The Earth's Mantle below the Oceans

Samples collected from the ocean floor reveal how the mantle's convective forces shape the earth's surface, create its crust and perhaps even affect its rotation

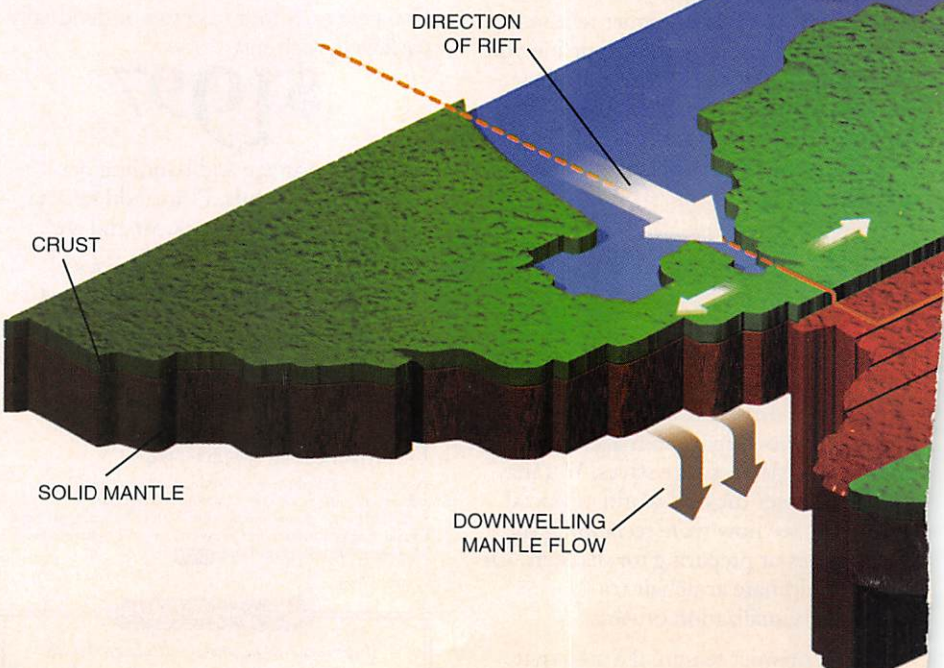
by Enrico Bonatti

Looking at a globe, one can easily imagine the continents and oceans as eternal, unchanging aspects of the earth's surface. Geophysicists now know that the appearance of permanence is an illusion caused by the brevity of the human life span. Over millions of years, blocks of the earth's rigid outer layer, the lithosphere, move about, diverging at midocean ridges, sliding about at faults and colliding at the margins of some of the oceans. Those motions cause continental drift and determine the global distribution of earthquakes and volcanoes.

Although the theory of plate tectonics is well established, the engine that drives the motion of the lithospheric plates continues to defy easy analysis because it is so utterly hidden from view. To confront that difficulty, several investigators and I have focused our research on the midocean ridges. The ridges are major, striking locations where the ocean floor is ripping apart. Examination of the composition, topography and seismic structure of the region along the midocean ridges is yielding results that often run contrary to conventional expectations. More complicated and fascinating than anyone had anticipated, the chemical and thermal processes in the mantle below midocean ridges dictate how new oceanic crust forms. Mantle activity may also cause different types of islands to emerge in the middle of oceans and some deep trenches to form at their edges. In fact, these processes may be so potent that they may even subtly affect the rotation of the planet.

The idea that the earth incorporates a dynamic interior may actually have its roots in the 17th century. René Descartes, the great French philosopher, made one of the first attempts to speculate scientifically about the earth's interior. In his 1644 treatise *Principles of Philosophy,* Descartes wrote that the earth had a central nucleus made of a primordial, sunlike fluid surrounded by a solid, opaque layer. Succeeding concentric layers of rock, metal, water and air made up the rest of the planet.

Geophysicists still subscribe to the notion of a layered earth, although their thinking has evolved considerably since the time of Descartes. In the current view, the earth possesses a solid inner core and a molten outer core. Both consist of iron-rich alloys. The earth's composition changes abruptly about 2,900 kilometers below the surface, where the core gives way to a mantle made of solid magnesium-iron silicate minerals. Another significant discontinuity, locat-



ENRICO BONATTI holds degrees in geology from the University of Pisa and the Scuola Normale Superiore in Pisa. After coming to the U.S. in 1959, he spent several years as a research scientist in petrology and marine geology at the University of California's Scripps Institution of Oceanography and as a professor at the University of Miami's Rosenstiel School of Marine Sciences. Since 1975 he has been with Columbia University's Lamont-Doherty Earth Observatory. Recently he has been teaching and researching in his native country. He has led or participated in expeditions in all the major oceans and in some remote but geologically intriguing lands, most recently in the polar Ural region of Russia.

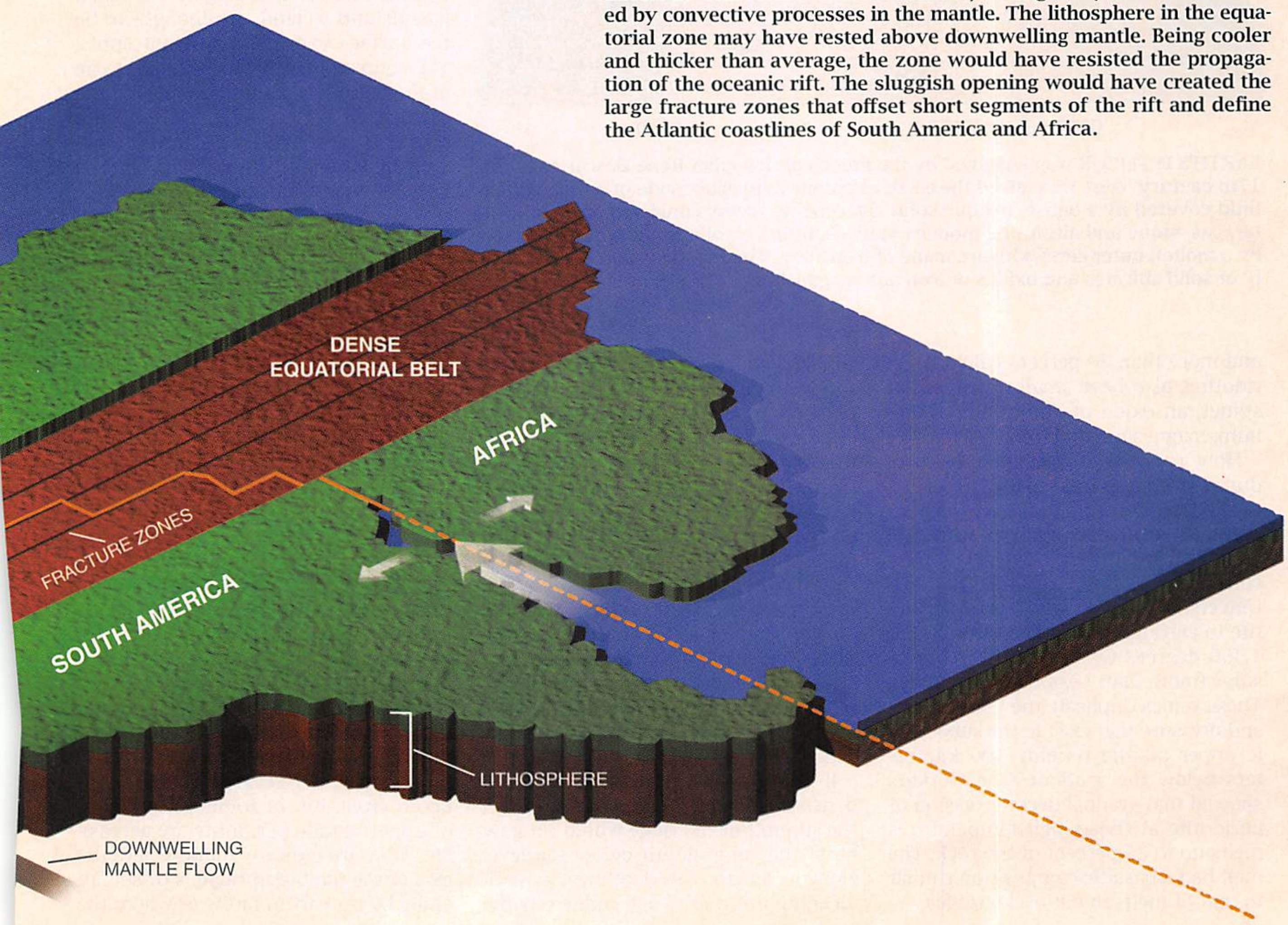
ed 670 kilometers below the surface, marks the boundary between the upper and lower mantle (the lattice structure of the mantle minerals changes across that boundary because of high pressure). An additional major transition known as the Mohorovicic discontinuity, or Moho, separates the dense mantle from the crust. The Moho lies 30 to 50 kilometers below the surface of the continents and less than 10 kilometers below the seafloor in the ocean basins. The lithosphere, which includes the crust and the upper part of the mantle, behaves like rigid plates lying above a hotter, more pliable lower part of the mantle called the asthenosphere.

