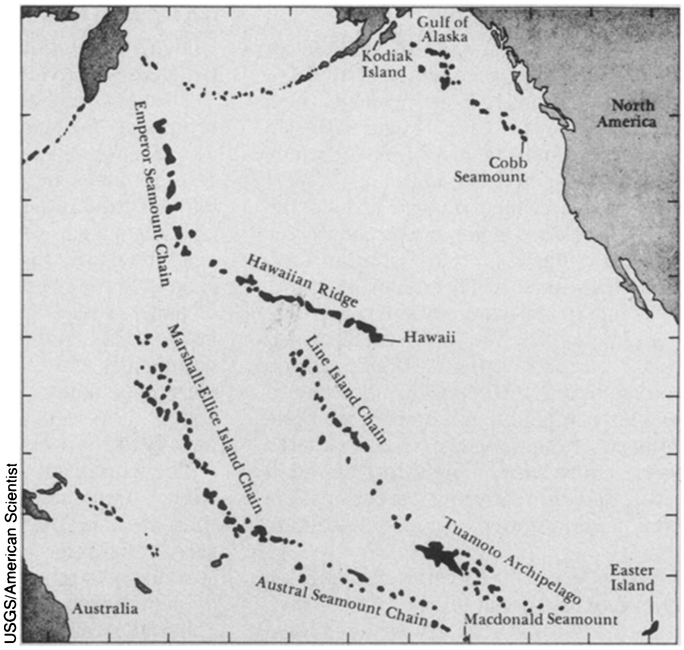
SPOTLIGHT ON HOT SPOTS

The melting spot hypothesis for origin of intraplate island chains and continental uplifts has achieved high status. But what's going on in the mantle remains unclear.

BY KENDRICK FRAZIER



USGS/American Scientist

Seamount and island chains in the Pacific Ocean. Their origin by motion of the Pacific plate over a hot spot now at the southeastern end seems likely.

Most of the world's volcanoes — by one estimate more than 99 percent — are situated at the margins of crustal plates. For example, the Ring of Fire, the great band of volcanoes around the rim of the Pacific Ocean, is the line of interaction where one plate of the earth's lithosphere, or outer rigid shell, is descending beneath another. Partial melting of the subducting plate material produces upwelling lavas that can create large arcs of islands, such as the Aleutians, Japan, the Philippines. Or it can push up chains of volcanoes on continental coasts, such as those along the western margins of South America, Central America and North America (the Cascades).

Likewise, where lithospheric plates are separating, at the mid-ocean ridges, basaltic lava oozes out in a continual process of undersea volcanism that creates new ocean-bottom material.

But many of the great volcanic island chains of the world are situated far from the margins of any of the dozen or so lithospheric plates. The Hawaiian Islands, for instance, are about as far from a plate margin as you can get. In the South Pacific, the Tuamotu group (Pitcairn, refuge for the *H.M.S. Bounty* mutineers, is its southeastern end) and the Austral group are similar chains. And the process is not confined to ocean floors. The continent of Africa is generally considered to be resting upon a single crustal plate, along with the western Indian Ocean and the eastern Atlantic Ocean. Yet Africa is rampant with volcanic activity.

These are all examples of what might be called intraplate volcanism — volcanic activity within a plate rather than at its margins. In July earth scientists from around the world gathered in Hawaii for a week-long symposium on intraplate volcanism. When they had concluded, the major hypothesis for explaining intraplate volcanism — the hot spot theory — was more intact than ever. They introduced abundant new evidence supporting the hot spot idea. They considered consequences of hot spots for continents. They debated enigmas and puzzles that pose problems to the hot spot hypothesis and did not fully resolve them. They discussed intriguing data that the earth's entire mantle may shift in relation to the spin axis. And through it all there was general agreement that no matter how solid the hot spot idea may be as an explanation of events at the surface, a true understanding of what is actually going on at depth still eludes science.

