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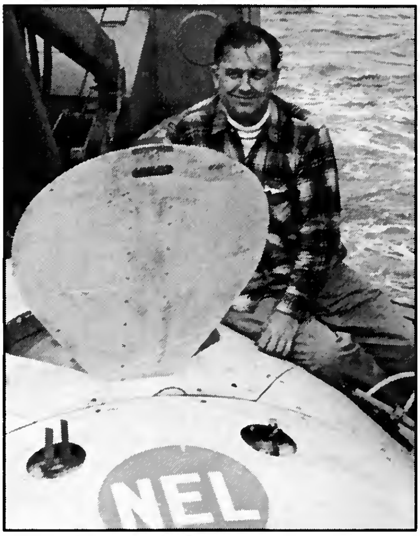
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ON THE COVER: An artist's concept of the mighty Mid-Atlantic Ridge and a glimpse of the Pacific Ridge are highlighted in the colors scientists use to indicate elevation.
(Watercolor by E. Paul Oberlander, WHOI Graphics)

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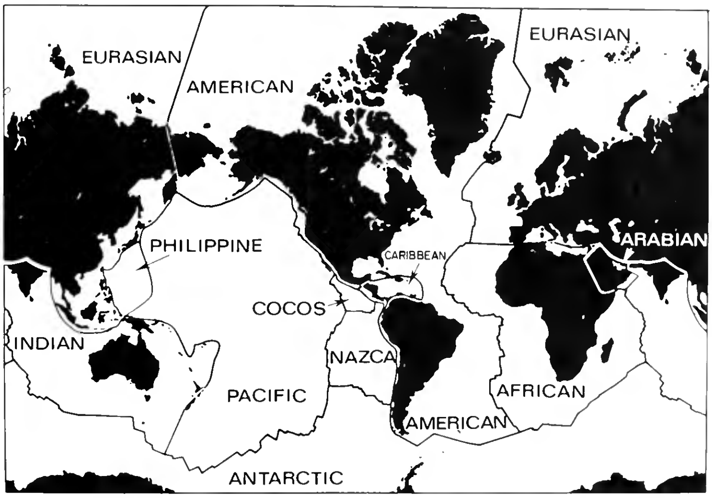
From the Editor

On Mid-Ocean Ridges

The theory of plate tectonics, the idea that the surface of the earth is made up of eight large and several small rigid plates that are in constant motion (at least in geologic time), was born in the late 1960s, a synthesis of the concepts of continental drift and seafloor spreading. Observations on the apparent fit of the bulge of eastern South America into the indentation of Africa date back at least 300 years. The first detailed theory of continental drift was proposed in 1912 by Alfred Wegener, a German meteorologist. He suggested that a single supercontinent he called Pangaea existed through most of geological time and that it began to break up about 180 million years ago. In 1937, Alexander DuToit, a South African geologist, suggested that rather than one primordial continent perhaps there were two, Gondwanaland in the south and Laurasia in the north. Neither proposed a mechanism for continental motion.



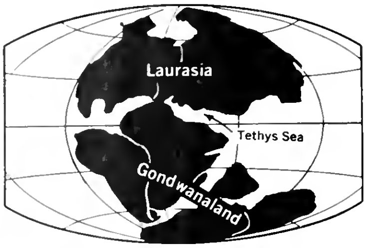
Boundaries of the large and some of the small crustal plates are diagrammed here.

New work in the 1950s brought mounting evidence for continental drift. During the early 1960s the theory of seafloor spreading was advanced by US geophysicist Harry Hess, who suggested that new crust is continually being generated by volcanic activity at the crests of mid-ocean ridges.

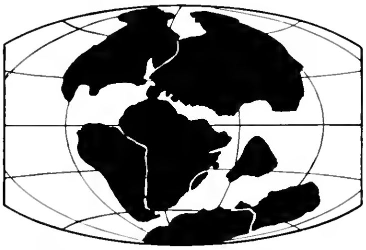
In a 1970 paper, US scientists Robert Dietz and John Holden reconstructed Pangaea and described a plausible sequence of continental dispersion, depicted overleaf, over the past 200 million years. "Continental drift," they wrote, "is a necessary consequence of plate tectonics in that the continents would be passively rafted on the backs of the conveyor-belt-like crustal plates. The drift of the continents may be conveniently thought of as a summation of sea-floor spreading."

Plate motion and the tectonic forces that create and destroy the plates are still being defined and understood, and we share with you in this issue of *Oceanus* some of the continuing excitement among Earth scientists about these forces and the phenomena they create. It is along the mid-ocean ridges, as Harry Hess surmised, that the crustal plates are created as molten material, called magma, from deep beneath the surface rises to fill the gaps or rifts created between plates that are moving or "spreading" apart. Our authors tell us that different spreading rates result in different surface expressions: The slowly spreading Mid-Atlantic Ridge, where about 30 millimeters of crust are created annually, rises steeply from surrounding seafloor and has a characteristic depres-

PERMIAN ·225 million years ago



TRIASSIC ·200 million years ago



JURASSIC ·135 million years ago

sion at its crest that is called a rift valley, while the fast-spreading East Pacific Rise that expands some 60 to 170 millimeters per year presents a more gently rolling topography and no rift valley. Seawater circulates down through the porous new volcanic crust, heating as it moves and accumulating elements absorbed from the rock. Eventually the heated, altered water rises again to erupt through vents in the seafloor and support colonies of unusual animals.

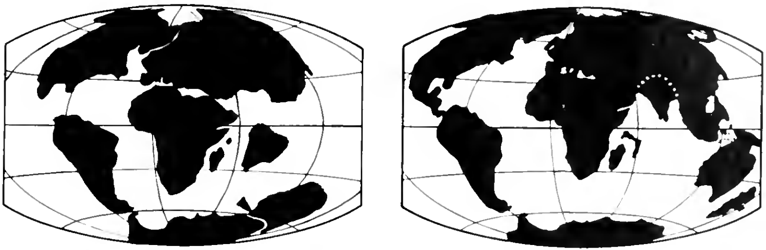
The new crust being created at ridges is balanced by destruction of crust on the opposite sides of the plates where deep-sea trenches mark subduction zones, areas where the heavier of two colliding plates is shoved back down toward the center of the earth. Characteristics of theses zones include curving island chains or island arcs, such as the Aleutian Islands and the islands of Japan, and volcanoes born of the melting edges of subducting plates. Alternatively, when there is no subduction, mountains result, such as the Himalayas that mark the colliding boundaries of the Indian and Eurasian plates.

Readers new to these concepts may find it helpful to begin with a review of the glossary that begins opposite and the profile of Bruce Heezen (page 100) in which Heezen's student, Jeff Fox, describes the meticulous assembly of mid-ocean ridge topography by Heezen and Marie Tharp. Their successive "physiographic maps" revealed the sharp relief of a seafloor previously thought to be largely flat and uninteresting. A world map on pages 24 and 25 shows ridges and research areas to help readers follow this issue's wide-ranging discussions of ridge research.

Author Joe Cann (Onions and Leaks…on page 36) notes that early in his career it was still possible to become well acquainted with every scientist working in marine geology while now that would be quite impossible."Thirty-five years ago," he writes, "most geologists were secure in the knowledge that continents did not move." As we mark just over two decades since the theory of plate tectonics gained wide acceptance, we invite you to join us for a review of the exciting, and still new, realm of a planet in motion.

Vicky Cullen

Acknowledgment:
The Oceanus *staff thanks G. Michael Purdy, Woods Hole Oceanographic Institution Department of Geology and Geophysics Chairman, for his advice on this issue.*



CRETACEOUS -65 million years ago **CENOZOIC**·Present

World maps similar to these were published in 1970 by Robert Dietz and John Holden depicting the breakup of the primordial supercontinent Pangaea and subsequent dispersion of continents over the past 200 million years. The action began when the southwest Indian Ocean rifted, splitting West Gondwana (South America and Africa) from East Gondwana, and India lifted off Antarctica. Then Laurasia (North America and Eurasia) separated from South America and the bulge of Africa. Later South America and Africa split. Spain rotated to form the Bay of Biscay, and Madagascar split from Africa. India continued its northward trek, and Australia separated from Antarctica. As Antarctica rotated westward, Australia made a remarkable northward flight and New Zealand dropped off its east coast. The North and South Atlantic oceans continued to open, Greenland parted company with Europe, Africa moved slightly northward and rotated, and India collided with Asia, raising the Himalayan Mountains.

Glossary

accreting plate boundary—the border between two separating crustal plates where new oceanic lithosphere or crust is being created

asthenosphere–the layer of the earth that extends roughly from 100 to 300 kilometers below the surface where temperature and pressure cause the rock to flow plastically.

axial—relating to a line that bisects a mid-ocean ridge. For example, an axial rift valley runs down the center of the Mid-Atlantic Ridge.

basalt—medium gray to black igneous rock that constitutes the uppermost 2 to 3 kilometers of oceanic crust and is the chief component of isolated oceanic islands, rich in iron, magnesium, and calcium

bathymetry—measurement and charting of ocean depths using echo soundings plotted on a chart to show seafloor contours

crust—the outermost layer of the earth, 6 to 8 kilometers thick beneath the ocean and 30 to 35 kilometers thick beneath the continents

diapir—a vertical columnar plug of less dense rock or magma that has risen through more dense rock

dike—a tabular body of igneous rock that intrudes pre-existing structures (see photo page 38)

echo sounding—generation of sound in water and recording the time lapse of the return or echo of the sound from a reflecting surface as a measure of depth

fault—rock fracturing that displaces the sides of the fracture relative to one another. Fault movement may be continuous creep or a series of abrupt jumps (earthquakes).

fault scarp—steep cliff formed by movement along one side of a fault

fissure—an extensive crack in a rock formation

fracture zone—area surrounding a large fault that crosses and displaces a mid-ocean ridge, often the site of intense seismic activity

gabbro—a group of granular, dark-colored igneous rocks composed largely of plagioclase and clinopyroxene

graben—a crustal block that is depressed relative to neighboring blocks, which are called horsts

horst—a crustal block that is raised relative to neighboring blocks, which are called grabens

hot spot—heat source from deep within the earth's mantle, surface manifestation of a rising plume of hot mantle material

hydrothermal—relating to heated water and its actions or products

igneous rock—rock of several types formed of molten material (magma) that upwells from the deeper part of Earth's crust and comprises most of the oceanic crust *hydrothermal—relating to heated water and its actions or products*

hydrothermal vent

isostasy—state of equilibrium with the earth's crust buoyantly supported by the plastic material in the mantle

lithosphere—Earth's outer shell including the crust and uppermost rigid layer of mantle. In plate tectonics, the lithospheric plates move over the plastic asthenosphere below.

magma—molten, mobile rock that is the product of melting deep within the earth's crust or upper mantle, the source of igneous rocks. Lava is magma that reaches the earth's surface. Magma that solidifies below the surface is called intrusive or plutonic and that emerging and solidifying above the surface is called extrusive or volcanic rock.

mantle—zone of the earth extending from below the crust to the core. The upper mantle extends to 400 kilometers depth followed by a transition zone from 400 to 1,000 kilometers and the lower mantle from 1,000 to 2,900 kilometers.

Moho—abbreviation of Mohorovicic discontinuity, the boundary between the crust and the mantle

offset—horizontal displacement of a topographic trend, commonly along a fault; also a spur or branch from a mountain range

ophiolite—masses of igneous rocks of oceanic crustal origin that have been pushed up onto continents by plate collisions

peridotite—coarse-grained igneous rock thought to be the primary component of the upper mantle, often associated with ophiolites

rift valley—the deep central cleft with a mountainous floor in the crest of a mid-ocean ridge. The valley results from plate separation; at fast-spreading ridges upwelling magma fills the rift and smooths the topography while at slow-spreading ridges the upwelling magma does not fill the rift but adheres to the trailing edge of the separating plates.

rift—a narrow opening in a rock caused by cracking or splitting

Ring of Fire—chain of volcanoes occurring in a rough circle around the perimeter of the Pacific Ocean

scarp—sequence of cliffs resulting from faulting

seep—place of contact between deep-sea sediments and limestone walls where hypersaline waters seep onto the seafloor and feed sulfide-dependent biological communities

seismic waves—the form (like sound waves) of the energy released by fracturing or abrupt slipping of rock along fault planes during an earthquake. Seismic waves provide valuable information about the regions they travel through; most importantly they map reflecting discontinuities, and measurement of the velocity at which the waves travel through different layers of rocks allows inferences to be made concerning the extent of various rock types within the earth.

sheeting—ruptures in massive rocks characterized by tabular surfaces that are slightly curved and parallel to the topographic surface

shield volcano—gently sloping volcano built by flows of very fluid basaltic lava erupted from a large number of closely spaced vents and fissures

strike—the direction taken by a structural surface, directional trend

strike-slip—movement parallel with the strike of a fault

Glossary continues on page 112

Introduction

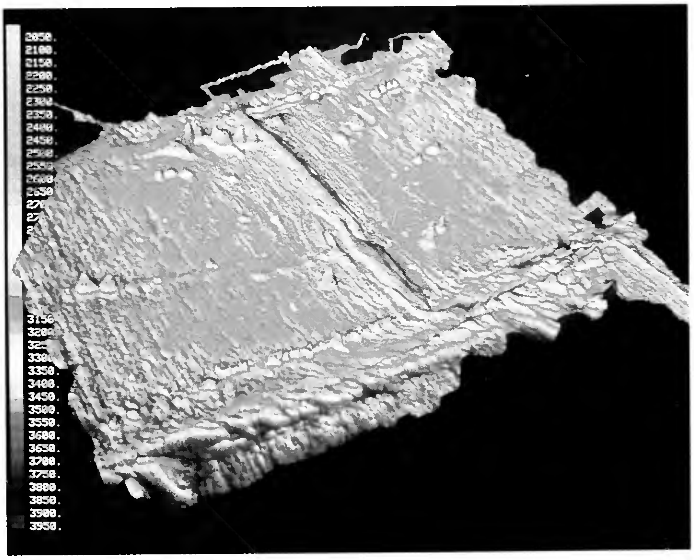
Mid-Ocean Ridges: The Quest for Order

Ken C. Macdonald

Every year, the chain of active volcanoes that comprises the mid-ocean ridge erupts, on average, ten times as much lava as the dramatic and disastrous Mt. St. Helens eruption in 1980. This is enough lava to pave the entire US Interstate freeway system with a layer of rock 10 feet thick. The largest and most volcanically active chain of mountains in the solar system, the mid-ocean ridge wraps around the globe for over 70,000 kilometers, much like the seam of a baseball. Along the ridge, brittle plates that comprise Earth's surface separate at rates of 10 to 170 millimeters per year. As the plates move apart, rock melts, separates from the solid residuum, and wells up from tens of kilometers deep. Some of the molten rock ascends all the way to the seafloor, producing extensive volcanic eruptions and building volcanoes, while the rest adheres to the edges of the parting plates. The late Bruce Heezen (see profile on page 100) aptly called this world-encircling system of ridges "the wound that never heals."

Over the last decade, an extraordinary confluence of diverse observations at mid-ocean ridges has led to a series of advances in our understanding of the seafloor and its spreading processes. Swath-mapping tools have been developed that can image large areas of the deep seafloor accurately. Structural maps based on these charts, combined with geochemical studies of rock samples, seismic and gravitational studies of velocity and density variations beneath the ridge, seafloor magnetization studies, and near-bottom imaging of hydrothermal-vent distribution, have revealed a fundamental partitioning of the ridge into segments bounded by discontinuities. These segments behave like giant cracks in the seafloor that can lengthen or shorten, and have cycles of increased volcanic, hydrothermal, and tectonic activity.

Most observations support the concept of a hierarchy in the



Merging Sea Beam and SeaMARC II swath bathymetry produced this shaded-relief image of the Office of Naval Research East Pacific Rise Natural Laboratory. In the foreground is the Siqueiros transform fault (a first-order discontinuity) and the 8°20'N seamount chain; the fast-spreading East Pacific Rise and the 9°N overlapping spreading centers are in the middle; and the Clipperton Transform Fault is in the background. Notice the numerous seamount chains. The actual image is approximately 300 by 300 kilometers, viewed toward the northeast. (This image is based on data from expeditions funded by the US Office of Naval Research.)

S.P. Miller/UCSB

segmentation of mid-ocean ridges. First-order segments are generally hundreds of kilometers long, persist for millions to tens of millions of years, and are bounded by relatively permanent, rigid, plate-transform faults (first-order discontinuities). A first-order segment is usually divided into several second-order segments. These segments are shorter, survive for less than several million years, and are bounded by nonrigid, second-order discontinuities that can migrate along the length of the ridge. Thus second-order segments lengthen, shorten, and even disappear. There are third- and fourth-order segments (and discontinuities bounding them) that are increasingly short, short lived, and peripatetic. For example, fourth-order segments, approximately 10 kilometers long, may survive as distinct structures for only 100 to 10,000 years. The longevity of individual segments and associated cycles of volcanic/hydrothermal/tectonic activity must influence the distribution and survival of exotic faunal communities that flourish at mid-ocean ridge hot springs (see The Biology of Deep Sea Vents and Seeps, page 75). For example, a violent eruption on the East Pacific Rise near 9°50′N in March and April 1991 wiped out a large community of tube worms, mussels, and other benthic fauna (and might have done the same to divers in the submersible DSV *Alvin* who arrived only hours to days later!).

Is the architecture of the global mid-ocean ridge system really so orderly, or is this concept of a "segmentation hierarchy" merely a human construct?

Thus, amidst frequent volcanic eruptions and seafloor temblors, there seems to be an orderly spatial and temporal pattern to magmatic, volcanic, hydrothermal, and tectonic processes associated with the birth of new ocean floor. Is the architecture of the global mid-ocean ridge system really so orderly, or is this concept of a "segmentation hierarchy" merely a human construct? To be sure, this model may be vastly modified or even abandoned, as new information and new minds contribute to the ongoing debate. In his superb book, *The Principles of Physical Geology*, Arthur Holmes recalled the words of Alfred North Whitehead, which are still appropriate to our exploration of the Mid-Ocean Ridge today: "There can be no living science unless there is a widespread instinctive conviction in the existence of an *Order of Things* and, in particular, of an *Order of Nature*."

Ken C. Macdonald is Professor of Marine Geophysics at the University of California, Santa Barbara, and a member of the Woods Hole Oceanographic Institution Corporation. Over the last 20 years he has focused on the tectonics on mid-ocean ridges and has been fortunate enough to participate in some of the first explorations of the ridge, using swath-mapping systems, remotely controlled vehicles, and submersibles.

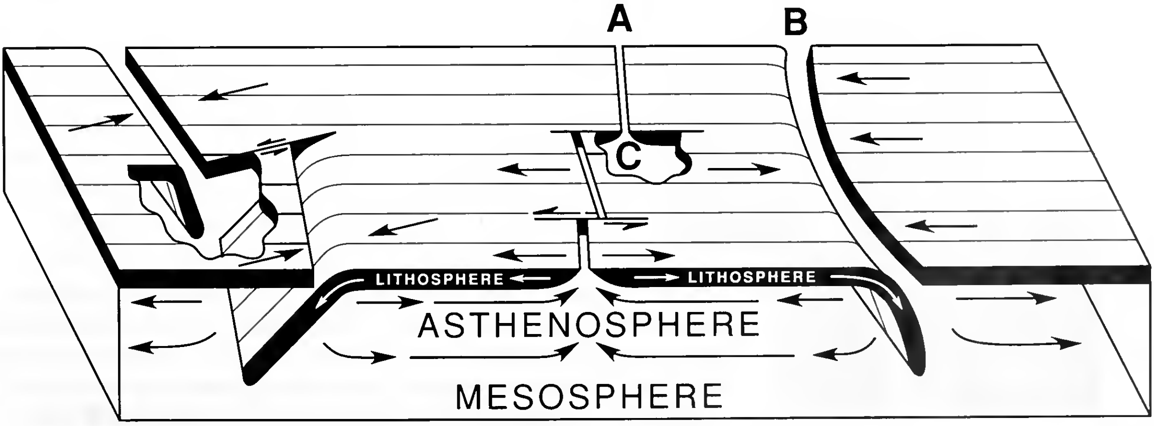
The Segmented Mid-Atlantic Ridge

Jian Lin

Nearly three decades ago, in 1964, an *Oceanus* article by Richard M. Pratt described an exciting R/V *Chain* expedition to the Mid-Atlantic Ridge. On echo-sounding profiles across the ridge crest some 2,500 meters beneath the ocean surface, Pratt and his colleagues saw familiar mountains and valleys on the ocean floor. But a peculiar feature caught his eye: The rift valley in one area had shifted laterally for tens of kilometers. Pratt, a Woods Hole Oceanographic Institution (WHOI) scientist, speculated in his article (Volume 11, Number 2, December 1964) that the shift of the ridge may have been caused by a "transverse" feature of unknown origin.

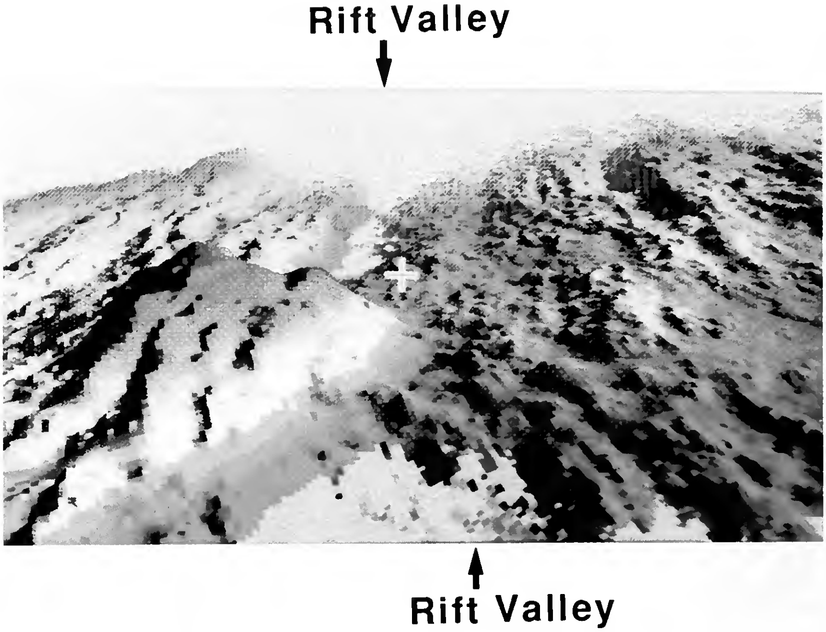
In the early 1960s, H. William Menard and Bruce Heezen discovered similar features on other parts of the Mid-Atlantic Ridge and on the East Pacific Rise. In 1965, J. Tuzo Wilson identified these transverse features as "transform faults:" boundaries formed perpendicular to the length of the Ridge. The anomalous transverse feature noted by Pratt is now known as the Atlantis Transform Fault. It is just one of many that offset the 60,000-kilometer-long global mid-ocean ridge system. The discovery and recognition of transform faults played an essential role in the development of the plate-tectonic theory in the late 1960s and early 1970s.

In plate-tectonic theory, Earth's outer 100 to 250 kilometers, called the lithosphere, breaks up into a set of rigid plates that move with respect to each other. The lithospheric plates, such as those of North America and Africa, drift over underlying, less rigid asthenosphere,



According to the theory of plate tectonics, Earth's lithosphere is broken into plates that move with respect to each other. The plates originate at mid-ocean ridges (A), subduct into the underlying asthenosphere at trenches (B), and slide by each other at transform faults (C).

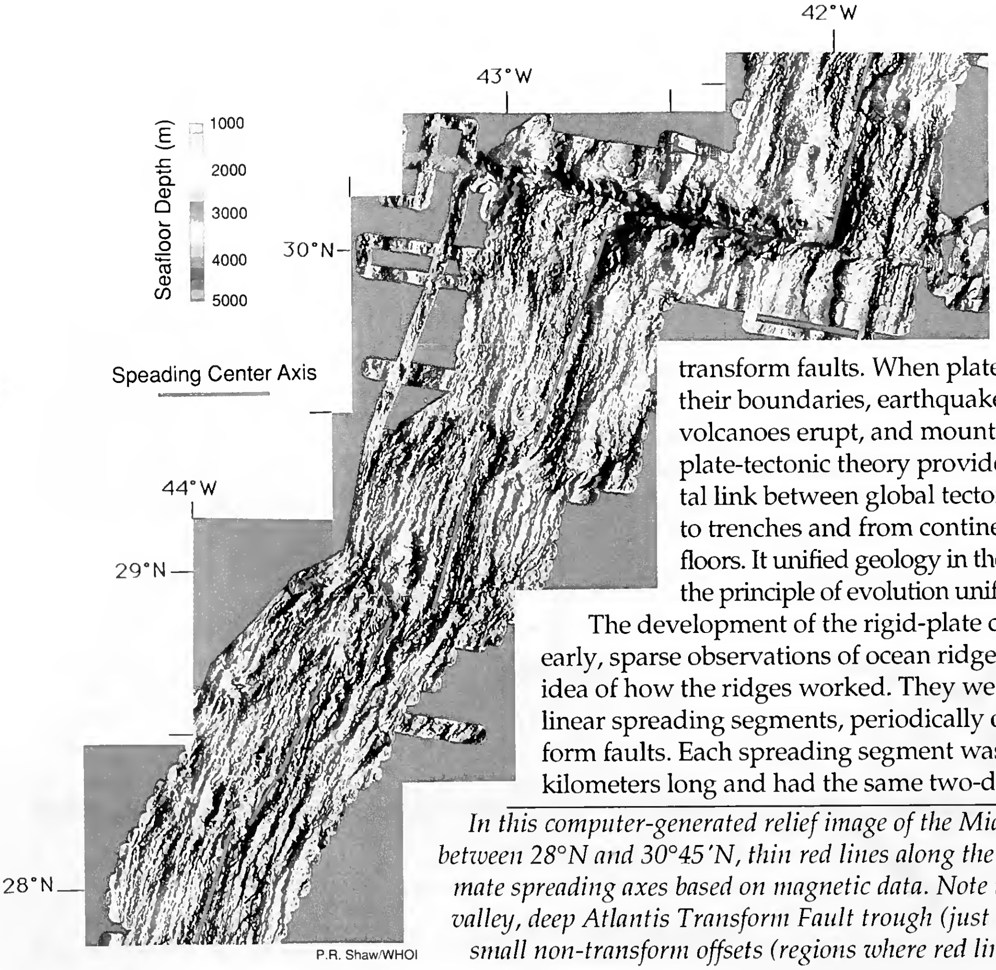
A computer-generated relief image of the rift valley of the Mid-Atlantic Ridge near 29°50′N (view towards the south). The rift valley is 20 to 30 kilometers wide and a few kilometers deep. The inner rift valley is covered by elongated volcanic hills and circular volcanoes. Large steplike normal faults run along the ridge axis, here shown at three-times vertical exaggeration.



Brian Tucholke/WHOI and Tom Reed/University of Hawaii

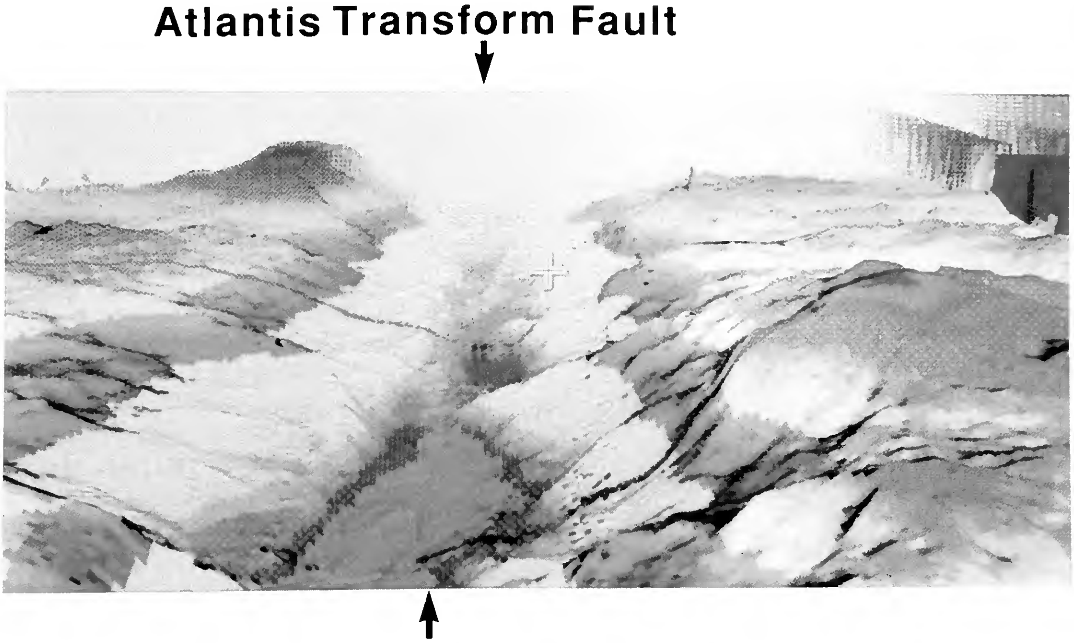
much like icebergs floating in the ocean. Plates are created at mid-ocean ridges, are consumed at subduction trenches, and slide by each other along transform faults. When plates interact at their boundaries, earthquakes strike, volcanoes erupt, and mountains grow. The plate-tectonic theory provided a fundamental link between global tectonics, from ridges to trenches and from continents to ocean floors. It unified geology in the same way that the principle of evolution unified biology.

