How Is New Ocean Crust Formed?

When the ocean crust is torn open, magma from the mantle oozes up to fill the gap, but the end result depends in many ways on how fast the crust opens

When the sea floor splits open along mid-ocean ridges, it spews lava that over eons has gradually formed the surface of three-quarters of the earth's crust. Using deep-diving submarines, sophisticated towed instrument packages, and new seismic surveying techniques, oceanographers are now taking a firsthand look at this 60,000-kilometer-long volcanic mountain range.

While studying how new crust forms, they have made some spectacular finds: unique colonies of giant clams, giant worms, and other exotic animals; hot springs; and fantastic lava formations. All these phenomena are intimately involved with the formation of new crust and provide clues about how it has happened. Oceanographers are finding that the appearance of mid-ocean ridges varies considerably depending on how fast the spreading occurs. In spite of many apparent differences, new crust everywhere always forms along a narrow strip of ocean bottom that is deceptively quiet most of the time.

In the mid-1960's, marine geophysicists realized that the rock beneath the soft mud of the ocean bottom had not been formed all at one time, but had apparently been continually squeezed out of mid-ocean ridges like toothpaste from a very wide tube. The magma that forms new crust on either side of mid-ocean ridges obviously wells up from the mantle, but no one is certain what makes it all go. It may be that as the new crust cools and becomes more dense, it first pushes the rest of the crust ahead of it. Once it dives into a submarine trench, it may tend to pull crust down with it (*Science*, 7 April 1978, p. 36).

Marine geophysicists discovered a record of this sea-floor motion in the weak magnetism frozen into the rock when it solidified at the ridge crest. The direction of this paleomagnetism is determined by the direction of the earth's own field at the time the crust cooled. Conveniently enough, the earth's field reverses its direction periodically over geological time, imprinting parallel magnetic stripes in the crust having the normal (or present-day) and the reversed directions. This "crustal tape recording" of the earth's magnetic field reversals became a crucial piece of evidence supporting the emerging theory of plate tectonics.

Somewhat to the chagrin of paleomagneticians, when they examined the rocks recovered by the Deep Sea Drilling Project (DSDP) from the crust of the Atlantic Ocean, the magnetic stripes were nowhere to be found. The recovered rocks not only were too weakly magnetized to account for the observed stripes, but their directions of magnetization were sometimes wrong. Instead of being constant down a drill hole, the magnetizations sometimes jumped between normal and reversed or even gradually rotated with increasing depth.

Because mid-ocean ridges rise to within the operating range of deep-diving research submersibles, oceanographers decided to investigate firsthand the cause of this and other unexplained phenomena. Three submersibles were used—the *Alvin* (operated by the Woods Hole Oceanographic Institution) and the French vessels *Cyana* and *Archimede*. The great advantage of diving in a submersible is that oceanographers can act like ordinary geologists in the field, inspecting small features, collecting samples, and conducting geophysical experiments. Researchers chose two short sections of the mid-Atlantic ridge rift valley (the central depression at the ridge crest) near the Azores Islands at about 37°N. These study sites were dubbed the FAMOUS (French-American Mid-Ocean Undersea Study) area and the AMAR (*Alvin*, Mid-Atlantic Ridge) area. Diving into these rift valleys, researchers found two seemingly different valleys, although they are only 50 kilometers apart.

In the FAMOUS area, the general V shape of the valley, its 2- to 5-kilometer-wide floor dotted with linear hills, and the towering 1200-meter-high walls could be detected by surveys from surface ships. But dives into the valley revealed that the sharp slope of the walls is actually broken up into numerous terraces. Close inspection of the linear hills, which more or less covered the valley floor, confirmed that they are volcanoes—that is, mounds of lava freshly extruded from beneath the ridge crest. In addition to the faults that divided the terraces from one another, other faults and open fissures were scattered about the valley floor.

In the AMAR area, in contrast, the youngest lava mounds are smaller and are confined to a narrow low area in the middle of an 8- to 10-kilometer-wide U-shaped valley. Overall, the AMAR rocks are much older and chemically less similar to the mantle than the FAMOUS rocks. The AMAR area is also more severely disrupted by faults and fissures.