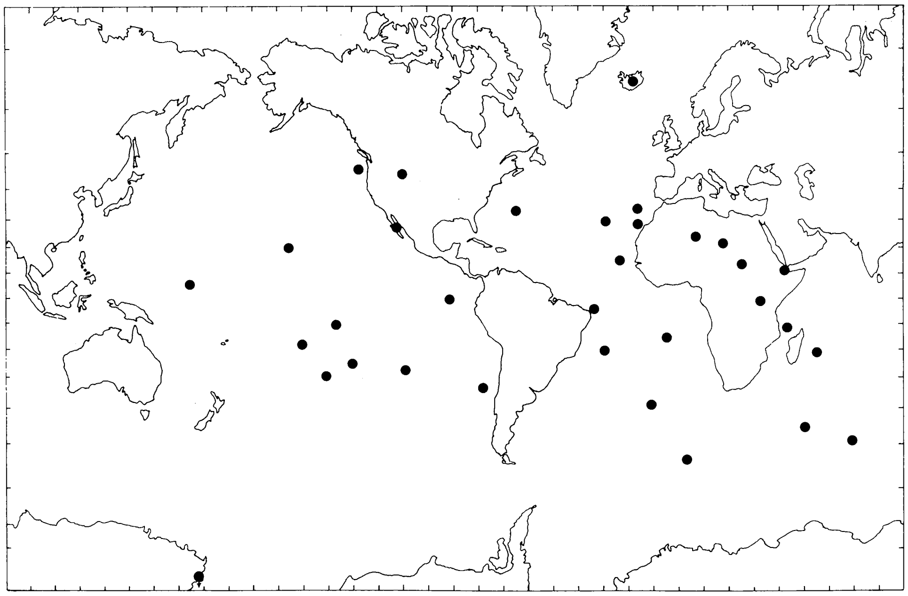
What exactly is a hot spot? Well, it's an anomalously warm spot in the earth's mantle capable of causing manifestations of partial melting (volcanism) or uplift at the surface. Kevin C. Burke of the State University of New York at Albany and J. Tuzo Wilson of the Ontario Science Center (Wilson is the originator of the hot spot hypothesis) have defined hot spots as "centers of volcanism that are not associated with plate boundaries and that form elevated domes with a diameter of up to about 200 kilometers." That may seem like defining a phenomenon by the events it is supposed to explain. But since surface manifestations are mainly what earth scientists have to work with in this topic, that seems understandable.

Burke and Wilson have mapped about 120 world hot spots. This might be called the "maximum list." S. Thomas Crough of Princeton University has prepared a map of what he calls the "minimum list." It shows 33 hot spots he has selected for which he has evidence that the volcanism either has persisted for greater than 10 million years or is associated with a large topographic swell. Since first drawing the map Crough has added about 10 more hot spots to his list. He says he suspects he may eventually have around 50. "Much of the difference between the lists," says Crough, "will be that I include neighboring volcanoes, such as Reunion and Rodriguez in the Indian Ocean, as the same hot spot, while Burke likes many small ones. In the ocean basins the lists agree to about 80 percent."

In both maps, several regions are counted as hot spots even though they lie on or close to mid-ocean ridges. These include Iceland, the Azores and Tristan de Cunha, in the South Atlantic. They are included partly because the volume of lava they have extruded far exceeds that of other areas along the mid-ocean ridges and partly because the lavas are alkali-rich basalts that are rare at mid-ocean ridges but typical of hot spots.

