# The Earth's Hot Spots

*These plumes of hot rock welling up from deep in the mantle are a key link in the plate-tectonic cycle. The marks they leave on passing plates include volcanoes, swells and midocean plateaus*

by Gregory E. Vink, W. Jason Morgan and Peter R. Vogt

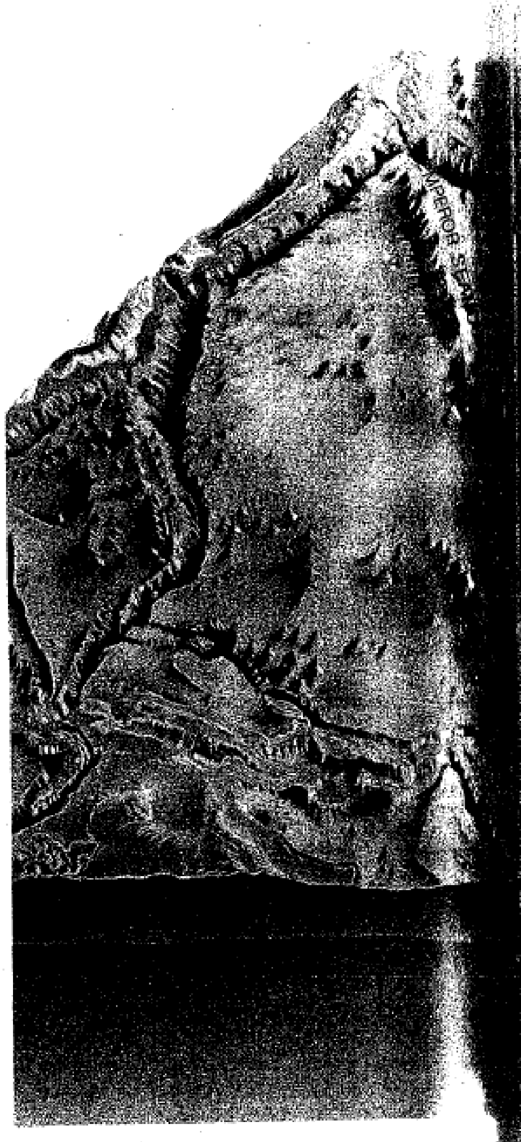
From deep inside the earth's mantle isolated, slender columns of hot rock rise slowly toward the surface, lifting the crust and forming volcanoes. The plumes well up all over the world, under continents and oceans, both in the center of the mobile plates that make up the earth's outer shell and at the midocean ridges where two plates spread apart. The marks they leave at the surface are superposed on the grand effects of plate motion. Volcanic eruptions and earthquakes associated with plumes occur far from plate boundaries, the site of most such activity; the upwelling currents also form broad anomalous swells in the ocean floor and in continental terrain. These isolated areas of geologic activity are called hot spots.

Mantle plumes are relatively stationary, and so the crustal plates drift over them. Often the passage of a plate over a hot spot results in a trail of identifiable surface features whose linear trend reveals the direction in which the plate is moving. If the plate is oceanic, the hot-spot track may be a continuous volcanic ridge or a chain of volcanic islands and seamounts rising high above the surrounding sea floor. The most prominent example is the Hawaiian Islands; it was a visit there that led J. Tuzo Wilson of the University of Toronto to put forward the concept of hot spots in 1963.

Wilson noticed that to the west of Hawaii the islands disappear into atolls and shoals, indicating they are progressively more eroded and therefore older. The same observation had been made more than a century earlier by the American geologist James Dwight Dana, but Wilson was the first to interpret the age progression as evidence of continental drift. He proposed that the island chain had been formed by the westward motion of a crustal slab over "a jetstream of lava" now situated under Hawaii itself, at the eastern end of the chain. The proposal came at a time when textbooks, including one coauthored just three years earlier by Wilson himself, mentioned continental drift only as an intriguing idea advanced in the 1920's but later discredited.

In the past two decades the idea has become generally accepted as part of the theory of plate tectonics. The earth's crust is now known to be embedded in the rigid plates of the lithosphere, which is between 100 and 150 kilometers thick under continents and about half as thick under oceans; the continual motion of the plates over the partially molten asthenosphere (the portion of the mantle extending to a depth of roughly 200 kilometers) explains the development of ocean basins and the formation of mountain ranges. A major task of contemporary geophysics is to understand how these surface processes are related to the slow convective "creep" of hot rock in the underlying mantle. Hot spots are an important part of this connection.

Indeed, if the upwelling plumes were to stop, the plates would grind to a halt. Ultimately the energy that drives plate motion is the heat released by the decay of radioactive elements deep in the mantle. The plumes provide an efficient way of channeling the heat toward the surface. Their efficiency is