These observations can be explained if the FAMOUS and AMAR areas happen to be at opposite extremes of a cycle of formation that all parts of the ridge are going through, according to Robert Ballard and Kathleen Crane of Woods Hole, Tanya Atwater and Debra Stakes of the Massachusetts Institute of Technology, Kenneth Macdonald of Scripps Institution of Oceanography, and Clifford Hopson of the University of California at Santa Barbara. They believe that the FAMOUS area was recently in a phase dominated by volcanic activity in which magma was rapidly supplied from the mantle to the valley floor, so that little fracturing would occur. That activity has now nearly died down.

In contrast, volcanic activity in the AMAR area died out long ago, and the valley is being shaped largely by the forces that lift the valley walls and drive sea-floor spreading. The spreading force fractures the valley floor as it tries to pull the new crust apart. At the same time, the lifting forces break off blocks along the edge of the wide valley floor and raise them up to form the terraces. Eventually, according to this theory, the valley floor will be narrowed to the width of the FAMOUS area by the formation of terraces, volcanic activity will resurge, and the cycle will be renewed.

Atwater and Macdonald estimate that it may take 0.5 to 1 million years for the mid-Atlantic ridge to pass from the wide AMAR stage to the narrow FAMOUS stage. A surge of volcanic activity, which creates a new lava mound, probably occurs about every 5,000 to 10,000 years. Eruptive episodes seem to occur

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on even shorter times scales because each central volcano is composed of about 25 different flows of lava, according to Atwater.

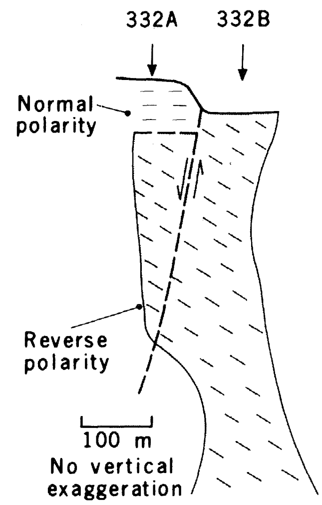
Observations on Iceland, where the spreading center rides up onto dry land, support the episodic nature of activity on the ridge. Historically, 5- to 20-year periods of volcanic and spreading activity in any one area of Iceland have been followed by 100 to 150 years of quiescence. The activity that began in 1975 near the volcano Krafla has itself come in short pulses every few months.

Paul Robinson of the University of California at Riverside and James Hall of Dalhousie University, Nova Scotia, have suggested some ways that this overlapping fracturing and volcanism could account for the DSDP paleomagnetic results. These mechanisms involve slippage along fractures, tilting of large blocks of the crust, and multiple episodes of volcanism at one site. For example, inconsistent paleomagnetic results were obtained from two holes drilled 100 meters apart in the same magnetic stripe near the ridge at about 38°N. Two different directions were found in the same hole, and one of these was rotated from the expected direction.

Robinson and Hall suggest that the top 580 meters of the crust, the depth sampled by drilling, formed as a solid block. It then tilted, causing the rotation of the paleomagnetic direction. After tilting but before being carried up out of the rift valley, the block broke between the two drill sites and slipped at least 25 meters along this new fault. This movement allowed fresh lava to pile up on the lower fragment of the block during the next episode of volcanic activity, which happened to be after the next reversal of the earth's magnetic field.

The variability of magnetic orientations on smaller scales might also be explained by similar mechanisms, according to Robinson and Hall. A driving force for this process would be the weight of new lava mounds, which could cause faulting, tilting, and subsidence of the crust as new lava was piled on. Such faulting has been observed from *Alvin* at the edges of mounds. Further rotation and overlapping by new flows of lava could occur when a mound is carried to the valley wall.

Of the two dominant forces responsible for this somewhat chaotic march—from the narrow volcanic zone, up over towering 2000-meter mountain ranges, and down into the abyssal depths—only the vertical force is supported by even a tentatively accepted theory. This vertical force may reside within the hot new crust itself. Norman Sleep of Stanford University has calculated that on the mid-Atlantic ridge, for example, magma rising through conduits would cool enough so that it would become rather viscous before it neared the surface. In effect, it would become stuck and solidify at a level lower than it would have had it not cooled so much. This rock would be less dense than its surroundings because of its higher temperature. The resulting bouyancy could then eventually lift the overlying rock, block by block, to the top of the crestal mountain.