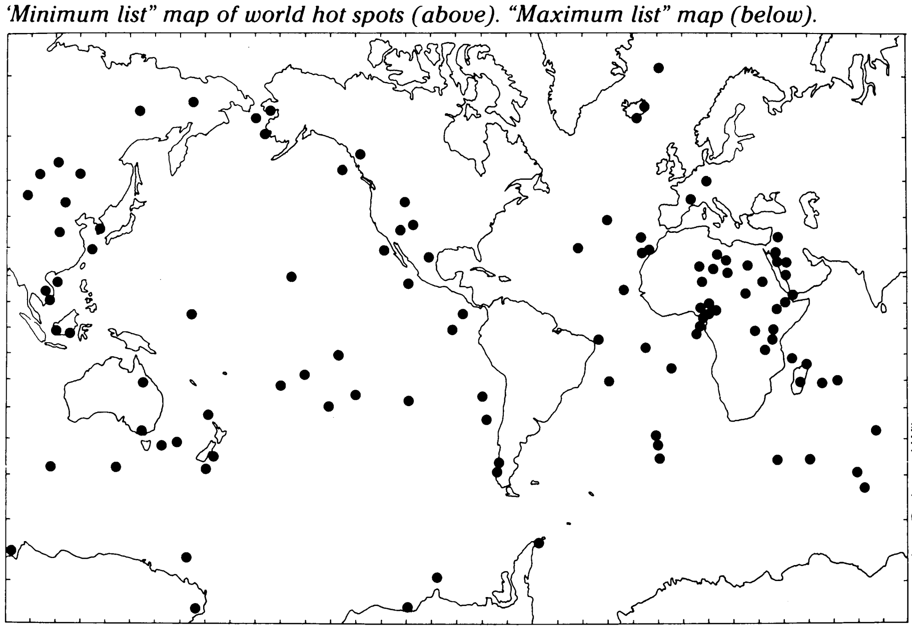
Burke believes the uplifts caused by hot spots are an even more prominent effect than volcanism they produce (SN: 8/4/79, p. 88). Judging from such uplifts in Africa, on ocean floors and elsewhere, Burke suggests hot spots vary across a broad range of diameters and magnitudes. He and his colleagues suggest that most hot spot uplifts are around 200 kilometers across, with a few up to 500 kilometers. They attribute 1,000-kilometer-wide swells to groups of hot spots; Crough tends to credit single large hot spots beneath such areas.

Couple the melting and uplifting power of a mantle hot spot with the slow but inexorable horizontal motion of large segments of the earth's upper surface



S. Thomas Crough

'Minimum list" map of world hot spots (above). "Maximum list" map (below).



Adapted from Burke and Wilson

(crustal plates) over the hot spots, and you have an explanation for the origin of those chains of volcanic islands that are not associated with plate margins. The Hawaiian Islands stand as the most beautiful example.

Even the early Hawaiians recognized a progression from northwest to southeast in the surface characteristics of the islands. Kauai at the northwest end is built of extinct volcanoes long ago eroded into jagged mountain faces and spectacular cut canyons. Hawaii at the southeast end shows the gentle rounded shape of the five shield volcanoes—two of them still active —that form the island, their smooth faces little marred by time and erosion. Such a progression is even evident within the island of Hawaii itself. Its northwest end is anchored by a much-eroded extinct volcano. Its southeast side is the site of highly active Mauna Loa and Kilauea (SN: 9/8/79, p. 170). American geologist James D. Dana in 1838 became the first scientist to recognize this progression. Ian McDougall of Australian National University confirmed it a century and a quarter later in 1964 with potassium-argon ages on the major islands in the group. The islands decrease systematically in age to the southeast, from Kauai (5.6 million years old) to Hawaii (less than 700,000 years old).

But the Hawaiian islands are just part of a huge chain of islands and seamounts (subsurface "islands") that extend far out northwest into the Pacific and then northward to the Aleutians. The whole sequence is known as the Hawaiian-Emperor chain, and it is one of the most striking geological features on the planet. It's built of somewhere between 80 and 110 volcanoes. David Clague of the U.S. Geological Survey in Menlo Park, Calif., says even most earth scientists don't realize its magnitude. "That's an incredible amount of stuff," says Clague. "A huge chain, a huge volume. Just an incredible amount of material."

