the effect of the uppermost layer of the mantle on the plume development. In the model — and theoretically in the earth — the plume pools up when it hits this cold layer, and molten rock may seep upward through cracks to form volcanoes.

Scientists originated the hotspot idea in order to explain the many linear chains of volcanic islands and seamounts on the earth. They theorized that slender columns of semi-molten rock slowly rise to the surface from deep within the earth. Hot and buoyant, this rock pushes up on the overlying crust, creating plateaus and sometimes even breaking through to produce a volcano. When plates pass over these regions, the hotspot punches out a linear track of islands or plateaus. The Hawaiian island chain in the center of the Pacific plate is one of the most famous and well-studied examples of hotspot activity.

For plate reconstructionists, hotspots seemed an ideal benchmark for tracing plate motion in the past; they literally left a trail on a plate as it passed overhead. Moreover, early evidence indicated that hotspots were fixed in the earth's mantle and would therefore enable scientists to measure the "absolute" plate motion, or motion with respect to the earth's interior.

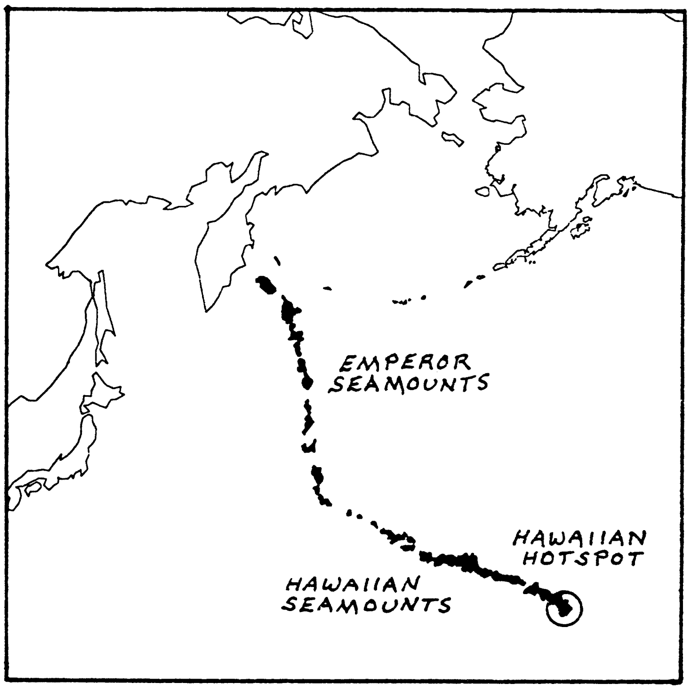
However, new evidence suggests otherwise, for it seems that these benchmarks may actually be drifting. Instead of rising straight up through the mantle, the columns of rock that feed hotspots might resemble palm trees in a storm, swaying in the surrounding turbulence.

The debate over hotspot motion is actually one of degree. Most earth scientists concur that hotspots do move, but the question is:



G. Schubert, C. Anderson/Olson

Allowing a view into the earth's interior, a numerical simulation of the mantle shows how thermal plumes rise through the mantle and interact with the earth's crust, forming a hotspot. Convection currents in the mantle may cause plumes to drift, thereby causing hotspots to wander. One possible source for the thermal plumes is an apparently turbulent area of the earth, located directly above the boundary between the core and mantle. Near the center of the simulation, a small bud indicates the birth of a plume.



The Emperor Seamount-Hawaiian Island chain is one of the longest and best-studied examples of a hotspot track. Despite the use of this term, the track is not created by hotspot motion, but rather by the motion of a plate over a relatively stationary hotspot. In the Hawaiian case, the Pacific plate is moving northwest over the Hawaiian hotspot. The bend in the chain was created by a redirection of the Pacific plate. Earlier than 40 million years ago, the plate moved almost directly north, as evidenced by the north-south trend of the Emperor Seamount chain.

How much does one hotspot move with respect to the others, and is this motion significant enough to cause problems for scientists who rely on hotspots as points of reference?

At the lower end of the motion spectrum is W. Jason Morgan, a geophysicist at Princeton (N.J.) University and one of the original hotspot theorists. In 1971, Morgan initiated this debate by suggesting that hotspots originate from deep within the mantle and radiate out like an irregular set of spokes. Along with other scientists from the fixed-hotspot camp, Morgan has calculated that if hotspots move, they do so at an indiscernible rate of less than 5 millimeters per year.