A cross section of the upper ocean crust at the site of the Deep Sea Drilling Project's drill holes 332A and 332B. The recovered rocks had varying magnetic directions that may have been caused by faulting and slippage between the two holes with subsequent fresh lava flows at site 332A. [Source: J. M. Hall and P. T. Robinson]

While extending their studies in the Atlantic, oceanographers encountered some startling contrasts as they began diving on Pacific spreading centers. In addition to the less rugged terrain—which was detectable from surface surveys—hot springs, unique colonies of animals, and fantastic lava forms appeared before them. Although the new crust in both oceans is formed along equally narrow strips (1 to 2 kilometers wide), many aspects of the ridge crest differ between the two oceans.

The critical factor seems to be the speed at which the sea floor spreads. Near the FAMOUS and AMAR areas, about 1 centimeter of new crust on the average forms on each side of the ridge each year. This rate of opening of 2 centimeters per year is relatively slow. The areas being studied in the Pacific (the Galápagos ridge, northeast of the Galápagos Islands, and the East Pacific rise, south of Baja California) have intermediate spreading rates of about 6 centimeters per year. Some ridges have spreading rates as high as 10 centimeters per year.

The most obvious difference between these faster spreading ridges and the mid-Atlantic ridge is the lack of towering mountain ranges enclosing the Pacific rift valleys. At the Galápagos ridge site, steep slopes lead directly from the valley floor to the bordering ranges only a few kilometers away. But at a height of only 100 to 250 meters, these are only hills. As Ballard and Tjeerd van Andel of Stanford University point out, the same volcanic processes and structural changes occur within this 5-kilometer band of low relief on the Galápagos ridge that occupy the 30-kilometer width of the rugged mid-Atlantic ridge.

Another contrast dependent on the rate of spreading is the different shapes that ocean-floor lavas take on as they cool. The Atlantic areas studied so far are dominated by pillow lavas, marine lavas which resemble piles of sandbags. Divers on the faster Pacific ridges encountered nearly equal amounts of pillow lavas and relatively smooth sheets of lava. Variously described as lobate, smooth, rippled, wrinkled, whorled, hackly, or jumbled, the sheet flows are punctured by numerous pits ranging in size up to hundreds of meters across and 25 meters deep. Ballard, van Andel, and Robin Holcomb of Stanford conclude that the sheet flows on the Galápagos ridge resulted from brief but voluminous eruptions while slower, steadier eruptions built up the piles of pillow lavas. While not totally absent on the mid-Atlantic ridge, sheet flows there appear to be inconspicuous compared to the much larger volume of pillow lava.

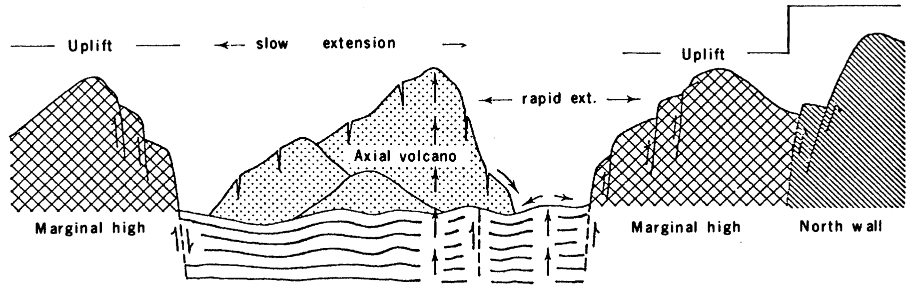
Another persistent difference has been the relative ease with which hot springs have been located in the Pacific compared to the failure to find any in the Atlantic. Many researchers had hoped to sample the heated seawater after it had circulated within the cooling crust in order to determine its effect on the chemistry of the ocean (*Science*, 9 June 1978, p. 1138), but in the Atlantic they found only a few traces of long-dead vents.

In the Pacific, however, hot springs have been relatively easy to find. Aided by broad surveys with an instrumented, towed, camera package called Angus, oceanographers have found springs both at the Galápagos site and on the East Pacific rise at 21°N, where the French submersible *Cyana* has also been diving. Elated when they at first found shimmering columns of 15°C water, *Alvin* divers were shocked to find meters-high rock chimneys at 21°N spouting black or white "smoke." These cloudy jets were so hot, at least 350°C, that they instantly destroyed the first, and as yet only, temperature probe inserted into them.