This ordered, layered structure might seem to imply that the earth's interior is static. On the contrary, the deep earth is quite dynamic. Thermal energy left over from the time of the earth's formation, augmented by energy released through the radioactive decay of elements such as uranium and thorium, churns the material within the earth. The heat travels across the earth's inner boundaries and sets into motion huge convection currents that carry hot regions upward and cold ones downward. These processes ultimately cause many of the broad geologic phenomena on the surface, including mountain building, volcanism and the motions of continents.

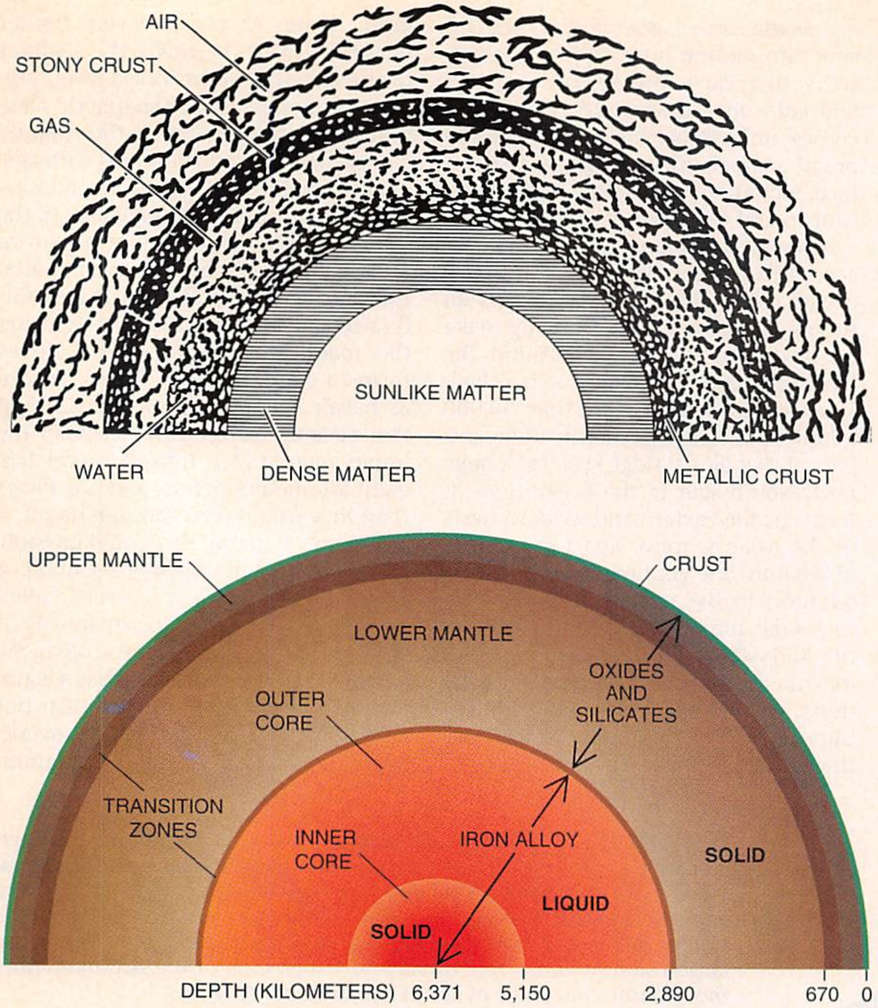
Among the regions offering the best access to the earth's insides are midocean ridges. These ridges dissect all the major oceans. They actually make up a system that winds around the globe like the seams of a baseball, stretching a total of more than 60,000 kilometers. The Mid-Atlantic Ridge is a part of that global ridge system. A huge north-south scar in the ocean floor, it forms as the eastern and western parts of the Atlantic move apart at a speed of roughly one centimeter per year. In addition to the frequent earthquakes that take place there, the summit of the Mid-Atlantic Ridge spews out hot magma during frequent volcanic eruptions. The magma cools and solidifies, thus forming new oceanic crust. The ridge is higher than the rest of the Atlantic basin. At progressively farther distances from the ridge, the seafloor deepens with respect to sea level, presumably because the lithospheric plate that forms the bottom of the Atlantic contracts as it gradually cools with age.

The magma that rises at the Mid-Atlantic Ridge obviously originates in the upper mantle. Geologists have known for years, however, that the material that surfaces at midocean ridges differs considerably from that composing the mantle. Magma at ocean ridges forms a common kind of rock known as basalt. But researchers have found that seismic waves travel through the upper mantle at a rate of more than eight kilometers per second, far faster than they would pass through basalt.