The development of the rigid-plate concept and early, sparse observations of ocean ridges led to a simple idea of how the ridges worked. They were thought to be linear spreading segments, periodically offset by transform faults. Each spreading segment was hundreds of kilometers long and had the same two-dimensional



P.R. Shaw/WHOI

In this computer-generated relief image of the Mid-Atlantic Ridge between 28°N and 30°45′N, thin red lines along the rift valley approximate spreading axes based on magnetic data. Note the prominent rift valley, deep Atlantis Transform Fault trough (just below 43°W), and small non-transform offsets (regions where red lines do not meet).



Brian Tucholke/WHOI and Tom Reed/University of Hawaii

This relief image of the Atlantis Transform Fault is viewed toward the east. The deepest parts of the transform valley are more than six kilometers below sea level. The vertical relief from the top to the bottom of the valley is more than four kilometers, and is shown at three-times vertical exaggeration. The red vertical bars on the top-right corner are an imaging artifact.

cross-sectional view along its strike.

Today, two decades after the birth of plate-tectonic theory, this view is rapidly changing. This article begins with a report on a recent expedition to the Mid-Atlantic Ridge, where Pratt visited 30 years ago. Using this and other recent studies as background, I will review current ideas on seafloor spreading at mid-ocean ridges and explain how the earlier two-dimensional ridge model must be expanded to allow for variations along strikes and with time.

The Mid-Atlantic Ridge

The huge Mid-Atlantic Ridge (MAR) mountain range runs down the middle of the Atlantic Ocean from Iceland in the north to near Antarctica in the south. Since it was first studied in 1873 by the British survey ship HMS *Challenger*, the ridge has been the focus of intense scientific curiosity. Perhaps the most detailed survey was Project FAMOUS (French-American Mid-Ocean Ridge Undersea Study) of the early 1970s, in which oceanographers investigated a 100-kilometer-long stretch of the rift valley near 37°N.

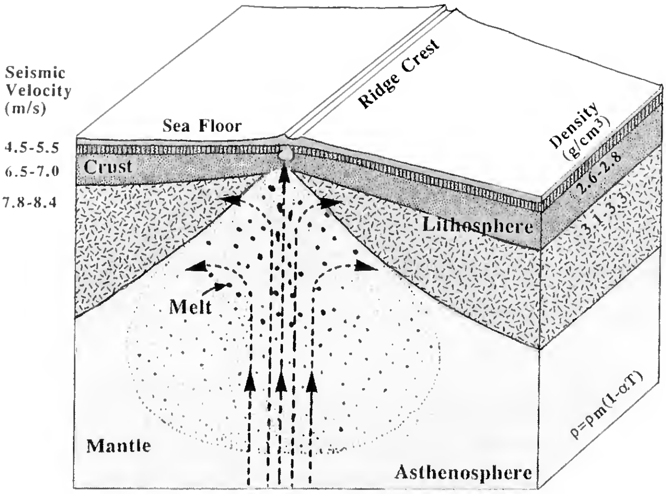
Early exploration of the Mid-Atlantic Ridge only identified transform faults of very large offsets. From observations of Earth's magnetic field, however, oceanographers in the early 1980s proposed that the MAR was composed of a string of about 50-kilometer-long spreading segments separated by small "zero-offset" transform faults.

To look closely at these "zero-offset" features, in 1988 and 1989, scientists from WHOI and the University of Washington examined a 900-kilometer-long stretch of the ridge. Our survey, which started near the Atlantis Transform Fault, included detailed ocean floor mapping and precise measurements of Earth's gravitational and magnetic fields. Our sonar sounding system, called Sea Beam, was much more capable than that used by Pratt in the early 1960s: It can map a 2-kilometer-wide swath of the seafloor in a single pulse. Never before had oceanographers seen such a long stretch of a slow-spreading ridge with such high-resolution sonar.

With Sea Beam sending back numerous ocean-floor images, we soon recognized many familiar features. The central rift valley, which is 20 to 30 kilometers wide and a few kilometers deep, runs nicely along the ridge crest. Volcanic hills and circular volcanoes—each tens to a few hundreds meters tall—blanket the rift valley's inner floor. The crust cracks along steep steps of normal faults, some of which run along the ridge for tens of kilometers.

We were intrigued by the immense size of the trough inside the Atlantis Transform Fault. This fault offsets the ridge axis by almost 70 kilometers, and the deepest parts of its floor are more than six kilometers below sea level. Its vertical relief from top to bottom is more than four kilometers, or twice the depth of the Grand Canyon.

Further down the ridge axis, however, we were totally surprised: The "zero-offset" features that we were searching for were not transform faults after all. The ridge breaks into many 20- to 80-kilometer-long spreading segments, but these segments often overlap one another at "nontransform" offsets. Unlike a transform fault, a nontransform offset does not contain a trough perpendicular to the ridge axis. By themselves, these nontransform offsets constitute a new type of unstable, transitory plate boundary.



Below a ridge, the mantle of the asthenosphere (orange) rises to fill the gap between two separating lithospheric plates (blue). As they rise, some rocks melt to form magmas. The buoyant magmas or melts then surge into a magma chamber (red). Material in the magma chamber further segregates into various layers of the oceanic crust (dark green). The crust is less dense than the mantle. In the mantle, density decreases with increasing temperature and with depth.

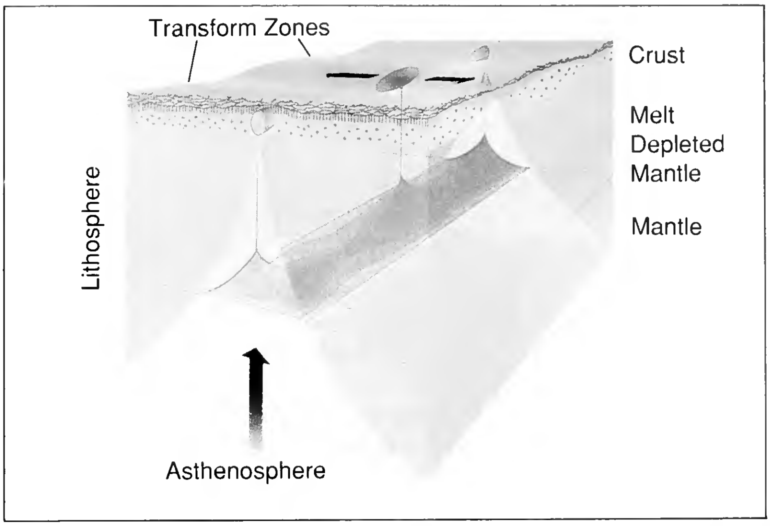
Why do the MAR volcanic chains break into short spreading segments? Is this phenomenon related to deep structures of the earth beneath the spreading axis? To answer these questions, we must first examine how oceanic crust is generated.

The Origin of Oceanic Crust

The mantle beneath lithospheric plates, known as the asthenosphere, creeps plastically because its temperature stays near its melting point. Below a ridge, however, the asthenosphere rises to fill the gap between two separating plates. While ascending, some mantle rocks fuse to form basaltic magmas, or melts, and the buoyant magmas float to the top of the mantle to form oceanic crust. Meanwhile, the unmelted mantle residual accretes to the oceanic lithosphere bottom. From studying the chemical composition of rocks dredged from the ocean floor, oceanographers have determined that melts are produced at depths of 20 to 80 kilometers and at temperatures of 1,150° to 1,400°C. Theoretical models further suggest that the rising asthenosphere reaches its maximum velocity in a partial melting zone, inside which the mantle has its minimum density and viscosity.

Buoyant melts from all depths surge into a magma chamber at the base of the crust. Inside the chamber, melts further separate into layers according to their densities. The least-dense lava erupts to form volcanoes on the ocean floor. The most-dense, called gabbro, accumulates at the chamber floor to form the lower crust. Between these two layers lies a layer of vertical dikes, narrow slabs of cooled melt that have risen to fill fissures in the crust. The end product of the melt segregation process, therefore, is a stable layering of light crust (its density is expressed as 2.5 to 2.8 grams per cubic centimeter) overlying heavy mantle (3.1 to 3.3 grams per cubic centimeter).

On the other hand, the partially molten asthenosphere under the lithospheric plates is not stable. This is because its density and viscosity are less than that of the overlying lithosphere, a situation analogous to a layer of high-density fluid overlying low density fluid. Laboratory experiments show that if the density and viscosity contrasts between two fluids are great enough, the less-dense fluid will rise and protrude into the upper layer, in the form of regularly spaced diapirs (see Box, page 19). In the mid-1980s, oceanographers proposed that diapirs may occur below mid-ocean ridges. They reasoned that the partial melting zone of the asthenosphere can develop gravitational instability, inducing regularly spaced diapirs of melts. The melt diapirs then percolate toward the surface to form discrete magma chambers that feed individual spreading segments.



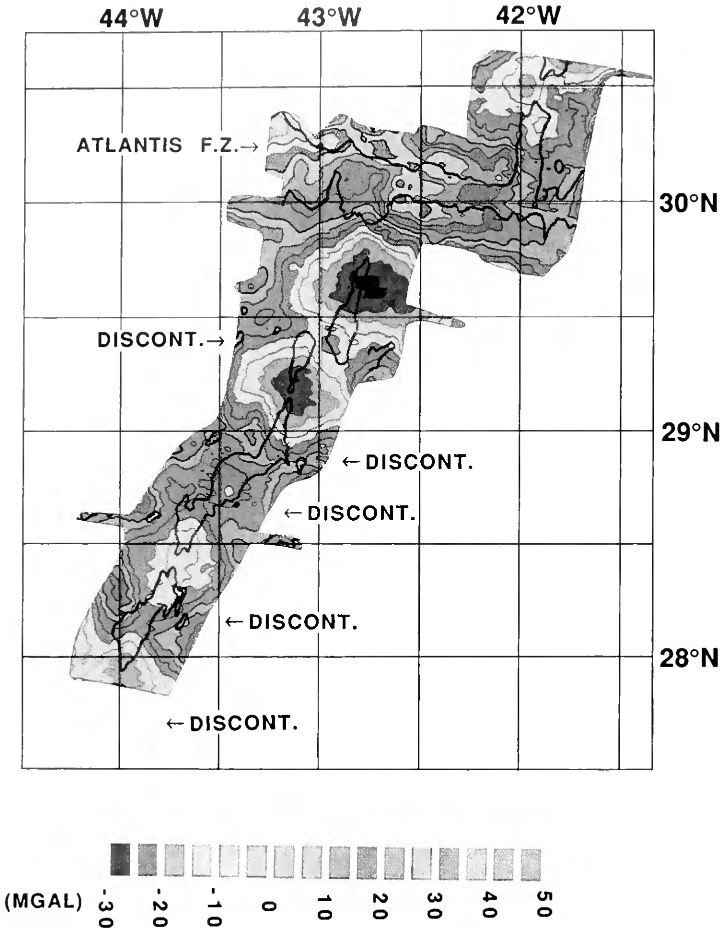
In this model of magma diapirs beneath a ridge, the partially molten asthenosphere (red) is not stable under the cold lithosphere (green). The gravitational instability of this partial melting zone will induce regularly spaced diapirs of magmas. The magma diapirs then percolate toward the surface to form discrete spreading segments.

Such diapir-induced segmentation models predict that ocean-floor topography should be shallowest at segment centers and deepest at segment boundaries. The models also predict that crustal thickness, which is a measure of melt production, should be greatest at segment centers and decrease toward segment edges. The first prediction was confirmed readily by detailed ridge-crest topography, including that obtained in our survey. To confirm the second prediction, however, techniques for probing into the earth are required. Two commonly used techniques are the studies of Earth's gravitational field and of seismic waves.

Gravity, Seismic, and Faulting Evidence

Geophysicists often use sensitive gravity meters to probe unseen material below ground. To examine the crust and mantle below spreading segments, we must first employ modeling to remove the gravitational effects of seawater and a model crust. The leftover signal, called the mantle Bouguer anomaly, should then reveal information about the mantle. Using this technique, researchers have detected an unusual "bull's-eye" shaped gravity low over a spreading segment in the South Atlantic. During our 1988 to 1989 survey, we found a string of such bull's-eyes in the North Atlantic.

In both the North and South Atlantic, most of the circular regions of gravity lows are centered near the shallow middle points of the spreading segments. In contrast, large positive values are located over the Atlantis Transform Fault and the nontransform offsets. There are two possible explanations for this gravity pattern. The first is that the crust, which is less dense than the mantle, decreases in thickness from segment centers to segment edges. The second is that the mantle beneath the segment mid-points is of unusually low density, most likely due to a combined effect of high temperature, the presence of limited melts, and density changes in the melted mantle. Both possibilities are consistent with the concept of diapir-induced segmentation. Similar gravity patterns have now been observed in other sections of the Mid-Atlantic Ridge, although substantial local variations exist.



Gravity data reveals gravity lows beneath the spreading segments of the North Mid-Atlantic Ridge. This pattern may be caused by thicker crust or less dense mantle beneath the midpoints of the spreading segments.

The study of seismic waves provides another powerful tool for probing the deep structure of ridges. In the 1980s, seismologists studied a half-dozen large-offset transform faults and a few nontransform offsets at the Mid-Atlantic Ridge. Their results generally confirmed that the oceanic crust is abnormally thin beneath segment boundaries, especially under large-offset transform faults. The gravity and seismic data together, therefore, confirmed that the punctuation of the ridge topography by offset features is indeed indicative of deep-seated, along-axis periodicity in the melt supply.

In addition to the gravity and seismic data, imprints of segmentation were found in the pattern of tectonic faulting and earthquakes on the ocean floor. Based on deep-sea observations from submersibles, researchers in the 1970s and 1980s determined that lithospheric plates do not spread steadily; instead, they move in a "stop-and-go" fashion, with long periods of tectonic stretching interrupted by short periods of volcanic construction. During prolonged periods of stretching, tectonic faults developed at the Mid-Atlantic Ridge. Recently we observed that tectonic faults are quite linear within spreading segments, indicating that the crust of each segment breaks in parallel fault arrays. In contrast, oblique faults are common near segment offsets, suggesting that the tectonic-volcanic cycles of neighboring segments are not synchronous with each other. The major faults of each spreading segment are seismically active, as indicated by large numbers of moderate-sized modern earthquakes (See Mid-Ocean Ridge Seismicity, page 60).

The Spreading-Rate Factor

The overall magma supply, as well as the style of segmentation, vary dramatically from slow- to fast-spreading ridges. From early, sparse observations, oceanographers noted that the gross axial topography of a mid-ocean ridge depends on the plate-spreading rate. The crest of the slow-spreading Mid-Atlantic Ridge, with full spreading rates of about 30 millimeters per year, is rugged, with faulted crust and a median valley. In contrast, the axis of the fast-spreading East Pacific Rise, with full rates of 60 to 170 millimeters per year, is much smoother, and is defined by an elevated crust a few hundred meters high. Theoretical models suggest that the rift valley of a slow-spreading ridge may result from thinning of the lithospheric plate similar to the "necking"of a plastic beam under tension. For fast-spreading ridges, topography is caused mainly by the upward push of the buoyant magma chamber.

The overall magma supply, as well as the style of segmentation, vary dramatically from slow- to fast-spreading ridges.

There are other major differences between slow- and fast-spreading ridges. Geophysicists have imaged the top of magma chambers at the fast-spreading East Pacific Rise and the intermediately fast-spreading Juan de Fuca Ridge and the Valu Fa Ridge of the Lau Basin, but no comparable structure was found at the slow-spreading Mid-Atlantic Ridge. The lithospheric plate at the MAR has a 3- to 10-kilometer-thick brittle lid in which moderate to large earthquakes can nucleate; at the fast-spreading ridges, the brittle lid is thinner than 2 kilometers, and moderate and large earthquakes are essentially absent. Other differences include gravity and bathymetry, which vary substantially along the slow-spreading ridges, but only slightly along intermediate- and fast-spreading ridges. There is mounting evidence, then, that overall magma supply is greater at fast-spreading ridges than slow ones.

Despite major differences in magma supply, both fast- and slow-spreading ridges break into spreading segments. Various types of ridge-crest offsets have been found at the East Pacific Rise, including transform faults, overlapping spreading centers, and deviations from axial lineality. Chemical-composition studies of seafloor rocks indicate that even small ridge offsets mark boundaries between two distinctive magma-supply units.

Global variability in ridge magma supply is, in some ways, analogous to global variability in climate. The mean air temperature (or overall climate) of Earth's polar regions is substantially lower than that of the equatorial oceans. In both the cold polar and warm equatorial regions, however, the temperature varies from one local area to another. Similarly, the mean magma supply at the slow-spreading Mid-Atlantic Ridge is lower than that of the fast-spreading East Pacific Rise. But in both ridges the magma supply varies locally from one segment to another, and from one part of the segment to another part.

The geophysical evidence discussed above and the present segmentation theories illustrate only the gross structure of ridge segmentation on length scales of a few to a few hundred kilometers. Smaller, shorter-lived segmentation features, which are beyond the detectabilitly of current instruments, are certainly possible. To further understand and eventually predict the global pattern of magma supply and ridge segmentation, we must develop better instruments, expand the data base, and formulate new theories.

The Future of Ridge-Magma Dynamics

In the past decade, theories of ridge-magma dynamics have advanced rapidly in conjunction with new oceanographic instruments and discoveries of exciting ridge features. As a result, we have a better understanding of how two-thirds of Earth's solid surface—the oceanic crust—was created.

Why do slow-spreading ridges differ dramatically from fast ones? How do spreading segments evolve in time over tens of millions of years?

The 1990s promise even greater understanding of ridge dynamics, a system once described by the late Bruce Heezen (see the Profile on page 100) as "the wound that never heals." Oceanographers have designed and are implementing an international decade-long program called RIDGE (Ridge Inter-Disciplinary Global Experiments; see the article on page 21) to study the interactions among complex ridge processes from magma dynamics to earthquakes, water column chemistry, and biology. In particular, the RIDGE program has designed specific oceanographic experiments to continuously explore the origin of mid-ocean ridge segments, posing such questions as, Why do slow-spreading ridges differ dramatically from fast ones, but both break into segments? How do spreading segments evolve in time over tens of millions of years? Why are transform faults longer and stable while nontransform offsets are shorter and transitory? Does segmentation in the volcanic ridge correlate with changes in ridge-crest hydrothermal vents, or even with the biological population at the ridge crest? These and many other questions await exploration in a new era of oceanographic studies.

Acknowledgments: The research reported in this article was supported by the National Science Foundation and the Office of Naval Research. G. Michael Purdy and Hans Schouten of WHOI, and J.-C. Sempere of the University of Washington were the leaders of the 1988-1989 Mid-Atlantic Ridge expedition. Thanks to Brian Tucholke and Tom Reed for permission to use the previously unpublished images at the top of page 12 and on page 13 and to P.R. Shaw for permission to use the previously unpublished image at bottom of page 12. The figure on page 11 is after Isacks, Oliver, and Sykes, 1968; that on page 14 is modified after RIDGE Steering Committee, 1989; on page 15 after Whitehead, Dick, and Schouten, 1985, and Dick, 1989; and on page 16 after Lin, Purdy, Schouten, Sempere, and Zervas, 1990.

Jian Lin is an Assistant Scientist at the Department of Geology and Geophysics, Woods Hole Oceanographic Institution. He was born when H. William Menard and Bruce Heezen discovered the first transform faults in the world's ocean basins. Today he enjoys the opportunity to further develop and challenge aspects of the great theory of plate tectonics. His research activity ranges from oceanographic measurements at sea to building quantitative ridge models on super computers. When not exploring undersea volcanoes, he studies earthquake faults in southern California and their threats to metropolitan areas. He is an Associate Editor of the Journal of Geophysical Research.

MODELING RIDGE SEGMENTATION...

ALL MID-OCEAN RIDGES seem to be segmented. In many places the ridges consist of a series of relatively straight segments divided by fracture zones. In other places they are divided by overlapping spreading centers. The spreading plates display a pattern of fairly orderly cellular structure, with spacing between the cells of approximately 30 to 80 kilometers. The spacing varies with the speed of spreading of the ridge. Those studying the ridge had often suggested that ridge segmentation was due to thermal contraction of the cooling plates as they spread apart.

In 1984 and 1985 we, along with Henry Dick, hypothesized something quite different—that the segmentation results from forces produced by hot mantle material rising under spreading centers and liberating melt. We knew that a layer of material with either enhanced melt or a higher temperature tends to develop a lower density, and there was reason to believe that it would also have a lower viscosity than the surrounding regions. We also knew that such a region is prone to develop fluid-dynamic instabilities. One example is called Rayleigh-Taylor instability. This happens when a layer of lower-density fluid underlies a layer of higher-density fluid. The interface between the two fluids develops undulations so that the lower density fluid can float upward through the denser fluid.

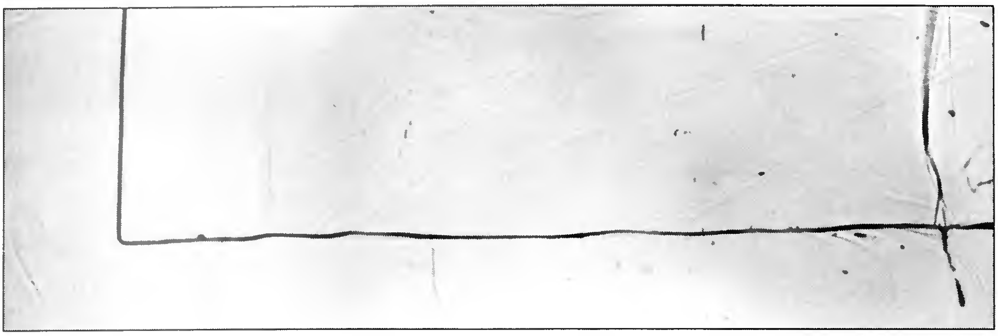
To demonstrate this we conducted some simple experiments in which a water-glycerine mixture was quickly injected into glycerine with a hypodermic syringe along a horizontal line. Although this line gradually rises because the water-glycerine mixture is less dense than the glycerine, an instability also develops (see the photos overleaf) and leads to the formation of semi-spherical pockets. It is reasonable to expect that a linear region of partially molten mantle in the earth will behave in a similar manner and will lead to fairly regularly spaced protrusions from which the melt will ascend to form magma chambers. We suggested this example as a possible model of what might be happening under oceanic ridges. To be specific, the idea was that segmentation was produced by buoyancy-induced instability (which ultimately leads to volcanism) rather than by thermal contraction of the cold plates.

Clearly, the model was too crude to apply to ridges in detail. However, at that time numerical models of spreading ridges were always taken to be two dimensional for simplicity and ignored segmentation. Unfortunately, if the segmentation is a process that enhances upwelling the two dimensional models would be incomplete. Recently, observations indicate that segmentation is indeed not just a surface feature of cooling plates but extends "deep" (tens of kilometers) under ridges. In addition, recent three-dimensional numerical models have been developed with flows that do break up into segments. Thus the crude idea that segmentation has deep origins seems to be borne out even though the detailed mechanics of the break up may be different in detail than our Rayleigh-Taylor models.

(continued on next page)

HANS SCHOUTEN AND JACK WHITEHEAD
WOODS HOLE OCEANOGRAPHIC INSTITUTION

...A Possible Mechanism



These two photographs were taken 30 seconds apart. In the upper photograph, the injecting needle was dragged from right to left. The gravitational instability of a horizontal line of water/ glycerine mixture in a bath of pure glycerine is shown below.

RIDGE:

Cooperative Studies of Mid-Ocean Ridges

Donna Blackman and Trileigh Stroh

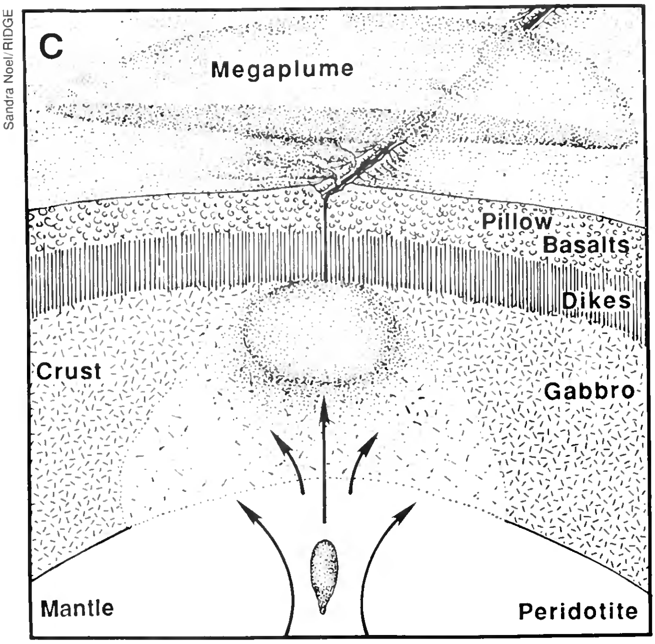
The Ridge Inter-Disciplinary Global Experiments (RIDGE) Initiative is a cooperative effort to study the mid-ocean ridges as a dynamic global system of focused energy flow from Earth's interior outward. The National Science Foundation supports the RIDGE Initiative, part of the US Global Change Research Program, through both its Global Change and Ocean Sciences divisions.

The program's key goals include:

- characterizing the global ridge structure,
- understanding crustal accretion and upper-mantle dynamics,
- charting the variability over time of volcanic and hydrothermal systems,
- mapping biological colonization and evolution at ridge crests,
- determining the properties of multiphase materials at ridge crests, and
- developing technology for ridge-crest experimentation.

By characterizing the ridge structure, researchers intend to provide a global perspective for the mechanics of plate separation, variable lava types, circulation of hot seawater, and biological characteristic of individual ridge sections. Swath bathymetry, sidescan sonar imagery, and widely spaced geologic and hydrologic samples will be used to develop large-scale maps of the ridge system. This will provide a basis for estimating the total flux of materials through ridge crests (hydrothermal input to the oceans, for example), as well as for making site-location decisions for more detailed study.

Crustal accretion results from convective upwelling of the mantle beneath a spreading center (see Onions and Leaks...,page 36). Basaltic melt segregates from the rising, decompressing mantle, and is delivered to a magma chamber at the ridge axis where it solidifies to form oceanic crust. Understanding this process requires a variety of information: the mantle's flow geometry, temperature, and composition beneath mid-ocean ridges; the nature of the subaxial magma chamber and the mode of volcanic extrusion on the seafloor; and the role of hydrothermal circulation in cooling the crust. Constraints on the upper-mantle structure are obtained from computer modeling and seismic- and electromagnetic-imaging studies that use large arrays of seafloor instruments. A magma chamber's size and shape are revealed by geophysical measurements including seismic refraction/reflection and gravity data; geochemical studies of rock samples from the ridge axes help determine the



Basaltic melt arriving from the mantle either reestablishes or replenishes a crustal magma chamber that solidifies to produce gabbro, diabase dikes, or basaltic lava flows. The geometry, longevity, and circulation of a subaxial magma chamber are topics of active inquiry.

history of the basaltic melt as it separates from the mantle and cools within the crust. Mapping the hydrothermal vent fields at ridge axes and the associated faulting of the seafloor illustrates the seawater-circulation pattern in the upper crust.

Although seafloor spreading is continuous on a geologic time scale, individual earthquakes, eruptions, and venting episodes affect only a short length of the ridge for a short time. Neither the spatial nor the temporal scales of specific ridge-axis events are currently known in detail, but both play critical roles in shaping seafloor morphology, local seawater properties, and biological diversity. Two important means for studying temporal variability in ridge processes are event detection and response and long-term deployment of instruments in a seafloor observatory. When a ridge-crest volcanic event, such as an earthquake swarm, is detected, airborne and shipboard instruments can be deployed to chart the activity pattern and map any new eruptions. Long-term monitoring can reveal linkages among complex, interrelated physical, geological, and biological processes at ridges. Diverse coordinated measurements made at permanent ridge-crest observatories will be essential in studying these relationships and developing improved theoretical models for ridge processes.

Mapping biological communities along mid-ocean ridge crests is fundamental for understanding the thermal and chemical requirements of these unique ecosystems. Sampling and laboratory studies will reveal the physiological and genetic requirements for living without sunlight at water depths exceeding 2,000 meters. Integrating biological and chemical studies will elucidate the dependence of different organisms on the temperatures and the chemical characteristics of hydrothermal vents. Determining a biological community's response time to changes in volcanic and hydrothermal activities will be an important aspect of this research.

Multiphase materials are present in virtually every part of the mid-ocean ridge system, from the upwelling mantle that contains basaltic melt, through the magma chamber where molten rock is crystallized, to the hydrothermal systems in which both liquid and gas aqueous solutions are likely to exist. Laboratory experiments on silicate aggregates under various temperature and pressure conditions are needed to define the behavior of the ascending mantle (viscosity, melt content, and composition). The chemical properties and crystallization sequences of mid-ocean ridge basalts must be determined at pressures appropriate for a crustal magma chamber. Modeling the effects of combined vapor and fluid phases in hydrothermal circulation should aid in understanding interactions between the cooling crust and seawater.

Developing extended-deployment seafloor instrumentation that can accurately measure the changing conditions at the ridge crest is an integral part of many of the above research topics. Examples of new technological advances include chemical sensors that detect minute changes in trace elements and compounds (such as hydrogen sulfide, methane, iron, manganese, and oxygen), geodetic instruments to measure uplift and tilt of volcano flanks, broadband ocean-bottom seismometers, and deep-water temperature and chemical profiling systems. Systems that can deploy and manipulate these sensitive instruments will also be required and may take the form of remotely operated seafloor vehicles or manned submersibles.