Ballard and van Andel have proposed a cyclic development of the Galápagos rift valley that includes some of these phenomena. According to this model, fresh lava is extruded as extensive sheet flows in a low area between the most recently formed mound of pillow lavas (the axial volcano) and a neighboring mound of a previous cycle. The latter, a former axial volcano, has already moved off the axis and been uplifted to form a parallel ridge called a marginal high. As the crust over the underlying magma chamber thickens, the rate of extension and lava flow would decrease, causing a shift from sheet flows to the slower accumulation of pillow lavas. This would begin to form a new axial volcano. Hot springs develop immediately on the new pillow lavas. As spreading continues, the new axial volcano is also lifted up to form a marginal high and eventually it becomes a part of the outer wall of the rift valley.

As in the Atlantic, a single volcanic cycle on the Galápagos ridge seems to be completed in about 10,000 years, according to Ballard and van Andel. Vigorous volcanic activity may occupy a very small portion of that cycle. Crane suggests that hundreds of meters of sheet flows may be extruded onto the sea floor in only a few years under the accumulated pressure built up in the magma chamber. After that pressure subsides, it may take several hundred years to build up the pillow lavas, but during the remainder of the 10,000 years, little or no volcanic activity seems to occur. Thus, at any one time lava is erupting on only a small part of the ridge.

Even the hydrothermal activity is probably short-lived. Partly on the basis of the age of giant clams near vents,



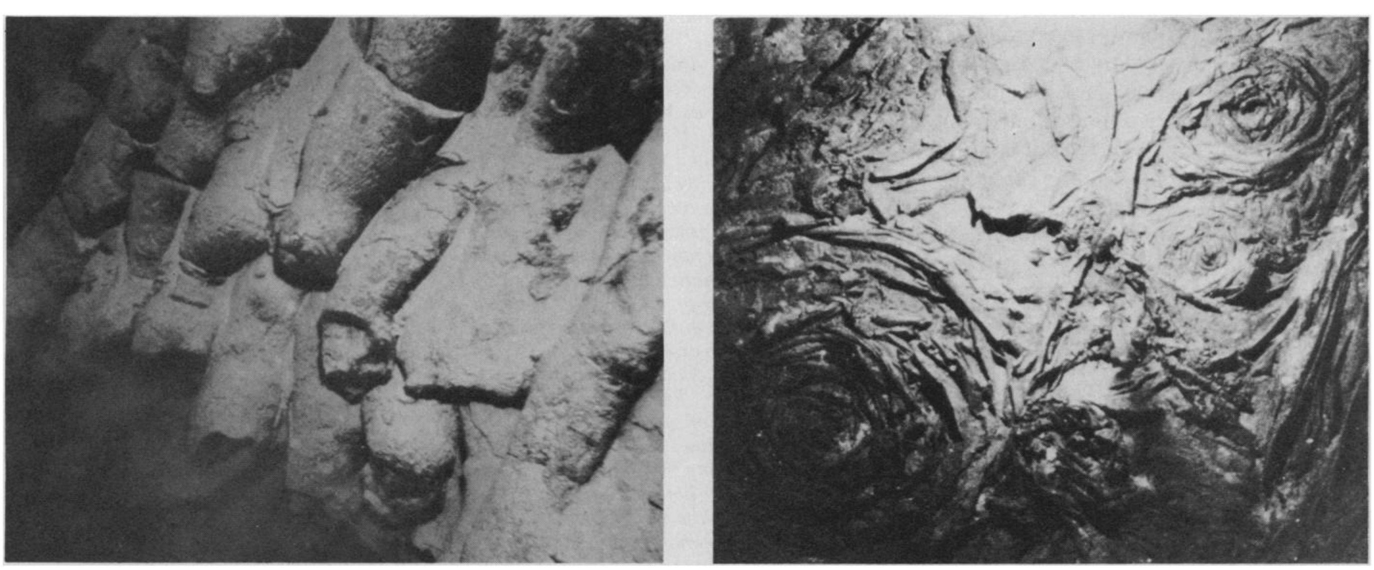
Model for sea-floor spreading in the Galápagos rift valley. Arrows show magma flow when new sheet flows are being initiated to right of axial volcano. [Source: T. H. van Andel and R. D. Ballard, in Journal of Geophysical Research*]*

Crane and Ballard estimate that hydrothermal activity persists for perhaps only decades before the fissures become clogged with minerals deposited from the hot seawater and the new crust becomes too cool.