The only material that could possibly allow such a high velocity of sound is a type of dense, dark-green rock called peridotite. Peridotite consists mostly of three silicon-based minerals: olivine, a dense silicate containing magnesium and iron; orthopyroxene, a similar but less dense mineral; and clinopyroxene, which incorporates some aluminum



BIRTH OF THE ATLANTIC 100 million years ago may have been affected by convective processes in the mantle. The lithosphere in the equatorial zone may have rested above downwelling mantle. Being cooler and thicker than average, the zone would have resisted the propagation of the oceanic rift. The sluggish opening would have created the large fracture zones that offset short segments of the rift and define the Atlantic coastlines of South America and Africa.



EARTH'S INTERIOR was imagined by the French philosopher René Descartes in the 17th century (*top*). He viewed the earth as having a nucleus made of a hot, sunlike fluid covered by a dense, opaque solid. Succeeding layers consisted of metal, water, gas, stone and air. In the modern view (*bottom*), a solid inner core is cloaked by a molten outer core; both are made of iron alloy. The mantle is composed mostly of solid silicates and oxides of iron and magnesium.

and more than 20 percent calcium. Peridotites also have small quantities of spinel, an oxide of chromium, aluminum, magnesium and iron.

How can basaltic magma be produced from a mantle made of peridotite? More than 20 years ago experimental petrologists such as Alfred E. Ringwood and David H. Green and their colleagues at the Australian National University exposed samples of peridotite to elevated temperatures (1,200 to 1,300 degrees Celsius) and high pressures (more than 10,000 atmospheres). These values duplicate the temperature and pressure that exist in the suboceanic upper mantle roughly 100 kilometers below the seafloor. The workers showed that gradual decompression of peridotite at those high temperatures melts up to 25 percent of the rock. The melt had a basaltic composition similar to that of melts in midocean ridges.

These experimental results support the view that hot, peridotitic material rises under the midocean ridges from depths exceeding 100 kilometers below the seafloor. As it moves upward, the mantle peridotite decompresses and partially melts. The melted part takes on the composition of a basaltic magma and separates from the periodotite that did not melt. It rises rapidly toward the surface. Part of the melt erupts on the seafloor along the crest of the midocean ridge, where it cools and solidifies and adds to the ridge crest. The remainder cools and solidifies slowly below the surface, giving rise to new oceanic crust.

If the model outlined above happened all along the Mid-Atlantic Ridge, the summit of the ridge would roughly be at the same depth below sea level along its length. This depth would mark an equilibrium level determined by the temperature and initial composition of the upper mantle below the ridge.

In the real world such consistency is highly unlikely. Small variations in mantle temperature along the ridge would cause the summit to settle at varying elevations. Regions of suboceanic mantle where temperatures are higher have lower densities. As a result, the ridge summits there will be higher. In addition, a hotter mantle would melt more and produce a thicker basaltic crust.

The summit of the Mid-Atlantic Ridge shows just such variations in depth below sea level. For instance, along the ridge between about 35 and 45 degrees north latitude lies an area of abnormally high topography. Earth-orbiting satellites have detected in the same region an upward swell in the level of the geoid (the equilibrium level of the earth's surface, roughly equivalent to the average sea level).

Researchers generally attribute this swell to the influence of a so-called hot spot centered on the Azores island group. Hot spots are zones that have high topography and excess volcanism. They are generally ascribed to unusually high mantle temperatures. Most oceanic islands, including the Hawaiian Islands and Iceland, are thought to be the surface expressions of hot spots. The source of the heat is thought to lie in the boundary zones deep inside the earth, even as deep as the core-mantle boundary [see "The Core-Mantle Boundary," by Raymond Jeanloz and Thorne Lay; SCIENTIFIC AMERICAN, May 1993].

My colleagues and I set out to test that theory by exploring how the topography along the Mid-Atlantic Ridge relates to the temperature, structure and composition of the underlying mantle. One way to collect such information is to examine the velocities of seismic waves passing through the mantle under the ridge. Another approach involves searching for local variations in the chemistry of basalts that erupted along the axis of the ridge. Those variations can be used to infer the extent of melting and the physical nature of the mantle source from which they derived.

I followed a third approach. I attempted to collect rock samples of mantle peridotite. Some peridotite is left as a solid residue after the basaltic magma component melts out of the upper mantle rocks. Mantle rocks normally lie buried under several kilometers of ocean crust, but in some cases blocks of upper mantle peridotite are accessible. They are typically found where the axis of the midocean ridge is offset laterally by transform faults or where the mantle rocks have been transported close to the seafloor, so that they can be sampled by drilling or dredging or retrieved directly through the use of a submersible.

In 1989, during a mostly French expedition organized by Jean-Marie Auzende of the oceanographic institution IFREMER in Plouzané, France, we used a small submersible to gather samples of a section of upper mantle at the Vema transform zone in the Atlantic, 10 degrees north of the equator. Here a transform fault, cutting a deep valley through the oceanic crust, offsets the axis of the Mid-Atlantic Ridge by about 320 kilometers. We planned to descend to the seafloor—more than five kilometers down—in the submersible *Nautile* to explore the walls of that transform valley. We hoped to find an exposed, pristine section of mantle and crust. Most of our colleagues viewed our task with skepticism: the prevalent opinion was that the normal sequence of upper mantle and crust is completely disrupted near a transform fault.

Nevertheless, we pressed on. We began a series of dives that started at the base of the transform valley wall and moved up the slope. Each dive lasted about 12 hours, about half of which was spent descending to the seafloor and returning to the surface. The cramped quarters of the *Nautile* accommodate two pilots and one scientist, who lies face down for the duration of the trip.

On our first dive we verified that the base of the section consists of mantle peridotite. On the second day we discovered a layer of gabbros—rocks that form below the seafloor when basaltic melts cool slowly—resting above the peridotite. According to widely accepted geophysical models, gabbros are the main component of the lower part of the oceanic crust.