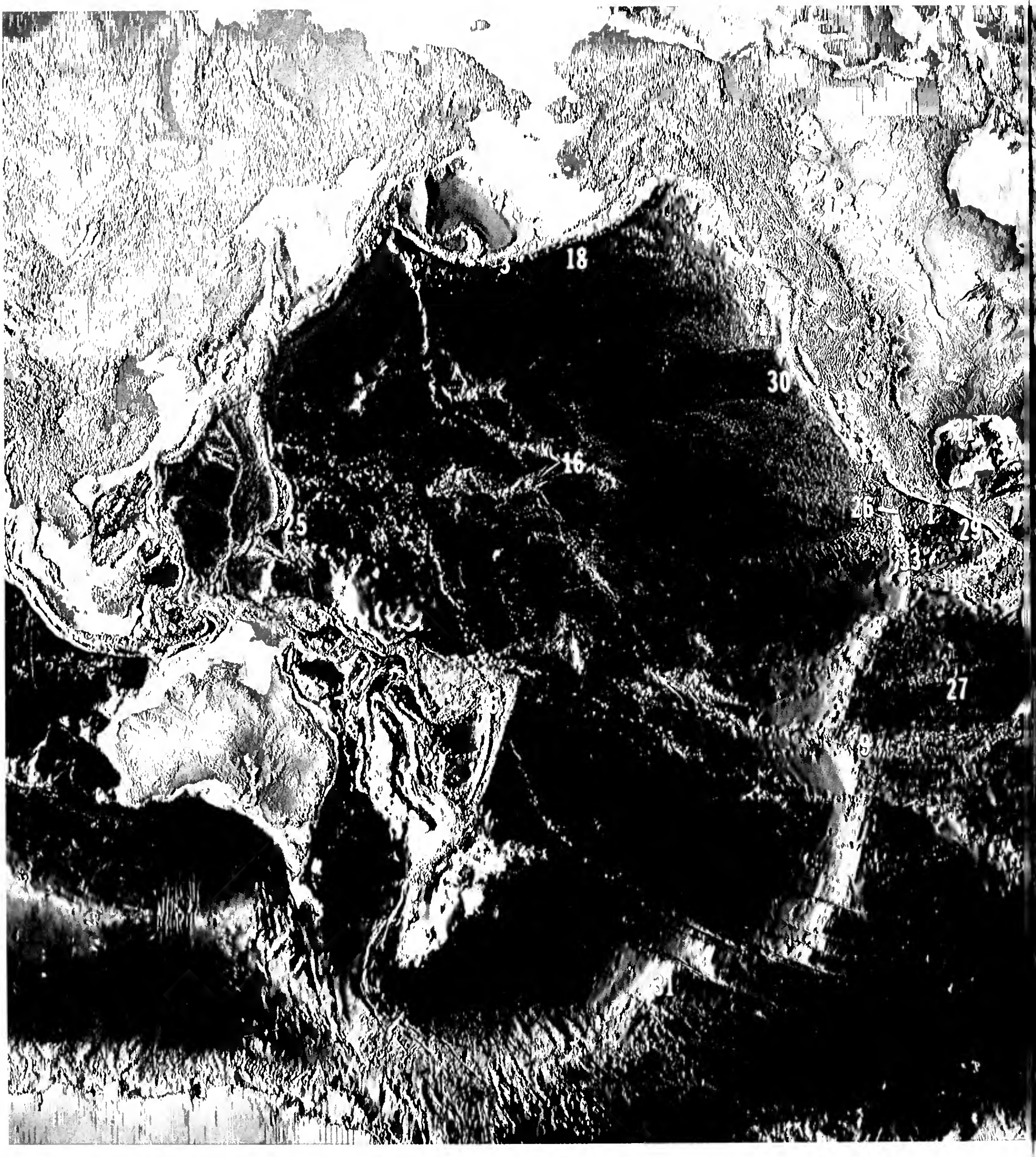
Donna Blackman is a post-doctoral research associate at the University of Washington studying mid-ocean ridge processes. At the time of writing, she is assisting with several projects at the RIDGE office.

Trileigh Stroh has been the RIDGE Coordinator and Editor of RIDGE Events *newsletter since 1988. In 1992 she will instead serve as Executive Administrator for the InterRidge office.*

InterRidge

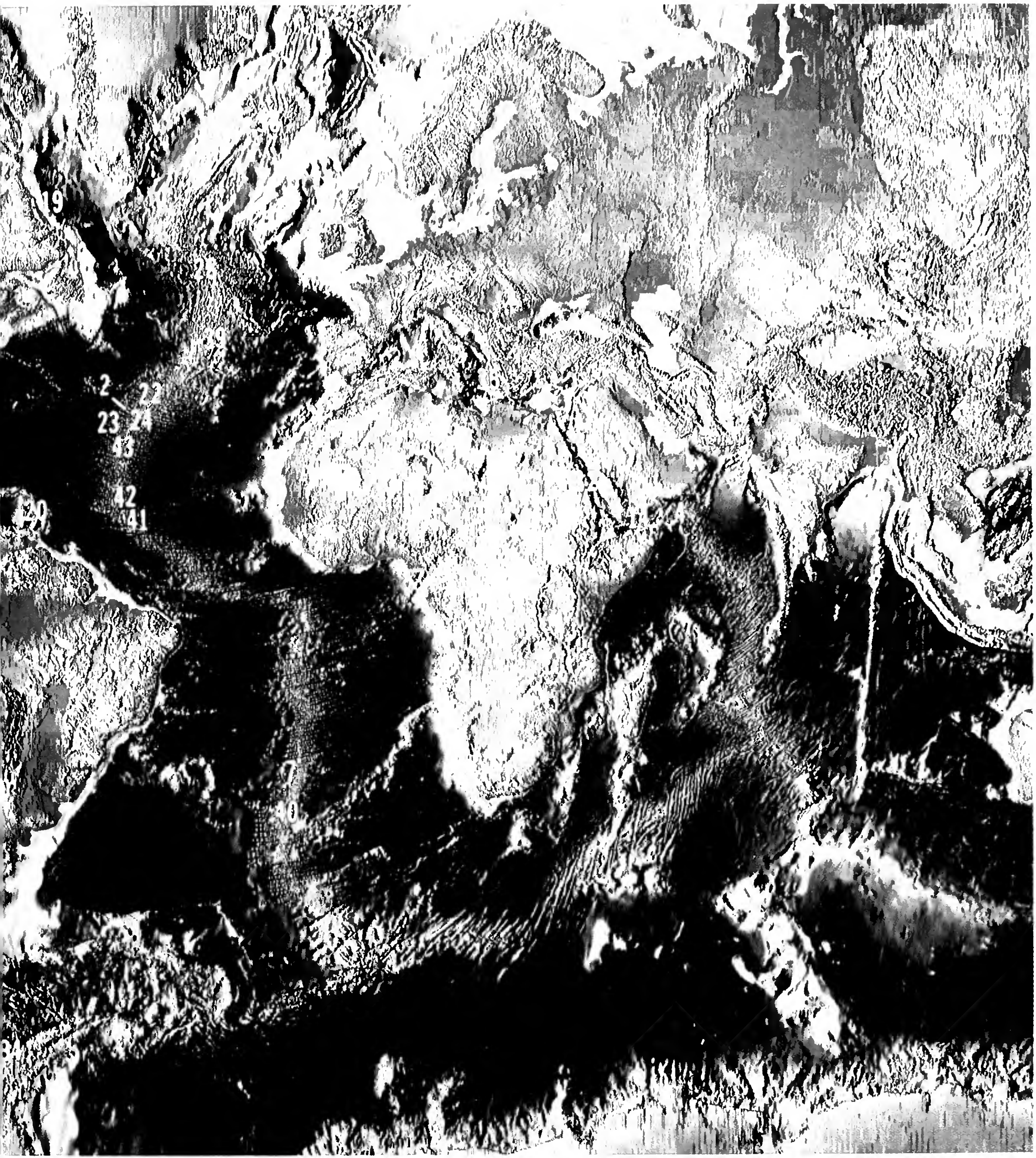
INTERRIDGE IS an international effort to coordinate and expand ridge-crest research. Representatives from scientific communities in Australia, Canada, France, Germany, Iceland, Japan, Norway, Portugal, UK, USA, and USSR have been meeting since 1989 to establish means for effective communication, program coordination, and data exchange among various national programs for mid-ocean ridge research. Ratification of an InterRidge program plan and establishment of an InterRidge office are expected in 1992. The Program Plan will propose three primary program elements: global studies, observatory development, and regional dynamics studies.

A recent response to events southwest of Iceland showed that international cooperation can produce insights into ridge-crest processes and their transient oceanographic signals. In November 1990, Icelandic scientists reported a series of earthquakes on the Reykjanes Ridge. Their report was followed by deployment of sonobuoys and expendable bathythermographs from a US Navy P3 aircraft. British, Icelandic, and American scientists used an Icelandic research ship to conduct several days of on-site mapping and sampling. Using the combined assets of several countries enhances the ability to quickly assemble a team of investigators at an eruption site, providing valuable opportunities to document ongoing ridge-crest activity.



Earth's Rifts, Ridges & Rises: *Areas of interest referred to within this issue*

1-Albatross Plateau
2-Atlantis Transform Fault
3-Aleutian Trench
4-Carlsberg Ridge
5-Chile Rise
6-Clipperton Fracture
7-Cox Transform Fault
8-East Pacific Rise
9-Easter Island
10-Galapagos Rift
11-Gorda Ridge
12-Guaymas Basin
13-Guaymas Transform Ridge
14-Gulf of Aden
15-Gulf of California
16-Hawaiian Islands
17-Juan de Fuca Ridge
18-Kula Rise
19-Labrador Sea
20-Lesser Antilles Arc
21-Louisiana Slope



This computer-generated map is courtesy of Peter W. Sloss, NOAA National Geophysical Data Center, Boulder, CO

22-AMAR Area
FAMOUS Area
23-TAG Area
24-MARK Area
25-Mariana Trench
26-Mathematician Rise
27-Mendoza Rise
28-Mid-Atlantic Ridge
29-Middle America Trench
30-Monterey Canyon
31-Pacific-Antarctic Ridge
32-Red Sea
33-Siqueiros Transform Fault
34-South Shetland Arc
35-Troodos Ophiolite
36-Valu Fa Ridge
37-West Florida Escarpment
38-Iceland
39-Azores
40-Tristan da Cunha
41-Vema Transform
42-15°20' Transform
43-Kane Transform

Ridges and Rises: A Global View

Peter Lonsdale and Chris Small

Slow spreading produces relatively steep-sided "ridges," while fast spreading produces more gently sloping "rises."

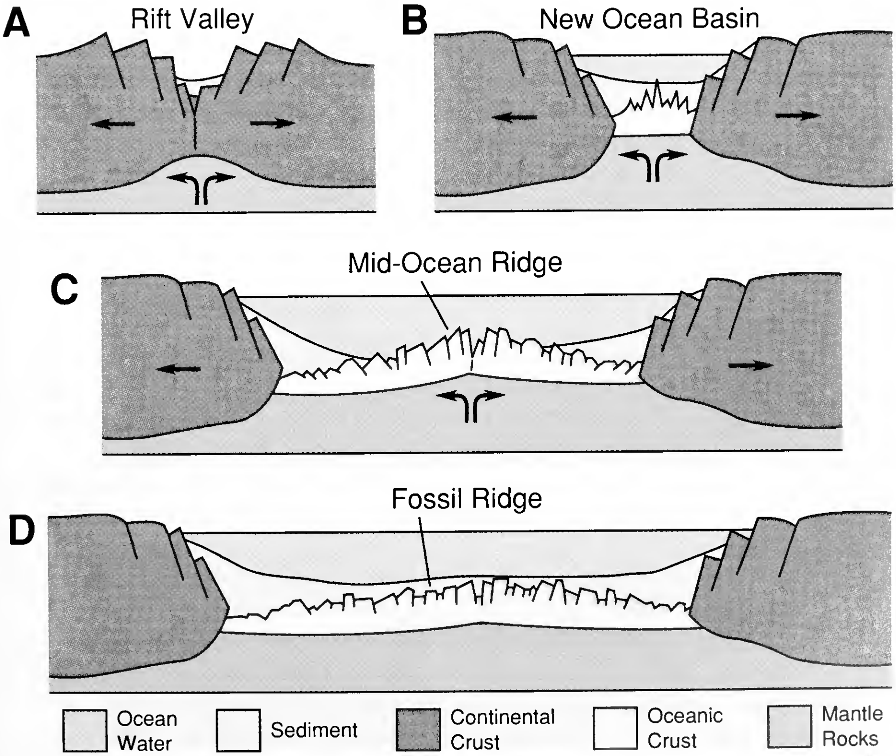
Seafloor spreading—the process that creates new material to fill in gaps between Earth's separating crustal plates—results in broad elevations with spreading centers along their crests. This is simply because crust formed by volcanic activity deepens as it moves away from the axes, cools, and contracts. The youngest, hottest crust stands highest, and the rate of deepening, which determines the regional slope gradients away from the spreading center, is proportional to the horizontal rate of crustal aging. Slow spreading produces relatively steep-sided "ridges," while fast spreading produces more gently sloping "rises." The regional side-slopes of spreading ridges and rises are concave curves, flattening out to imperceptible gradients where the crust is about 100 million years old. Even on the steepest, youngest part of slow-spreading ridge flanks, the regional gradients are actually so low that "ridge" may seem a misnomer; the popular concept of the Mid-Atlantic Ridge as a mighty chain of undersea mountains seems somewhat overblown given that the regional slope halfway down its flanks is no steeper than the eastward slope of the North American Great Plains. Of course, the small-scale topography of the Mid-Atlantic Ridge is rougher, but it took the truly global perspective provided by the very low resolution of exploratory bathymetric data (piano-wire soundings, hundreds of kilometers apart) for 19th-century oceanographers to recognize this "ridge" as a major feature of Earth's surface.

Long before oceanic crust attains an age of 100 million years, the cooling-induced slope of its upper surface is altered by other seafloor processes; the outer margins of mid-ocean ridges are generally defined by the topographic boundary between the landward structural slope of cooling lithosphere and the seaward depositional slope of continent-derived sediment. In the Atlantic Ocean, this boundary usually occurs where the crust was created about 70 million years ago, so the Mid-Atlantic Ridge is a 1,500- to 2,000-kilometer-wide structure that includes all the crust created since then. It covers half of the seafloor. Narrower basins have proportionately narrower mid-ocean ridges. Young examples are in the Gulf of Aden and the mouth of the Gulf of California, where the ridges are less than 100 kilometers wide. Ridges may even be disproportionately narrow where basins are exposed to the rapid influx of sediment from adjacent continents, and in extreme cases (such as within the Gulf of California and the Red Sea) smothering sediment completely inhibits ridge-building volcanic eruptions, and seafloor spreading proceeds without construction of a mid-ocean ridge. Rapid burial of a ridge and obliteration of its characteristic relief can also occur if spreading stops because of a change in continental drift patterns. A buried mid-ocean ridge underlies a sediment plain in the center of the Labrador Sea, where spreading between Greenland and Labrador stopped 45 million years ago.

Mid-Ocean Ridges and Ocean Basins

These examples can be arranged in sequence to illustrate a familiar model of the development and demise of mid-ocean ridges in growing "Atlantic-type" intercontinental ocean basins. Such basins have been abundant on Earth for the last 300 million years, as the supercontinent Pangaea broke up and its fragments drifted apart. There are other types of ocean basins, with other types of spreading ridges, especially in the whole hemisphere occupied by the Pacific Ocean.

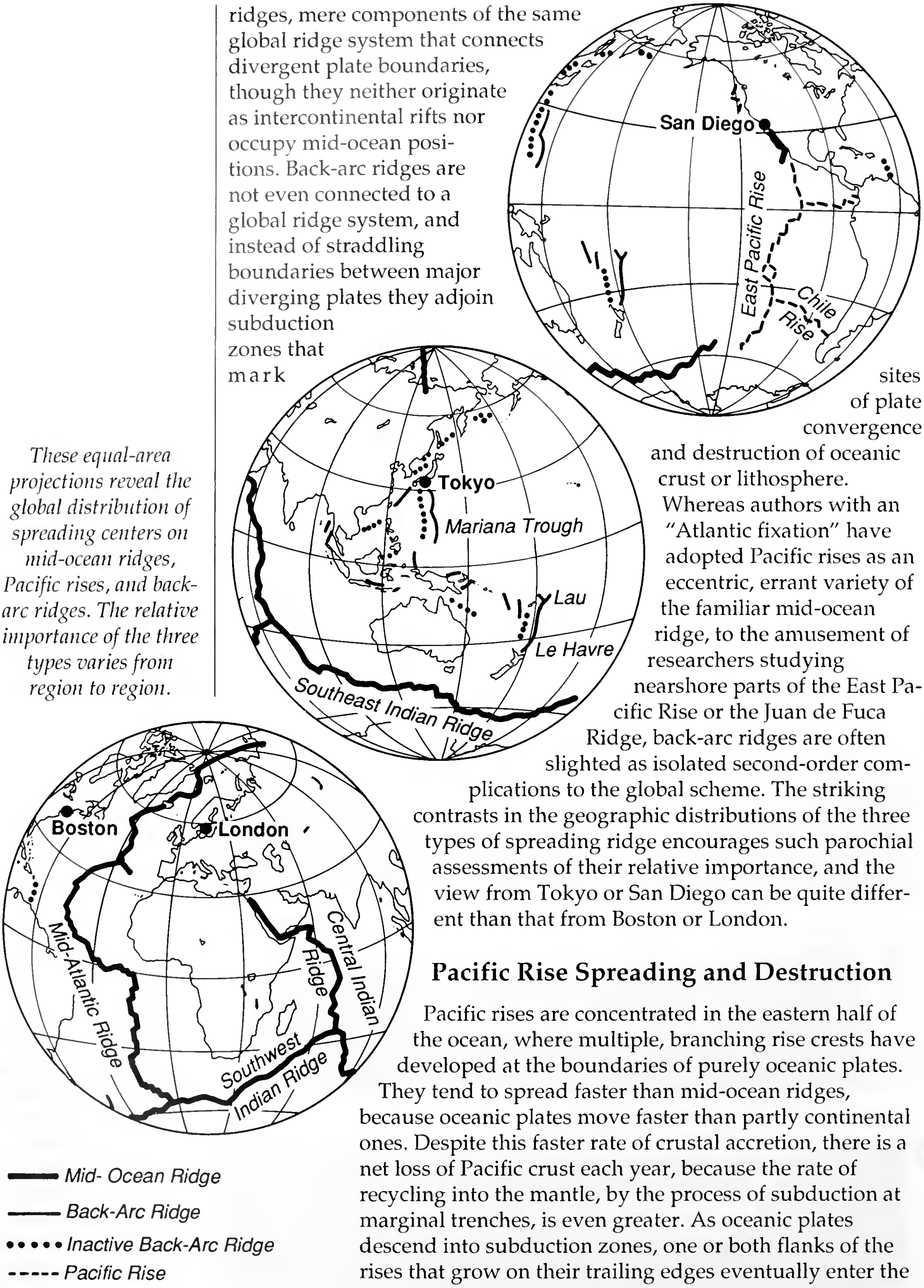
Speculative reconstructions of supercontinents that preceded Pangaea suggest that the Pacific Ocean may have originated by spreading at a mid-ocean ridge between North America and Antarctica, but that was in late Precambrian times, about 700 million years ago, and all the crust formed during this expansionary phase has long since been recycled into Earth's mantle at subduction zones. None of the Pacific Ocean's present floor is older than 250 million years, and all the time it was being created the ocean basin was getting smaller as adjacent continents converged on it. During this prolonged contractional phase, two distinctive types of spreading ridges have been active: Pacific rises (typified by the East Pacific Rise), and back-arc ridges (such as the Mariana Trough Ridge). Rises are generally considered variants of mid-ocean



Jack Cook/WHOI Graphics

The development and demise of a mid-ocean ridge. ***A:*** *Incipient separation of two continental blocks causes faulting and thinning of the continental crust, and development of a rift valley (e.g., East African Rift).* ***B:*** *Continued crustal separation produces a gap that is partly filled by sediment washed off the continents and partly by melting of the mantle to produce oceanic crust (e.g., Gulf of California).* ***C:*** *As the gap between the separating continents increases, oceanic crust formation by seafloor spreading at the crest of a rifted mid-ocean ridge becomes fully developed (e.g., North Atlantic).* ***D:*** *If continental separation stops, seafloor spreading ceases and the mid-ocean ridge subsides as it cools and gradually becomes covered with sediment.*

ridges, mere components of the same global ridge system that connects divergent plate boundaries, though they neither originate as intercontinental rifts nor occupy mid-ocean positions. Back-arc ridges are not even connected to a global ridge system, and instead of straddling boundaries between major diverging plates they adjoin subduction zones that mark sites of plate convergence and destruction of oceanic crust or lithosphere. Whereas authors with an "Atlantic fixation" have adopted Pacific rises as an eccentric, errant variety of the familiar mid-ocean ridge, to the amusement of researchers studying nearshore parts of the East Pacific Rise or the Juan de Fuca Ridge, back-arc ridges are often slighted as isolated second-order complications to the global scheme. The striking contrasts in the geographic distributions of the three types of spreading ridge encourages such parochial assessments of their relative importance, and the view from Tokyo or San Diego can be quite different than that from Boston or London.

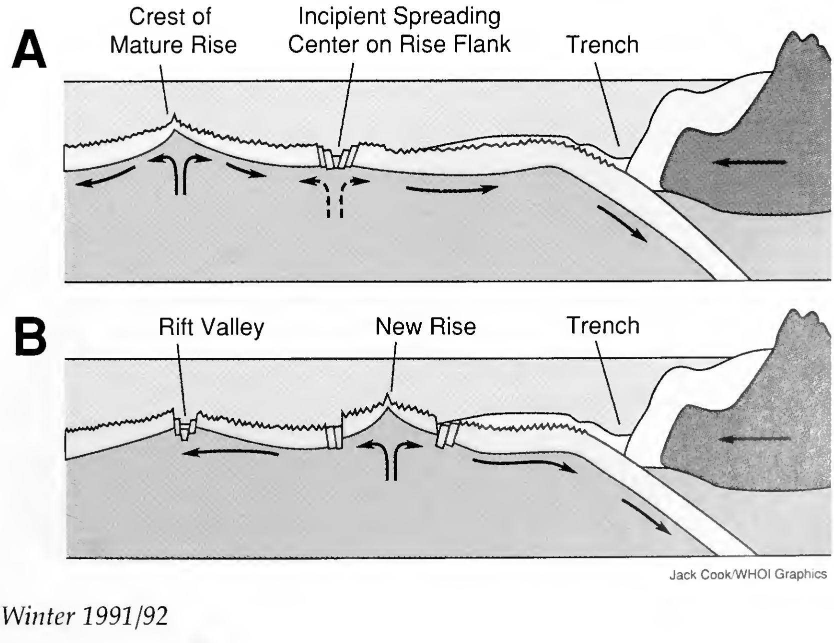

These equal-area projections reveal the global distribution of spreading centers on mid-ocean ridges, Pacific rises, and back-arc ridges. The relative importance of the three types varies from region to region.

Pacific Rise Spreading and Destruction

Pacific rises are concentrated in the eastern half of the ocean, where multiple, branching rise crests have developed at the boundaries of purely oceanic plates. They tend to spread faster than mid-ocean ridges, because oceanic plates move faster than partly continental ones. Despite this faster rate of crustal accretion, there is a net loss of Pacific crust each year, because the rate of recycling into the mantle, by the process of subduction at marginal trenches, is even greater. As oceanic plates descend into subduction zones, one or both flanks of the rises that grow on their trailing edges eventually enter the trenches and are destroyed. If one flank is completely consumed, the actively spreading rise crest may collide with the continental margin, as parts of the Chile Rise are now doing off southern Chile.

More commonly, a rise crest drifting toward the margin of the ocean basin ceases spreading before it ever enters the trench, and it is an inactive or "fossil" rise crest that is consumed. The northernmost part of the Pacific Basin is now occupied by the south flank of a rise (Kula Rise) that was 2,000 kilometers long and 2,000 kilometers wide when it stopped spreading 42 million years ago; since that time the Aleutian Trench has consumed almost all of its north flank, and all but 75 kilometers of the fossil rise crest. In the same period a trench along the western margin of North and Central America has consumed most of the east flank of the northern East Pacific Rise. Along parts of this margin, off northern and southern California, there was a collision between the active rise crest and the continent, but off central California and Baja California, spreading ceased when the rise crest was within 50 to 100 kilometers of the trench. Fortunately, subduction (removal of oceanic crust) ceased at the same time, so the record of 20- to 10-million-year-old fossil-rise crests is preserved on the present ocean floor. Further north, off Oregon and Washington, part of the East Pacific Rise that had been approaching North America began to move away from it about 20 million years ago, thereby escaping subduction and surviving as the rise system now called the Juan de Fuca Ridge.

The Juan de Fuca Ridge acquired its new identity, and a unique rate and pattern of spreading, when it became isolated from the main rise system by continental collision. Some altogether new rises got started with the fission of an oceanic plate that was being pulled in two different directions toward trenches along different parts of its margin. About 25 million years ago this was the fate of the largest eastern Pacific plate, which split into the "Cocos Plate" moving toward the Middle America Trench and the "Nazca Plate," which built a rise that extends east-west just north of the equator. A more common origin is when new spreading centers open up along the flanks of existing rises, generally in response to changes in plate-motion direction. After a few million years with both

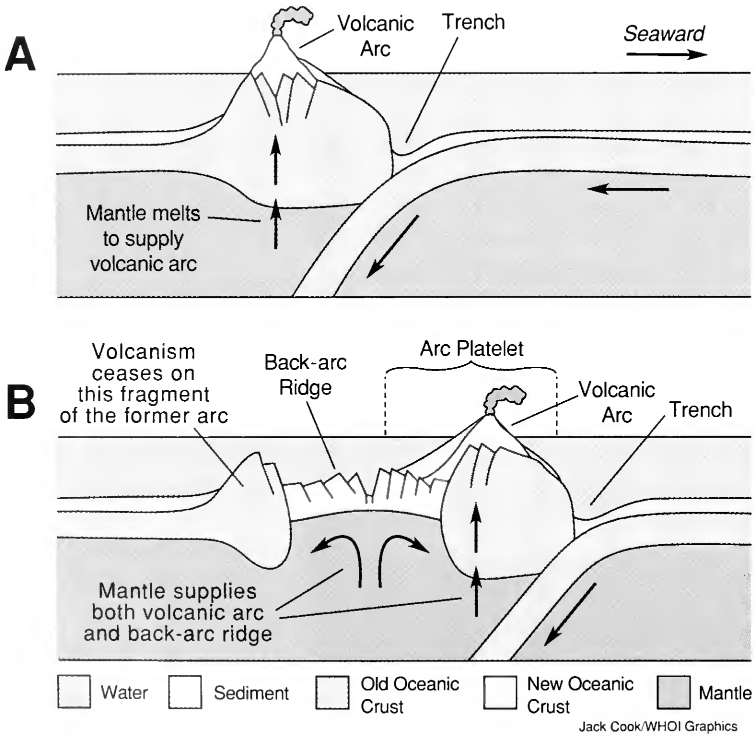


Jack Cook/WHOI Graphics

The development of a new Pacific rise by replacement of an old one. ***A:*** *A Pacific rise, producing crust that is reentering the mantle at a marginal trench, develops a new extensional plate boundary (with rifted oceanic crust) on its flank.* ***B:*** *The site of seafloor spreading shifts to the new plate boundary, where young hot crust forms a new rise (e.g., East Pacific Rise), right. This new rise may in turn become inactive, especially if it approaches a trench too closely. The original rise crest becomes inactive and its axis forms a rift valley (e.g., Mathematician Rise), left. The color key is identical to the one for the figure on page 27.*

rise crests active, the older one is generally replaced by the new one and becomes extinct.

This process commonly recurs at different times along various parts of the same rise, making these parts of different age, and thereby confusing the nomenclature. Some authors consider almost all the Pacific floor east of the Hawaiian Islands to be the partly subducted remnant of the East Pacific Rise, while others restrict the term to crust that has formed since the most recent new start and reorientation, which occurred 20 million years ago at latitude 20°S (replacing the now-fossil Mendoza Rise), 10 million years ago at 10°S (replacing the Galapagos Rise), and 5 million years ago at 18°N (replacing the Mathematician Rise). As further illustration of this rise's hybrid origin, the northernmost and youngest part of the present East Pacific Rise crest, in the mouth of the Gulf of California, is an exceptional 200-kilometer-long mid-ocean ridge, where intercontinental spreading between Baja California and the Mexican mainland has occurred for the past 3.5 million years. This local expansion of the Pacific Basin occurred when the tip of the spreading center, which had intersected the continental margin, propagated a short distance into the interior to link up with fault systems developing in the Gulf of California.



Jack Cook/WHOI Graphics

The origin of a back-arc ridge. A: Crust overlying a downgoing slab of old oceanic crust is thickened by arc volcanism. B: The seaward movement of the trench and adjacent part of volcanic arc causes rifting of the arc and growth of a back-arc ridge in a new basin.