Although studies of DSDP samples and observations from manned submersibles have been tremendously informative about how ocean crust is created, they have left nearly untouched the 5 kilometers of crust that is normally out of reach of camera and drill. This zone includes all of the crust that is formed from magma that never reaches the sea floor. Researchers are probing this region by using new versions of several geophysical techniques and by finding places around the world, in and out of the ocean, where these rocks are lifted above the surface for convenient study.

Oceanographers using a relatively new geophysical technique, a high resolution form of seismic refraction, have for the first time detected the source of all the new sea floor observed from submersibles—the magma chamber underlying the ridge crest. Seismic refraction studies, in which acoustic waves are passed nearly horizontally through the crust from ship to ship, could not resolve the small chambers expected beneath ridges. This limitation has been overcome by placing the listening devices directly on the sea floor rather than on surface ships.

With these ocean bottom seismometers in place, John Orcutt and his colleagues at Scripps Institution of Oceanography have found likely magma chambers on the East Pacific rise at 8°N, 21°N (the location of the 350°C "smoker" vents), and 12°S. Preliminary analysis of results from another seismic refraction survey by Orcutt and Macdonald and a gravity survey conducted by Bruce Luyendyk of the University of California at Santa Barbara seem to confirm the presence of a chamber at 21°N. By determining how the seismic signals are slowed by the molten rock, Orcutt estimates that the chamber typically begins about 2 kilometers below the sea floor, extends downward perhaps 4 to 5 kilometers, and is less than 20 kilometers wide. Macdonald and Orcutt's survey may provide more precise values for its depth because theirs is the first to bring both the seismic source, a hammer blow from *Alvin*


(Left) Pillow lavas on a central volcano in the AMAR area of the mid-Atlantic ridge. (Right) Sheet flow on the Galápagos ridge.

against bottom rocks, and the listening device to the sea floor.

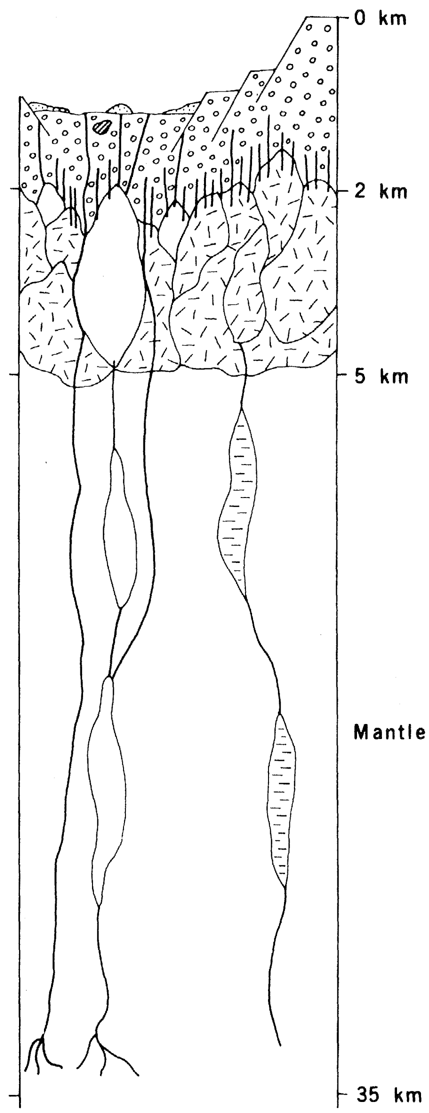
Seismic refraction data cannot provide a more exact width for the chamber, but a complementary method, seismic reflection, can (*Science*, 10 February 1978, p. 672). A group at Lamont-Doherty Geological Observatory headed by Paul Stoffa has applied seismic reflection techniques, which were first used by the oil exploration industry, to the ridge crest. The advantages of the method include a more powerful seismic source in order to penetrate more deeply into the crust and more sophisticated computer programs to remove extraneous reflections from the data.

With these advantages, the Lamont group detected reflections from about 2 kilometers beneath the East Pacific rise, near Orcutt's study site; these reflections may coincide with the top of the chamber located by seismic refraction. The width of the reflection was only about 7 kilometers compared to the upper limit of 20 kilometers provided by seismic refraction. Looking deeper, they detected reflections from the Moho, the boundary between the crust and mantle, that were weak or absent only within a 3-kilometer-wide strip on the ridge crest. Thus, the lower crust would seem to form rather quickly, leaving a narrow gap for magma to pass through into a wide chamber above.