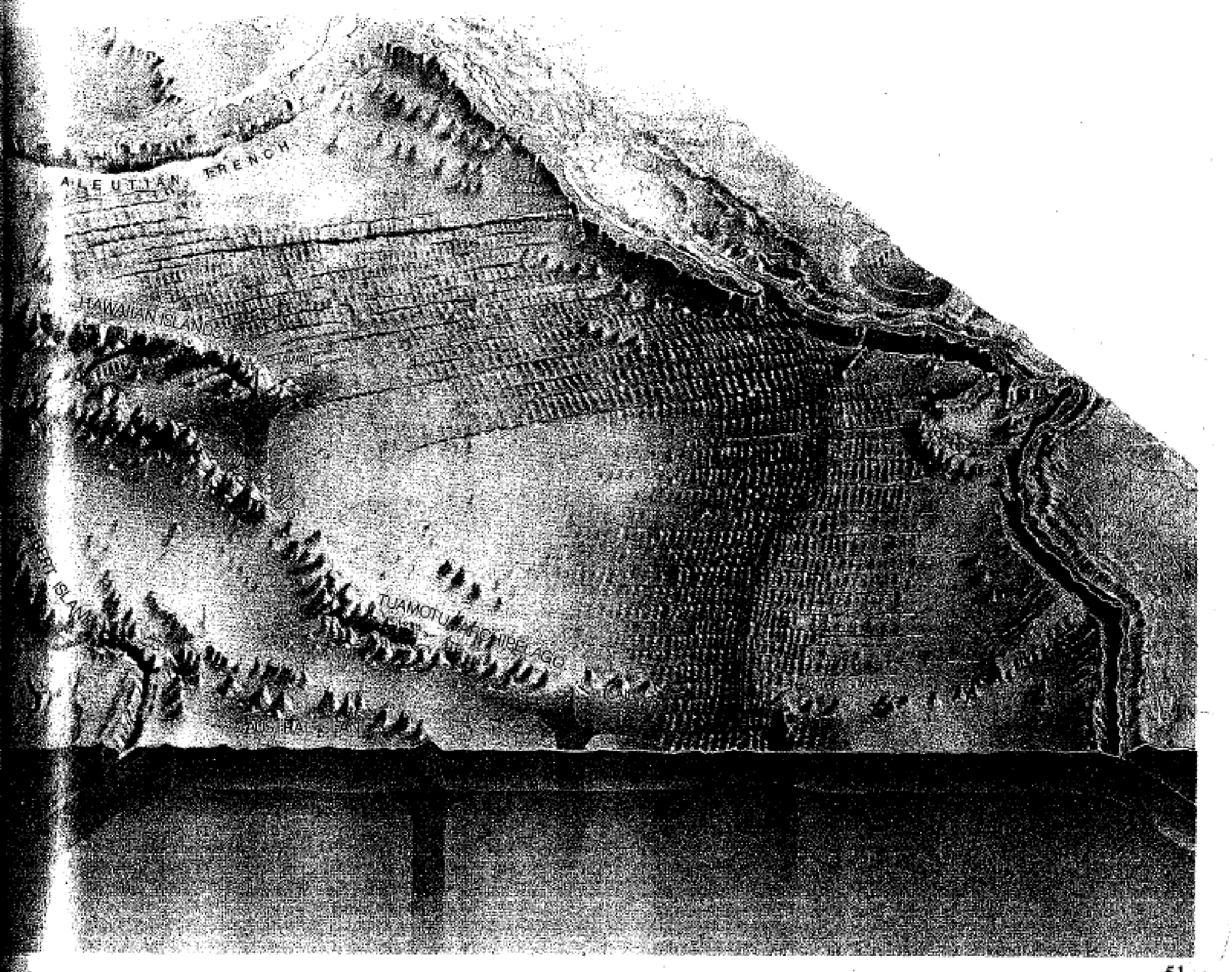
**MOTION OF THE PACIFIC PLATE over three fixed mantle plumes has produced three parallel island chains: the Hawaiian Islands and Emperor Seamounts, the Tuamotu and Line islands, and the Austral, Gilbert and Marshall islands. The chains lie in the center of the plate, proving they were formed by a mechanism different from the one that produced the volcanic island arcs of the western Pacific, which are associated with the subduction of the plate at oceanic trenches. The plumes originate deep in the mantle, and their surface tracks reveal the path of the plates. About 40 million years ago the Pacific plate switched to its present westward course from a more northerly heading; the change shows up as a bend in the hot-spot chains. Active volcanoes, such as Kilauea on Hawaii, are at the southeastern end of the chains. To the northwest the volcanoes are extinct and progressively older.**

attributable to a property of mantle rock: its viscosity, or resistance to flow, is reduced dramatically by relatively small increases in temperature (say 100 degrees Celsius) or in the content of volatile elements such as water. Less viscous material produced by variations in temperature or volatile content tends to collect and rise toward the surface through a few narrow conduits, much as oil in an underground reservoir rises through a few boreholes.

It would be misleading, however, to say that the plumes propel the plates. Rather, the two are different parts of the same convective cycle. As plates spread apart at a midocean ridge, molten rock from the asthenosphere wells up at the spreading axis to form oceanic crust; the new lithosphere cools as it moves away from the ridge and is eventually destroyed at oceanic trenches, where two plates collide and one of them sinks deep into the mantle. The deep mantle feeds the plumes. They in turn empty matter heated by radioactivity into the asthenosphere, which in addition to serving as the source of new sea floor provides a hot and fluid layer for the plates to glide across. The asthenosphere is constantly being destroyed as it cools and attaches to the base of the lithosphere; the boundary between the two layers is essentially a thermal one. Were it not replenished by the plumes, the asthenosphere would soon vanish, and the motion of the plates would stop.

It is worth emphasizing that this "plume model" of the convective circulation in the mantle is just that: a model. The plumes have not been observed directly. The deep mantle can be explored only through the analysis of earthquake waves, and so far the resolution of seismic studies has not been good enough to detect plumes; the upwelling currents may be just a few hundred kilometers in diameter and only moderately different from their surroundings in temperature and density (the properties that determine the seismic-wave velocity in a region).