Back-Arc Ridges: Episodic Rifting

The Pacific Ocean's complex western margin is the locale for most "back-arc ridges," a phrase that describes their tectonic setting at the back or landward side of the rows or arcs of subduction-zone volcanoes that form the "Ring of Fire," where oceanic plates underthrust the Pacific Rim at marginal trenches. Around a contracting ocean basin, the subduction zones must migrate seaward. As they do, a narrow sliver of the rim, including the landward side of the trench and the volcanic arc, migrates with them. Detachment of this "arc platelet" and its subsequent drift away from the parent landward plate causes back-arc spreading. The process is characteristically episodic. Rifting begins in the volcanically weakened arc crust, which is split lengthwise, and the landward half becomes inactive. Spreading between the volcanically active and inactive halves of the arc opens up a back-arc basin, with a spreading ridge whose crest migrates seaward at only about half the speed of the arc platelet, thereby becoming increasingly distant from the trench. The back-arc ridge generally becomes inactive after spreading and building the basin floor for several million years, but if subduction and arc volcanism continue, the process may repeat, with rifting renewed in the arc. In this manner, a series of successively younger back-arc basins, floored by extinct or actively spreading ridges, has been added to the western margin of the Pacific. Exceptions to the rule that back-arc ridges are features of contracting trench-ringed ocean basins are two isolated examples associated with Atlantic island arcs: an inactive (and sediment-smothered) one behind the Lesser Antilles Arc in the eastern Caribbean, and an active back-arc ridge behind the remote South Shetland Arc.

The Pacific Ocean's complex western margin is the locale for most "back-arc ridges," at the back or landward side of subduction-zone volcanoes

Characteristics of Spreading Ridges

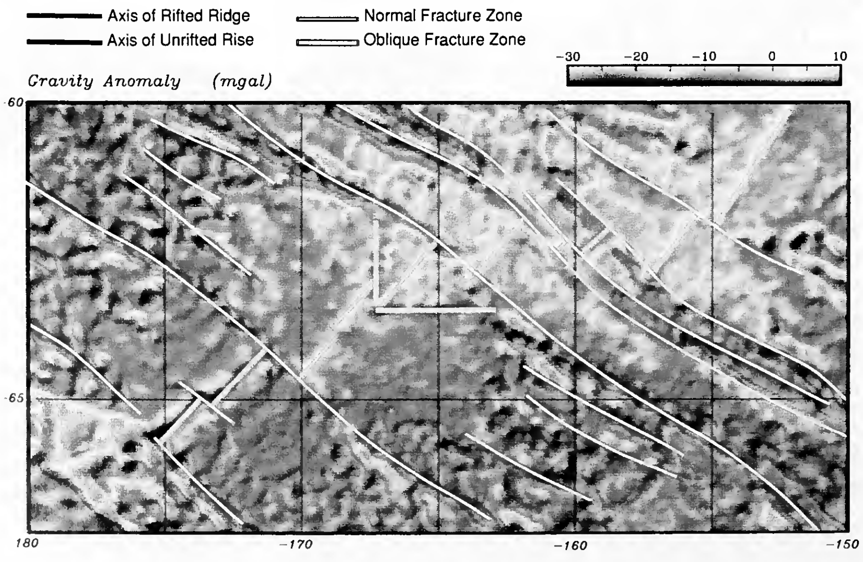
How do mid-ocean ridges, Pacific rises, and back-arc ridges differ in gross topography? Their diverse histories and tectonic settings result in a variety of sizes, sediment covers, and symmetries. Short-lived, back-arc ridges tend to be narrower, their ocean-margin location makes them more vulnerable to sediment smothering, and an asymmetric sediment supply (mainly from adjacent volcanic arcs) threatens that even if ridge development is not suppressed, the seaward flank may be buried by sediment fans. In many back-arc basins there is even evidence for encroachment of arc volcanism onto the seaward flank of the ridge. Asymmetric topography, in contrast to the striking bilateral symmetry of mid-ocean ridges, is also a feature of some nearshore Pacific rises that have unequal sediment loading on the two flanks; for example, most of the landward east flank of the Juan de Fuca Ridge lies beneath a thick lens of sediment brought by turbidity currents from the nearby continental margin, whereas the west flank is sheltered from the effects of such currents by the relief of the rise crest itself. A more fundamental cause of asymmetry on many Pacific rises is varying amounts of flank removal at marginal subduction zones. Once a whole flank has been consumed and the crest collides with the continental margin, the "rise" is merely a steadily deepening ramp leading from the margin to the continental interior, as exemplified by the westward slope of the seafloor between California and Hawaii.

The processes of sediment burial and plate consumption that cause some gross differences between the three genetic types of spreading ridges are secondary to the volcanic, tectonic, and hydrothermal processes that create oceanic crust and shape the medium- and small-scale topography at ridge and rise crests. These processes seem to work in remarkably similar ways at all three types. Variations in ridge-crest structure and relief are more clearly related to the rate of crustal accretion than to the origin and history of the spreading center.

The current spreading rate (the width of the crustal strip added per unit of time) at the divergent boundaries of major plates, varies from 12 to 14 kilometers per million years (or, 12 to 14 millimeters per year) along mid-ocean ridges in the Arctic and between the slow-moving African and Antarctic plates. It is more than 10 times this speed along most of the East Pacific Rise. Active back-arc spreading centers cover a similar spectrum of spreading velocities, and geologic study of old oceanic crust indicates that the same range of rates has prevailed throughout the past 200 million years, though the worldwide average rate has fluctuated significantly during this period. The spreading rates of the mid-ocean ridges and Pacific rises that are now active fall into four classes: slow, medium, fast, and ultra-fast. The longest ridges are in the slow-spreading class, which includes many Atlantic and Indian mid-ocean ridges; but the most productive in terms of total area of crust added each year is the ultra-fast class, which only includes the central part of the East Pacific Rise.

Unrifted Rises and Rifted Ridges

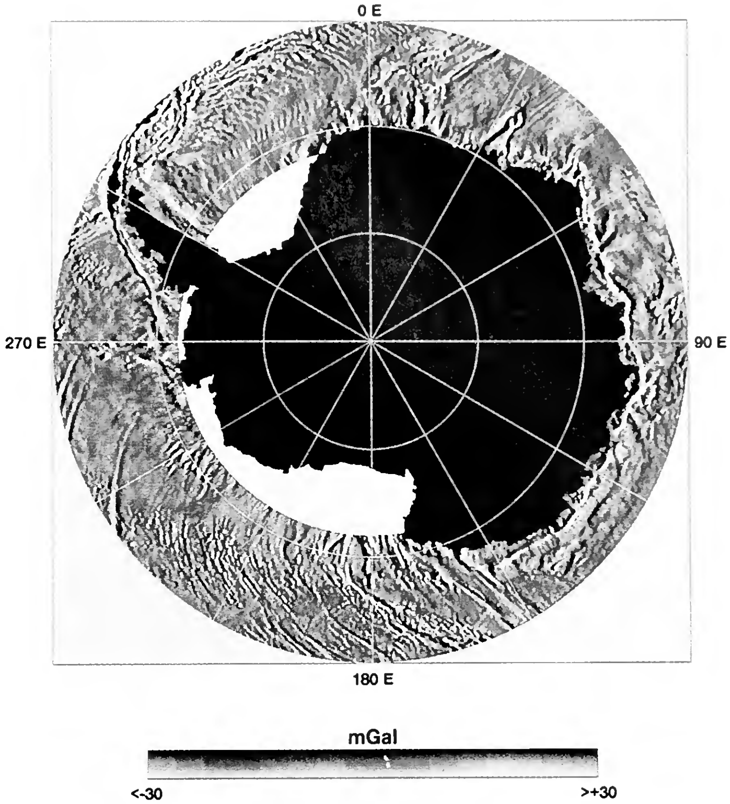
Although there are four speed classes, and speed of opening affects ridge crest structure, we recognize just two fundamental structural types: unrifted rises and rifted ridges. The former, characteristic of both the fast and the ultra-fast classes, have narrow 100- to 300-meter-high, 2- to 10-kilometer-wide "axial ridges" along their spreading axes. The elevation of the axial ridge is readily explained by its location over a body of hot, partly molten rock, including a thin, narrow magma chamber (see Tomographic Imaging of Spreading Centers, page 92). Despite the "unrifted" apellation, the axial ridge contains a volcanic rift zone much like the rift zones on Hawaiian volcanoes: an elongated zone of weakness into which vertical bladelike sheets of molten rock are injected from underlying magma sources. When the sheets freeze within the ridge, tabular intrusions known as "dikes" are formed, and gaping fissures open up in the overlying seabed. If the magma pressure is great enough, the sheets reach the seafloor and lava erupts from fissures along the axial ridge crest. The remarkably narrow zone of intense dike injection and fissure eruptions, typically less than 1 kilometer wide, is usually marked by a shallow "axial summit graben" only 10 to 100 meters deep and formed by collapse of the axial ridge crest between major eruption events. The fissured floor of this summit graben is a favored site for mineral-precipitating discharges of hydrothermal fluids that are heated



Both rifted ridges and unrifted rises occur in this gravity anomaly plot.

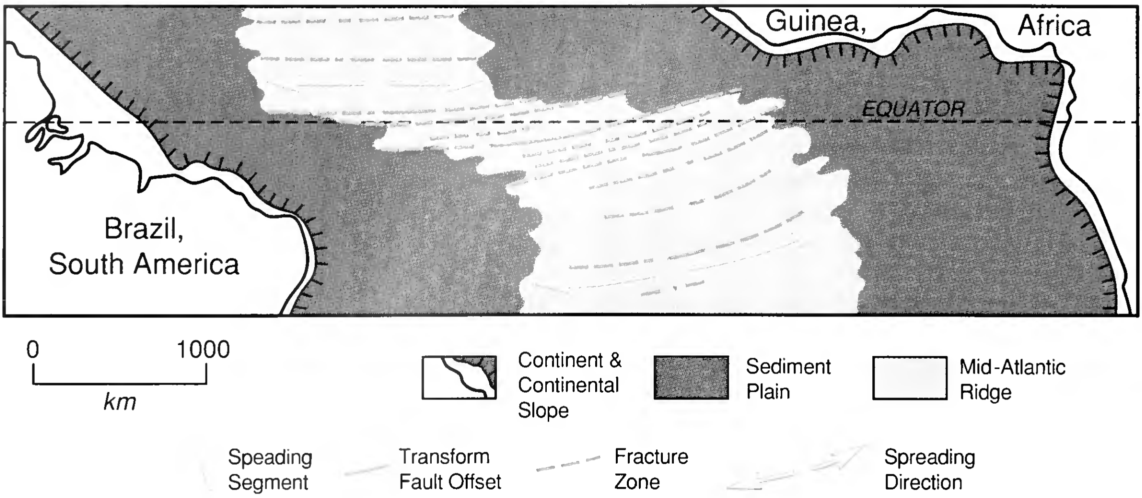
by contact with the hot fractured seabed.

Rifted ridges are those mid-ocean and back-arc ridges on which the plate boundary does not crop out along the crest of the highest volcanic ridge, but along the floor of a 100- to 3,000-meter-deep axial rift valley that is typically 10 to 40 kilometers wide, and bordered by uplifted fault blocks called rift mountains. Much has been written on the nature and origin of axial rift valleys since they were discovered by reconnaissance echo sounding more than 50 years ago (see Onions and Leaks…, page 36 and Tectonics of Slow Spreading Ridges, page 51 for some of the newer ideas and observations). The discussion here summarizes their global distribution, which has recently been clarified by satellite observations.



This map depicts the gravity field of the Southern Ocean, as derived from Geosat altimetry. The southernmost portions of the Pacific-Antarctic and Southeast Indian ridges appear as a complex chain of positive gravity anomalies between 150° and 210°E. This map is available in both digital and poster form from the NOAA National Geophysical Data Center (Report MGG-6, Marks and McAdoo, 1992).

Radar altimeters carried by some mapping satellites, notably Seasat, Geosat, and ERS-1, measure variations in the shape of the sea surface, which is affected by seafloor topography because water piles up over ridges that exert a gravitational attraction. After processing to remove the influence of waves, tides, and long-wavelength variations, altimeter profiles can be displayed as maps of sea-surface gravity anomalies, with positive anomalies over axial ridges and negative anomalies over the floors of axial rift valleys. Data from systematic global coverage by satellite altimeters combined with more patchy mapping by ships equipped with echo sounders shows that axial rift valleys are most impressive on slow-spreading ridges; at spreading rates of 15 to 60 millimeters per year, there is a crude negative correlation between spreading rate and rift-valley depth. However, a rift valley's presence and size are probably controlled by the rate at which molten rock is supplied from the mantle to the accreting plate boundary, and not necessarily the correlated spreading rate. Where the magma supply is voluminous and steady (a prerequisite for fast spreading and a feature of slow-spreading ridges that happen to be near unusual "hot spot" magma sources), a permanent reservoir of partly molten rock underlies the spreading axis and creates an axial ridge. At spreading centers with smaller, more episodic magma supplies, like most slow-spreading ridges that are far from unusual "hot spot" magma sources, plate separation and crustal extension leads to rift valley formation. In the medium-spreading speed class, many axes have well developed, albeit shallow, rift valleys, but axial ridges similar to those of fast-spreading rises also occur, sometimes on adjacent parts of the same spreading center. At



Jack Cook/WHOI Graphics

these intermediate spreading rates (60 to 80 millimeters per year) the presence or absence of a rift valley is probably sensitive to local and spatial and temporal changes in the magma supply rate.

Ridge-Crest Segmentation

Fracture zones, and the rise-crest offsets that create them, are also essential features. Ridge-crest segmentation is one of the most fundamental features of spreading centers and one of the most active areas of current research. The crustal-accretion belt along a ridge crest is not continuous, but is broken by several types and sizes of ridge offsets into laterally displaced segments tens or hundreds of kilometers long. Individual spreading segments are oriented at right angles to the spreading direction, and are frequently arranged in a staircase with offsets systematically stepping left or right. In such cases the relative lengths of spreading segments and offsets is determined by how oblique the ridge is to the spreading direction; for instance, the equatorial part of the Mid-Atlantic Ridge strikes almost east-west, and has long left-stepping offsets linking short spreading segments, while further south, where the overall strike is more nearly north-south, lateral offsets are shorter and more widely spaced. There is also empirical evidence of an inverse correlation between segment length (offset spacing) and spreading rate. Only a small fraction of the global ridge system has been surveyed with the high-resolution tools needed to locate small offsets, however, so their mapped abundance partly reflects the relatively small survey effort. The spreading rate certainly influences the structure of the ridge offsets. On slow-spreading ridges, all but the shortest offsets contain transform faults, which are narrow zones of "strike-slip" (horizontally sliding) faulting at right angles to the spreading segments. Similar transform faults subdivide fast-spreading rise crests, but only where offsets are longer than 50 to 100 kilometers. Shorter steps in the plate boundary are much more abundant, and have broad zones of deformation that are said to be "nontransform" because they lack strike-slip faults. Both transform and nontransform offsets, known as "fracture zones," leave recognizable

Where the overall strike of the ridge is highly oblique to the spreading direction, as in the equatorial part of the Mid-Atlantic Ridge, the offsets between spreading segments are longer and more closely spaced.

trails on the rise flanks, belts of distinctive topography that interrupt the abyssal hill pattern because they have spread from disruptions of the spreading center. Fracture zones produced at long transform faults have high relief that was easy to discern even with early echo sounders. Conversely, locating fracture zones produced at nontransform offsets generally requires high-resolution mapping of abyssal-hill or crustal-age patterns, because their subtle relief is unpredictable: Nontransform offsets migrate along the rise crest at variable speeds and directions, rather than maintaining a stable location, as transform offsets do. The V-shaped feature in the middle is a good example of a pair of oblique fracture zones produced by a migrating nontransform offset, in this case one that has migrated steadily southwest at a rate about twice that of the spreading rate.

Much remains to be learned about the origin of ridge-crest segmentation, and the reasons for segmentation-pattern changes. Why, for instance, do some spreading segments grow in length at the expense of their neighbors, causing the offsets between them to migrate along the plate boundary? Different approaches being used to tackle this problem include making detailed studies of the rise-crest processes at a few convenient locations and preparing a global inventory of all such offsets, to see how their directions and rates of migration correlate with such factors as spreading rate, segment length, rise-crest depth, etc. For the latter task, a much more complete description of the global ridge system is needed, implying many more months of survey effort with the sophisticated multibeam mapping sonars now available on research ships. Satellite observations may have sufficient resolution to partly supplement the shipboard work, and provide an immediate global perspective. Unfortunately, the best satellite data now available has been classified as a military secret (except in the "nonstrategic" Antarctic region), and is therefore unavailable to most researchers, just as the results of multibeam sonars were a decade ago. This impediment to understanding the pattern and relief of spreading ridges will disappear as military satellites are replaced by civilian ones, like the ERS-1 that is now in orbit and busy collecting altimeter profiles across all the world's ridges.

Ridge-crest segmentation is one of the most fundamental features of spreading centers and one of the most active areas of current research.

Peter Lonsdale is a Professor of Oceanography and Research Geologist with the Scripps Institution of Oceanography (SIO). He has spent two or three months in each of the past 20 years examining the ocean floor with echo sounders, cameras, and submersibles, about half of this effort being on Pacific rises and back-arc ridges.

Chris Small is a graduate student at SIO, with a special interest in using satellite altimeters for structural studies of mid-ocean ridges.

Onions and Leaks: Magma at Mid-Ocean Ridges

A Very Personal View

Joe Cann

Thirty-five years ago, most geologists were secure in the knowledge that continents did not move.

In 1992 we see mid-ocean ridges clearly, forming a complex, 50,000-kilometer-long web of seafloor mountain chains that encircle Earth. Along the mountain crests there is a narrow belt of activity, marked by shallow earthquakes, seafloor volcanic eruptions, and hot springs, where new ocean crust is constructed at the rate of a few centimeters every year (about as fast as fingernails grow). Recent intense study of this zone has sharpened our picture, refocused it here and there, brought sudden insights, and revealed errors of perception, until we have reached new levels of clarity.

This year seems especially propitious for reviewing mid-ocean ridges. We are pleased that our new models are good, that our understanding is secure. There are difficulties to be sorted out, but most are within our grasp. Now we should settle down to explain what we know. And in that spirit we write, and you read, this issue of *Oceanus*.

Our certainty is not new. Thirty-five years ago, most geologists were secure in the knowledge that continents did not move, that the oceans were permanent, unchanging features of Earth's surface, containing sediments as old as ocean water itself and interleaved here and there with lava flows. Mid-ocean ridges might be fold-mountain belts like submarine Rockies, or rift mountains like submerged East African highlands, but were certainly explainable in sensible continental terms. Within a few years this comfortable picture was to be turned upside down by the very people who then possessed such certainty of belief.

Thirty five years ago I was a geology undergraduate. Our first-year text was by Arthur Holmes who, in about 1930, focused attention on the mid-ocean ridges with his concept that Earth's deep interior might be slowly convecting as it was heated by the radioactive decay of potassium, uranium, and thorium. He thought that deep-Earth convection currents might move the continents apart, and that upwelling currents might rise in the centers of those oceans that had matching coastlines on either side, such as the Atlantic and Indian oceans. At first, Holmes thought that the Mid-Atlantic Ridge was a strip of continent left behind as Africa and America split apart, but in our 1944 textbook he replaced the continent with oceanic crust. That diagram looks very much like the sketches we draw today.

In student seminars we talked about Wegener and du Toit, pioneers of continental drift theories. We argued whether the oceans might be young, as they said, or ancient, and whether animals had crossed the oceans on land bridges or floating tree trunks, or maybe had wandered from place to place when the continents were joined to form Gondwanaland, Laurasia, or, earlier, Pangaea. Our professors cautioned us against believing Holmes too literally, indicating that ideas about drift were based on woolly speculation. Harold Jeffreys, the most eminent geophysicist of the time, had proved that drift was impossible. How could we disagree? The pioneers of rock magnetism certainly did so. They showed that ancient rocks are magnetized very differently from recent ones, suggesting that they originated at latitudes other than those they now occupied. Could Earth's spin axis have changed? Or had the continents moved? Jeffreys skeptically pointed out that iron could be remagnetized by striking it with a hammer, a tool traditional with geologists.

Drum Matthews (red shirt), Tony Laughton (blue hat), and Ron Oxburgh work amid basalt lavas at the Gulf of Tadjura, Djibouti, in January 1967. The Gulf of Tadjura is where the Gulf of Aden spreading center comes ashore, and is splitting apart slowly. The lavas come from magma chambers below the seafloor.

Then marine geology and geophysics began to take a hand. Inspired by service at sea and trained in antisubmarine warfare, young marine scientists brought new talents and instruments to the oceans. It was a curious time. Marine scientists were few, and nearly everyone knew nearly everyone else. Even when I came into marine geology in 1962 as a young post doc, I was able to rapidly meet almost all of the players in the game. That would be quite impossible today. Many of the leaders in the field worried more about their next expedition than about publishing the results of their last, but all were willing to talk. Ideas developed by word of mouth, shortcutting publication, so that often it was—and still is—difficult to lay credit where it properly belongs.

Harry Hess, one of the most charismatic scientists of his time, was a reluctant but remarkable speaker: Quiet, with a cigarette dangling from his fingers, he was seemingly casual, yet profoundly convincing. He first took a semi-fixist view, in which convection currents stirred the mantle, but continents did not move. He ascribed the existence of mid-ocean ridges to transformation of dense mantle peridotite to light serpentinite, by way of water seeping up from the rising convection currents. Soon he moved into the mobilist camp, and allowed that convection moved continents. In the first breakthrough since Holmes, Hess suggested that new ocean crust is continually created at mid-ocean ridges and spreads away as the ocean grows.

This became the theory of ocean-floor spreading, and from it emerged the first model of mid-ocean-ridge processes. Hess thought that the rising limbs of deep-Earth convection currents not only split the ocean floor apart, but also contributed basalt magma and water to the growing crust. Magma would be erupted at the ocean floor to form the seafloor lavas that were now being collected regularly, and water would circulate down through the porous lavas to alter the uppermost mantle to serpentinite, creating the lower part of the crust. The base of the crust would thus mark the lowest level that serpentinite could form at the ridge axis, representing the temperature at which serpentinite dehydrates back to peridotite.

The demonstration that Hess had been broadly right was a triumph of the 1960s. From data gathered by towing a magnetometer across the oceans, Fred Vine and Drum Matthews explained that magnetic anomalies were created as the result of ocean floor spreading, while Earth's magnetic field periodically reversed. Tuzo Wilson invented the concept of transform faults to account for the great oceanic fracture zones. A sequence of other important papers transformed ocean-floor spreading to plate tectonics and convinced all but the most recalcitrant oil-company geologist that the mobilist view was correct. But that is all part of a different story, and shed no further light on what is happening at mid-ocean ridges.

At the Troodos ophiolite complex in Cyprus, a road cut shows the top of a seafloor magma chamber formed 1 to 2 kilometers below the ancient seafloor. The pale rocks are gabbros and trondhjemites produced by crystallization of the top of the magma chamber. The gray stripes are dikes intruded from another chamber nearby. Hazel Prichard is the figure, once a student of the author and now at the Open University in the United Kingdom.

That revelation was already being achieved elsewhere, namely in the Cyprus Geological Survey. In Cyprus (and in other places such as Newfoundland, Oman, and Papua New Guinea, a combination that accounts for some curious stamps in my passport), there is a thick slab of rock, an ophiolite complex, made up of basalt, peridotite, and serpentinite, containing seafloor lavas and deep-sea sediments. Smaller fragments of similar rocks had long been known from mountain belts, and had been studied by, among others, Harry Hess. Now the Cyprus Survey, spurred by the discovery of iron, copper, and zinc sulphides, and chrome ore, decided to map the Troodos ophiolite, which was 100 kilometers long by 50 kilometers wide. The first map was started by R.A.M. Wilson. His work was a masterpiece of acute observation and justified interpretation that is a pleasure to read, even today.

Within the ophiolite structure, which forms a gently warped and eroded sheet several kilometers thick, he found a unit composed entirely of dikes soon called the sheeted-dike complex. Dikes are thin, vertical sheets of magma, relics from when magma intruded into vertical cracks and became frozen there. They are common in the rock record, and show that the rock has been stretched when magma was around. In some places on the continents they make up perhaps five percent of the terrain, which up to that time had been considered a large amount. In Cyprus, Wilson showed that they make up 100 percent of one unit that is 1 kilometer thick and stretches for 70 kilometers across the mountains.

Here was ocean-floor spreading frozen into geology, 70 kilometers of it, though Wilson did not make the connection at first.

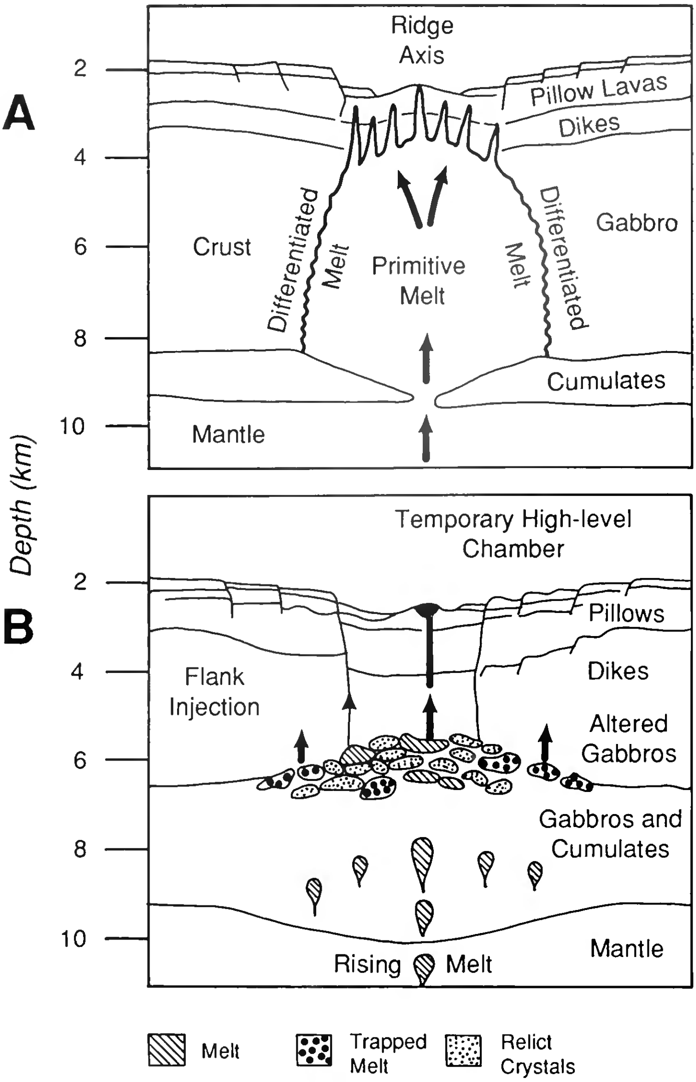
By the mid-1960s the link had been made, and the oceanic and ophiolitic strands of evidence became inextricably tangled. In the oceans it is possible to observe active mid-ocean ridges, especially using geophysical methods, but very difficult to see what is happening below the seafloor, except by inference. In ophiolites the processes ceased long ago, but it is possible to wander over the countryside, passing deeper below the ancient seafloor at will, and reconstruct past events using the standard tools of geology. The two approaches are complementary, but communication between them presented problems. Certainly there seemed to be a conflict between what Hess predicted for mid-ocean ridges and what was observed in ophiolites.

When I first came into marine science, I trod warily, watching in admiration as my geophysical colleagues manipulated mathematics, patched instruments at sea, and set apparently arbitrary constraints on what was and was not possible. After all, I was an impeccably orthodoxly trained microscope man. Some moments were magical, as when Tuzo Wilson first propounded his transform-fault theory, grinning like a Cheshire cat that had swallowed the cream and snipping newspapers with a large pair of scissors to show how his theory worked. Other moments were more prosaic, and I gradually realized that geophysicists did not hold a monopoly on truth—or perhaps I just learned some geophysics.

Was it possible to make a simple model of ocean-crust construction at mid-ocean ridges that drew on all of the evidence available, ophiolitic and oceanic, geophysical and geological? I had a false start: My first model was undone by a graduate student's simple question, "What determines the position of the Moho, the boundary between crust and mantle, in your model?" I said something in reply, floundering, hoping that he wouldn't notice. I expect he did.

Then, a month or so later, digging the sandy soil of our garden in Norwich, I suddenly saw what was wrong—perhaps also what was right. Suppose that magma rose up from the mantle as the plates moved apart. Suppose it rose high in the crust, not far below the seafloor, and collected there as a magma chamber, stretching along the axis of the mid-ocean ridge at a shallow depth. When the crust cracked above it, magma could rise along the crack to make a dike and then feed seafloor lava flows. The dike would intrude older dikes, and in turn cut yet older ones. When the magma chamber froze it would make a layer of gabbro in the lower crust. Crust produced

Author Cann cooking porridge over a steam vent in northern Iceland in August 1991. The vent is part of the Theistareykir hot spring field, lying in the Theistareykir rift zone, and heated (almost certainly) by a magma chamber deep below the rift. Note that Iceland marks where the Mid-Atlantic Ridge comes ashore, though it is anomalous in many ways.



The "infinite onion" model (above) for magma chambers beneath fast-spreading ridge segments is compared to the "infinite leak" model (below) for magma storage beneath slow-spreading ridge segments.