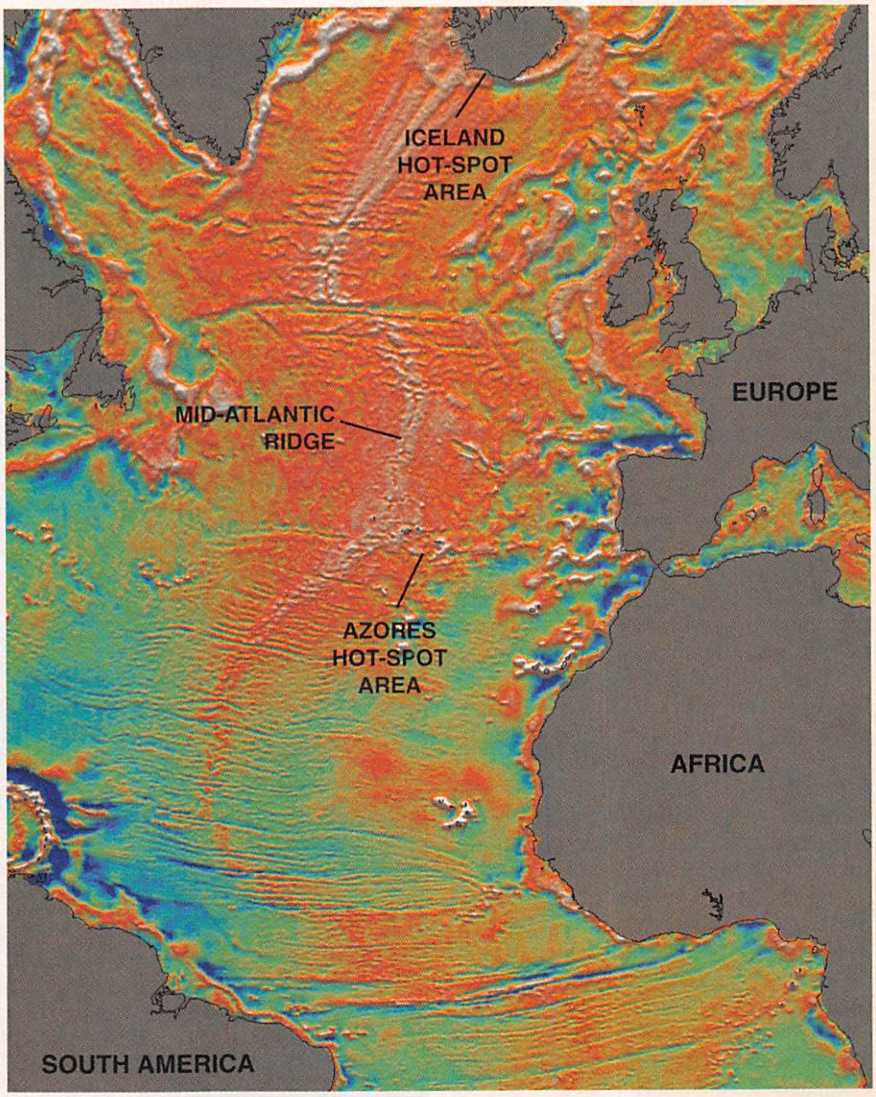
The next day I took the *Nautile* on a dive that started from the level reached by the submersible the previous day. As I progressed along the slope, skimming the seafloor, a spectacular rock formation called a dike complex gradually revealed itself to my eyes. Theory holds that dike complexes form where hot molten material from the mantle squirts upward toward the seafloor through many narrow fissures in the crust. Never before had a dike complex been observed on the seafloor.

The dike complex, about one kilometer thick, was topped by a layer of pillow basalt, the form taken by basaltic magma when it cools and solidifies rapidly on eruption to the seafloor. During the next several days, we explored a different section and confirmed our previous findings. We were quite excited because no one had ever before observed a complete and relatively undisturbed section of oceanic upper mantle and crust. We immediately documented our discovery in a short paper that we mailed to *Nature* as soon as we docked a few weeks later.

During the dives, we had used the *Nautile*'s mechanical arm to grab a number of samples of mantle peridotite. Those samples, along with many others I and other researchers collected along the ridge, enabled us to search for regional heterogeneities in the chemistry of the upper mantle.

To analyze the mantle minerals in the Atlantic peridotite samples, my colleagues Peter J. Michael and Monique Seyler, then at the Lamont-Doherty Geological Observatory, and I used an electron microprobe. This instrument focuses a beam of electrons only a few microns in diameter onto a slice of rock. In response, the mineral emits x-rays of characteristic wavelengths. An analysis of the wavelengths and intensities of these x-rays allows a determination of the chemical composition of the mineral. Collaborating with Nobumichi Shimizu of the Woods Hole Oceanographic Institution, we also used a different instrument—an ion microprobe—to determine the concentration of trace elements such as titanium, zirconium and rare-earth elements. The ion probe focuses a beam of ions onto a sample, which dislodges other ions in the sample for measurement. The method enabled us to determine the concentrations of trace elements down to a few parts per billion.

Such analyses reveal much about the



SATELLITE MAP of the North Atlantic reveals the topography of the seafloor. The satellite used radar to measure variations in sea level, which correlate with the bumps and depressions underwater. The Mid-Atlantic Ridge is clearly visible. The ridge swells into broad platforms above the hot spots associated with Iceland and the Azores. A large fracture zone breaks the ridge between the hot spots.

conditions in the mantle where the sample rocks formed, because the temperatures and pressures there produce distinct compositions in the peridotites. Petrologists, including Green and A. Lynton Jaques of the Australian Geological Survey Organization, have shown that partial melting modifies the relative abundances of the original minerals in the peridotite. Some minerals, such as clinopyroxene, melt more easily than do others and hence rapidly decrease in abundance during the melting. Moreover, the partial melting process changes the composition of the original minerals: certain elements in them, such as aluminum and iron, tend to follow the melt. Their concentration in the minerals decreases as melting proceeds. Other elements, such as magnesium and chromium, tend to stay behind, so that the solid residue becomes enriched with them. Thus, as a result of partial melting, olivine (a silicate of iron and magnesium) becomes more magnesium-rich and iron-poor; orthopyroxene and clinopyroxene lose some of their aluminum; the ratio of chromium to aluminum in spinel increases; and so on.

Our data showed that substantial regional variations exist in the composition of the mantle. For instance, the chromium-to-aluminum ratio of spinel is highest in peridotites sampled from a broad area between about 35 degrees and 45 degrees north latitude. The ratio suggests that the degree of melting of the upper mantle lying below this region may reach as high as 25 percent. In most parts, about 10 to 20 percent of the mantle melts during the trip upward. This area of above-average melting corresponds to the Azores hot-spot region, lending credibility to the theory that hot spots result from unusually hot mantle plumes upwelling deep within the earth. Other findings support that idea, including work by Henry J. B. Dick of Woods Hole, who also studied oceanic peridotites, and by Emily M. Klein working with Charles H. Langmuir of Lamont-Doherty, who independently examined the chemistry of basalts along the Mid-Atlantic Ridge.