Even more remarkable, the whole chain, it turns out, shows a progression in age to the northwest.

Potassium-argon ages of 27 volcanoes in the chain show a linear increase in age with distance from Hawaii. Midway is 27 million years old, the point where the Hawaiian-Emperor chain bends northward is 43 million years old, and Suiko Seamount near the north end of the Emperor chain is 65 million years old. Deep sea cores taken in the summer of 1977 during Leg 55 of the Deep Sea Drilling Project (SN: 10/1/77, p. 215) produced strong evidence both from paleomagnetic studies and fossil types that Suiko Seamount and the entire Emperor chain were formed at low latitudes, not at their present location. The cores also confirmed the northward age progression of the seamounts. Progressing north, the ages of the four seamounts drilled turned out to be 55, 58, 65 and 70 million years.

It all fits beautifully with J. Tuzo Wilson's original proposal that the Hawaiian Islands were formed by the northwestward movement of the Pacific plate over a fixed (or relatively fixed) hot spot in the earth's mantle. The plate rides over the heat source, which punches up volcanoes in sequence. The older ones then are carried on to the northwest. The currently active volcanoes are at the southeast end.

G. Brent Dalrymple of the U.S. Geological Survey in Menlo Park believes there's no longer any need to doubt it: "The data ...confirm the hot spot hypothesis for the origin of the Hawaiian-Emperor chain. The Hawaiian Islands, the seamounts on the Hawaiian ridge, and the Emperor seamounts are a single volcanic chain that was generated by continuous movement of the Pacific plate relative to a single source or hot spot."

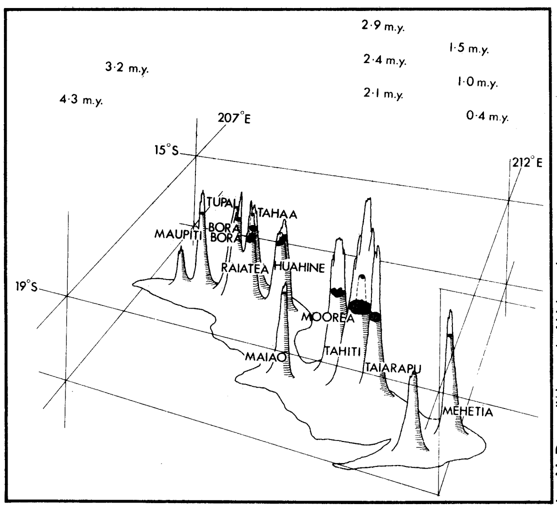
Others agree. Australia's Ian McDougall recently completed age measurements on the main lavas of Kauai. Some earlier expressed views had indicated that Kauai might not fit the linear-progression model after all. McDougall found otherwise. It fits in with the age trend exactly. Volcanism has progressed southeastward at the rate of 9.4 centimeters a year. "For the last 28 million years," says McDougall, "migration of volcanism in the Hawaiian chain has been very regular indeed."

But what of the other intraplate island chains in the Pacific? McDougall has studied the islands of the South Pacific and finds the same linear trends. "A similar monotonic decrease in age of volcanism toward the southeast occurs in the Marquesas, Society and Austral Islands in the South Pacific, with rates of migration on the order of 11 cm per year. These results together with those from the Hawaiian Islands, the Pitcairn-Gambier Islands and the Pratt-Welker seamounts [off the coast of British Columbia] are consistent with movement of the Pacific lithospheric plate over magma sources that are fixed in the upper mantle relative to one another."

David Epp of the University of Hawaii's Institute of Geophysics has examined age and tectonic relationships among volcanic chains on the Pacific plate. He prefaced his description of it at the Hawaii symposium with a revealing comment about the high favor in which the hot spot hypothesis is now held. "In case there's anyone out there who doesn't believe in hot spots, I'm going to describe another test. The results agree with what you've heard today."