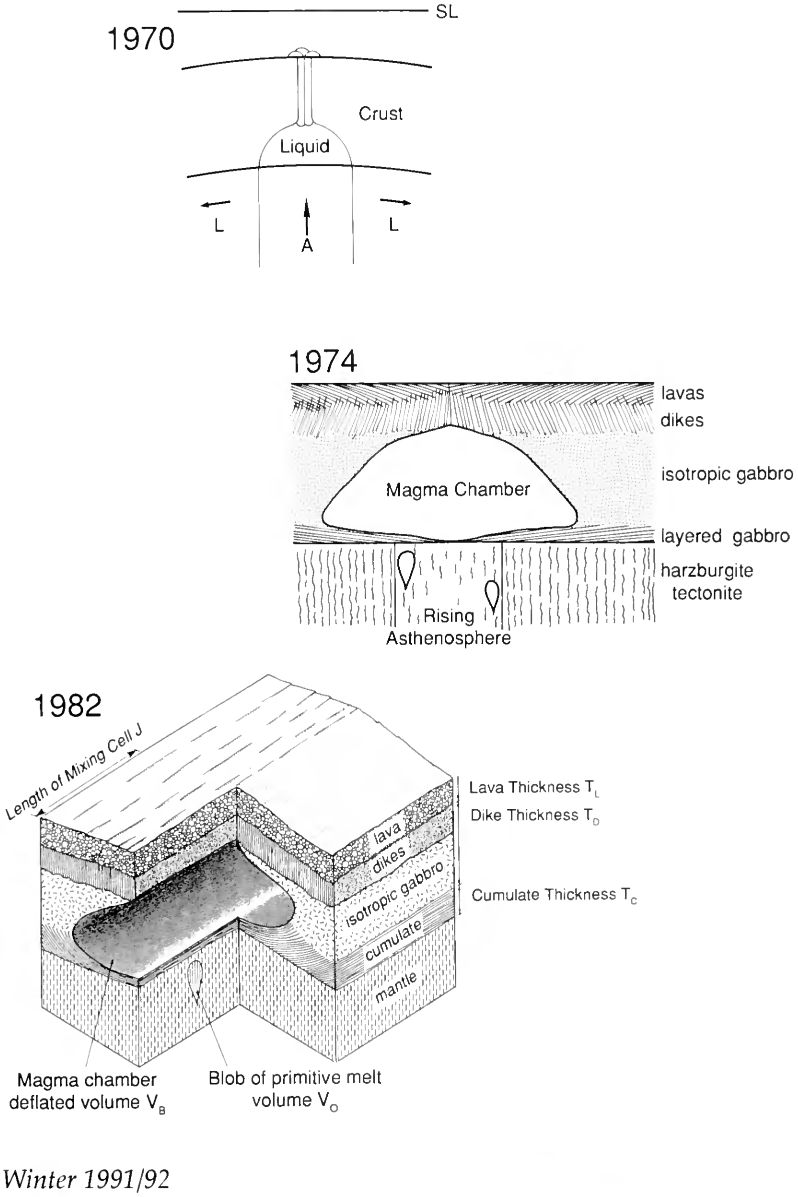
this way would have the same structure as the Cyprus (and now the Oman) ophiolites, and a shallow magma chamber might fit the geophysical observations, too.

This outline evolved into the infinite-onion model, since in its ideal form it required a magma chamber that was onion-shaped in cross section and as long as that part of the ridge. Soon I was involved in stout defense of the onion. It proved very difficult to make the seismic observations that would test it properly, and inconclusive tests were regarded by skeptics as negative evidence. Soon it became clear that, in its simplest form, the model did not hold at slow-spreading ridges such as the Mid-Atlantic Ridge. Euan Nisbet and Mary Fowler devised an alternative, punning infinite-leak model to cope with that. Recently Debbie Smith and I have come up with observations that support infinite leaks in the Atlantic.

But in the Pacific, where spreading rates are faster, there seemed every reason to expect the infinite onion. People looked for and found hot mantle, but no magma; they were looking for magma in the wrong place, it turned out. John Orcutt said he could see the magma. I liked his evidence, perhaps naturally, but many others stonewalled. Eventually, Bob Detrick (I simplify—John and Bob will have to stand for the teams they led) managed to image the top of the magma chamber for tens of kilometers along the ridge, using seismic reflection, just as the oil companies do to find oil—oil and magma look surprisingly similar by seismics. The chamber was much thinner than I had originally predicted, but the top was just at the right level (1 to 2 kilometers below the seafloor), as could have been predicted from ophiolites.

And the onion? So far Bob and John stand out against the spike on the top of the chamber that would make the onion complete, but one day in the future...? Do I need to say that I still feel it is there? And what then? There is no space to tell of the other successful models of mid-ocean ridges, of George Constantinou in Cyprus showing that the ore deposits there were formed from hot springs on the ocean floor, thus leading the way toward black smokers; or the recent recognition that the third dimension, the variation of ridges along the axis, has as much of a story to tell as the across-ridge models we started with. But models are there to be overthrown: Perhaps the second-best experience as a scientist is to see a model elegantly destroyed. The best? To do it yourself by creating a new one, of course. In spring 1992, Debbie Smith and I will be leading an expedition to the Mid-Atlantic Ridge, trying hard to do just that.

Joe Cann is Professor of Earth Sciences at the University of Leeds in the UK and Adjunct Scientist at Woods Hole Oceanographic Institution. He took his Ph.D. in 1962 and is thus one of the old fogies of marine geology, but he is still trying hard to destroy his and other people's models of mid-ocean ridges. For the last few years he has been worrying more about black smokers than magmas, but recently he has come back into seafloor volcanoes. He works happily at sea or on land (in Greece or Cyprus) with a microscope, or a computer, or an X-ray set, especially on figuring out how the different aspects of mid-ocean ridges knit together.



In the last 35 years, geological "certainty" has changed enormously. Models are created, proved, then sometimes disproved—with the end result, ultimately, of better understanding. Simple diagrams of models from the last 20 years illustrate (in a punctuated manner) this evolution.

From Pillow Lava to Sheet Flow

Evolution of Deep-Sea Volcanology

Wilfred B. Bryan

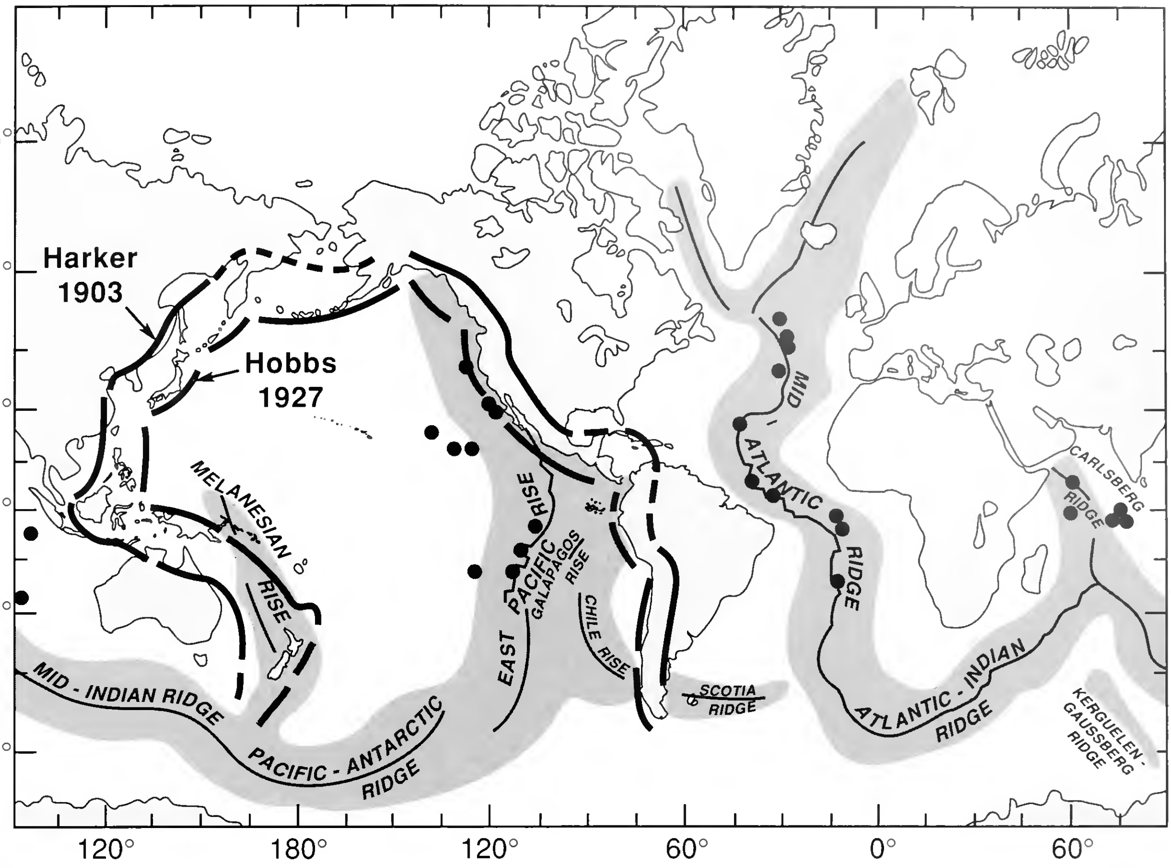
The first volcanic rocks from a mid-ocean ridge were accidentally sampled during cable-laying operations in the North Atlantic in 1874.

The black, fine-grained volcanic rock called basalt has long been associated with ocean basins, though sometimes for the wrong reasons. Today, basaltic lava is a familiar sight to millions of tourists who have visited Hawaii, and millions more have watched it flowing into the sea on television news programs. But 200 years ago in western Europe, basalt was known mostly by its association with sedimentary rocks containing marine fossils, and so was widely regarded as a chemical precipitate from seawater. A few practioners of the new science of geology at that time recognized the similarity of basalt to the lavas of nearby volcanoes such as Vesuvius. This led to one of the first major controversies in geology, between the so-called "neptunists" and the "plutonists," who believed that basalt was the product of volcanic eruptions. That issue was eventually solved when one of the supposed basalt precipitates was traced back to its source at an obvious volcanic vent. But the nature and extent of volcanic rock on the deep seafloor would not be known for many more years. Prior to the mid-1960s, scientific papers on this subject still were largely constrained to rocks observed and collected on land; their association with sedimentary rocks typical of the deep seafloor continued to be the principal evidence for their deep-sea origin.

The first volcanic rocks from a mid-ocean ridge were accidentally sampled during cable-laying operations in the North Atlantic in 1874, about 200 nautical miles east of what we now know to be the Mid-Atlantic Ridge (MAR). The dark basalt was dismissed as having been dropped from a drifting iceberg, although the 27.5-ton tension required to recover the cable would seem to suggest this was not a loose fragment. In 1898 P. Termier described basaltic glass also recovered from the MAR at about 47°N, during cable repairs. He correctly deduced that this material indicated a volcanic origin for the seafloor at this location, but it would require another 60 years of study before the true extent and nature of the Mid-Atlantic Ridge would be known. Meanwhile, in the Pacific, widely scattered dredges recovered by the *Challenger* Expedition included samples of dark basaltic rock, also indicating a likely volcanic origin for the deep seafloor.

Throughout the first half of the 20th century the seafloor was widely

Sketches for this article are by the author.



Locations are plotted from which oceanic basalts were dredged as early ridge petrologists defined compositional and structural boundaries between oceanic and continental crust. Harker's "Pacific" boundary and Hobbs's "andesite line" bracket the circum-Pacific "Ring of Fire."

assumed to be basaltic, but evidence for this assumption was still sketchy and indirect. A "basaltic" and therefore "volcanic" seafloor was consistent with the arguments based on isostasy and bathymetry that remain valid today: The continents must stand high, because they are composed of relatively thick, light granitic rock that literally floats higher on the underlying mantle than does the thinner, heavier rock comprising the oceanic crust. Also, petrologists generally assumed that basalts of volcanic islands such as Hawaii or Iceland were representative of the rocks to be found on the deep seafloor. Although there are often striking differences between continental volcanic rocks and the deeper crustal rocks on which they have been erupted, the shaky logic of this analogy as applied to the seafloor does not ever appear to have been challenged.

Finally, with the recognition of the reality of seafloor spreading and plate tectonics in the mid-1960s, mid-ocean ridge volcanism became a logical geometric necessity for creating new seafloor. The spreading model predicted that seafloor of similar basaltic composition but of regularly increasing age should extend to the margins of the ocean basins, a relation that was soon confirmed by basement samples recovered during legs 2 and 3 of the Deep Sea Drilling Program. Attention could now be redirected toward defining the nature of volcanic processes on mid-ocean ridges and the nature and extent of compositional variation in volcanic rocks erupted there.

Chemical Variations

Because of their very fine-grained or glassy nature, volcanic rocks are most easily studied quantitatively by their chemical composition. Chemical analyses of volcanic rocks in and around the major ocean basins began to appear in the latter half of the 19th century. By the beginning of the 20th century there were already enough data to support speculation on the global distribution of volcanic rock types; in these schemes it was implicit that the volcanic rocks somehow reflected the nature of the ocean floor with which they were associated. One of the best-known global distributions was proposed by the British petrologist Alfred Harker in 1909. He recognized three main groups, which were named for the ocean basins in or adjacent to which they were first identified. The "Atlantic" type was characterized by the dominance of soda (sodium oxide), the "Mediterranean" type by potash (potassium oxide), and the "Pacific" type by lime (calcium oxide). Harker's "Pacific" type, however, was based entirely on data from volcanoes and volcanic islands from the "Ring of Fire" around the Pacific margin. Almost immediately, new data from various Pacific Islands proved similar to those from the Atlantic, and Harker's scheme was discredited.

About 20 years later, W.H. Hobbs called attention to the compositional differences between volcanic rocks from islands within the Pacific Ocean basins and those of the volcanic-island arcs and continental volcanoes along the Pacific margins of Asia and North and South America. It is interesting to compare this boundary, which Hobbs called the "andesite line," with the boundary drawn by Harker between the "Pacific" and "Atlantic" rock groups. Following Hobbs, most geologists and volcanologists quickly accepted the andesite line as the structural and compositional boundary between oceanic and continental crust. It was not until detailed mapping and sampling of some of the circum-pacific volcanic-island arcs in the 1950s and 1960s that Harker's boundary was rediscovered.

Some of the most intriguing compositional features of ocean-ridge basalts are found in their trace-element and isotopic signatures.

Chemical analyses of rocks specifically associated with mid-ocean ridges were not published until the 1930s in papers by C.W. Correns and J.D.H. Wiseman. Their samples came from the Mid-Atlantic Ridge and the Carlsberg Ridge in the Indian Ocean. Both authors recognized the unusually low potash contained in these rocks compared to both the island basalts and continental rocks, and correctly deduced some of the chemical effects of seawater alteration on basalt. Wiseman's paper contained the first carefully detailed drawing of crystal forms observed with a petrographic microscope; Correns recognized the similarity of his sample to those collected in the Pacific by the *Challenger* Expedition, and suggested that these might be typical of the seafloor as a whole.

Some of the most intriguing compositional features of ocean-ridge basalts are found in their trace-element and isotopic signatures, but these data had to await the mid-1960s development of more sophisticated analytical technology. Analyses of basalts dredged both from the Mid-Atlantic Ridge and the East Pacific Rise showed that, compared to typical basalts of continents and oceanic islands, ocean-ridge basalts are highly depleted not only in potash but in many trace elements chemically similar in behavior to potash, such as lanthanum, rubidium, thorium, and uranium. Because these elements are concentrated in typical volcanic rocks on Earth's surface and upper lithosphere, geochemists refer to them as "large-ion-lithophile elements."

Based on these data, some geochemists emphasized the depleted and homogeneous nature of ocean-floor basalt. This view was quickly challenged when new analyses of basalts from the northern Mid-Atlantic Ridge that were enriched in these same chemical elements were presented. However, the most extensive early collections of samples from a mid-ocean ridge were recovered from the Mid-Atlantic Ridge between 22° and 30°N, and the "depleted" chemical character of these basalts became established as the definitive signature of "normal MORB" (mid-ocean ridge basalt).

At the University of Rhode Island, Jean-Guy Schilling published a series of pioneering papers that first conclusively showed the gradational nature of geochemical variability along ocean ridges. First demonstrated in the North Atlantic, these along-ridge variations are now known to continue through the equatorial region into the South Atlantic, and are also present along the Galapagos Rift and southern East Pacific Rise. Sections of ocean ridges enriched in potash, trace elements such as lanthanum, thorium, and uranium, and with high strontium-87/strontium-86 were shown to be associated with shallow bathymetry or island platforms such as Iceland and the Azores. This appeared consistent with the idea that these are "hot spots," characterized by extensive melting of a mantle source enriched in these elements and in radiogenic isotopes such as strontium-87.

Major hot spots are now recognized along the Mid-Atlantic Ridge at Iceland, the Azores, and near Tristan da Cunha.

Hot Spots: How Normal is Normal?

Although models remain sketchy and highly speculative, a popular view is that hot spots are the locis of upwelling "mantle plumes" that bring new, hot, and previously undepleted mantle from a deep, previously untapped source to a sufficiently shallow level, permitting partial melting and the escape of basaltic magma to the surface. On the other hand, depleted, supposedly "normal" mid-ocean ridge basalt is presumed to be derived from relatively shallow mantle, perhaps the "low-velocity zone" defined by seismic surveys, which may have been depleted by partial extraction of magma in previous melting events. Mixing between melts derived from these two sources may account for much of the intermediate isotopic and trace-element variability. Major hot spots are now recognized along the Mid-Atlantic Ridge at Iceland, near 45°N; the Azores, near 15°N; and near Tristan da Cunha, at about 36°S in the South Atlantic. The chemical signature of the larger plumes extends hundreds of kilometers along-ridge, and it can be asked, at least in the Atlantic, if "plume" MORB isn't actually more normal than "normal" MORB!

In the Pacific, the Galapagos Rift crosses the best-documented hot spot, but another must exist on the East Pacific Rise near Easter Island, and there are several small ones along the Gorda-Juan de Fuca Ridge systems. Ridges have been less systematically sampled in the Indian Ocean, but the available dredges and Deep-Sea-Drilling-Program basement samples indicate both "normal" and "plume" chemistry in basalts recovered there. There now is even a "cold spot" recognized along the Pacific-Antarctic Ridge, characterized by extreme depletion in large-ion-lithophile elements. Most recently, researchers at the Lamont-Doherty Geological Observatory have shown that systematic along-ridge variations can be demonstrated in major-element chemistry as well as in trace elements and isotopes, and also can be correlated with bathymetry and the location of hot spots.

Petrography and Mineralogy

Much of the early work on ocean-floor basalts was based on chemical analyses and ignored mineralogical details of the rocks. In 1972, I described in detail for the first time the sometimes-bizarre crystal morphology that results from rapid underwater quenching of magma. An unexpected result of this paper was the recognition of similar quench-crystal morphology in Archean pillow lavas that are up to 3.5 billion years old. Previously these morphologies were believed to have been caused by chemical changes over time, accompanied by recrystallization. Now it was obvious that these basalts had changed little since they originally erupted on ancient seafloor, and both their chemistry and morphology could be used to interpret volcanic processes in some of the oldest seafloor known, now uplifted and exposed on land.

While many of these ancient basalts resemble their modern counterparts, others do not, including some unique varieties that are very enriched in magnesium, nickel, and chromium. Mineralogically, these rocks, known as komatiite, are unusually rich in olivine, the major mineral component of the upper mantle. One possible interpretation of these komatiites is that they were derived from an oceanic lithosphere much thinner and with a much steeper thermal gradient than that observed today, resulting in more complete melting of the mantle source.

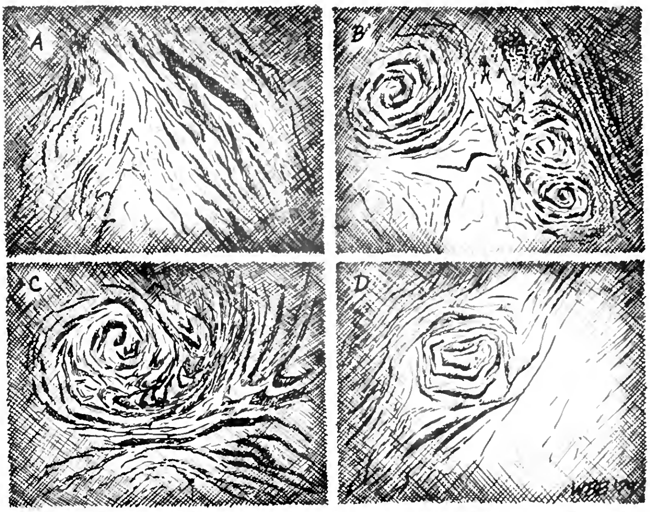
Author Bryan (left) and T.H. Pearce (right) on an expedition in Quebec stand in front of classic Archean pillow lavas.

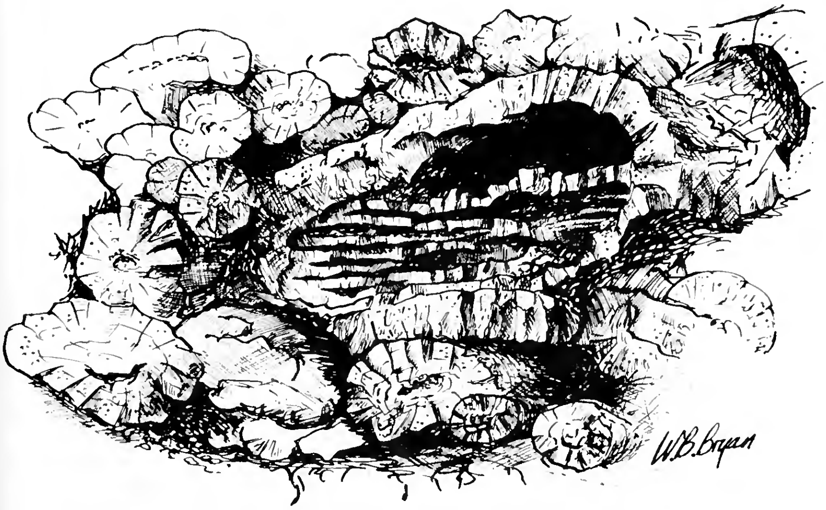
Morphology and Volcanic Processes

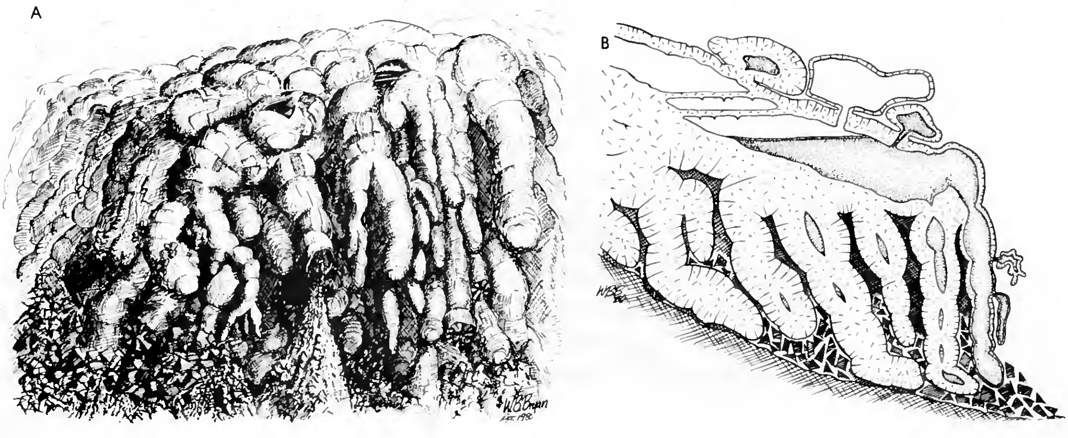
The size, shape, and other morphologic details of ocean-ridge lava flows and associated volcanic structures provide important clues to the locations of eruptive vents, rates of eruption, flow mechanisms, and lava distribution on the seafloor. As for deep-sea basalt compositions, the question whether deep-sea lavas had a unique morphologic character was heatedly debated for nearly a century.

Exposures of these lavas in cliffs, road cuts, or on glacially eroded and smoothed outcrops on land were largely two-dimensional, and left much room for arguments about the lateral extent of individual flows, their three-dimensional forms, and the nature of the larger volcanic structures they built. In cross section many of these lava flows consist of elliptical to circular masses, 2 meters to over 1.5 meters in diameter; these classic "pillow lavas" have been cited as proof of eruption underwater at least since the first half of the 19th century. However, whether these pillows are spherical or tubular in three dimensions, and whether they uniquely indicate underwater eruption, was argued for many years.

Central to these debates was a

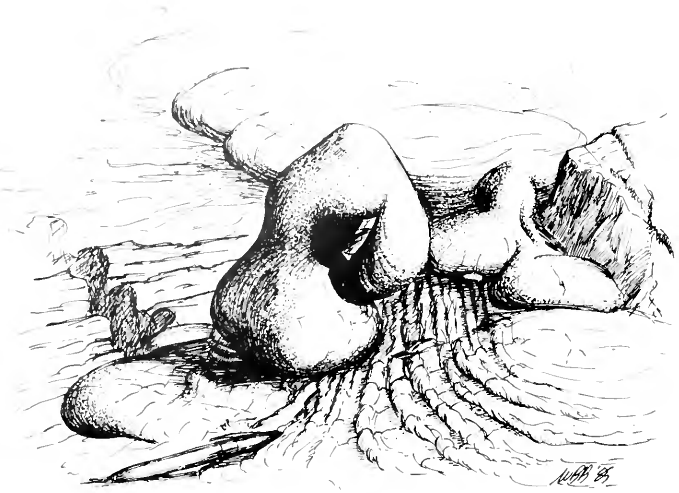






The sizes and shapes of lava flows reveal information about the mechanics of eruptions. Sheet flows from the East Pacific Rise (above) and a layered lava tube in subglacial pillow lava in Iceland (left) are vastly different morphologically. A typical flow from the FAMOUS area (below, left) is further illustrated with a schematic cross section that reveals the draining of lava.

question: Should the term "pillow lava" be reserved only for circular or spherical structures in lava erupted underwater (or at least in wet mud), or should it also be applied to morphologically similar lavas formed on land? The case for purely descriptive use of the term "pillow" was well argued as long ago as 1938 by J. T. Stark, who pointed out that in his even earlier 1914 review of the subject, J.V. Lewis had cited 98 descriptions of "pillow lava" dating back to 1834, of which more than half were probably formed on land. Nevertheless, questions continued to arise as to whether similar morphologies could be produced in different ways. For example, in 1968, J.G. Jones documented "pillow lava" composed of interconnected and elongated tubular lava fingers analogous to the tubular "pahoehoe" lava commonly observed in Hawaiian lava flows (as also advocated by Lewis in 1914!). This interpretation was challenged, and the issue would not be put to rest until the mid-1970s, when scuba divers observed pillows forming on the submarine extension of an active lava flow in Hawaii, and the first direct observation of deep-sea lavas was made by diving scientists in the Project FAMOUS (French-American Mid-Ocean Undersea Study) on the Mid-Atlantic Ridge in 1974. These lavas were indeed composed of elongated tubes, which grow downslope by budding, as Lewis long ago deduced. Recent observations of new submarine flows in Hawaii also confirm that they are fed by master feeder channels that are direct extensions of the adjacent island's pahoehoe lavas.



This "elephant seal" pillow formed at the end of a Hawaiian pahoehoe lava flow.

Diving scientists have provided abundant photographic records, direct observations, and descriptions of the great variety of morphologic details in lavas of the mid-ocean ridges. These observations make it clear that elongated, tubular lava units are common on steep-flow fronts, but pillows take many forms: On the upper flow surfaces some are hollow bubbles, but others are highly ornamented sculptures that resemble animal or human forms. Many similar forms are also found on land on pahoehoe lava flows

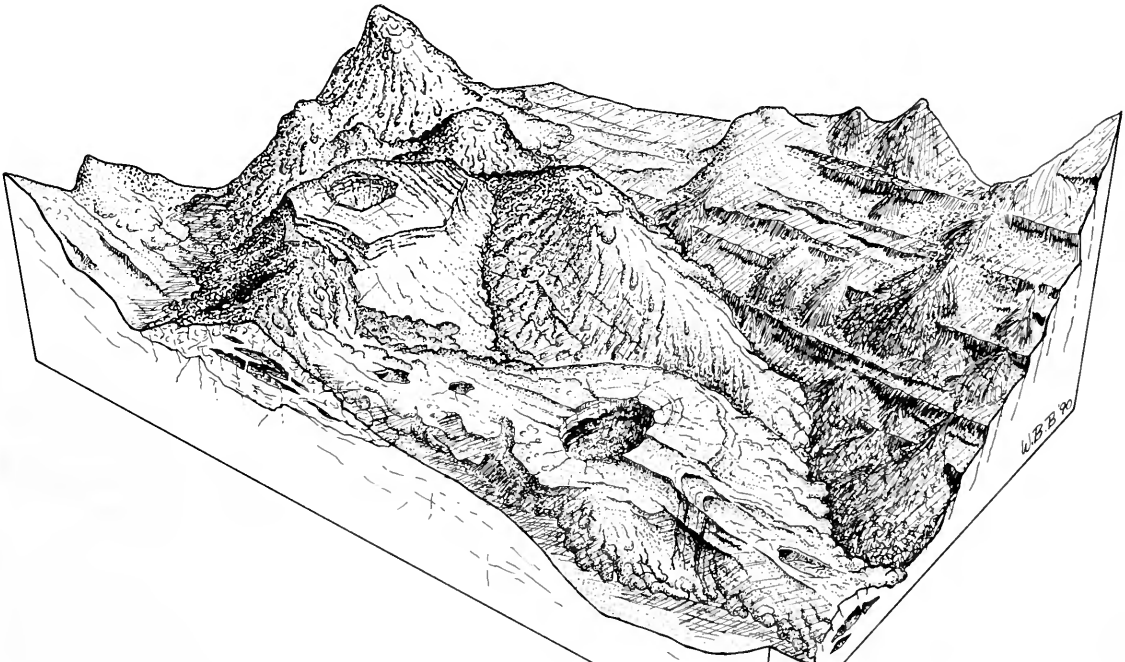
The first submersible dives on the East Pacific Rise showed that many lavas are not pillowed at all, but are composed of slabby plates ornamented with swirls and wrinkles suggestive of drapery or a wrinkled tablecloth. These "sheet flows" form when lava is temporarily ponded. The lava sheets are produced by quenching against the overlying seawater. When lava pressure breaks the barrier and lava drains away, successive layers form as the level of the pond drops. Hollow columns of lava surrounded by "bathtub rings" form within these pits, where trapped water vapor has risen through the lava and quenched it. On land, analogous features are found in "shelly pahoehoe," where lava has temporarily ponded around trees, and in collapse pits formed in lava that erupted onto wet ground. It is now obvious that this diversity of form can be related to a variety of factors, including the steepness of the flow surface, the rate and volume of lava extrusion, and the influence of the underlying seafloor morphology, and that the morphologic differences resulting from quenching in air or water are relatively minor.