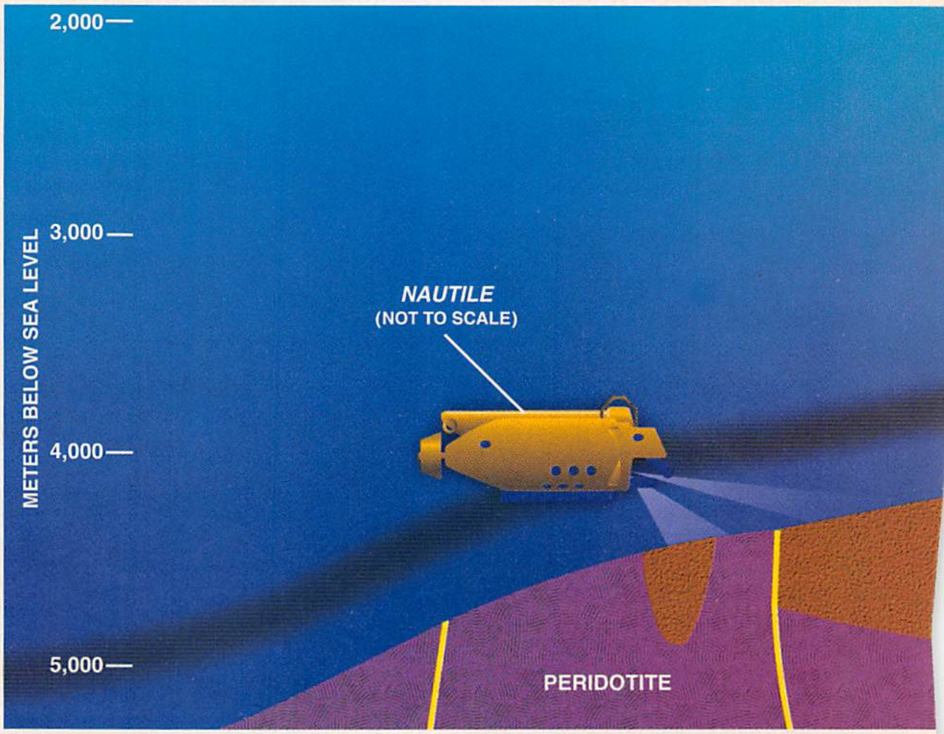
Clearly, a hot spot would seem to be the cause of so much melting. In fact, assuming that temperature alone causes the melting in the Azores hot-spot region, we calculated that the hot-spot mantle would need to be about 200 degrees C warmer than the mantle from elsewhere below the ridge.

Is there a way of testing the validity of this temperature estimate and its underlying assumption? A number of geothermometers have been proposed. They are based on the observation that certain mineral pairs that coexist in equilibrium in the mantle undergo temperature-dependent chemical reactions. For instance, the orthopyroxene and clinopyroxene in a mantle peridotite react with each other until they reach an equilibrium composition that depends on temperature. Laboratory experiments have calibrated that relation. Thus, determining the composition of the coexisting mineral pair can indicate the temperature at which the members of the pair reached equilibrium.

I applied two geothermometers, one devised by Donald H. Lindsley of the State University of New York at Stony Brook and the other by Peter R. A. Wells of the University of Oxford, to the Mid-Atlantic Ridge peridotites. The results were surprising. They did not show higher temperatures in the hot-spot region; if anything, the region gives temperatures that are slightly lower.

Why did we not find higher mantle temperatures for a region that displays high melting? One possibility is that the upper mantle there has a composition that causes it to melt more easily. Water could be the main factor. Experiments by Peter J. Wyllie of the California Institute of Technology, Ikuo Kushiro of the University of Tokyo and the Carnegie Institution of Washington, and several others have demonstrated that trace amounts of water and other volatile elements in peridotite drastically decrease its melting temperature. So, if such a "wet" mantle upwelled under a stretch of midocean ridge, it would start melting more deeply in the earth than normal, "dry" mantle would. By the time the peridotite reached the surface, it would have undergone a degree of melting significantly greater than that of dry mantle under similar temperatures.

Is there any evidence that the upper mantle below the Azores hot-spot area is wetter than the mantle elsewhere below the Mid-Atlantic Ridge? Indeed there is. A few years ago Jean-Guy E. Schilling and his co-workers at the University of Rhode Island reported that basalts from the segment of the hot spot situated between 35 and 45 degrees north latitude contain three to four times more water than do normal midocean ridge basalts. The basalts also have abnormally high concentrations of other volatile elements such as chlorine and bromine. Moreover, Schilling found that the basalts from the hot-spot ridge segment contain a much greater abundance of several chemical elements (mostly light rare-earth elements) than do the normal midocean ridge basalts. The anomalously high concentration of those elements means that the parent mantle in the hot-spot

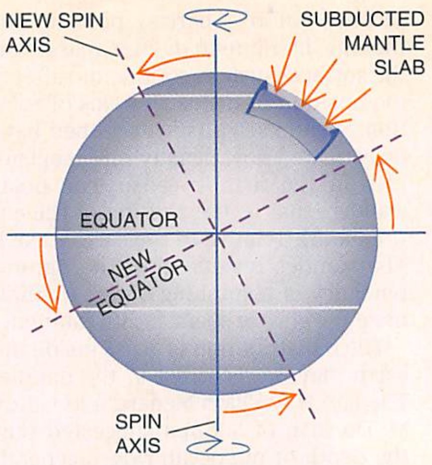


EXPLORATION OF THE SEAFLOOR by the *Nautile* occurred at the Vema transform fault, which lies in the northern section of the Mid-Atlantic Ridge. Along the southern wall, mantle peridotites were found to outcrop in the lower part of the slope. Above them were gabbros, rocks created by the slow cooling of basaltic melt (the

areă harbors an enriched supply of these elements.

It seems, therefore, that the mantle below the Azores hot spot differs from the normal sub-Mid-Atlantic Ridge mantle not so much by being hotter as by having incorporated at some stage water and other fluids that changed its chemical composition and melting behavior. This chemical transformation of mantle peridotite by fluids is called metasomatism. It would explain why wet mantle near the surface would have experienced more melting than normal mantle would. It may also explain why the equilibrium temperatures estimated from peridotites at the Azores hot spot do not appear higher than average. Melting reactions consume heat, so that partial melting of upwelling mantle may actually have cooled the surrounding mantle. The higher the degree of melting, the greater the heat loss.

Where does the water that produces mantle metasomatism come from? One possible source is the sinking of slabs of old oceanic lithosphere in subduction zones at the margin of the oceans. This process recycles water into the mantle. Water could also be released in the upper mantle during degassing processes. For instance, methane, a gas that might be present in the deep mantle, could be oxidized once the upwelling reaches the upper mantle region.



SHIFTING OF THE EARTH'S AXIS can be influenced by the sinking of cold, dense slabs of mantle. Such sinking occurs in subduction zones, such as those surrounding the Pacific Ocean. The earth's axis of rotation would tend to shift so that the equator would move closer to the dense slabs.