The indirect evidence for deep mantle plumes, however, is substantial. Satellite measurements of the earth's gravity field have shown hot spots to be areas of anomalously high gravity and thus of excess mass; the excess mass can be attributed to broad bulges in the surface produced by the upwelling plumes. A second line of evidence comes from geochemical studies of basalts erupted at hot-spot volcanoes. Compared with the basalts dredged from midocean ridges, these rocks are enriched in volatile elements and in other elements such as potassium that are "incompatible" with the crystals of ordinary mantle rock. They also contain anomalous amounts of isotopes derived from radioactive decay processes. The differences in composition suggest that hot-spot lavas are derived from rock welling up from below the



asthenosphere, which feeds the oceanic spreading centers. According to the plume model, as material from the deep mantle flows into the asthenosphere, the part rich in volatiles and other incompatible elements melts, and some of it rises to the surface at hot-spot volcanoes.

Recent advances in seismology encourage the hope that someday workers will observe the plumes directly [see "Seismic Tomography," by Don L. Anderson and Adam M. Dziewonski; SCIENTIFIC AMERICAN, October, 1984]. In particular, a proposed new global network of seismometers may improve the resolution of seismic studies to the point where it is possible to determine the size of plumes and the depth of their roots.

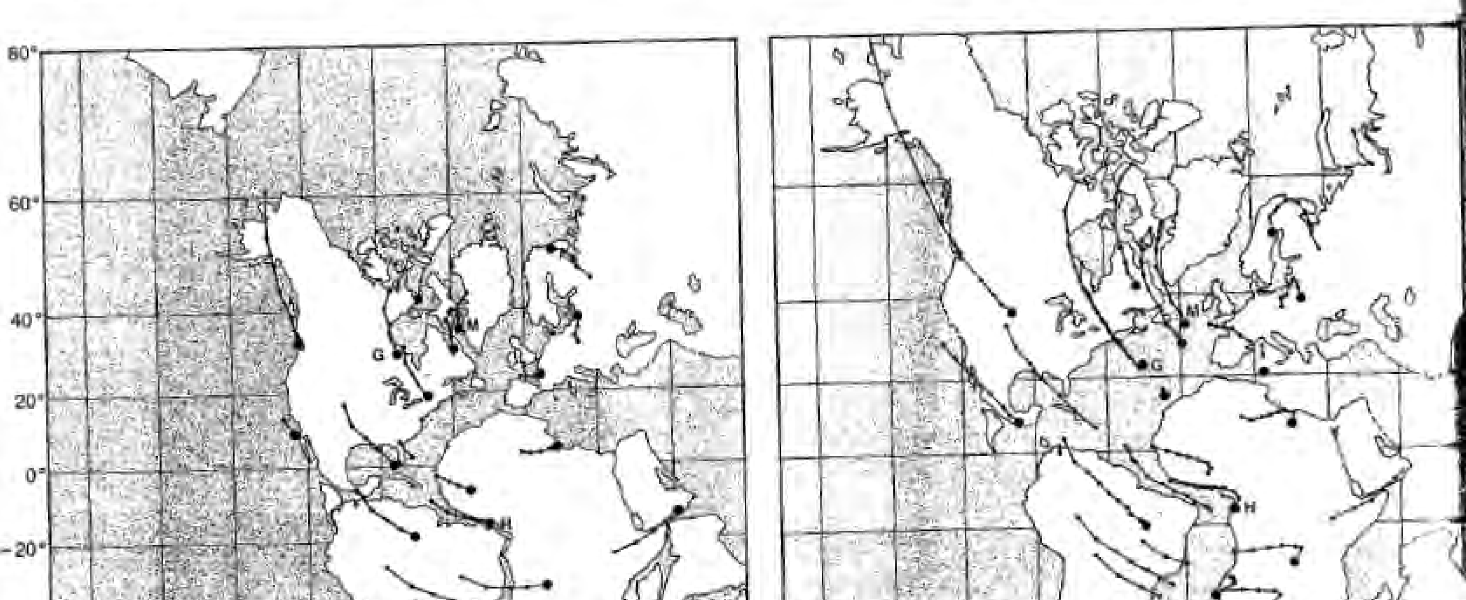
The plumes are certainly not uniform; differences in their isotope signatures imply that they come from various depths. Comparisons of the volume and frequency of eruptions at different hot spots indicate they also come in a range of sizes. Furthermore, individual plumes are not immutable. After examining the volume of rock extruded along the Hawaiian hot-spot track, one of us (Vogt) has suggested that the discharge rate of a plume may vary over time. Geochemical evidence supports the conclusion. Jean-Guy E. Schilling of the University of Rhode Island has proposed that plumes consist of rock rising in blobs rather than in a continuous flow.

Sometimes a hot spot may fade away entirely, and new ones may be formed; from the tracks it appears the typical life span of a plume is on the order of 100 million years. Moreover, the position of a hot spot seems to change slightly. As a result the tracks on the surface are not all as neatly linear as the Hawaiian chain.

Compared with the plates, however, the mantle plumes are relatively stationary. The first evidence of their fixity came in 1970. One of us (Morgan) showed that three volcanic island groups in the Pacific—the Hawaiian Island-Emperor Seamount chain, the Tuamotu Archipelago-Line Island chain and the chain formed by the Austral, Gilbert and Marshall islands—are approximately parallel and could all have been formed by the same motion of the Pacific plate over three fixed hot spots. In each case the most recent volcanic activity has taken place near the southeastern end of the chain, and the islands and seamounts get progressively older to the northwest. The Pacific plate is currently moving toward the northwest; it switched to that course from a more northerly heading about 40 million years ago. The course change shows up as a bend in the hot-spot tracks.

Because the motion of the hot spots is insignificant, they provide a worldwide reference frame for tracing the absolute motions of the plates with respect to the earth's interior. For some time workers have mapped the paths of the plates in relation to one another and have thereby been able to reconstruct the opening of ocean basins. The boundaries between plates—the ridges and trenches—also move, however, and so the relative motions do not reveal where on the globe a plate was at a given time. Nor do they indicate whether two diverging plates have been moving at the same speed, or whether instead one plate has remained stationary. Such questions can be answered by converting the known relative motions into absolute motions in the hot-spot reference frame, in which each hot spot occupies an unchanging latitude and longitude.