Small conical or moundlike volcanic structures form over eruptive vents on the seafloor as they do on land, but few have been described in detail. Some appear to be typical extrusive lava mounds similar to those that form over active lava tubes or along eruptive fissures in Iceland or Hawaii. Larger cratered cones and mounds, common on the Mid-Atlantic Ridge between 22° and 26°N, have been a special focus of study by geologists at Woods Hole Oceanographic Institution. One of these, named Serocki Volcano after one of the Ocean Drilling Program engineers, has been mapped in detail, observed at close range from a submersible, and even penetrated by drilling. These studies indicate Serocki has a flattish, pancakelike form and is probably not a true volcano but rather a "rootless vent." Originally a thick lava delta, the north flank of Serocki broke open, allowing lava trapped within to escape to a lower level, where it again ponded temporarily to form another delta. This delta in turn also broke open, and was drained; collapse of the unsupported surface crust on both deltas created the central craters.

Looking Toward the Future

About 25 years ago, marine geologists and geophysicists first became aware of the vast extent and importance of volcanic activity along mid-ocean ridges. Following initial hopes that the resulting volcanic rocks

Author Bryan sketched this cross section of the Serocki volcano region based on Sea Beam bathymetry, Sea MARC sidescan images, and observations by diving scientists in DSV Alvin. *The Serocki volcano is the large opening at left.*



would prove to be unique and homogeneous, we are continually recognizing the great geochemical and mineralogical variability in ocean-ridge basalts. The morphological similarities of submarine lavas and other volcanic structures to lava flows on well-studied land volcanoes indicates that processes of magma generation and eruption are similar in both environments; thus, lessons learned in the study of the more accessible land-based volcanoes can be applied to volcanic processes on the deep seafloor. Already, some consistent correlations are beginning to appear between certain chemical parameters and first-order geophysical and morphological seafloor properties such as depth, gravity field, and spreading rate. The most profitable future work is likely to come from geophysical and petrologic studies carefully designed to integrate both compositional data and physical properties of the ocean crust into comprehensive models for melt generation, ascent, and the "plumbing system" beneath ocean ridges.

Long-term observatories will be required on selected parts of the Mid-Ocean Ridge system to document eruptive events.

Just as has been true of land volcanoes, long-term observatories will be required on selected parts of the Mid-Ocean Ridge system to document eruptive events, associated seismic activity, and subsequent hydrothermal processes. Although the long controversy about the significance and mode of pillow-lava formation has ended, much remains to be learned about the growth of submarine volcanoes and the mechanisms of lava distribution on the deep seafloor. Individual lava flows must be mapped and sampled in detail, and their morphologies carefully documented. Many morphologically diverse small volcanoes and seamounts associated with active ridges must be imaged, sampled, and restudied as they evolve with successive eruptions.

Such long-term observations are being discussed and planned as part of the National Science Foundation-sponsored RIDGE initiative (See article, page 21), but the magnitude of the commitment required for definitive results is sobering. For example, observations carried on for over 50 years at Kilauea Volcano in Hawaii are only now beginning to yield a meaningful understanding of the volcano's eruption mechanics and deep plumbing system. Further, this length of time still has not been long enough for all styles of activity, as deduced from older lava and ash deposits, to have been repeated for recording and analysis using modern instrumentation. Emulating this work on our largest terrestrial basaltic volcano, the 60,000-kilometer-long Mid-Ocean Ridge system, remains a major challenge.

Wilfred B. Bryan is a Senior Scientist in the Department of Geology and Geophysics at the Woods Hole Oceanographic Institution. He was Chief Diving Scientist in Project FAMOUS, and has participated in studies of volcanic activity on other parts of the Mid-Atlantic Ridge and East Pacific Rise. He was a principal investigator in lunar volcanic landform studies for the Apollo Program and has documented volcanic morphology and processes in Hawaii, the Southwest Pacific, Iceland, Italy, and the western US and Canada.

Tectonics of Slow-Spreading Ridges

Jeffrey A. Karson

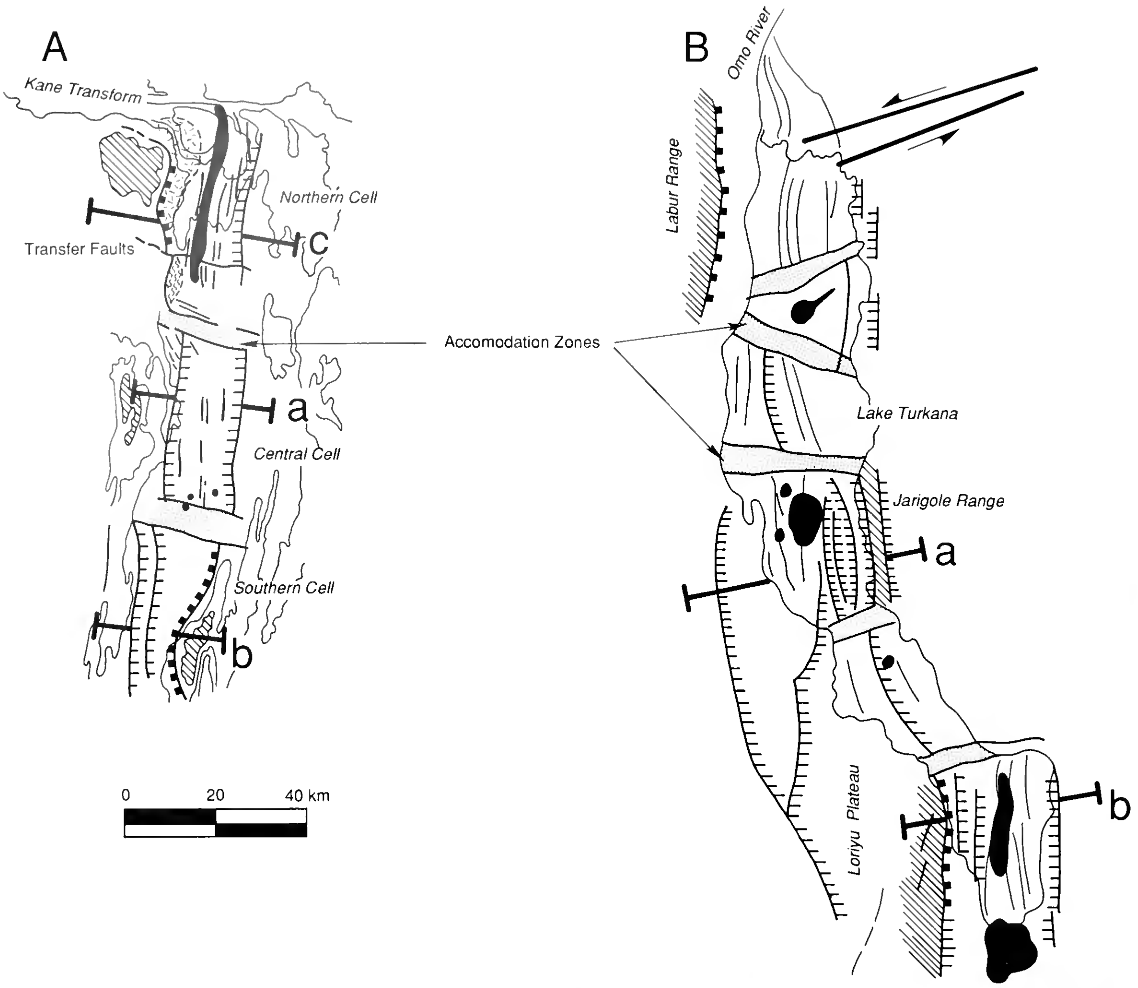
As oceanic plates diverge at mid-ocean ridge spreading centers, two major processes produce and modify oceanic lithosphere. The most familiar of these is magmatic construction in the form of volcanic extrusion onto the seafloor, probably accompanied by the intrusion of dikes and larger bodies of coarse-grained, igneous material beneath the seafloor. Just as important, however, are the effects of mechanical extension, faulting of brittle surface materials, and plastic flow of hotter material in the lower crust and upper mantle. At fast-spreading ridges, magmatism nearly keeps pace with plate separation, so each increment of separation is accompanied by sufficient igneous activity to fill any cracks and fissures in the seafloor and bury most of the minor fault scarps created since previous eruptions. In general, the wound inflicted along the ridge axis is regularly healed, resulting in the formation of what geologists call an "axial summit graben atop a very elongated shield volcano." At any instant in time, the plate boundary resembles a series of linked cracks in brittle material similar to cracks in a pane of glass.

In contrast, slow-spreading ridges display a completely different interplay of mechanical extension and magmatism. Here the magma supply is insufficient to completely restore the faulted axial crust. Magmatism is discontinuous and episodic along the ridge axis despite the relentless separation of the plate edges. The result is that the axial crust at those edges is stretched and faulted in a manner similar to that of continental rifts. This article describes some new insights gained from submersible studies and continental rift analogs.

At any instant in time, the plate boundary resembles a series of linked cracks in brittle material similar to cracks in a pane of glass.

Ridges and Rifts: A Morphologic Comparison

In the late 1950s Bruce Heezen and colleagues at Lamont-Doherty Geological Observatory discovered a deep cleft in the crest of many parts of the mid-ocean ridge system. Based on similarities to profiles of the East African Rift, they considered this cleft to be a rift valley produced by extensional faulting of the oceanic crust. Much that has been learned in the past 30 years about the geologic architecture of land and the seafloor has stimulated a cross-pollination of ideas that derive from the different constraints and limitations of these environments.

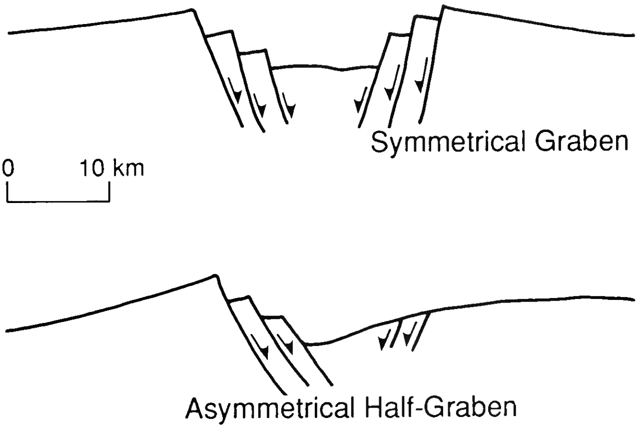


The generalized geologic structure of the MARK Area on the Mid-Atlantic Ridge (A) and the Turkana Rift of northern Kenya (B) allow a comparison of slow-spreading oceanic and continental rifts. Both are composed of a series of discrete rift segments several tens of kilometers in length linked by accommodation zones (stippled). Some segments have neovolcanic ridges (A) or quaternary volcanic centers (B) (black). Hatched areas are rift-shoulder uplifts; dashes are exposures of plutonic rocks; squiggles are serpentinites; bold lines with boxes are major normal faults; and lines with or without tick marks are normal faults and fissures. Bars labeled A, B, C indicate cross sections referred to in the text.

Although continental crust is typically about 35 kilometers thick compared to only about 6 kilometers for oceanic crust, rifts in these two settings are very similar both in scale and form. This is a result of the dominating effect of temperature, which determines the lithosphere's strength and thickness. The lithosphere is hot, thin, and weak at rifts, but becomes thicker and stronger as it cools or moves away from a rift. As it cools, the mantle beneath the crust becomes strong and controls the rifting process. Oceanic lithosphere has a greater proportion of this strong mantle than does continental lithosphere of similar thermal structure or lithospheric thickness, limiting rift development in old oceanic lithosphere.

If the oceans were drained, Earth's slow-spreading ridge systems would resemble the well-known continental rift valleys, for example, the 4,000-kilometer-long East African Rift. The Mid-Atlantic Ridge occupies nearly one-third of the seafloor beneath the Atlantic Ocean. It is broad and undulating, with crests at hot spots like the Azores and Iceland. This large-scale morphology is similar to the 100-kilometer-wide topographic domes of Kenya and Ethiopia, upon which the East African Rift is superimposed. On a finer scale, the continental and oceanic rift valleys are segmented, that is, they are made up of a series of discrete fault-bounded rift valleys. Each segment is several tens of kilometers long and is linked end-to-end with adjoining valleys to form a nearly continuous structure thousands of kilometers in length. Minor offsets, misalignments, and overlaps of the rift-valley segments are typical of both oceanic and continental rifts. This segmentation is also evident in the gravity, magnetics, and seismic characteristics of rifts in both settings.

Viewed in profile, opposing rift valleys are commonly asymmetrical; one bounding wall is higher and steeper than its mate across the axis. Major faults with hundreds to thousands of meters of displacement occur on the steep sides, and smaller faults and smoothly bent layers occur on the lower sides. Thus, half-graben forms are more common than the symmetrical full grabens with equal-sized faults on both sides of the valley. The valley depths are comparable, generally around 2,000 meters. Lavas partially fill both types of rift valley, and sediments deposited in rivers, lakes, and deltas reach several-kilometer thicknesses in the continental rifts. Where the faulted rift-valley walls overlap, the roughly symmetrical fault-bounded troughs called grabens or uplifted blocks called horsts are created. Other areas, where no overlap occurs, may have no rift valley at all, just a rugged, faulted terrane that occupies the ridge axis.



Symmetrical rift segments produced by graben structures are common in many rifts, for example areas marked by bars labeled "A" opposite. Asymmetrical half-graben rift segments are also common, for example areas marked by bars labeled "B" opposite. Note that half-grabens may overlap to create a symmetrical graben morphology.

The Neovolcanic Zone

The neovolcanic zone of the mid-ocean ridge system is the fresh bead of lava that welds the ridge axis together. Along slow-spreading ridges this most-recent volcanic material forms an imperfect seam, with many large globs and gaps. The globs are referred to as neovolcanic ridges; their lustrous lavas and very thin sediment dusting indicate they are only a few thousand years old. The gaps are filled with faulted and fissured lavas that erupted tens to hundreds of thousands of years ago, an earlier version of the neovolcanic zone. The discontinuous nature of the young lavas reveals that these areas are fed by a sputtering magma supply and that the temperature of the lithosphere along the ridge axis is highly variable. The discontinuity of the neovolcanic zone, as well as seismic studies of the rift valley, indicate that there is no continuous magma chamber beneath the axis of slow-spreading ridges. A similar scenario applies to continental rifts. Major differences exist in the eruptive styles of typical oceanic and continental rifts. In continental (subaerial) rifts, extensive basaltic outpourings may precede the formation of a rift valley, and explosive volcanism that produces cinder and ash cones is common. In contrast, submarine rifts are dominated by monotonous fields of pillow-lava mounds and ponded sheet flows.

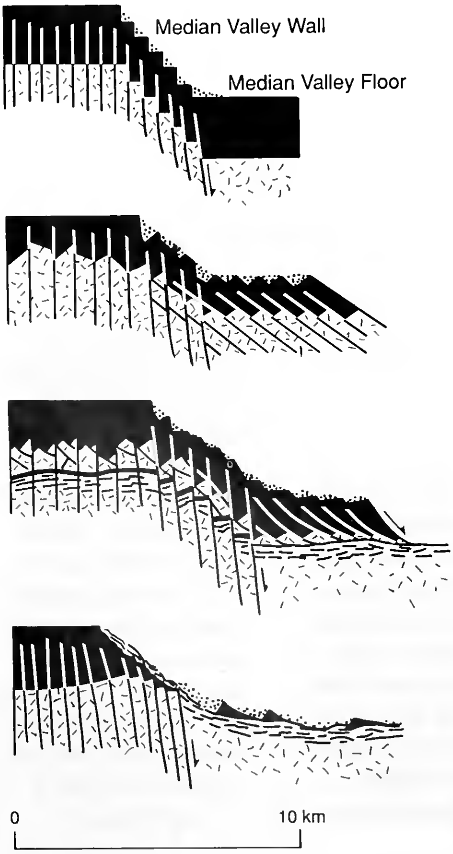
In both continental and oceanic rifts, it appears that young magmatic centers are associated with the rift-valley segments. Whereas small volcanoes appear to have reached the surface through conduits provided by various faults, the largest neovolcanic ridges appear to be centered in well-defined grabens or half-grabens; thus the spacing of volcanic centers appears to be similar to that of rift-valley segments. The distribution of very young volcanic rocks along slow-spreading ridges is known in only a few areas, but in the eastern branch of the East African Rift, extending from the Afar Triangle to northern Tanzania, the young volcanic centers have a remarkably regular spacing of about 3 to 5 kilometers along the rift axis. Future seafloor mapping will determine if a similar volcanic chain exists along the mid-ocean ridge axis.

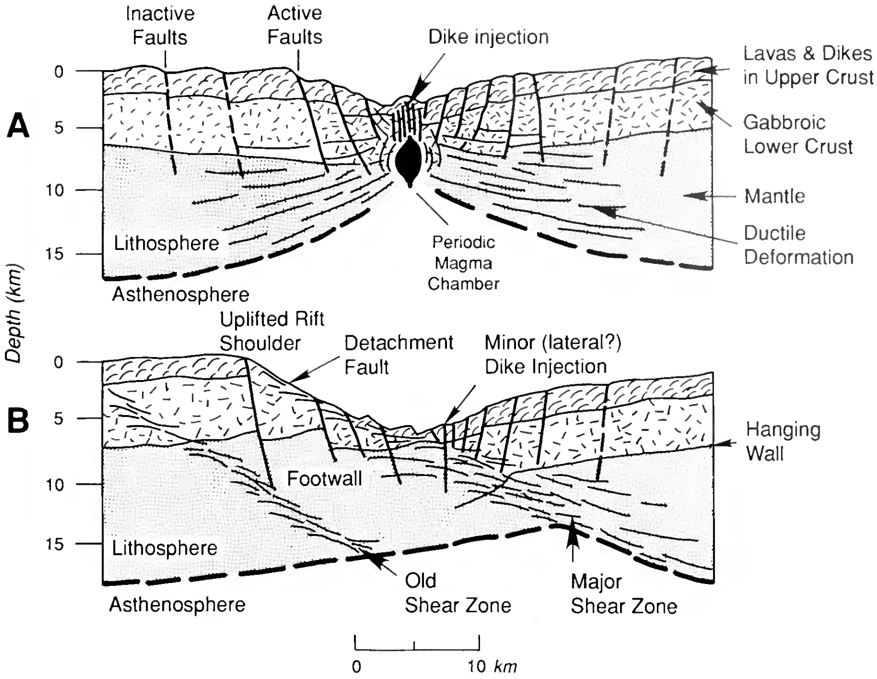
Fault Structure

Axial lithosphere stretching is accommodated by faulting in the upper crust. A number of factors determine the depth of faulting; the most important is the temperature of the lithosphere. In some places, where the lithosphere along the ridge axis is very cold, and where there has not been a recent (less than 1 million years) magmatic event, faulting marked by earthquakes affects the entire crust and even the upper mantle beneath the spreading center. Because the axial lithosphere is relatively thick and strong in such cases, faulting affects a wide area, including the rift-valley walls. In ridge segments where magmatic events have occurred recently (perhaps marked by neovolcanic ridges), the lithosphere is relatively thin and hot and faulting affects only the narrow axial region. It is likely that some ridge segments vacillate between these two situations as axial temperatures wax and wane. Almost certainly a similar variation occurs in continental rifts, but it is complicated by the breaking of thicker, less uniform continental crust with its many preexisting zones of weakness. Still, hot, weak areas are expected to develop a rift architecture distinct from that of cooler areas.

Scientists participating in the first submersible studies of the mid-ocean ridge in the early 1970s described rift-valley walls with numerous closely spaced faults separating narrow blocks of crust and displacing them to form a stair-step structure. Subsequent studies have shown that this is just one of a family of ridge fault structures that includes simple planar faults, curved

Various types of normal faults occur in rifts, including steeply dipping planar faults (top), rotated planar faults creating a domino fault-block pattern (second), listric (curved) faults merging downward into a horizontal detachment fault (third), and detachment faults cutting across the full thickness of the crust (bottom). Steep planar faults dominate the median valley walls of the Mid-Atlantic Ridge creating a stair-step shape and cutting any earlier faults of the median valley floor.





Ductile stretching of the crust and mantle is punctuated by periodic injection of basaltic dikes beneath a symmetrical rift valley with a neovolcanic ridge (A). A deeper, broader, asymmetrical rift valley is created by concentrated slip on a major detachment fault in cooler lithosphere (B), for example section "C" on the left figure on page 52. Episodes of magmatic (A) and amagmatic (B) spreading may alternate over periods of a few hundred thousand years in the same ridge segment. Adjacent spreading segments may be as different as these two extreme examples or an intermediate stage.

"listric" faults, and very large continuous fault zones. All of these have been studied in great detail in continental environments, but links between processes of plastic flow and magmatic intrusion in the lower crust and upper mantle are poorly understood at present.

Although only a few examples of rift-valley faulting have been studied to date, they appear to follow a relatively simple pattern. Areas with relatively high magma supplies that do not display large amounts of extension have simple planar fault structures, and tend to form symmetrical rift valleys where only basaltic rocks are exposed. Good examples are known from the FAMOUS and AMAR rift valleys of the Mid-Atlantic Ridge. Areas with somewhat larger amounts of stretching and less magmatism become asymmetric as faulting on one side of the rift valley begins to dominate. Listric and low-angle detachment faults occur in some limited areas such as the TAG site. More stretching results in extreme extension along gently to moderately inclined fault zones, and may result in the exposure of materials once deeply buried. In the most extreme situation known, a chaotic faulted assemblage of mixed upper-crustal and mantle materials occurs across a ridge axis in the MARK area. Although some cross sections in this area lack a clearly defined rift valley, the ridge axis is nevertheless very highly extended. This spectrum of fault structures mimics that of continental rifts. In both settings, the amount of crustal stretching and displacement that individual faults have sustained can be read in the types of rocks exposed just beneath the fault surfaces. In the oceans, small amounts of extension result in exposure of only basaltic rocks of the upper crust, while large amounts can expose once deeply buried lower crustal rocks. In oceanic areas, where the crust is only 6 kilometers thick, even upper-mantle rocks can be exposed.

Highly Extended Terranes

In both oceanic and continental rifts, prolonged periods of plate separation with little or no magmatic activity result in extreme stretching of the crust and upper mantle as described. Such highly extended terranes are well known in continental areas such as the Basin and Range Province of the western US, where faulting has been localized along individual fault surfaces called "detachment faults." These gently inclined dislocation surfaces cut across rock units and smaller faults of the upper crust that are free to rotate in a fragmented upper plate. Beneath, more plastic flow occurs in a lower plate.

There is continuing debate concerning the inclination of these faults when they were actually slipping. One school of thought argues that only steep faults are mechanically feasible, and that the detachments were formed by the rotation of steep fault segments that coalesced into a single longer segment. Others propose that low-angle detachments have maintained their near-horizontal attitude as fault blocks rotated above them, allowing the detachment fault and lower-plate rocks to come closer to Earth's surface. Still another hypothesis holds that the detachments are individual giant faults, along which lower-plate rocks have been pulled from deep beneath the overlying upper plate. In this case, the detachment surface would be warped by vertical movements driven by gravitational adjustments, maintaining a gently inclined attitude.

In the past few years, seismic reflection studies have provided remarkable new images of the oceanic crust's internal structure.

Regions of significant stretching also appear to exist along mid-ocean-ridge spreading centers. Like continental detachment faults, they are marked by major fault surfaces that expose deep crustal or even upper-mantle rocks at the surface, or juxtapose them with shallow-level rocks. In these areas, faulting must have been localized along single-fault surfaces for long periods of time as plate separation continued. As a result, 2 to 5 kilometers of crustal rocks have been stripped of underlying deep-crustal and upper-mantle materials.

Unfortunately, areas of such exceptional faulting are difficult to find. At present, there is no unambiguous link between the morphology of the rift valley and the type of fault structure and rocks exposed there. This is because numerous steep faults often cut and break up the large detachment surfaces, giving even highly extended rift valleys a form not unlike their less-stretched cousins. Studies of continental rifts show that earthquakes detectable with conventional instruments occur only on steeply inclined faults. Slip on buried, low-angle detachments is known to occur in some areas from the study of surface structures, like upper-crustal faulting. Although required to link upper-crustal faulting to flow in the lower crust, slip on such surfaces appears to occur without major earthquakes. In the oceans, such seismically quiet displacement could be taking place undetected, because we have no detailed seismic studies or maps of surface faults.

In the past few years, seismic reflection studies have provided remarkable new images of the oceanic crust's internal structure. One surprising feature of these sonograms is that they reveal numerous low-angle reflectors cutting across the entire crust and sometimes intersecting the surface at probable fault scarps. These structures appear to be major detachment faults in the oceanic crust, spaced at about 30-kilometer intervals. This translates to a periodicity for major faulting and magmatic events of about 300,000 years, some 30 times longer than estimates based on the apparent ages of lavas in the median valley floor. At present, the interpretation of these features (as well as other intracrustal reflectors) is still debated; however, considering the rift valley's presently known geology, detachment faulting is the most logical explanation.

Detachment faulting is also the most likely means of exposing coarse-grained gabbroic and peridotitic rocks of the deep crust and upper mantle along oceanic rift walls. The conditions that result in extension with little or no magmatism could conceivably occur in any ridge segment. However, persistently cool spots along the spreading centers would be very likely places for these conditions. The intersections between rift segments and oceanic transform faults where a ridge axis abuts a cold transform-fault wall are thought to be lithospheric cool spots that may have very limited magma supplies. They are, therefore, likely places for this type of extreme faulting. If cool, stretched crust were formed at a ridge-transform intersection, it would pass laterally along a transform fault and become the wall of an oceanic fracture zone. This may explain the common occurrence of deep-level rocks along fracture zones.

Connecting Structures

The diversity of fault structures along slow-spreading ridges suggests that transfer zones are important components of rift valleys.

Individual rift segments are connected end-to-end by various types of linkages. Some are discrete crustal faults while others are more diffuse regions of bending or shattering. These features can be considered collectively as "transfer zones," a term first used to describe linkages in compressed and folded rocks of mountain belts, and useful to describe the geometry and kinematics of rift linkages as well. Transfer zones in continental rifts take many different forms, depending upon the character of the faults in the rift segments they join. The diversity of fault structures along slow-spreading ridges suggests that transfer zones are important components of rift valleys. For example, different types of transfer zones link rift-segment pairs that differ in amount of crustal stretching, amount and timing of magmatic events, rate of stretching, and style of faulting. In many cases asymmetrical rift-wall faults overlap to create a class of transfer structures referred to as "accommodation zones" that are typical of continental rifts. If small amounts of extension have occurred, simple ramps or folds may suffice to transfer the effects of faulting from one rift segment to the next. This geometry appears to be typical of many oceanic and continental rifts. However, major faults with large horizontal displacements may be required if large amounts of extension occur in even one segment. The well-known transform faults that occur along spreading centers can be regarded as just the largest of a family of these transfer structures.

The asymmetry of the median valley of the Mid-Atlantic Ridge and the geometry of steep linear slopes that suggest major faults create a pattern very similar to that of continental rifts. At present, however, the details of fault geometry and slip directions for mid-ocean-ridge spreading-center segments and possible linking transfer zones are almost completely unknown. The morphologic similarity, however, suggests that the growing body of detailed information on continental-rift faulting can be applied at least in a general way to slow-spreading ridges.

It is important to recognize that the morphology of oceanic and continental rifts is not necessarily a reliable indicator of their fault structures. In particular, low-angle faults and strike-slip faults that do not produce significant topographic or bathymetric relief are difficult to detect with remote mapping systems such as multi-beam echo sounders, including Sea Beam, or sidescan sonar systems like Sea MARC. Thus, the present perception of oceanic rift structure is strongly biased by steep faults with significant vertical offsets. These are certainly important components of oceanic rifts; however, in some cases they represent only a small amount of the total extension revealed by fault structures and lithologic associations documented by detailed near-bottom investigations. It is clear that mapping seafloor morphology with remote-sensing systems will not be sufficient to evaluate the geometry and extent of faulting for segments of the mid-ocean ridge system. Much more detailed near-bottom sampling and mapping from submersibles such as *Alvin* or remotely operated vehicles like *Argo-Jason* will be required.