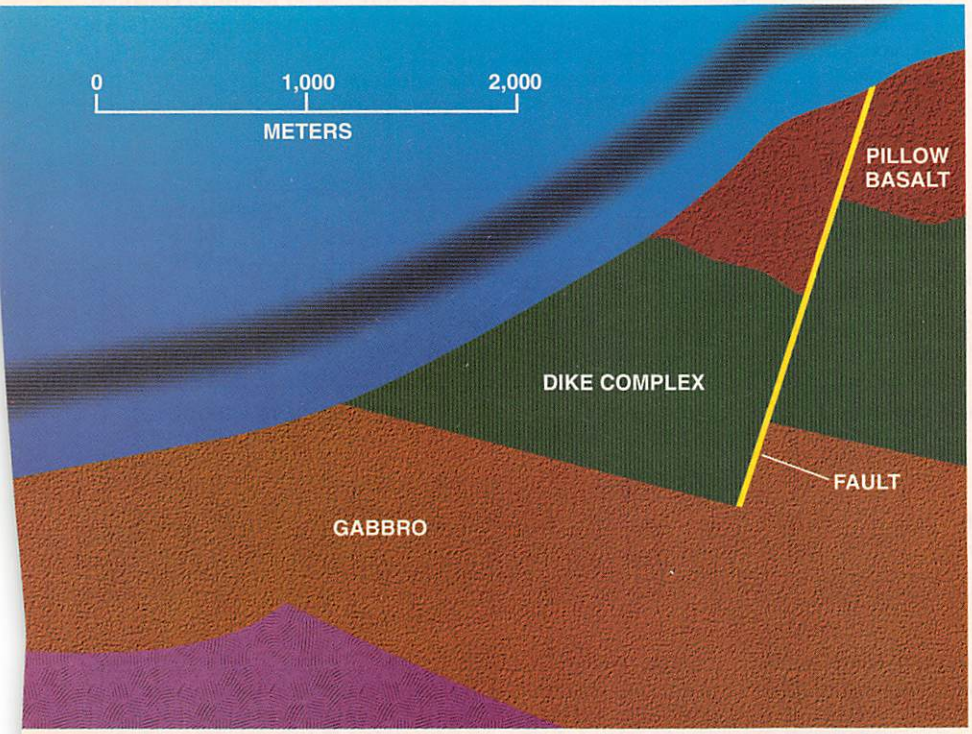
The reaction would yield water (plus carbon, either as diamond or graphite).

Because of its inferred below-average mantle temperature, the Azores hot spot clearly does not fit into the usual definition. How is one to distinguish the different types of hot spots (those that are really hot and those that are not so hot) and deduce their origins? Helium gas may lead us toward an answer. The element can form two stable isotopes: helium 3 and helium 4. Helium 4 is produced continuously in the earth's crust by the radioactive decay of uranium and thorium. Most investigators believe helium 3 stems from an incomplete escape of primordial gases that were incorporated within the earth in the early stages of its history. The ratio of helium 3 to helium 4 in the earth's atmosphere and in seawater is roughly one to one million.

Yet that ratio is different in rock samples retrieved from midocean ridges. Groups led by Harmon Craig of the Scripps Institution of Oceanography and Mark D. Kurz of Woods Hole have shown that the helium 3 to helium 4 ratio of basalts along midocean ridges is about eight times higher than the atmospheric ratio. The ratio at hot spots such as those under Hawaii and Iceland is even higher, perhaps reaching 30 times the atmospheric ratio. The large amount of helium 3 suggests that ancient gases are escaping at those sites. Thus, hot-spot areas with high ratios confirm the notion that they represent upwellings of hot plumes from deep within the earth.

A few hot spots—the Azores one among them—have basalts with a ratio of helium 3 to helium 4 lower than those of the midocean ridge basalts. The primordial component of those hot spots was somehow lost or diluted. The Azores hot spot may thus be a melting anomaly of relatively superficial origin in the mantle. It may not be linked to a thermal plume originating from the deep mantle or the core-mantle boundary. These hot spots may not be truly hot and perhaps are best classified as "wet spots," for the key role fluids may play in their formation.

Our studies of mantle peridotites from the Mid-Atlantic Ridge suggest that some areas with cooler mantle temperatures may represent the return strokes of the convection cycle in the mantle—that is, the downwelling regions. To understand the deduction, we must look south of the Azores region, to the equatorial zone of the Mid-Atlantic Ridge. The mineral composition of peridotites recovered from the equatorial Atlantic indicates that they underwent little or no melting, which implies that the mantle temperature was exceptionally low. Nadia Sushevskaya of the Vernadsky Institute of Geochemistry of the Russian Academy of Sciences reached similar conclusions in her study of basalts from the equatorial Atlantic. Moreover,



melted part of peridotite). The *Nautile* also discovered a dike complex, formed when basaltic melt cools and solidifies before reaching the seafloor. Above the dike complex lay pillow basalt, the form taken by basaltic melt that erupts on the seafloor and cools rapidly on contact with ocean water.

the crust of the equatorial Mid-Atlantic Ridge lies deeper below the geoid than that of the ridge at higher latitudes, and the velocity of the seismic waves is faster in the upper mantle below the equatorial Mid-Atlantic Ridge than at higher latitudes. Both these observations imply a denser, colder upper mantle below the equatorial region of the Atlantic. The temperature of the upper mantle there may be more than 150 degrees C lower than the mantle temperatures elsewhere below the ridge.

A plausible explanation for the relatively cool and dense equatorial upper mantle is that it results from downwelling mantle currents. Upwelling plumes from the northern and southern Atlantic mantle domains may meet here, give up their heat to their cooler surroundings and then sink.

Klein, Jeffrey Weissel and Dennis E. Hayes and their co-workers at Lamont-Doherty found a somewhat similar situation in a stretch of midocean ridge that runs between Australia and Antarctica. This ridge is exceptionally deep, and the basalts recovered from its crest give evidence of having been produced by extremely limited melting in the mantle. Their findings are consistent with the idea that broad mantle convection currents sweeping from the Pacific and the Indian Ocean converge and sink between Australia and Antarctica.

The equatorial position of the downwelling Atlantic mantle belt may not be arbitrary. It is possible that the earth's rotation and convection in the mantle are intimately connected phenomena. In the late 1800s George Darwin (the second son of Charles) pointed out that the distribution of large masses on the surface (such as continents) affects the position of the earth's axis of rotation. Several scientists since then have investigated how density inhomogeneities in the mantle cause true polar wander (that is, the shifting of the entire mantle relative to the earth's axis). The wander results from the natural tendency of a spinning object to minimize the energy spent for its rotation.

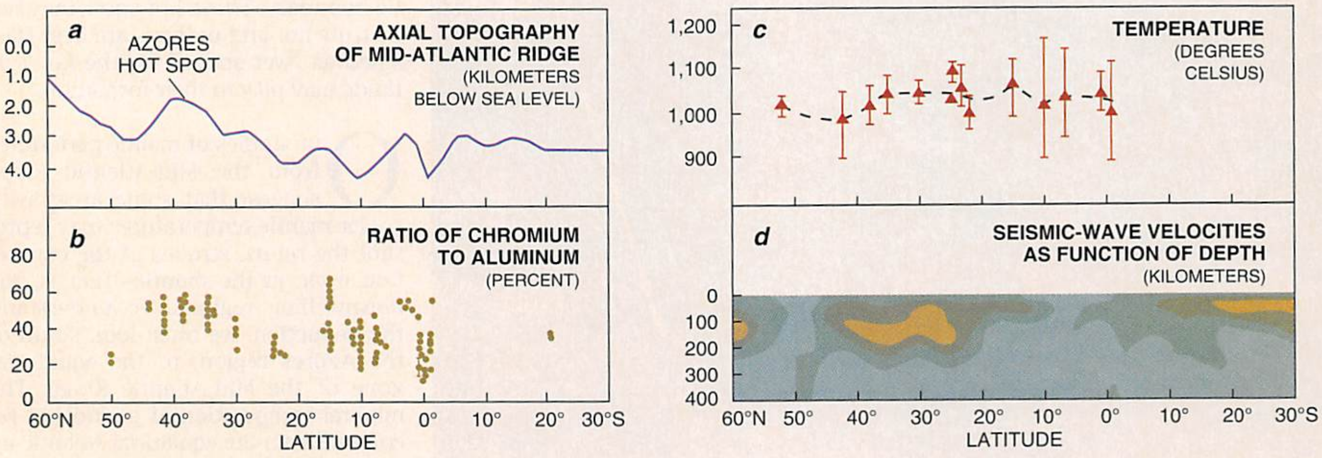
The redistribution of mass inside the earth may be recorded in the mantle. The late H. William Menard and LeRoy M. Dorman of Scripps suggested that the depth of midocean ridges generally depends on latitude: ridges become deeper toward the equator and shallower toward the poles. Moreover, gravity measurements revealed that an excess of mass sits below the equatorial areas. These data imply that abnormally cold and dense masses exist in the equatorial upper mantle.