But according to a recent study by Joann Stock and Peter Molnar of the Massachusetts Institute of Technology (MIT) in Cambridge, hotspots are moving at a much faster rate, which can actually be measured. In fact, they found evidence that during the last 50 million years, the Hawaiian hotspot has drifted with respect to other hotspots at a rate of 10 to 20 mm per year. This study, says Stock, "implies that there might be latitudinal drift between hotspots, so that you can't always assume that the same hotspot was at the same latitude at all times in the past."

The MIT researchers arrived at this conclusion though a series of complex plate reconstructions. In a simplified version of their technique, imagine two plates, called East and West, that are gradually moving away from each other. A hotspot lies under each of the plates, and as the plates separate, the hotspots create tracks of volcanoes on each plate.

Stock and Molnar would pick an ancient volcano — say, 35 million years old — from the middle of the West plate. Then, as if placing a record on the spindle of a turntable, they would move the entire West plate so that the ancient volcano rested over the location of the hotspot. This is where the West plate would have been 35 million years ago.

They would then push the East plate back toward the West plate until they had erased 35 million years of motion between the two. At this point, both the East and West plates would be in their ancient positions, "locked" to the earth's interior by the Western hotspot.

The crux of the experiment rests on the Eastern hotspot. If this plume were to poke up underneath a 35-million-year-old volcano in the track on the East plate, it would mean that both hotspots had remained fixed. On the other hand, if the Eastern plume were to surface at some other point on the plate, then this hotspot would have to have moved with respect to the Western one. In effect, the plumes would have shifted position.

Using this type of analysis, Molnar and Stock compared the past positions of five separate hotspots with respect to the Hawaiian volcanoes. They found that the hotspots were out of position by distances ranging from several hundred kilometers to more than 1,000 km. When the offsets were translated into speeds, they amounted to hotspot drift rates between 10 and 20 mm a year. Because plates move at rates that are only slightly faster (20 to 100 mm a year), these hotspot speeds are quite significant, says Stock.

Such motion could present problems for those who study the history of the earth's plates. Working under the assumption that hotspots are relatively stationary, many researchers have used the global network of hotspots as a fixed set of reference points.

Most other reference points, like a specific continent, are inherently flawed because they are in constant motion. While researchers can reconstruct the history of the plates in reference to one continent, they cannot be sure how the continent itself has moved with respect to the interior of the earth.

If hotspots were fixed to the interior of the earth, they would offer a system of absolute reference points — in effect, an absolute reference frame. However, says Stock, "if [hotspots] are in relative motion with respect to each other, then they do not define an absolute reference frame."

For more than a decade now, scientists have been voicing similar doubts about the immobility of hotspots, but the accuracy of previous studies on hotspot motion had been limited. Any interplate analysis that included the well-documented Hawaiian track could not reliably go farther back in time than 35 million years. Before that time, the history of the Pacific plate became fuzzy. Plate historians were convinced that some ancient boundary had separated the Pacific plate from East Antarctica, but this boundary proved to be quite elusive.

Earlier this year, however, Stock and

Molnar reported that they had located this boundary off the West Antarctic coast. With this knowledge, they could trace the hotspot track as far back as 65 million years, thereby increasing the accuracy of their hotspot measurements, which they published in the June 18 NATURE.

According to the researchers, these findings imply that reconstructions based on the assumption of fixed hotspots must include a built-in error that is much larger than previously suspected.

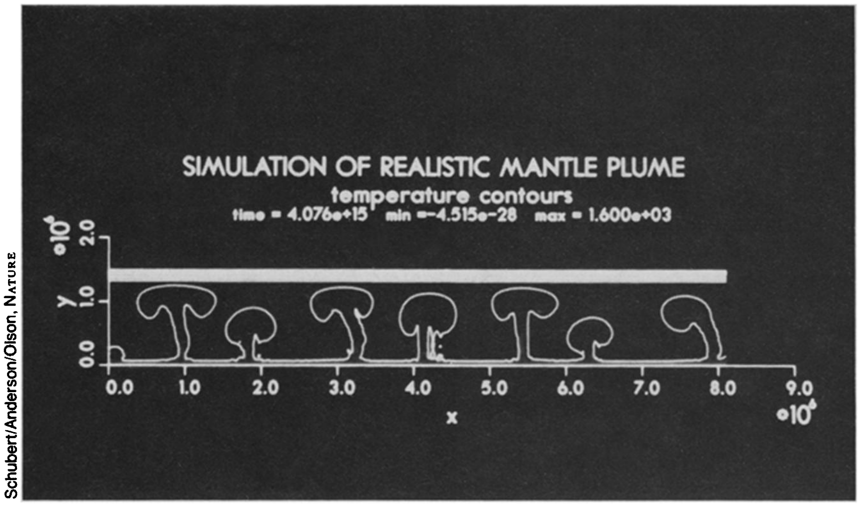
Many significant questions must be answered, however, before the earth science community at large accepts the conclusion that hotspots are moving at a discernible rate. Richard G. Gordon, a geophysicist at Northwestern University in Evanston, Ill., believes that the obscure histories of the plates do not presently allow the kind of resolution that Stock and Molnar need for their study.