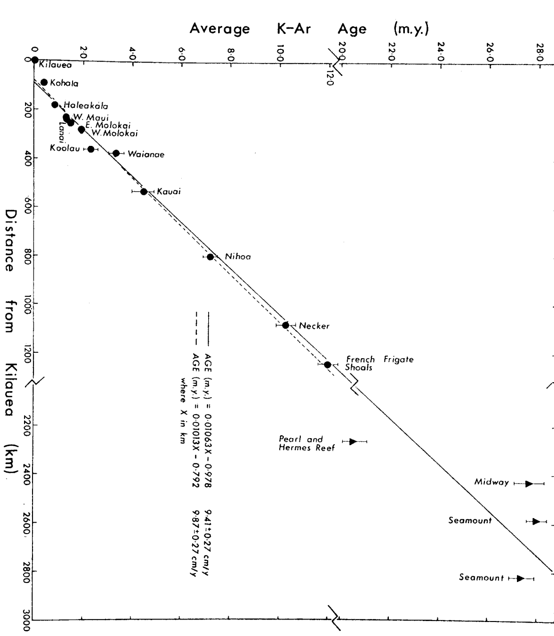
Epp starts his test by assuming that the Hawaiian-Emperor chain formed at a hot spot and that other hot spots beneath the Pacific Ocean are fixed relative to each other. If so, he reasons, then the motion of the Pacific plate determined by the ages and configuration of the Hawaiian-Emperor chain should also predict the ages and configurations of the other Pacific volcanic chains. In other words, segments of the same age range in each volcanic chain would trace roughly the same directional path.

"Using this technique," reports Epp,



Ian McDougall/Journal of Volcanology

Society Islands: Ages increase regularly to northwest.



Ian McDougall

Hawaiian volcanoes increase in age regularly to the northwest, from the youngest (Kilauea) out to Midway and beyond.

"most of the volcanic chains on the Pacific plate can be attributed with confidence to a hot spot origin."

Epp notes that volcanic chains are of different lengths, "indicating that the life of hot spots varies." Also he finds notable variations in the number of hot spots active at any given time. In the past 23 million years, 12 volcanic chains have formed. In the preceding 20 million years, only three were formed. And in the 25 million years before that (taking us back to 68 million years ago), only three were formed. "In addition," he notes, "some hot spots, for example, Hawaii, produce relatively large volumes of extrusive material resulting in large, well-defined volcanic chains, whereas other hot spots produce much less extrusive material. This suggests that there are variations in the volume, depth, degree of melting, and amount of heat supplied to hot spot melting anomalies. Once formed, however, hot spots in the Pacific move very little relative to each other."

Epp's latter point seems to have broad consensus (although Kevin Burke sees evidence that hot spots in other places such as the South Atlantic do move relative to one another). Nevertheless, several questions about the Pacific hot spot situation remain.

One is, what accounts for the northward bend in the Hawaiian-Emperor chain? Under hot spot theory the bend implies that prior to 42 million years ago the Pacific plate was moving northward over the hot spot responsible for the chain. After that time it switched to its present northwestward movement. But what would have caused the shift in plate direction?

Allan V. Cox of Stanford University thinks he has the answer. He begins with the idea that the direction of plate motion results from a combination of plate push at the ocean ridges and plate pull from the trenches where the forward edge of the plate descends into ther mantle. Prior to 42 million years ago, he says, the only zone of subduction for the Pacific plate was along its northern edge, at the Aleutian trench. Thus the Pacific plate was pulled and pushed northward. The new thing that happened 42 million years ago, says Cox, was the creation of additional subduction zones along the western and southwestern edge of the Pacific plate. The plate's movement was thus pulled more to the west, beginning the northwesterly movement it still maintains today.

Cox has used the known ridge and trench geometries to calculate the expected plate motion and thus the expected tracing of the hot spot that created the Hawaiian-Emperor chain. He then compared the trend to the actual configuration of the chain. "The trends seem to fit very well," he says. "It's almost embarrassing. The calculated trend goes exactly the way the Emperor trend goes. So it seems to support the hot spot idea fairly well."