But it probably is not that simple. "The reflection from the apparent top of the chamber is not symmetrical with respect to the ridge," Peter Buhl of the Lamont group notes, "and there seem to be large and significant differences between two points along the ridge only 10 kilometers apart. The chambers detected by refraction are most likely localized."

In fact, such variability along the ridge may have been identified by seismic refraction studies further north on the East Pacific rise by Brian Lewis of the University of Washington. He was able to identify a low-velocity zone at one point on the crest at 22.5°N but not at another nearby site. This section of the spreading center opens more slowly than it does to the south, but faster than the mid-Atlantic ridge. Orcutt speculates that this apparent tendency of the magma chamber to become more discontinuous with decreasing spreading rate may be a factor in the failure to locate any chambers in the Atlantic.

Indirect geophysical measurements can be frustratingly imprecise to someone accustomed to holding the rocks themselves in their hands, but over the last decade geologists have realized that slices of the ocean crust have actually been shoved up onto dry land where they can be studied firsthand. These exposures of the deep ocean crust, termed ophiolite complexes, have been found in Oman, New Zealand, Newfoundland,



A cross section of the ocean crust and mantle beneath the mid-Atlantic ridge crest according to a possible model for magma generation and movement (not drawn to scale). In this model, magma is generated at a depth of about 35 kilometers as mantle rock partially melts. Being lighter, this magma begins to rise, but it can be held up at several places. It may be held temporarily in deep mantle chambers, where its chemical composition can change due to the formation of new mineral crystals or the injection of a new batch of magma from the mantle. At higher levels, it can once again be trapped in magma chambers of varying sizes in the suspected layer of gabbro in the lower crust. This rock is produced by the slow cooling of magma in a chamber. From there, any magma remaining after the formation of gabbro can finally be extruded into sheet flows and pillow lavas, the volcanic rocks forming the upper layer of the crust. The boundary between this layer and the gabbro beneath it is cut by sheeted dikes, the remains of the conduits that carried the magma between the two layers. [Source: J. M. Hall and P. T. Robinson]

Cyprus, and elsewhere. Although it has proved difficult to be sure exactly what the crust looked like before it was exposed on land, ophiolite complexes are now thought to provide a reasonable cross section of the ocean crust.

At a generalized ophiolite complex, the three rocks thought to make up the crust would be sandwiched between deep-sea sediments and mantle rock. First among the crustal rocks are the pillow lavas. Below them is a sheeted dike complex, the fingered pattern of old magma conduits thought to supply magma to the pillow lava layer. Below the dikes is a layer of gabbro. This rock type only forms during slow cooling within a magma chamber; it is never extruded onto the sea floor. Instead, it may form layers on the chamber walls or fall to the chamber floor as large crystals.

Although an understanding of the details of ocean crust formation is only beginning to emerge, some reasonable guesses are being made about how the crustal material got where it is. Hall and Robinson have presented one possible model for the process beneath the mid-Atlantic ridge. They drew on the data available from DSDP drilling, submersible dives in the FAMOUS and AMAR areas, and seismic studies. They also included results from studies of the minerals composing the recovered rocks. Minerals preserve in their compositions information about how the initially liquid magma rose from its source in the mantle and eventually solidified. Hall and Robinson conclude that the magma must sometimes follow a tortuous path—mixing with other batches of magma and losing some components when crystals form on the walls or settle to the bottom. Other times the magma apparently rises directly to the sea floor. The loss of minerals to the walls, which in effect are the growing edges of the crust, has been compared to an onion forming layer by layer from the inside. This may be how the crust forms more than 1 kilometer beneath the sea bottom.

Only a few tens of kilometers of ridge out of 60,000 have been studied intensely. No fast spreading ridges have been studied yet, largely because of their logistically inconvenient location in the southeast Pacific. Intersections of ridges with transform faults, which offset short sections of ridges, appear to alter the spreading process, but studies have been limited. Although no hot springs have been found in the Atlantic, several different kinds of evidence indicate that they are there. A lot of interesting sea floor remains to be covered.

—RICHARD A. KERR