The relative motion of diverging plates—the sea-floor-spreading history—is determined by analyzing magnetic anomalies in the sea floor. Throughout geologic history, at regular intervals averaging about 100,000 years, the earth's magnetic field has reversed its polarity, for reasons that are poorly understood. A record of these reversals is preserved in the oceanic crust.




**HOT-SPOT TRACKS reveal how the plates have moved with respect to the earth's interior during the opening of the Atlantic Ocean. Because the hot spots (*large dots*) are anchored deep in the mantle, they remain relatively fixed; that is, their latitude and longitude remain unchanged. The tracks consist of extinct volcanoes, magma intrusions and swells in the crust formed by the upwelling plumes and then carried away by the plates. Each small dot represents 10 million years of plate motion. In reconstructing the plate motions one begins with one or two well-defined tracks, such as that of the Great Meteor hot spot (*G*), which also formed the New England Seamounts and magma intrusions in the White Mountains. The tracks of other hot spots are then calculated from the recon-**

The magnetic minerals in lava erupting from midocean ridges align themselves with the prevailing field, and as the molten rock cools and solidifies, the field direction is permanently locked in the crust.

The magnetized crust is transported away by the diverging plates in bands that roughly parallel the ridge axis. Each band has a characteristic magnetic anomaly and is made up of crust formed at the same time, and so the bands are called magnetic isochrons. The age of various isochrons, and therefore the sea-floor-spreading rate, has been established through radiometric dating of rocks retrieved in deep-sea drilling expeditions. By superposing corresponding isochrons from opposite sides of the spreading axis, one can reconstruct the relative position of the plates at the time the isochron pair was formed. (The superposition in effect removes from the map all sea floor created after the particular magnetic reversal.)

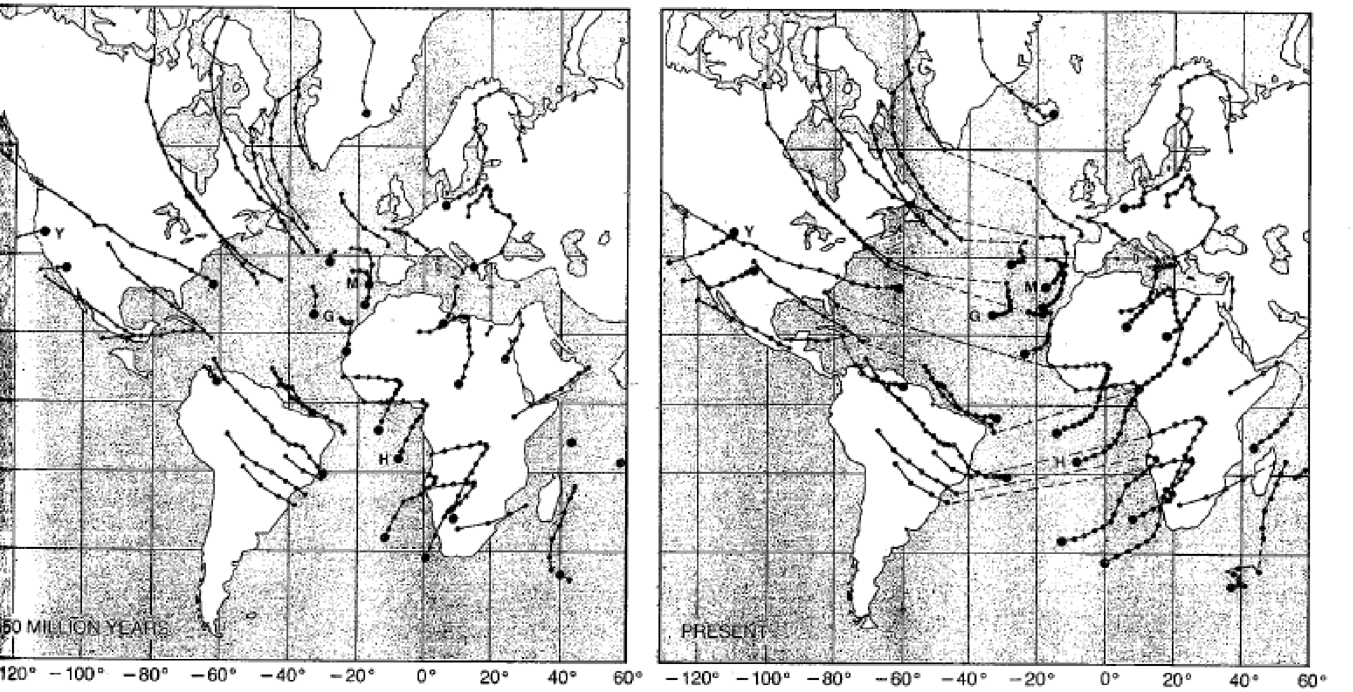
If the motion of one of the plates over the plumes is known, then their relative motion allows the path of other plates in the hot-spot reference frame to be deduced. The general procedure is to begin with a well-defined hot-spot track on one plate—say a chain of seamounts—and then adjust the more ambiguous tracks until the "best fit" is achieved: the absolute plate motions that best satisfy the constraints established by the hot-spot evidence and the relative motions.