Fast-spread crust is likely to be uniform and continuous; slow-spread crust is apt to be much more heterogeneous.

Implications of Major Faulting on Slow-Spreading Ridges

The recognition of major faulting in the median valley of slow-spreading ridges has some important implications for understanding seafloor-spreading processes and oceanic-crust production in these environments. First, the extreme faulting found in some places, like the MARK area and some transform-valley walls, suggests that long periods (perhaps as long as 1 million years) of plate separation occur with little or no magmatic construction. This implies that long magmatic "droughts" occur at least locally along the ridge axis, contrasting sharply with observations on fast-spreading ridges that suggest a persistent, robust magma supply. It follows that the end products of accretion of fast- and slow-spreading ridges may be very different geologically. Whereas fast-spread crust is likely to be characterized by a generally uniform and continuous geologic structure, slow-spread crust is apt to be much more heterogeneous. Swaths of slow-spread crust tens of kilometers across probably resemble that created at fast-spreading ridges. However, if the geology of the present-day median valley of the Mid-Atlantic Ridge is a valid guide to slow-spreading processes in general, there must also be patches of highly disrupted and broken crust that might be essentially a jumbled mass of faulted oceanic crustal and upper-mantle blocks that are locally welded together by intrusive dikes and lava flows. This inference must somehow be reconciled with the well-documented fact that the seismic structures of fast- and slow-spread crust are nearly identical. It is probable that the seismic structure is dictated by fractures and rock porosity rather than rock compositions, a possibility that would limit the usefulness of seismic studies in oceanic geology investigations.

The extreme type of faulting described above also raises some questions regarding the origin of lineated marine magnetic anomalies. How can they persist if the basaltic layer of the crust, generally thought to be the source of magnetization, is highly faulted and even discontinuous? Typical lineations are found over several areas where basaltic rocks have been faulted away to expose deep-crustal or even upper-mantle rocks. These occurrences suggest that magnetic lineations can also be produced by the magnetization of metamorphosed deep-crustal and upper-mantle material. This seems feasible if the magnetization is acquired during faulting close to the median valley, the same place the basalts have their magnetization frozen-in during normal spreading.

Faulting produces the major fracture porosity in all parts of Earth's crust. If the fault patterns of continental rifts can be used as a template for slow-spreading ridges, it should be possible to predict the fault and porosity patterns of the seafloor at least in a general way. Faulting and fracture porosity are likely to control the locus of magmatism and hydrothermal venting along spreading centers, just as they do in continental settings. This relation could help explain patterns of volcanoes and black smoker vents that are just beginning to emerge from near-bottom studies, and might even prove important as a prospecting tool for spreading-center ore deposits.

There is a growing awareness that fast- and slow-spreading ridges function in very different ways. The sputtering magma supply of slow-spreading ridges results in substantial periods of plate separation that involve stretching and faulting of relatively cool oceanic lithosphere with little or no magmatism. The fault patterns of the median valley appear to mimic those of continental rifts; however, at least locally, very highly stretched and thinned masses of crust and upper mantle occur. The median-valley geology and fault structure documented by near-bottom studies predict a very heterogeneous geological structure in slow-spread crust. This result is yet to be clearly defined or reconciled with the geophysical expression of the crust away from spreading centers. Future studies of the geometry and kinematics of faulting on slow-spreading ridges will determine the nature of faulting over much larger areas than have been studied to date, and will help contribute to the overall understanding of how the lithosphere is pulled apart to form rifts in both the continents and the seafloor.

There is a growing awareness that fast- and slow-spreading ridges function in very different ways.

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Mid-Ocean Ridge Seismicity

Eric A. Bergman

Seismologists soon realized that a relatively narrow band of earthquakes could be traced through many of the world's ocean basins.

The earliest observations of earthquakes in deep-ocean basins were reported by seamen whose ships were rocked by undersea disturbances, and by residents of oceanic islands such as the Azores and Iceland. Scholarly studies based on eyewitness accounts of so-called "seaquakes" began in the late 19th century, but systematic investigations of oceanic seismicity did not begin until a global network of earthquake observatories was established in the early decades of this century. By the 1920s the International Seismological Summary (ISS) was routinely compiling data from cooperating stations, and publishing earthquake locations. Seismologists soon realized that a relatively narrow band of earthquakes could be traced through many of the world's ocean basins. The earthquakes were associated with the mid-ocean mountains that had been revealed by early oceanographic surveys, but the global continuity of mid-ocean ridge seismicity was not demonstrated until the mid-1950s.

For several decades after these initial discoveries, mid-oceanic earthquakes attracted relatively little research interest. Most seismic stations were in the northern hemisphere and most instruments recorded at low gains (that is, the signals were not magnified). As a result, the long-distance, or teleseismic, detection threshold varied dramatically in different regions, and the accuracy for locations in remote oceanic areas was poor. Magnitudes could be estimated only for the largest earthquakes. Limited knowledge of the geology of the mid-ocean ridge system also inhibited seismological research.

This humble status began to change in the late 1950s. Seismology was invigorated by the emphasis on global geophysical observations during the 1957-58 International Geophysical Year (IGY) project. Also, deployment of new seismic stations to monitor tests of nuclear explosions resulted in improved detection and location capabilities for earthquakes as well. In addition, the introduction of computers for data processing and earthquake location made global monitoring of smaller earthquakes possible.

The importance of mid-ocean ridge seismology soared in the late 1960s, when it provided compelling evidence for the plate-tectonic hypothesis. Growing catalogs of accurately located earthquakes brought clear delineation of plate boundaries on seismicity maps, and first-motion studies confirmed predictions regarding the geometry of faulting at different types of plate boundaries. This success can largely be attributed to the establishment in 1963 of the World-Wide Standardized Seismograph Network (WWSSN), a global network of about 100 seismic stations equipped with well-calibrated and standardized seismometers. The improved global distribution of these stations and their relatively high magnification of seismic signals significantly lowered the detection threshold in oceanic regions. A notable advance was establishment of a central archive from which complete seismograms from all the WWSSN stations could be obtained quickly. For the first time it became relatively easy for a researcher to collect all the data needed for a detailed source study of an earthquake almost anywhere in the world.

Analytical techniques for digitized wave-form seismic data (both body and surface waves) were developed in the 1970s. Except that they had to be hand-digitized, the long-period WWSSN data were well-suited for studies on the moderate-sized earthquakes typical of mid-ocean ridges. At the same time, the first digital seismometers were deployed. These stations eliminated the unpleasant task of digitizing analog records for analysis, but the early instruments were best suited to earthquakes that were larger than is typical for mid-ocean ridges. Also, there were simply too few stations deployed to use them exclusively for source studies in most areas. This situation is changing rapidly: Broadbanded digital stations are being deployed by institutions and countries, with the goal of obtaining global coverage at least as good as what WWSSN provided. Seismologists will soon have the luxury of working exclusively with digital data for global earthquakes studies.

With the proliferation of digital seismic stations, digital analysis techniques for earthquake source studies have become quite sophisticated. It is now standard practice to perform a formal inversion for source parameters such as depth, focal mechanism, and seismic moment (a measure of earthquake size that has many advantages over magnitude). Systematic studies of mid-ocean ridge earthquakes have produced many insights concerning the tectonics of accreting plate boundaries. Application of these techniques is still limited to the largest mid-ocean ridge earthquakes, however; further progress depends on improvements in our ability to study smaller earthquakes.

Systematic studies of mid-ocean ridge earthquakes have produced many insights concerning the tectonics of accreting plate boundaries.

Establishment in 1964 of the International Seismological Centre (ISC) stimulated global seismology significantly. The ISC collects phase readings from thousands of seismic stations, associates them with particular earthquakes, locates the earthquakes, and publishes the data and results in a widely circulated bulletin. A whole new class of seismological research is based on the availability of the entire ISC data set since 1964 in machine-readable format (magnetic tape and CD-ROM).

Techniques are now being applied to mid-ocean ridge earthquakes that improve epicenter location for smaller earthquakes and help to correlate epicenters with geological features. These techniques, which simultaneously locate many earthquakes in a region, provide useful information about the location of mid-ocean ridge earthquakes with magnitudes as low as 4.5 on the Richter scale (a logarithmic scale of earthquake magnitude from -3 to 9—the highest recroding to date is 8.9).

In the 1970s we began to study smaller oceanic earthquakes using temporary (up to a few weeks) deployments of sonobuoy arrays and ocean-bottom seismometer (OBS) and hydrophone arrays. Epicenters and focal depths can be determined with great accuracy for microearthquakes occurring within the array, but the relatively low rate of occurrence of earthquakes on mid-ocean ridges and the technical difficulty of deploying (and recovering) enough instruments to permit useful seismological analysis has doomed many such studies to disappointment. Progress in battery and data-storage technology, however, is extending deployment times. Technology that permits rapid deployment of seismometers on targets of opportunity will play a significant role in the future of mid-ocean ridge seismology.

The maximum magnitude of earthquakes occurring in close association with spreading segments is strongly correlated with spreading rate.

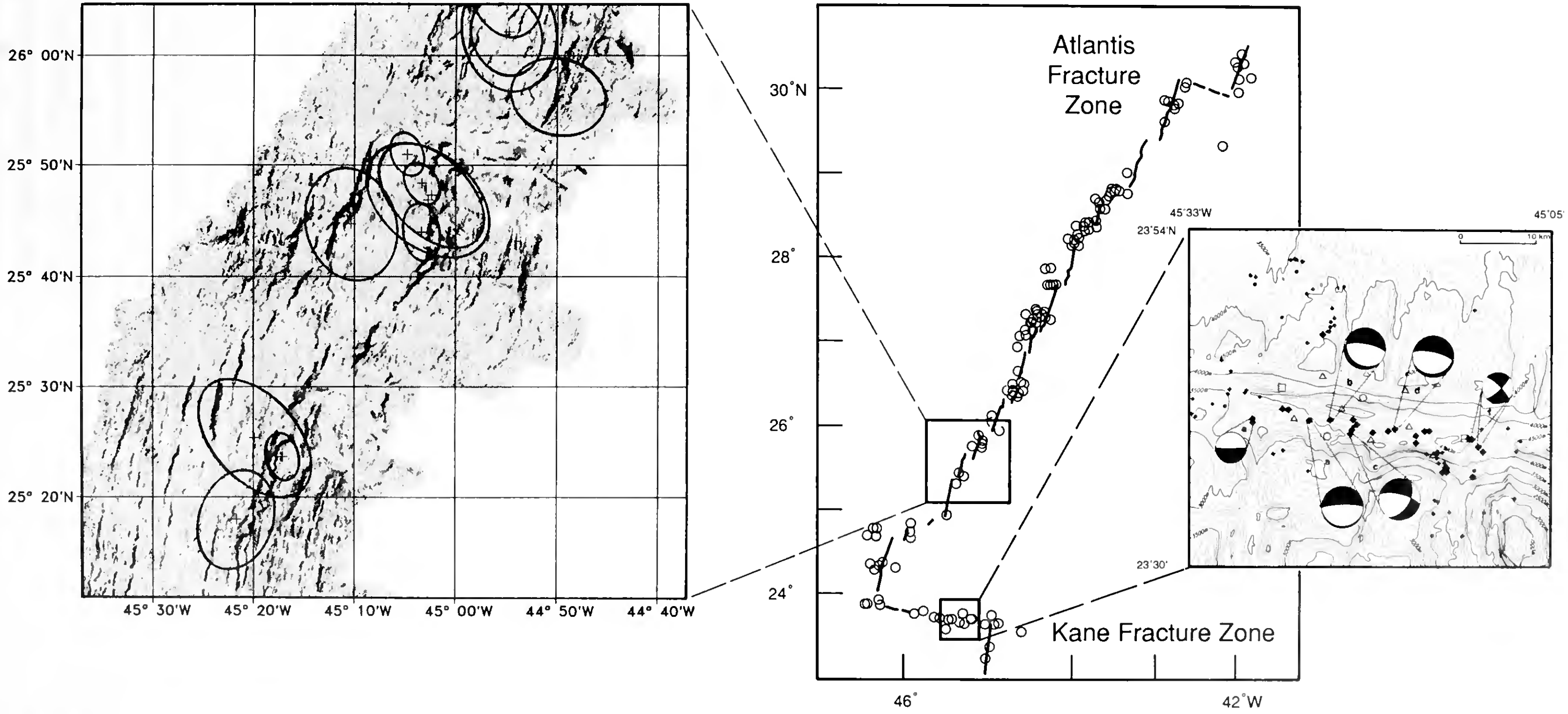
A Note on the Importance of Thermal Structure: Before discussing the characteristics of mid-ocean ridge earthquakes, it is worth emphasizing that the depth distribution of earthquakes is closely linked to the thermal structure of the lithosphere. Earthquake faulting is commonly considered to be analogous, if not identical, to the phenomenon of brittle failure, which is the usual mode of deformation of small samples of crustal and upper-mantle rocks at low temperatures. At sufficiently high temperatures, ductile deformation relieves an applied stress before the brittle-failure limit is reached, and no earthquakes occur. In any given tectonic environment, therefore, the depth distribution of seismicity provides information about the thermal structure. Conversely, prior knowledge of the thermal structure can be used to interpret the seismic data more fully.

Earthquakes on Spreading Ridges

Given the difficulty (so far) in observing an actual spreading episode on any deep-ocean ridge segment, earthquakes are perhaps the most dramatic indicators of the tectonic processes involved in the creation of new oceanic crust. A major issue in mid-ocean ridge seismology has been the extent to which earthquakes signal active magmatism at shallow crustal levels. The observations summarized below are beginning to reveal the answer to this question, but much work remains to be done.

The maximum magnitude of earthquakes occurring in close association with spreading segments of the mid-ocean ridges, so-called "ridge-axis" events even though few probably occur in zero-age (true ridge axis) crust, is strongly correlated with spreading rate. At slow-spreading ridges with well-developed rift mountains and a median valley, such as the Mid-Atlantic Ridge (MAR), earthquakes reach a maximum magnitude of about 6.0, while at the fast-spreading ridges of the East Pacific Rise (EPR), very few earthquakes reach even the teleseismic detection threshold, about 4.7, and the ridge segments appear to be aseismic on global seismicity maps. Microearthquake surveys show that these ridge crests are seismically active at lower magnitudes, however.

Ridge-axis seismicity frequently occurs as swarms of earthquakes that usually last a day or two, although a few sequences lasting weeks are known. As much as 50 percent of the ridge-axis seismicity is estimated to be associated with this sort of cluster, so understanding the tectonic significance of this seismicity is an important research goal. Because swarm seismicity is frequently observed in terrestrial volcanic centers, ridge-axis swarms are sometimes thought to reveal ongoing



Charting seismicity on the Mid-Atlantic Ridge between the Kane and Atlantis transforms as determined from bathymetric, gravity, and magnetic data reveals the traces of active spreading segments. Sea Beam swath-mapping data were used to create the base map at left, where earthquake epicenters on a portion of the Mid-Atlantic Ridge between Kane and Atlantis transforms are plotted. Ellipses indicate the 95 percent confidence region for the location of each event. Regions of high slope are darkened, emphasizing the major fault scarps that bound the median valley. Note the association of the earthquake epicenters with these bounding scarps. At right, microearthquakes located by ocean bottom hydrophones and seismometers on the eastern end of the Kane transform are shown by the diamonds. Fault-plane solutions were determined from first motions. Instrument locations are shown by open symbols. (Figures at center and left are courtesy of Jian Lin; figure at right is courtesy of W.S.D. Wilcock.)

volcanism. Many characteristics of swarm seismicity on the MAR are more consistent, however, with the view that most such earthquakes are expressions of extensional tectonics, in particular, formation of the steep scarps bounding the median valley. With few exceptions, seismicity directly related to ongoing volcanism probably occurs at magnitudes below the teleseismic detection threshold; this is one of the reasons for the current emphasis on monitoring mid-ocean ridge seismicity at microearthquake magnitudes.

Ridge-axis seismicity is well correlated with the segmentation of slow-spreading ridges, which is revealed by bathymetric, magnetic, and gravity data. The larger swarms sometimes extend for several tens of kilometers along the axis, but the length of individual fault scarps seldom exceeds about 10 kilometers. Together with the limit on depth of faulting discussed below, this fact largely explains the upper limit on magnitude (about 6.0) for MAR ridge-axis earthquakes. The seismically active portion of the ridge is about 10 to 20 kilometers wide, comparable to the median-valley width. Few earthquakes are located beyond the rift-mountain crests, except for relatively rare intraplate events farther from the ridge.

The seismically active portion of the ridge is about 10 to 20 kilometers wide, comparable to the median-valley width.

Studies of the depth ranges of seismic activity show that earthquakes of all magnitudes are generally confined to the upper 8 to 10 kilometers of slow-spreading ridge segments, and the depth limit becomes shallower with increasing spreading rate. The depth limit on ridge-axis earthquakes reflects the depth of a limiting isotherm that is determined by the balance between heat input from the upper mantle and heat removal from the upper few kilometers of the crust by hydrothermal circulation. At higher spreading rates, the increased heat input reduces the volume of crust capable of supporting brittle failure to the point where no earthquakes that can be detected from land-based seismic stations occur.

To explain the seismological observations summarized here, as well as other types of geophysical studies on mid-ocean ridges, a current hypothesis holds that the median valley of slow-spreading ridges is formed by the necking of a mechanically strong brittle lithosphere under regional horizontal extension, and that the thickness of this necking zone corresponds to the maximum depth of seismic activity. When mid-ocean ridge seismicity is analyzed with this model, seismogenic extension in the median valley is found to account for about 20 percent (at most) of the plate-separation rate. The remainder must be taken up by nonseismogenic processes, notably the creation of new ridge-axis crust by volcanic activity.

Transform Fault Earthquakes

Transform faults are the most seismically active portions of the mid-ocean ridge system. Even at high spreading rates, where ridge-axis seismicity apparently vanishes, transforms are usually well defined by earthquake epicenters. Transform faults also produce significantly larger earthquakes than ridge segments, commonly up to about magnitude 7. Perhaps the most important parameter controlling earthquake size on a transform is the age offset, that is, the age of the lithosphere opposite each ridge-transform intersection. Given two transforms with equal

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lengths but different age offsets, the transform with the greater age offset should support larger earthquakes because the isotherm that limits the maximum depth of faulting on the transform will be deeper.

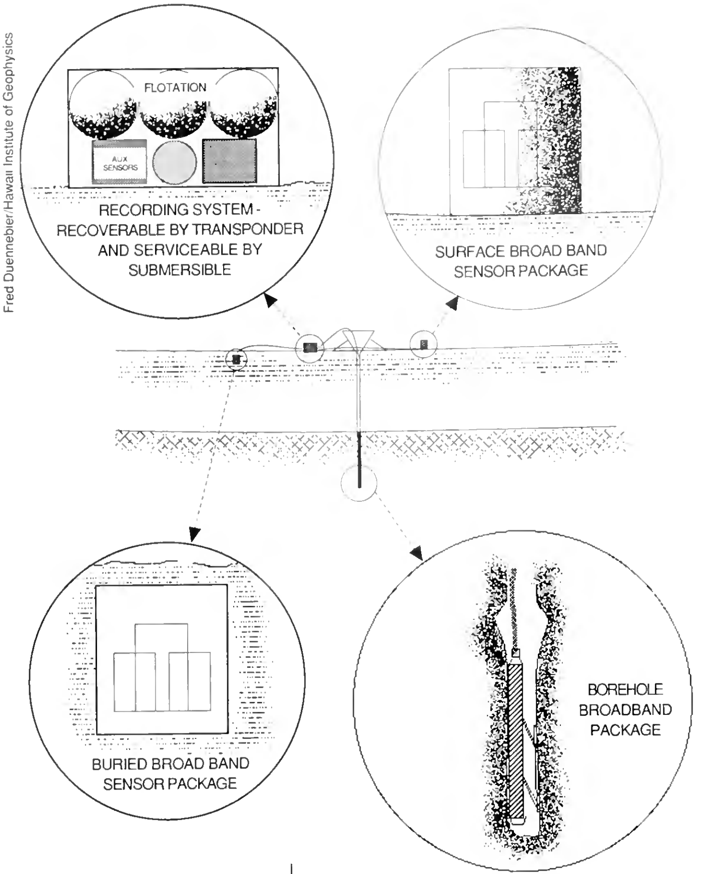
Early first-motion studies of transform earthquakes revealed strike-slip faulting on near-vertical fault planes, striking parallel to the direction of plate motion. Detailed source studies using wave-form inversion methods generally confirm these results. All known strike-slip events have a sense of slip that is consistent with the transform hypothesis, but it appears that there are exceptions to the "near-vertical fault plane" observations: two large events on the western end of the Vema Transform (10°N on the MAR) both have fault planes that dip into the north, toward younger lithosphere, at angles of 50° to 60° from the horizontal. Also, several cases of transform earthquakes with largely compressed or extensional focal mechanisms are known, and complex rupture histories are rather common in the larger strike-slip earthquakes. The main pulse of rupture is often preceded or followed closely by smaller pulses that sometimes appear to have a faulting geometry different from that of the main rupture. Dip-slip faulting, whether expressed as a subevent during a dominantly strike-slip transform event, or as an individual earthquake, is thought to be caused by heterogeneities in the fault system on which transform motion occurs. These narrow (less than about 5 kilometers) zones apparently migrate within the larger transform valley in response to variations in the regional crustal structure and stress system.

The largest transform earthquake in the last three decades on the northern Mid-Atlantic Ridge was a magnitude-7 event on the Vema Transform in 1962.

The observed segmentation of many transforms raises the issue of whether an entire transform ever slips in a single earthquake. Such events appear to be rare. Shorter transforms with relatively linear fault zones would be the most likely candidates for a "home run" of this sort, but the largest earthquakes generally occur on the longest transforms. Long transforms are likely to develop heterogeneities that would tend to prevent a rupture, once initiated, from propagating to both ends of the fault zone. For example, the largest transform earthquake in the last three decades on the northern MAR, a magnitude-7 event on the Vema Transform in 1962, has a rupture length of about 40 kilometers, compared to the 300 kilometer length of the transform. It is not even clear that the entire length of all transforms produces large earthquakes. Most transforms contain sections that have not slipped during the few decades for which reliable records are available.

The depths of large, shallow, strike-slip earthquakes are especially difficult to determine using wave-form analysis techniques. The transform events that have been studied with these methods all appear to rupture through to the seafloor, but for some events only an upper bound on the maximum faulting depth can be assigned. Large transform events on the MAR north of the equator appear to involve rupture no deeper than 15 to 20 kilometers. The depth-limiting isotherm appears to be 900° plus or minus 100°C for most of these transforms. Depths of transform earthquakes in the Gulf of California are consistent with a limiting isotherm of about 800°C. Recent large earthquakes on the 15°20′ Transform appear to be an exception to this pattern, however; they have maximum depths of faulting of about 10 kilometers, corresponding to a nominal isotherm of about 600°C. One explanation for this observation is that the limiting isotherm for this transform may be at shallower depths than calculated from a standard thermal model; this could reflect recent changes thought to have occurred in the geometry and location of the North America–South America–Africa triple-plate junction.

Few microearthquake surveys are available for transforms, but a recent study on the Kane Transform produced two surprising results: the microearthquake activity was concentrated off the expected zone of transform motion, both to the north and south; and the focal mechanisms of the microearthquakes indicated normal faulting and strike-slip faulting (inconsistent with transform motion) with the axis of horizontal extension oriented across the transform. Proposed geodynamic models predict stress fields in the vicinity of oceanic transforms, but the underlying theory is controversial and there is little evidence available to test the hypothesis. Further microearthquake studies are needed to determine whether the observations on the Kane Transform are representative of oceanic transforms.



Fred Duennebier/Hawaii Institute of Geophysics

Several approaches are being investigated for deploying high-dynamic range, broadband seismometers in deep ocean basins for the Ocean Seismic Network. These types of instruments would greatly enhance the ability to monitor mid-ocean ridge seismicity.

Transform faults are an end member of a spectrum of geologic features associated with offsets of mid-ocean ridge spreading segments. Little is known about the seismicity associated with very small offsets. From a seismological point of view, it is natural to define a transform as an offset capable of producing an earthquake with the characteristic strike-slip focal mechanism. This definition may not be consistent with one based on morphology; the issue has yet to be investigated. Obstacles to such a study include obtaining sufficiently accurate epicenters to unequivocally place earthquakes on small ridge offsets and the lack of a reliable means to determine focal mechanisms for earthquakes with magnitudes less than about 5.

The Future

The continued application of modern seismological analysis techniques for improved location and source studies will undoubtedly help to clarify some of these issues. The next significant pulse of activity in mid-ocean ridge seismology is likely to be driven, however, by technologies and observing programs that allow earthquakes to be studied at lower magnitudes than is possible with any conceivable land-based seismograph system, and for longer times and over wider areas than is possible with the current ship-deployed OBS technology.

One current plan for monitoring the seismicity of selected mid-ocean ridge segments at magnitude levels well below the teleseismic threshold makes use of waterborne T-phase data recorded at permanent hydrophone arrays operated by the US Navy. These data would be especially valuable for monitoring swarm seismicity that may indicate active volcanism. Researchers are also discussing strategies for responding rapidly and effectively to such events when they are observed. A recent successful response to earthquake swarms on the Reykjanes Ridge included dropping sonobuoys and other geophysical instruments from long-range military patrol planes flying from Iceland, and diverting oceanographic research vessels that happened to be in the area (see Box on page 23).

Permanent seafloor geophysical observatories are also on the horizon. In some plans, instruments would be deployed autonomously on the seafloor or in boreholes, in others they would be attached to old undersea telephone cables that have been converted for scientific use. One such cable crosses the Mid-Atlantic Ridge in the FAMOUS region near 37°N. If these technologies are developed and deployed, they will undoubtedly spark a new round of interest in mid-ocean ridge seismology.

Eric A. Bergman is a Geophysicist at the National Earthquake Information Center of the US Geological Survey. His research interests include the seismotectonics of oceanic mid-ocean ridges and intraplate regions, analysis techniques for improved determination of earthquake locations and source characteristics, and the state of stress in the lithosphere. He is currently active in the International Seismological Observing Period Project, a program to coordinate and enhance the observational activities of seismic observatories worldwide.

Seabeam Maps of the Mid-Atlantic Ridge Available

A limited number of copies are available
of a map series that covers
the crest of the Mid-Atlantic Ridge
between latitudes 24°-31°N.

The Seabeam data are presented at a contour interval of 50 meters and a scale of 30 inches per degree of longitude in a series of eleven color plates each measuring approximately 36 by 42 inches. These are reprints of the maps published in *Marine Geophysical Researches*, Volume 12, pages 247-252, 1990. They are suitable both for original studies of the morphological characteristics of slow-spreading ridges and for teaching practical classes in the understanding and interpretation of high resolution multibeam bathymetry data.

Upon request, copies of these maps will be mailed at no cost to U.S. academic institutions or Government agencies, providing a brief statement is supplied that describes their intended use. Multiple copies are available for teaching purposes if a clear statement of the nature of the course is provided. Requests from outside the U.S. will be honored only if resources permit. Please send requests to:

Dr. G.M. Purdy, Department of Geology and Geophysics,
Woods Hole Oceanographic Institution, Woods Hole, MA, 02543.

Hydrothermal Vent Systems

Margaret K. Tivey

Hydrothermal systems transfer large amounts of heat and mass from Earth's interior to the oceans.

It's difficult to imagine that just 15 years ago no one had ever seen a "black smoker chimney;" now they seem to be found at mid-ocean ridge crests whenever we take a close look. Black smoker chimney is the term used to describe a smokestacklike structure composed of sulfide and sulfate minerals. "Black smoke" refers to the abundance of dark particulates that form when extremely hot (350°C) hydrothermal fluid rapidly exits the chimney opening and mixes with cold (2°C) seawater. These chimneys, which would draw attention no matter what the setting, are all the more spectacular since they cap seafloor hydrothermal vent sites that are oases of activity on the otherwise rather barren terrain of mid-ocean ridge crests.

Hydrothermal systems transfer large amounts of heat and mass from Earth's interior to the oceans. Fluids exiting the chimneys are metal-rich, hot, and acidic, and vent at velocities on the order of meters per second. A striking feature of black smoker chimneys is how remarkably thin their walls are: They vary in thickness from about 5 inches to as little as .25 of an inch. Across this thin layer is a temperature difference of 300°C or greater, and similar steep elemental composition gradients also exist. Chimney structures are thus fascinating subjects for scientific study. Many questions come to mind when first seeing these chimneys in action such as,

- Where is all the fluid coming from?
- Why is it flowing so fast?
- How did it get so hot?
- Where did all the particulates come from?
- How do the chimneys form? And equally puzzling,
- Why did it take so long to find them?

The existence of large-scale hydrothermal convection (fluid circulation) within oceanic crust near mid-ocean ridges was predicted in the mid-1960s, more than a decade before the first discoveries of active vents. It was recognized that oceanic crust could act as a porous medium, a magma chamber or newly solidified rock as a heat source, and seawater as a convecting fluid. But at this time, ridge crests were not well explored on the scale of tens of meters, the size of most vent fields. In 1977, active hydrothermal vents on mid-ocean ridge crests were first discovered on the Galapagos Rift, venting warm (25°C) fluid. The first discovery of high-temperature fluids actively forming chimneylike mineral deposits occurred in 1979 on the East Pacific Rise at 21°N. Since then numerous additional seafloor vent sites have been discovered in both the Pacific and Atlantic oceans. All detailed studies of vent sites have employed submersibles to photograph and map vent fields, measure temperatures of fluids, collect fluids, and recover fragile chimney samples.