The sinking of cold, dense slabs into the mantle appears to influence true polar wander. Evidence strongly suggests that the mantle is less viscous near the surface than it is deeper down. Any dense masses that find their way to the mantle, such as those that occur in subduction zones at the edge of some oceans, will affect the position of the rotation axis. The equator would tend to shift toward the dense masses. If high-density masses are near the equator, downwelling and cooler mantle spots are likely to prevail in the equatorial upper mantle. That phenomenon would explain at least qualitatively the cold upper mantle belt and resulting lack of normal melting in the equatorial zone of the Atlantic and probably the Pacific.

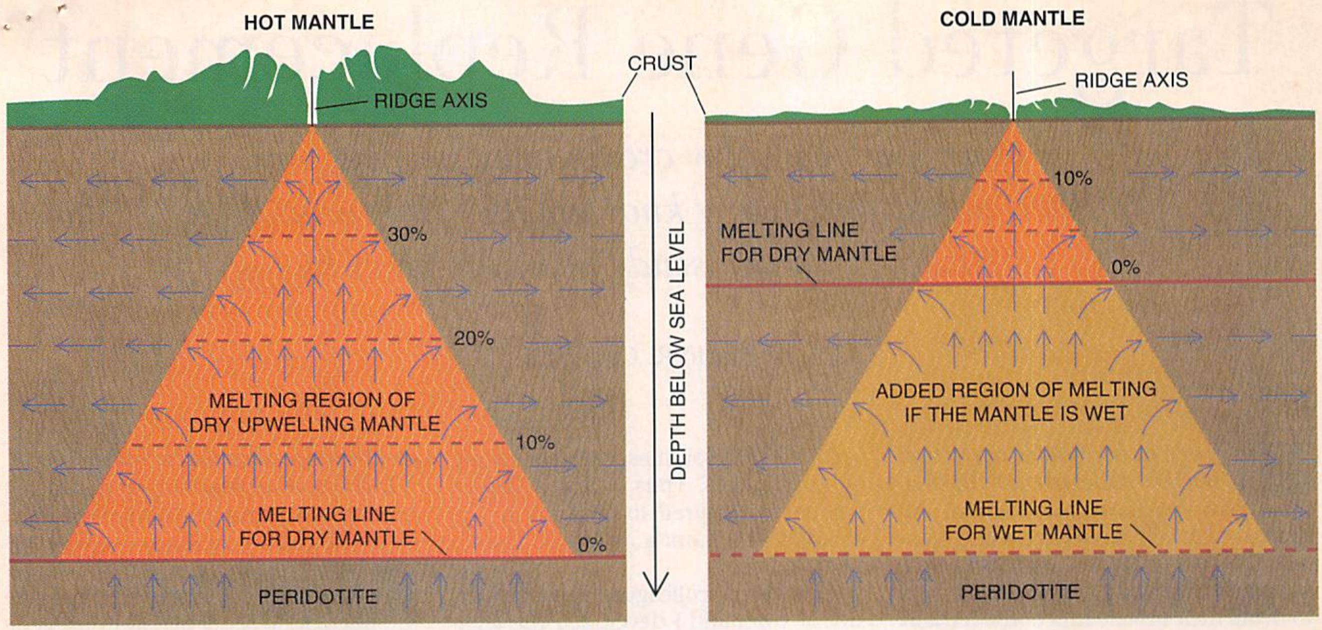
A downwelling mantle boundary could account for the peculiar geology of the equatorial region. In 1835, during his famous voyage with the H.M.S. *Beagle,* Charles Darwin landed on some desolate, small rocky islets that barely reached above sea level. The islands, now known as the St. Peter-Paul rocks, are in the center of the Atlantic, just a few miles north of the equator. Darwin described how nesting colonies of the seabirds called sulas compete with large red crabs for each parcel of available space on the rocks. The same contest can be observed today.

Darwin also noted that the islets are geologically different from most oceanic islands, insofar as they are not volcanic. This observation has been confirmed, most recently by William G. Melson of the Smithsonian Institution and Mary K. Roden of the State University of New York at Albany and their co-workers. The St. Peter-Paul rocks are in fact made of peridotites and represent an uplifted body of upper mantle.

The peridotites of the St. Peter-Paul rocks, however, differ from those collected elsewhere along the Mid-Atlantic Ridge. The chemistry of the St. Peter-Paul minerals indicates that they underwent little or no melting. The materials equilibrated in the mantle at a low temperature. They resemble peridotites from continental, or "preoceanic," rifts (such as those exposed in the island of



PROFILES ALONG THE AXIS of the Mid-Atlantic Ridge reveal the anomalous nature of the Azores area. Here the seafloor broadly swells (*a*). Measurements of the ratio of chromium to aluminum in spinel, a component of mantle peridotite, indicate that the mantle melted most here (*b*). These data suggest that the Azores region is a hot spot, an area of hot mantle. A discrepancy emerges, however, when temperature calculations are incorporated: the Azores region appears to be slightly cooler (*c*). The Azores area may have undergone much melting because the mantle material there is wet, as indicated by measurements of the velocities of seismic waves moving through the upper mantle (*d*). Wet areas have below-average densities, so seismic waves travel more slowly (*yellow*) through them. The equatorial area shows fast seismic velocities (*blue*), suggesting the presence of dense material and perhaps marking a site of mantle downwelling.



UPWELLING MANTLE melts to an extent that depends on whether the mantle is hot (*left*) or cold (*right*). The percentages indicate the amount of peridotite that melts. Melting proceeds until the peridotite stops rising and starts flowing horizontally. The hotter the mantle, the deeper the melting begins. As a result, more of the mantle melts, creating a thicker crust. Cold mantle melts less, unless it harbors fluids. In that case, it begins to melt much more deeply in the earth and may even melt more than hot mantle can. Wet mantle may explain why the Azores hot spot is rather cool.

Zabargad in the Red Sea) rather than those from ocean ridges. Moreover, they show signs of having been strongly affected in the mantle by metasomatism—more so than did the samples we collected from the Mid-Atlantic Ridge.