"I wonder," says Gordon, "if all the assumptions they're making are correct because they have had to assume that they know where all the plate boundaries are when they really don't have complete information. They've also had to assume that all the plates are rigid when we really don't know what the limits of plate deformation are. When you add this up over tens of million of years, it might be significant."

In particular, he says, the Antarctic remains a weak link in the chain of plate reconstructions. Stock and Molnar assumed that the Antarctic was made of only one plate during the last 65 million years, but many scientists believe that two plates might have created this continent by crashing together. The researchers also did not account for any internal motion of the Antarctic plate such as the deformation that accompanies the birth of a mountain range. Both of these conditions would alter estimates of hotspot motion.

Morgan, who also questions the Antarctic assumptions, suggests that a more accurate test of hotspot motion would confine itself to one plate or two plates with a well-studied boundary. The most direct test, he says, would compare two different hotspot tracks on the same plate. "For example," says Morgan, "if you were age-dating different chains within the Pacific itself, there would be no reconstruction problem."

Anthony Watts of Lamont-Doherty Geological Observatory in Palisades, N.Y., and his colleagues have applied exactly that technique to two widely separated tracks on the Pacific plate. By comparing the Emperor chain in the North Pacific and the Louisville seamount chain in the South Pacific, they reasoned that any motion between the two hotspots over the last 62 million years would cause the two tracks to follow different paths.



Schubert/Anderson/Olson, NATURE

In the simulation, a heated lower boundary layer creates thermal plumes, which rise toward the cold boundary at the surface, where they blossom. Some plumes "lean" because of inter-plume reactions. This is unrelated to the kind of plate-tectonic convection that might cause hotspots to wander.

However, according to coresearcher Robert Duncan of Oregon State University in Corvallis, the Louisville chain "exactly parallels the Hawaiian-Emperor chain, and the dating we've done along it from dredge samples confirms the dating that's been done along the Hawaiian-Emperor chain in the sense that the two were formed by hotspots fixed relative to one another." The results of this test of hotspot motion will appear in an upcoming issue of the JOURNAL of GEOPHYSICAL RESEARCH.

The debate over moving hotspots will most certainly require more information and more comparisons between widely separated tracks. However, if Stock and Molnar are correct, then their conclusions appear to solve a vexing mystery in the field of geodynamics. "If hotspots are really fixed with respect to each other, for indefinite periods of time, then they represent something for me that is really strange and hard to fathom from the point of view of physics," says Peter Olson of Johns Hopkins University in Baltimore.

Olson and others who study the earth's mantle know this part of the planet as a turbulent area, resembling a pot of boiling water. Huge currents of rock creep through the mantle at a slow but undeniable pace as part of the convection process that drives the motion of the plates (SN: 8/16/86, p.106).

Geodynamicists, therefore, find it hard to reconcile the concept of stationary hotspots with this kind of upheaval in the mantle. How is it possible, they ask, for the plume of a hotspot to rise through all this vertical and horizontal motion and still remain fixed with respect to other hotspots?

Olson and his colleagues have run computer and physical models of the mantle and in both cases have found that hotspots would drift over time. With these results and the evidence of large-scale mantle convection, says Olson, "I find it gratifying that people now think they can see slow motion of hotspots."

Plate historians would prefer the global network of hotspots to be fixed, thereby preserving its status as a favored reference tool. However, hotspot motion, if it exists, may actually have some uses of its own, and this possibility has attracted the interest of many scientists. In fact, according to Morgan, "the Ocean Drilling Program [ODP] is going to place a higher emphasis on testing the fixity of hotspots."

The ODP is a series of drilling expeditions designed to retrieve core samples from the ocean floor. And at a recent planning conference for the ODP, many researchers proposed that some upcoming projects should focus on the hotspot question by examining the tracks of various hotspots.

The reasoning behind these suggestions, says Morgan, is that hotspot motion could be related to motion within the mantle. "If you could show what the drift velocity of one hotspot relative to another was, you would have information about the deep convection within the earth," he says.

At rest or in motion? For now, this hotspot question must remain unanswered. But it appears that these phenomena will continue to serve as geophysical benchmarks of one sort or another. For those studying the mantle, a benchmark in motion may be as useful as a benchmark at rest. □