Using this procedure, we have reconstructed the opening of the Atlantic and Indian oceans. The reconstructions can be tested: surface features along the hot-spot tracks must by their nature and age fit the hypothesis that they were formed by the passage of a plate over an upwelling plume. This should be true not only along the well-defined portions of the tracks but also in regions where the tracks have simply been extrapolated from the calculated plate motions and evidence of hot-spot activity has not previously been observed.

Although the available data are fragmentary (particularly concerning the ages of sea-floor features), in general the reconstructions pass the test. A good example is the track of the hot spot that formed the Great Meteor Seamount south of the Azores [*see illustration on these two pages*]. Two hundred million years ago the area northwest of Hudson Bay on the Arctic Circle was over the Great Meteor plume; 50 million years later the hot spot was under Ontario. The exposure of the Canadian shield from Manitoba to Ontario can be attributed to uplifting of the crust by the plume: in an uplifted area sediment covering the basement rocks is more likely to be eroded away over time.

One hundred million years ago the track had reached the young and narrow Atlantic off Cape Cod. The passage of New Hampshire over the hot spot is recorded by magma intrusions in the metamorphic rock of the White Mountains; the intrusions are between 100 and 124 million years old. For the period from about 100 to 80 million years ago the track follows the trend of the New England Seamounts. Based on radiometric dating of rocks collected from the seamounts, Robert A. Duncan of Oregon State University has shown that the volcanoes get progressively younger toward the southeast along the chain. Their ages coincide with their passage over the hot spot. From the ages and the distances between the seamounts Duncan has calculated the velocity of the North American plate during that period: about 4.7 centimeters per year.

Approximately 80 million years ago the Mid-Atlantic Ridge migrated westward over the plume. The track continues on the African plate and ends at the Great Meteor Seamount. At present the hot spot should be about 500 kilometers southwest of Great Meteor. Although there is a swell in that region




**structions, which must fit the relative plate motions derived from sea-floor-spreading history. When the midocean ridge separating two plates drifts over a plume, the track continues on the other plate but is interrupted (*broken lines*) by sea floor formed at the ridge after it passed over the hot spot. A plate motion is a rotation, and so the tracks approximate concentric circles rather than parallel straight lines. Along the Madeira (*M*) and St. Helena (*H*) tracks continents have later rifted apart; the plumes may promote rifting by thinning a passing plate. The Snake River plain, where the lithosphere has been weakened by the track of the Yellowstone hot spot (*Y*), may be the site of a future rift. Not all hot spots are present in each reconstruction because new ones form and old ones fade away.**

of the sea floor, there is no sign of current volcanism; the plume may have become inactive.

A swell in the ocean floor, like an exposed continental shield, is an area of uplifted crust. Some time ago Robert S. Detrick and S. T. Crough, then at the University of Rhode Island, proposed that a plume produces uplift not by bending the lithosphere but by thinning it, replacing cold, dense lithosphere with hot, buoyant rock from the asthenosphere. After passing over an active hot spot, both sea-floor and continental swells presumably cool and gradually sink back to their former altitude. Swells on the sea floor are interruptions of the process in which the lithosphere cools, thickens and sinks as it moves away from a midocean ridge, eventually plunging into the asthenosphere at a trench.

The hot-spot anomalies, however, are by no means insignificant interruptions. There are some 40 active hot spots, and the swells associated with them have an average diameter of about 1,200 kilometers. Thus swells cover roughly 10 percent of the earth's surface. This observation led Crough and Richard Heestand of Princeton University to suggest that the depth of the sea floor in a particular region is controlled not only by the progressive cooling of the lithosphere but also by the time elapsed since the region passed over a hot spot.

In the same way hot spots could control the thickness of the continental lithosphere. Moreover, the thinning and weakening of continental plates by mantle plumes may produce more dramatic effects than the exposure of basement rock: it may cause them to rift apart. In the early 1970's Kevin C. Burke of the State University of New York at Albany noticed that some hot spots are associated with three-arm rift systems, in which two of the arms have formed a plate boundary whereas the third has failed. The failed rifts form valleys extending into the continents; an example is the Niger River valley.