Hence, the St. Peter-Paul islets expose what appears to be a mantle typical of a continental rift rather than of a midocean ridge. Indeed, geochemistry work by Roden and her colleagues suggests that the metasomatism that affected the St. Peter-Paul mantle occurred about 150 million years ago; that time marks a rift stage that preceded the separation of Africa and South America in the equatorial Atlantic (that is, sometime during the breakup of Pangaea).

How could blocks of originally subcontinental mantle have been left in the center of the Atlantic Ocean? The answer may lie in the way Pangaea broke up in the face of a cold, dense upper mantle in the equatorial region.

A colder-than-normal equatorial mantle when the Atlantic first opened would imply a colder and thicker continental lithosphere along the equatorial belt. (The equator 100 million years ago crossed the future Atlantic coastlines of Africa and South America roughly along the same position as it does today.) The cold and thick equatorial lithosphere must have resisted the rift propagating from the south. The equatorial region may have behaved as a "locked zone" (in the sense used by French geologist Vincent E. Courtillot). As a result, the equatorial Atlantic opened sluggishly. This slow opening may have created the large equatorial fracture zones, visible today as east-west breaks that offset short segments of the midocean ridge.

During the opening of the equatorial Atlantic, these fracture zones were subjected to strong compressional stresses and intense vertical motions of lithospheric blocks. As a result, blocks of crust may periodically have sprung up through the ocean and sunk back down. Some slivers of continental lithosphere, however, might have been left behind in the middle of the ocean—such as that whose summit we identify as the St. Peter-Paul islets. Hence, just as hot, upwelling mantle regions create distinct types of volcanic islands, so too can cold, downwelling zones cause a different type of island to emerge.

It is interesting to speculate on how the rise and fall of such islands may have influenced life on the earth. One example is the migratory behavior of the green sea turtle (*Chelonia mydas*). These turtles live along the Brazilian coast but make an arduous 2,000-kilometer journey to Ascension island to breed. This curious act may be rooted in the behavior of their ancestors, which thrived 80 million years ago, when the equatorial Atlantic was narrow. The ancient turtles may have used islands that emerged close to the Brazilian coast as breeding grounds. As the Atlantic opened and some of the islands sank, their descendants were forced to extend their trek by hundreds of kilometers.

Much remains to be done before geologists develop a complete picture of mantle convection and its influence on surface geology. Because sending submersibles to the ocean floor is not always practical, other techniques, such as seismic tomography, must be further developed to distinguish wet spots from hot spots. Debate persists as to the origins of the mantle convection and whether it extends into the lower mantle. Indeed, symposia that include theoreticians, geophysicists, geochemists and petrologists invariably yield heated discussions and much dissent. On one point there is unanimity: the earth's mantle is very much alive and is an exciting region to study.

FURTHER READING

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Targeted Gene Replacement

Researchers can now create mice bearing any chosen mutations in any known gene. The technology is revolutionizing the study of mammalian biology

by Mario R. Capecchi

Every cell of our bodies has within its nucleus an instruction manual that specifies its function. Although each cell carries the same manual, different cell types, such as liver or skin, use different parts of this manual to detail their unique functions. Perhaps most remarkable, the manual contains the information that allows a one-cell embryo, the fertilized egg, to become a fetus and then a newborn child. As the child matures physically and intellectually, he or she is still using the information within the instruction manual. We are each unique, and the manual is slightly different for each of us; it specifies most of the physical and many of the behavioral characteristics that distinguish us as individuals.

This extraordinary manual, otherwise known as the genome, is written in the form of nucleotides, four of which constitute the entire alphabet—adenylate (*A*), cytidylate (*C*), guanylate (*G*) and thymidylate (*T*). It is the precise sequence of the nucleotides in DNA that conveys information, much as the sequence of letters in a word conveys meaning. During each cell division, the entire manual is replicated, and a copy is handed down from the mother cell to each of its two daughters. In humans and mice, the manuals each contain three billion nucleotides. If the letters representing the nucleotides were written down in order so that a page carried 3,000 characters, the manual would occupy 1,000 volumes, each consisting of 1,000 pages. Thus, a very complex manual is required to orchestrate the creation of a human or mouse from a fertilized egg.

Recently my colleagues at the University of Utah and I developed the technology for specifically changing a letter, a sentence or several paragraphs in the instruction manual within every cell of a living mouse. By rewriting parts of the manual and evaluating the consequences of the altered instructions on the development or the postdevelopmental functioning of the mouse, we can gain insight into the program that governs these processes.

The functional units within the instruction manual are genes. We specifically change the nucleotide sequence of a chosen gene and thereby alter its function. For instance, if we suspected a particular gene were involved in brain development, we could generate mouse embryos in which the normal gene was "knocked out"—that is, completely inactivated. If this inactivation caused newborn mice to have a malformed cerebellum, we would know that the gene in question was essential to forming that part of the brain. The process by which specified changes are introduced into the nucleotide sequence of a chosen gene is termed gene targeting.

Much of what is learned from gene-targeting experiments in mice should benefit humans, because an estimated 99 percent or more of the genes in mice and humans are the same and serve quite similar purposes. Application of the technology in mice is already clarifying not only the steps by which human embryonic development occurs but also the ways in which our immune system is formed and used to fight infection. Gene targeting should also go far toward explaining such mysteries as how the human brain operates and how defects in genes give rise to disease. In the latter effort the technique is being used to produce mouse models of human disorders—among them, cystic fibrosis, cancer and atherosclerosis.

Excitement over gene targeting stems from another source as well. It promises to expand on the knowledge generated by the genome project. This large-scale undertaking aims to determine the nucleotide sequence of every gene in the mouse and human genomes (approximately 200,000 genes in each). Currently we know the functions of only a minute percentage of the genes in either species. The nucleotide sequence of a gene specifies the amino acids that must be strung together to make a particular protein. (Proteins carry out most of the activities in cells.) The amino acid sequence of a protein yields important clues to its roles in cells, such as whether it serves as an enzyme, a structural component of the cell or a signaling molecule. But the sequence alone is not sufficient to reveal the particular tasks performed by the protein during the life of the animal. In

TARGETED MUTATION can be generated in a selected cellular gene by inserting mutated copies of the gene (*green-and-gold strips at far left*) into cells and allowing one copy to take the place of the original, healthy gene (*gold fragment at far right*) on a chromosome. Such altered cells are helping researchers to produce mice carrying specific genetic mutations. The finding of a curled tail and a balance-and-hearing disorder in one such mouse (*above*) led to the discovery that the affected gene, *int-2*, participates in development of the tail and the inner ear.

MARIO R. CAPECCHI, who was born in Verona, Italy, is an investigator at the Howard Hughes Medical Institute and professor of human genetics at the University of Utah School of Medicine. In addition to developing the techniques described in this article, Capecchi has helped elucidate the mechanism of protein synthesis. He has also contributed to the discovery of enhancers in DNA and to the development of a now widely used technique for directly injecting DNA into the nuclei of cells.