Although most of the Pacific volcanic chains seem to have been traced out by hot spots, several don't completely fit the theory. The Line Islands, for example, offer several discrepancies. But Epp says there are now two potassium-argon dates in these islands that do fit the ages predicted by a hot spot origin. He says the remaining discrepancies probably are due to that chain's structural complexity. Epp says the Marquesas Islands are the only volcanic chain in his analysis that shows a definite age progression different from the predicted age. "This discrepancy is, as yet, unresolved."

Donald L. Turcotte of Cornell University is one of the few proponents of an alternative to the hot spot hypothesis for the origin of intraplate island chains. He proposes that some of the chains were created by a propagating crack in the lithosphere, allowing magma to well up in a line. But his is a minority view not widely shared.

Although Turcotte agrees that the age-progression data for Hawaii and other island chains fit the hot spot hypothesis almost perfectly, he says he's bothered by absence of evidence of any anomalous mantle beneath Hawaii, where the hot spot should now be. But at the Hawaii symposium in July, William L. Ellsworth of the U.S. Geological Survey presented just such evidence. His three-dimensional seismic imaging to depths in excess of 150 kilometers beneath the island of Hawaii finds a low-seismic velocity region at a depth of 100 to 150 km directly beneath Hawaii, with its most intense zone just seaward of Hawaii's northeast coast. It's about as wide as the Hawaiian chain.

"The existence of these localized low velocities strongly supports the idea that a hot spot underlies the island of Hawaii," concludes Ellsworth. "I think the hot spot hypothesis is very firm," says Epp. "But there is still lots we don't know about what's happening in the mantle."

One of the uncertainties brings up the possibility that the mantle itself is moving in relation to the earth's spin axis. There is general agreement that hot spots, at least in the Pacific, are fixed in relation to each other. Yet several analyses indicate the Pacific hot spots have moved slightly. Dalrymple, for instance, reports that the deep sea drilling data indicate that the Hawaiian-Emperor hot spot was 5 to 10 degrees north of its present position beneath Hawaii relative to the spin axis when it created Suiko Seamount. Epp, in a paper in NATURE (March 22, 1979) with University of Hawaii colleagues Stephen R. Hammond and Fritz Theyer, reports discrepancies in the calculated northward rate of movement of the Pacific plate depending on whether paleomagnetic data are used (5 to 6 centimeters a year) or whether hot spot or sedimentary data are used (2 to 3 centimeters a year). The differences reported by Hammond, Epp and Theyer can be resolved either by invoking a long-term drift in the orientation of the geomagnetic field or a motion of the Hawaiian hot spot relative to the earth's spin axis.

Epp says the discussion in the NATURE paper is still valid. The July symposium gave him the impression that "people were more willing to accept movement of the mantle relative to the spin axis than movement of the magnetic field relative to the spin axis." W. Jason Morgan of Princeton University likewise reports evidence of motion of the mantle (with the hot spots embedded in it) with respect to earth's axis.

What does it mean? No one is sure. But, says Epp, "If the assumptions about the deep origin of hot spots and the geocentricity of the magnetic field are correct, then we're seeing the effects of deep mantle convection."

The case for the existence of hot spots now is overwhelming. Yet virtually everyone accumulating evidence for their validity notes the uncertainties about their origins in the mantle. "There is very little information concerning the exact mechanism responsible for the Hawaiian hot spot," says Dalrymple. Equally uncertain is what feeds and holds them in place. "The means by which the thermal anomaly underlying each volcanic chain is maintained within the mantle remains unclear," says McDougall.

So now the emphasis turns to the mantle itself and what the hot spots may be able to tell earth scientists about its dynamics. Somewhere the hot spots carry a message about the mantle. Deciphering it poses a challenging, but exciting, task. □