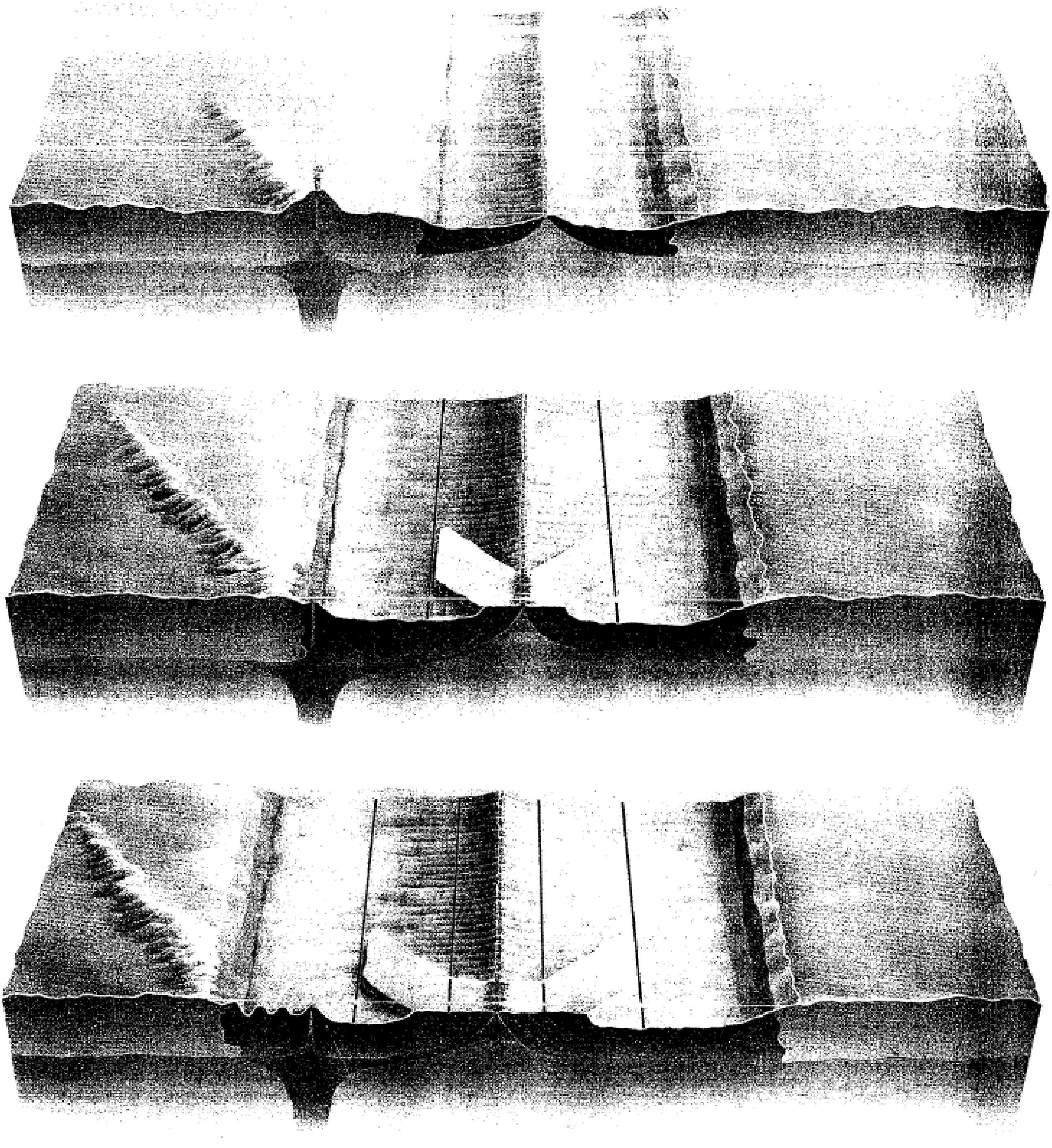
The reconstructions of the Atlantic opening reveal a number of hot-spot tracks along which continents have subsequently broken up, probably millions of years after the plates passed over the plumes. The track of the hot spot that formed the Madeira Islands, for example, runs between the west coast of Greenland and the east coast of Baffin Island and Labrador; the plume that created St. Helena can be traced along the south coast of West Africa and the north coast of Brazil. In the future a rift may develop in the Snake River plain, where the North American plate has been weakened by

**MID-ATLANTIC RIDGE is at present positioned over several hot spots; the flow from these plumes adds to the normal upwelling of magma at the ridge, producing thicker crust. In the computer-plotted topographical map brown regions are shallow and green regions are deep. Iceland is perched on the ridge axis and also has a large hot spot under its southeast coast; the plume has raised the crust above sea level by lifting and thickening it. The tapered structure of the ridge segment south of Iceland, called the Reykjanes Ridge, reflects the flow of plume material down the axis. Similar topography southwest of the Azores suggests material from that hot spot is also flowing along the ridge. The Iceland hot spot may have formed the plateau southeast of Iceland (including the Faeroe Islands) by feeding a now extinct spreading axis at the center of the plateau. William F. Haxby of Columbia University's Lamont-Doherty Geological Observatory prepared the map from data compiled by Joseph E. Gilg and Roger Van Wyckhouse of the U.S. Naval Oceanographic Office.**

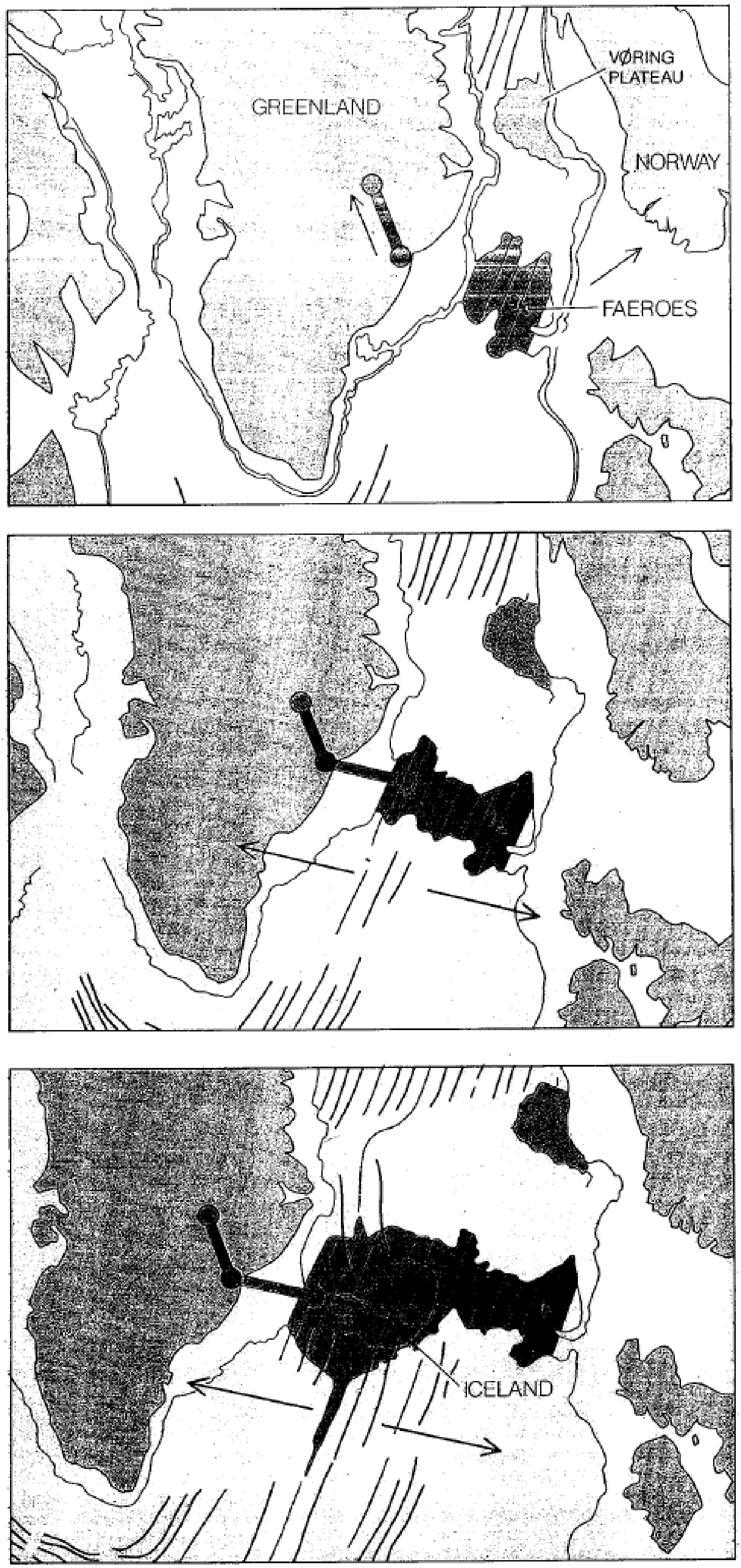
the track of the hot spot now under Yellowstone National Park.

Mantle plumes explain much of the geologic activity in the center of the plates. As the plates move over the hot spots, however, so do the plate boundaries, including the midocean ridges; unlike the hot spots, the ridges are not anchored deep in the mantle. What happens when a plume is under or near a spreading axis?

A plume directly under a spreading center augments the flow of molten rock welling up from the asthenosphere to form new crust. The crust over the hot spot is therefore thicker than it is along the rest of the ridge, and the result is a plateau rising above the surrounding sea floor. The most striking example is Iceland, a hot-spot is-



**HOT SPOT MAY FEED A RIDGE from a distance, thickening the crust and forming an oceanic plateau. Early in the opening of the ocean basin (*top*) the hot spot is under a thick continental plate moving to the northwest; material from the plume cannot yet reach the spreading center. Millions of years later (*middle*) the motion of the plates has brought the ridge closer and has carried continental shelf over the hot spot. Plume material has begun to flow along the lithosphere to the nearest section of the rise. As the excess material erupts it is carried away on the plates; the V shape of the resulting plateau reflects both the spreading of the plates away from the ridge and their motion with respect to the hot spot. A change in plate motion (*bottom*) forms a bend in the hot-spot track and in the plateau.**




land that straddles the Mid-Atlantic Ridge: there the upwelling is so intense and the crust so exceptionally thick that the plateau is above sea level. Geochemically the Icelandic crust is distinctly different from typical oceanic crust; it shows clear evidence of a hot-spot contribution. Gravity measurements indicate that the core of the plume is under the southeastern part of the island. The volcanic peaks there are visible signs of a powerful upwelling current: as much as 5,500 feet high, they are covered by the Vatnajökull glacier. (In 1918 an eruption under the glacier unleashed a flood of meltwater at a discharge rate 20 times that of the Amazon River.)

Some of the material in the strong Iceland plume also seems to spread out under the lithosphere. The lithosphere slopes upward toward a spreading axis, and one of us (Vogt) has proposed that the axis north and south of Iceland has acted as a pipeline, channeling partially molten rock away from the hot spot. In both directions along the ridge the excess plume material produces abnormally elevated topography out to a distance of about 1,500 kilometers. To the south of Iceland the broad plateau tapers to form the typical Mid-Atlantic Ridge. The tapered structure probably arises from the fact that most of the volatile-rich, easily melted plume rock is used up near Iceland. Indeed, Schilling has found that the chemical composition of basalts dredged from the ridge becomes progressively more like "normal" oceanic crust with increasing distance from Iceland, suggesting that the relative contribution of the hot spot gradually declines.

On the flanks of the ridge south of Iceland there are symmetrical pairs of secondary ridges. Each pair forms a southward-pointed V whose apex is on the spreading axis. These features could have been produced by "waves" of intensified flux or of unusually hot

**GREENLAND-FAEROE Plateau might have been formed by the Iceland hot spot. The parallel colored lines are magnetic isochrons used to reconstruct past positions of the plates. Fifty million years ago (*top*) the hot spot was under the coast of Greenland and began feeding the ridge. The V shape of the plateau reflects the hot-spot track. By 36 million years ago (*middle*) the plates had changed course; the change is reflected in the new section of the plateau. At about that time the spreading axis moved west over the hot spot, which by then was under oceanic lithosphere. Hot-spot-fed spreading has continued in the west until now (*bottom*), forming Iceland. At an earlier time when it was close to a northern ridge the plume may have built the Vøring Plateau.**

and buoyant material from the plume. A wave traveling down the ridge would generate anomalously thick crust, affecting the area nearest the hot spot first. The elevated crust would then be carried away on each side of the axis by the spreading plates, forming the V-shaped secondary ridges. From the known spreading rate and the angle between the secondary ridges and the spreading axis one can estimate the speed of the plume material; it seems to flow down the axis at a rate of five to 20 centimeters per year.

Because the midocean ridges move, a hot spot is unlikely to be situated under a spreading center for more than a geologically brief period. It is conceivable, however, that a plume might feed a spreading axis from a distance, provided it is close enough to the region in which the base of the lithosphere slopes up toward the axis. This concept helps to explain some unusual surface features in the Iceland area.

The plateau that includes Iceland stretches from Greenland in the west to the Faeroe Islands in the east. The section of the plateau east of Iceland and east of the current spreading center has long puzzled geologists. Its linear trend suggests a hot-spot origin. Yet it could not simply have been formed by the motion of a plate over a fixed plume, because it does not coincide with the track of the Iceland hot spot, which is known from the reconstructions of the early Atlantic. Some workers have interpreted this as a sign that the hot spot has not remained stationary but has instead wandered about, forming the plateau by occasionally punching through the plate. The argument implies that the reconstructions are inaccurate: if plumes are not fixed, they provide no absolute reference frame for mapping plate motions over the mantle.

Our own hypothesis is that the Iceland hot spot has remained stationary and that the Iceland-Faeroe plateau section was made by rock flowing eastward from the hot spot to a now extinct spreading center. The hypothesis can be tested. Presumably the plume would feed the closest point on the ridge. Thus at any time during the formation of the plateau a line representing the shortest distance from the plume to the ridge should intersect the center of the plateau. The plateau would be symmetrical about the ridge axis, but not necessarily perpendicular to it. With respect to the hot spot, the plates might have a component of motion parallel to the axis, and the orientation of the plateau would be obtained by adding that component to the relative motion of the plates (perpendicular to the axis). Finally, the age of the plateau at any point would be the same as that of the surrounding sea floor, because the two were formed at the same time. None of these predictions would hold if the plateau were formed by a wandering hot spot that was not feeding a ridge.

To test the model one of us (Vink) reconstructed the opening of the Norwegian-Greenland Sea and the formation of the plateau. The method is the same as that used for reconstructing the early Atlantic: superposing magnetic isochrons reveals the relative position of the plates at the time of a given magnetic anomaly, and the hot-spot track shows the plate motions in the hot-spot reference frame.

During the early opening of the basin, some 50 to 60 million years ago, the Iceland hot spot was under eastern Greenland. Its southerly track reflects the northward motion of the Greenland plate. The passage of the plate over the plume probably produced the extensive igneous rock formations southwest of Scoresby Sound, which from radiometric evidence are judged to be roughly 55 million years old. About 50 million years ago the Greenland continental shelf moved over the hot spot. At that time excess plume material could have begun flowing along the base of the oceanic lithosphere to the spreading center, and the plateau would have started to form. The Faeroe Islands, now at the eastern end of the plateau, would have been created first; their basalts are between 50 and 60 million years old. In the reconstruction of the period the nascent plateau is roughly symmetrical about the spreading axis, and the V shape of its northern edge reflects the northerly motion of the plates with respect to the hot spot.

By 36 million years ago the plates had switched to a more westerly course, causing the hot-spot track to bend to the east. The change is apparent in the geometry of the plateau: the V is split by a younger segment with an east-west heading, perpendicular to the spreading axis. The plateau remains symmetrical about the axis, and a line from the hot-spot position intersects the axis at the center of the plateau. Both observations indicate the plume was continuing to channel molten rock to the ridge.

By that time the hot spot was under oceanic lithosphere, which is somewhat thinner than continental lithosphere. The plume would have thinned it further. Our model assumes that the ridge subsequently jumped to the area of weakened lithosphere, leaving an extinct spreading center on the eastern section of the plateau. Although the existence of such a relic is still being debated, geologic activity seems indeed to have ceased in the east at about the time the spreading axis would have jumped to the west; rocks collected from a drill hole near the center of the eastern section are roughly 40 to 43 million years old.

Sea-floor spreading continued at the western end of the plateau. With the hot spot positioned under the spreading axis, plume material began to flow down the axis, giving the ridge its present tapered structure to the south. The westward-moving plates soon pushed the axis off the hot spot, but the plume continued to feed the ridge. The oldest outcrops on Iceland are found near the east and west coasts, as one would expect on an island formed at a spreading axis; their ages suggest the island was born between 16 and 12 million years ago. Iceland remains geologically active. In the past few million years eastward movements of the spreading axis have once again placed the ridge over the hot spot.

The reconstructions show that a fixed Iceland hot spot could well have produced the observed geometry of the Greenland-Faeroe Plateau. It may also have formed the Vøring Plateau, even though the latter is now 500 kilometers to the north of Iceland. The hypothesis rests on the assumption that a plume will always feed the closest section of a spreading axis. Just before the formation of the Greenland-Faeroe Plateau, when the hot spot was still under Greenland, it may have been closest to a northern ridge segment. During that period it could have produced the Vøring Plateau. The northerly motion of the Greenland plate later brought the southern spreading axis closer to the hot spot, and so the plume switched targets.

Like plate tectonics itself the notion of hot spots is a simple but powerful concept. It explains many features of the earth's surface that once seemed disparate, and further research will undoubtedly lead to the attribution of other effects to upwelling plumes in the mantle. At the same time the concept is appealingly intuitive. Indeed, it is only embellishing the truth a little to suggest the Hawaiians recognized the track of their hot spot centuries before it caught the attention of modern geologists. According to Hawaiian legend, Pele, the fiery-eyed goddess of volcanoes, originally lived on Kauai, at the western end of the island chain. When the god of the sea evicted her, she fled to Oahu. Forced again to flee, she continued to move east, to Maui, and finally to the island of Hawaii. She now seethes in the crater at Kilauea.