Where Is All the Fluid Coming From? Why Does It Circulate? How Does It Get So Hot?

At all of these locations, the general processes of porous media convection, interaction between fluid and rock, and mineral deposition are similar. The schematic cross-sectional view across a ridge axis shows the ridge axis underlain by a heat source, either a magma chamber or newly solidified hot rock. The overlying crust, formed by volcanic activity, is permeable, owing to contraction and cracking as it cools. Seawater percolates down into these cracks, and circulates through hot basalt. Heat is transferred from the hot rock to the fluid.

As water is heated, its physical properties change. It expands, becoming less dense, and its viscosity decreases, so that it flows more easily. If this circulation occurred on land, drastic changes would occur when the temperature of the water reached 100°C, the boiling point of water. But at the depth of mid-ocean ridge crests, 2,000 to 4,000 meters below sea level, at pressures of 200 to 400 bars, the boiling point of seawater is much higher. Fluid can reach temperatures as high as 350°C without boiling. (The boiling point of seawater is 370°C at a pressure of 200 bars, and 404°C at 300 bars.) Fluid of this temperature is extremely buoyant, with a density less than seven-tenths that of seawater. If this fluid finds an open path to the seafloor, for instance a large open crack, or a series of interconnected cracks and void spaces, it will rise rapidly to the surface.

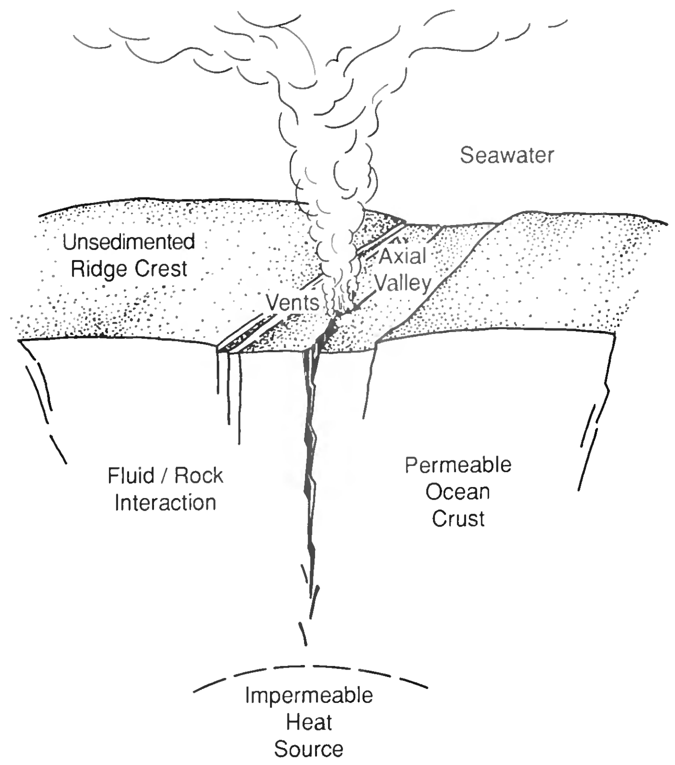
DSV *Alvin*/Dudley Foster

A black smoker chimney from the East Pacific Rise at 21°N vents 350° fluid at velocities on the order of 1 to 5 meters per second. The plume of black particulates (smoke) forms when the hot, low pH vent fluid mixes turbulently with the surrounding cold, higher-pH water.

How Do the Fluids Become Metal-Rich? Where Do the Particulates Come From? How Do Chimneys Form?

As the fluid circulates within the crust, it interacts with basaltic rock at high temperatures. Clay and sulfate minerals precipitate from seawater as it is initially heated, resulting in a modified fluid with little to no magnesium or sulfate, ions that are abundant in seawater. At higher temperatures, metals, silica, and sulfide are leached from the rock. The result is a hot, acidic (low pH) fluid with abundant silica, hydrogen sulfide, and metals, relative to seawater.

The hot, buoyant, metal-rich fluid exits the seafloor at velocities on the order of meters per second. When hydrothermal fluid mixes with



A schematic cross section of a seafloor hydrothermal system shows an impermeable heat source (magma chamber or hot rocks) overlain by permeable ocean crust at an unsedimented ridge crest. Fluid circulates within the crust, driven by temperature differences. During this circulation seawater is modified by fluid/rock interaction to hot, metal-rich fluid that is buoyant, and vents on the seafloor.

seawater, changes in pH and temperature result in the precipitation of minerals, the formation of black smoke, and black smoker chimneys. Black smoke is composed dominantly of fine-grained sulfide and oxide minerals (pyrrhotite, chalcopyrite, sphalerite, and amorphous iron oxides). Black smoker chimneys are concentric hollow spires up to 20 feet high, with inner channels .5 to 4 inches in diameter, that vent fluid in excess of 300°C. Early stages of black smoker chimney growth involve emplacement of an anhydrite-rich wall around the vent opening. Anhydrite (calcium sulfate) precipitates when seawater, rich in calcium and sulfate, and hydrothermal fluid, rich in calcium but depleted with respect to sulfate, mix. Anhydrite is an unusual mineral that is more soluble at low temperatures than at high temperatures. In seawater, it is saturated (and therefore should precipitate) at temperatures above approximately 150°C. Once a wall is formed around the vent opening, mixing between hydrothermal fluid and seawater is restricted. The wall gradually becomes less permeable as hydrothermal fluid and seawater mix through the wall, and sulfide and sulfate minerals precipitate. The inner side of the wall is in contact with hydrothermal fluid and chalcopyrite is deposited on this surface. The result is a concentrically zoned structure with an inner channel lined with chalcopyrite, and outer layers composed of varying amounts of anhydrite, and iron, copper-iron, and zinc sulfide minerals (such as pyrite and marcasite, chalcopyrite, bornite, sphalerite, and wurtzite).

Variations Among Vent Sites

Black smoker chimneys, and fluids with temperatures in excess of 300°C, are found at most active vent sites, reflecting the similarities in the general processes of fluid circulation and mineral deposition occurring at unsedimented mid-ocean ridge crests. Details of these processes, however, vary, resulting in distinct fluid compositions, and differences in the mineralogy, size, and gross morphology of the hydrothermal deposits. Sizes of vent deposits range from relatively small (fields about 10 meters in diameter) to those that resemble ore deposits exposed on land (up to 200 meters in diameter). Variations also exist in fluid composition, maximum fluid temperature, mineralogy, shape of deposits, and geologic setting. While the past decade of research focused on sampling the highest temperature fluids present at each site and the associated mineral precipitates, the focus is now shifting toward understanding the causes of variations and differences among vent sites.

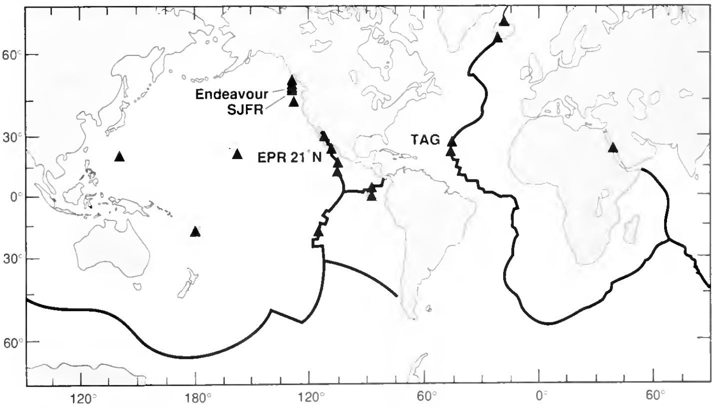
Fluid Composition. All of the solutions sampled at vent sites on unsedimented ridge crests are acidic, sulfide-rich, and capable of carrying large amounts of ore-forming elements. Fluid composition differs from site to site with respect to concentrations of chloride, metals, hydrogen sulfide, silica, and carbon dioxide, as well as pH and temperature. These variations reflect differences in fluid/rock interactions, including the amount of fluid being seen by each piece of rock during fluid circulation, depth of circulation and reaction, mineral assemblages present at each depth, and temperatures of reaction. Fluid composition can also be affected by processes occurring near the surface: Fluid can be cooled and minerals deposited directly beneath the seafloor, either by conduction (heat loss, with no addition of cold seawater) or from mixing with cold seawater.

Within each vent site there is a range of exiting fluid temperatures, compositions, and velocities. Scientists hypothesize that at each vent site there is one highest temperature, or end-member solution, and that ranges in temperature and composition within the vent field can be accounted for either by conductive cooling of the end-member solution, or mixing of the solution with seawater.

Size and Shape of Deposits. Vent sites on the East Pacific Rise at 21°N were the first ones analyzed for both fluid chemistry and mineralogy, and are (to some extent) the type of vent system that all other systems are compared to. At 21°N, chimney structures are up to 6 meters high, and have open channels 1 to 10 centimeters in diameter that are lined with chalcopyrite. Maximum fluid temperatures are 350°C, and flow velocities range from 1 to 5 meters per second. The chimneys sit on top of low-lying basal mounds. The surfaces of these mounds are comprised of fine-grained sulfide-rich mud and partially oxidized sulfide-rich fragments, some of which appear to be pieces of fallen chimneys. The interiors of the mounds have not been sampled or studied in detail. When they are ruptured, small black smokers form, suggesting that the temperature of fluid circulating within the mounds is high. The vent deposits are spaced along the center of a narrow (5-kilometer wide) axial valley at 100- to 1,000-meter intervals, and are located on fresh lava flows. At each of these sites the amount of heat being transported from Earth's interior to the ocean is very large, yet the amount of metal-rich minerals deposited is small relative to ore deposits exposed on land. It is not clear whether these deposits will ever grow to a large size; whether they are truly analogous to ore deposits is thus open to question.

The vent sites with fluid chemistry most different from 21°N are those on the southern Juan de Fuca Ridge. These vent sites are both

Location of known seafloor hydrothermal vent sites (closed triangles) are shown below. Solid lines indicate ridges. The lack of known sites on ridge crests in the South Pacific and Indian oceans, and along much of the Mid-Atlantic Ridge, is indicative of areas that have not been adequately explored. SJFR indicates Southern Juan de Fuca Ridge, EPR indicates East Pacific Rise.

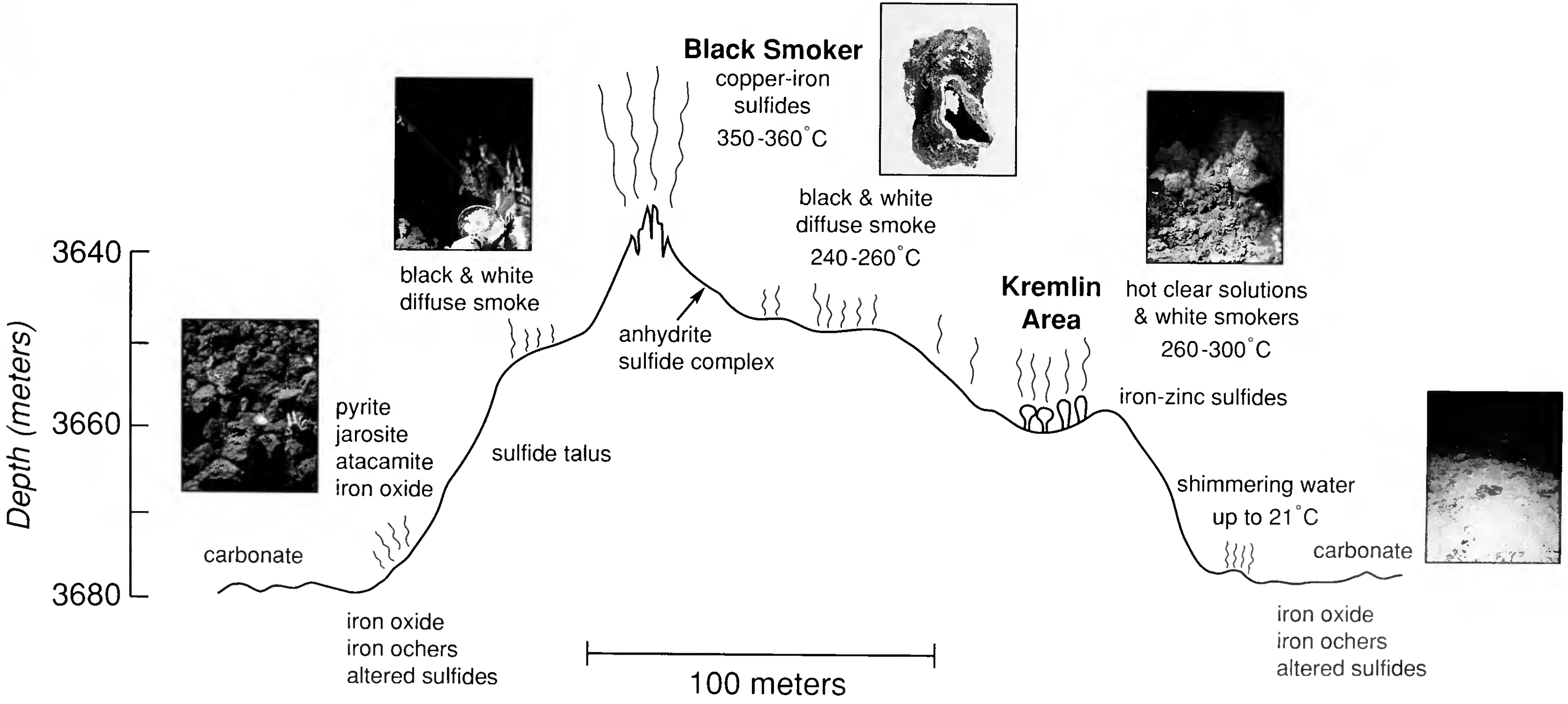


similar and different when compared to those on the East Pacific Rise. On the southern Juan de Fuca Ridge, chimneys and spires are the dominant form of mineral deposition, and vent sites are located in the center of the axial valley on fresh basalt. The morphology and mineralogy of the chimneys, however, differ from those at 21°N. In general the chimneys are small (2 to 6 feet tall), and instead of exhibiting strong concentric zonation around a large open channel, they are texturally more complex and contain multiple small (1- to 10-millimeter-diameter) fluid channels. Flow rates are less than at 21°N. Mineralogy is dominated by zinc sulfide (wurtzite and sphalerite) instead of copper-iron sulfide, and the innermost copper-rich layer that is common in East Pacific Rise chimneys is absent. Some of these differences are accounted for by the lower temperature (less than 300°C) and different composition of the venting fluid that is forming the deposits, the most striking of which is the chlorinity: Chloride concentration is up to twice that of seawater, and metal concentrations (except copper) are also high since metals are present in solution as chloride complexes (for example, iron chloride, lead chloride, and zinc chloride). Low copper content could reflect that either the temperature of the fluids never got high enough to leach copper from basaltic rock during fluid circulation, or that copper-iron sulfides had been deposited in the subsurface directly beneath the vent sites. Again, as with the deposits at 21°N, the amount and distribution of material deposited on the southern Juan de Fuca Ridge is not currently analogous to ore deposits.

The vent site most analogous to ore deposits exposed on land is the active TAG mound located at 26°N on the Mid-Atlantic Ridge.

The vent site most analogous to ore deposits exposed on land is the active TAG (Trans-Atlantic Geotraverse) mound located at 26°N on the Mid-Atlantic Ridge. The irony of this is that in the early 1980s researchers felt that the slow-spreading Mid-Atlantic Ridge could not sustain high-temperature hydrothermal activity. Hydrothermal systems transfer large amounts of heat from magma or newly solidified rock; on slow-spreading ridges (spreading at a half-rate of 13 millimeters per year as opposed to 30 millimeters per year at 21°N), such heat was not thought to be available. The TAG mound, however, is not only active, but larger in diameter by an order of magnitude than mounds at sites in the faster-spreading Pacific Ocean.

The active TAG mound is 200 to 250 meters in diameter and is located at the east side of a wide axial valley that is coated with carbonate sediment. The outer low-lying portion of the mound is composed of carbonate ooze, metalliferous sediment, sulfide blocks, and basalt talus. The inner portion of the mound is 150 to 170 meters in diameter, and is covered entirely with hydrothermal precipitates. The edges of the inner mound are steep talus slopes of sulfide and iron-oxide material that rise 20 meters above the outer mound. The center of the mound is dominated by a cluster of black smoker chimneys venting fluid at temperatures up to 363°C.The composition of this fluid is similar to fluids from the East Pacific Rise vent sites. The chimneys are chalcopyrite and anhydrite rich, and sit atop a 10- to 20-meter high, 40- to 50-meter-diameter cone of sulfide and sulfate. The surface of the cone is platelike. It is composed of chalcopyrite and pyrite with interspersed blocks of corroded massive anhydrite. Black smoke seeps from small, fingerlike protrusions and cracks in the cone surface and flows upward along the surface into the plume of black smoke above.



A cross section of the active TAG mound shows the wide range of hydrothermal precipitates. The basalt floor around the mound is covered with a layer of carbonate sediment. Steep talus slopes of sulfide (pyrite) and red to yellow iron-oxide material lead up to the top of the mound. The mound is capped by a cluster of black-smoker chimneys venting 350° to 360° fluid. Fluid samples were recovered from these vents using titanium water samplers. The black smoker chimney samples recovered are similar to chimney samples from other sites: Outer layers (dark) are composed of mixed sulfide and anhydrite, the inner layer is chalcopyrite. High temperature fluids and chimney samples of distinctly different compositions are present in the southeast quadrant of the mound (the Kremlin Area). The zinc-rich white smoker chimneys stand 1 to 2 meters high, and vent clear 260° to 300° fluids.

Cross-section illustration by Geoff Thompson. Photo credits, from left to right: Stephen Molyneaux; Carl Worsen and Cindy Van Dover; M. Sulanowska (sample is actually from Endeavor segment); Mark Hannington; and Peter Rona and Mark Hannington.

At a lower elevation in the southeast quadrant of the mound, lower temperature fluids (300°C and lower) exit "white smoker" chimneys. These chimneys, which are mineralogically and structurally very similar to spires from the southern Juan de Fuca Ridge site, are composed dominantly of sphalerite (zinc sulfide) and exhibit numerous millimeter-diameter flow conduits. The fluid venting from this portion of the mound is not only cooler than fluid venting from the cluster of black smokers, but is copper poor and has a low pH relative to the higher temperature fluids. The lower temperature fluid may form as a result of conductive cooling of the 363°C end-member solution. Diffuse, low-temperature fluids emanate from the remainder of the top of the mound, which is composed of fragile amorphous iron-oxide and silica crusts and blocky to bulbous lobes of mixed zinc, iron, and copper-iron sulfides. The overall size and concentric zonation of the mound, with highest temperatures in the center, and lower temperature sulfides and iron-oxides distributed near the outside, are similar to ore deposits exposed on land. How the active TAG mound grew to such large size is a current study topic, and whether or not deposits in the faster spreading Pacific will ever attain this size is unknown.

How the active TAG mound grew to such large size is a current study topic.

A New Set of Questions

Studies done in the last decade on seafloor hydrothermal systems have led to an understanding of the basic processes involved in hydrothermal circulation and mineral deposition—and have also shown how little we know. The next decade of research will address such questions as,

- What is the extent of hydrothermal venting at mid-ocean spreading centers and back-arc basins?
- What is the significance of variations in fluid composition, temperature, flow rate, and composition of solid precipitates among hydrothermal sites?
- How long are vent sites active?
- Does fluid composition change with time, and if so, on what time scale?
- What proportion of minerals is deposited at the vent site versus dispersed into the water column as black smoke?

All of these questions must be answered to estimate the contribution from hydrothermal processes to global heat budgets and geochemical cycles. While we now have a general understanding of hydrothermal vent systems, we still have much to learn, and large sections of the mid-ocean ridge system have yet to be explored.

Margaret K. Tivey is an Assistant Scientist in the Chemistry Department at Woods Hole Oceanographic Institution. Her research focus is mineral precipitation at seafloor hydrothermal vents.

The Biology of Deep-Sea Vents and Seeps

Alvin's Magical Mystery Tour

Richard A. Lutz

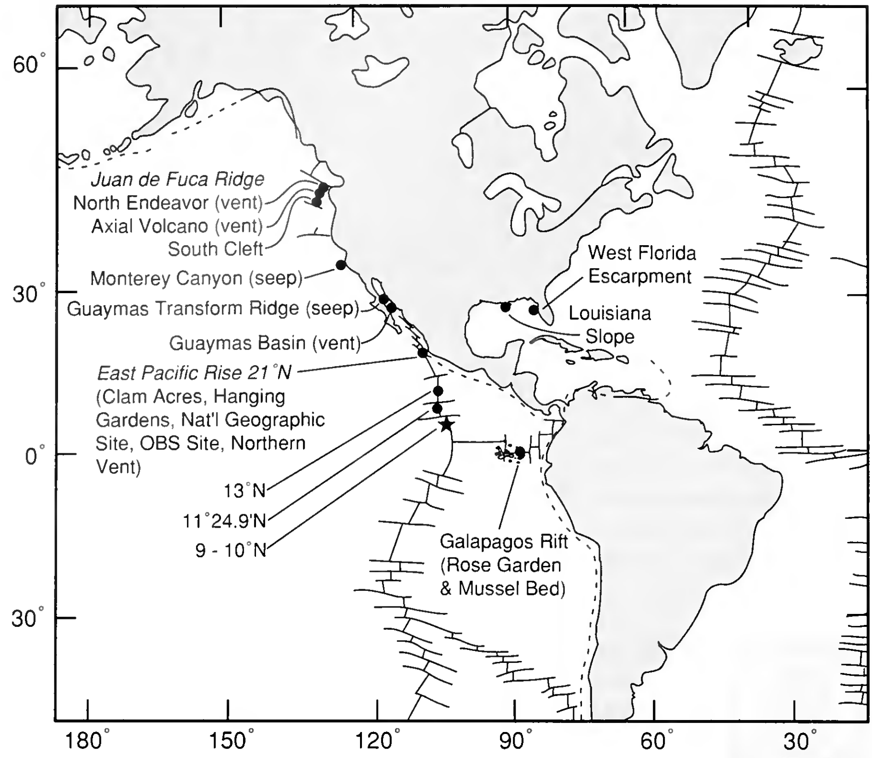
Over the past 12 years, the biology of deep-sea hydrothermal vents and cold-water seeps has been discussed in *Oceanus* several times. (For example, see Summer 1979, Fall 1984, and Winter 1988/89.) Here I provide an overview of a number of recent DSV *Alvin* expeditions to the East Pacific and the Gulf of Mexico that have expanded our knowledge of biological communities present at deep-sea vents and seeps in these oceanic regions. From May 1990 through August 1991, we (Bob Vrijenhoek and I, both of Rutgers University) organized several biological expeditions, collectively known as the "Magical Mystery Tour," as part of an ongoing National Science Foundation-funded project to study the genetics and dispersal mechanisms of organisms inhabiting vent environments. During this "tour," *Alvin* visited 14 deep-sea hydrothermal vent fields and 4 cold-water-seep areas. In April 1991 an additional expedition, known as the ADVENTURE (Alvin Diving in the VENTURE hydrothermal fields) cruise, led by Rachel Haymon (University of California at Santa Barbara) and Dan Fornari (Lamont-Doherty Geological Observatory), visited an extensive series of hydrothermal vents located between 9° and 10°N along the East Pacific Rise (EPR). A number of observations, ranging from faunal changes that had occurred at sites previously visited by *Alvin* to the nature of communities encountered at new areas, are summarized below.

An oceanographic expedition without a proper T-shirt is just another cruise—this is the logo for the Magical Mystery Tour T-shirt.

Hydrothermal Vents

Galapagos Rift

Rose Garden. Scientists diving in *Alvin* visited the Rose Garden hydrothermal vent site (named for the abundance of red-plumed tube worms found there) in 1979, 1985, and 1988. Bob Hessler (Scripps Institution of Oceanography), who dove extensively at this site during each of these



Deep-sea hydrothermal vents and cold seeps visited by Alvin *between March 1990 and August 1991 on the Magical Mystery Tour are plotted here.*

previous visits, returned to the site in May 1990. From Bob's perspective, while significant faunal changes had occurred between 1979 and 1985 (notably a decrease in tube worm abundance, an increased dominance of mussels and clams, a crash in anemone and serpulid populations, and increased numbers of galatheid crabs and whelks), the community structure had not changed significantly between 1985 and 1990.

Mussel Bed. During May 1990 the vent area known as Mussel Bed was also revisited. In 1979 this area was inhabited by an extensive population of large, living mussels (*Bathymodiolus thermophilus*), numerous specimens of the giant clam *Calyptogena magnifica* (as well as significant numbers of empty clam shells), brachyuran crabs (*Bythograea thermydron*), galatheid crabs (*Munidopsis* sp.), whelks (*Phymorhynchus* sp.), pink bythitid vent fish very close to vent openings, two or three small tube worms (*Riftia pachyptila*) in the narrow vent openings, and

The Rose Garden vent site along the Galapagos Rift as it appeared in 1979 (left) and 1985 (right).

R. R. Hessler

L. W. Fritz

many species of limpets. The 1990 visit found a vent environment that had changed remarkably little since 1979; mussels remained the dominant megafaunal constituent, live and dead clams were present in significant numbers, bythitid vent fish were still present around vent openings, and two or three small tube worms were seen in narrow vent openings. In contrast to the marked changes that had occurred at Rose Garden since 1979, time appeared to have stood remarkably still at the Mussel Bed site over the same 12-year period.

9° to 10°N Along the East Pacific Rise

Rachel Haymon, Dan Fornari, and their co-workers have recently described a series of established and newly formed hydrothermal vents between 9°16′ and 9°54′N along the East Pacific Rise. Sampled vent organisms include:

- three species of tube worms (*Riftia pachyptila, Tevnia* sp., *Oasisia* sp.),
- the clam *Calyptogena magnifica,*
- the mussel *Bathymodiolus thermophilus* (with an associated commensal polychaete living in the mantle cavity of over 75 percent of the collected specimens),
- nine species of limpets (*Eulepetopsis vitrea, Lepetodrilus cristatus, L. elevatus, L. ovalis, L. pustulosus, Neolepetopsis densata, Peltospira delicata, P. operculata,* and *Sutilizona theca*),
- six coiled archaeogastropods (*Bathymargarites symplector, Cyathermia naticoides, Melanodrymia* n.sp., and three unidentified species),
- the mesogastropod *Provanna*sp.,
- one unidentified turrid gastropod,
- one or possibly two species of galatheid crabs within the genus *Munidopsis,*
- the brachyuran crabs *Bythograea thermydron* and *Cyanograea praedator* (and possibly a third new undescribed brachyuran species),
- at least two species of barnacles (one stalked),
- several species of bacteria occurring in thick mats and thin coatings on basalt and sulfide substrates,
- the polychaete *Amphisamytha galapagensis,*
- the Pompei worm, *Alvinella pompejana,*
- one or possibly two species of tubiculous polychaetes within the genus *Paralvinella,*
- an unidentified serpulid polychaete,
- the commensal polychaete *Branchipolynoe symmytilida* (which inhabits the mantle cavity of the mussel *Bathymodiolus thermophilus*), and
- numerous other unidentified polychaetes, amphipods, brittle stars (ophiuroids), sea stars (asteroids), leptostracans, anemones, sponges, copepods, and benthic foraminifera.

R A Lutz

Tube worms, mussels and a zoarcid vent fish at the 9° to 10°N hydrothermal vent fields along the East Pacific Rise.

Zoarcid vent fish were commonly observed, although not sampled, in several vent areas throughout this stretch of the EPR ridge axis.

11° 24.9′N Along the East Pacific Rise

Biologists dove to this site for the first time in June 1990 to find a vent environment characterized by one active black smoker and a few areas with low-temperature venting. Dominant members of the vent megafauna included mussels (*Bathymodiolus thermophilus*), tube worms (*Riftia pachyptila*), galatheid crabs (*Munidopsis* sp.), and brachyuran crabs (*Bythograea thermydron*). Many empty shell valves of the clam *Calyptogena magnifica* were present, but only one living specimen was observed through the submersible's viewport. Other sampled characteristic vent organisms include:

- four species of limpets within the genus *Lepetodrilus* (*L. cristatus*, *L. elevatus*, *L. ovalis*, and *L. pustulosus*),
- the "transparent limpet" *Eulepetopsis vitrea*,
- the slit limpet *Clypeosectus delectus*,
- two coiled archaeogastropods (*Bathymargarites symplector* and *Melanodrymia aurantiaca*),
- the brachyuran crab *Cyanograea praedator*,
- the tube worm *Tevnia* sp.,
- two polychaetes within the genus *Paralvinella* (*P. grasslei* and *P. pandorae*),
- the ampharetid polychaete *Amphisamytha galapagensis*,
- an unidentified serpulid polychaete,
- the commensal polynoid *Branchipolynoe symmytilida*, present in the mantle cavity of over 75 percent of the mussels sampled,
- amphipods, leptostracans, and several unidentified species of polychaetes, which were also abundant in sieve washings and appeared to be associated with clumps of *Riftia* and *Tevnia* tube worms,
- numerous anenomes and brittle stars, which were abundant throughout the hydrothermally active areas, and
- one specimen of an unidentified turrid gastropod.

Numerous specimens of a stalked (goose-necked) barnacle, presently unidentified, were attached to basaltic rocks throughout the vent field. Colonial siphonophores ("dandelions") were observed, but not sampled, in peripheral areas of the vent field, and zoarcid vent fish were relatively common among tube worms attached to the side of the active black smoker.

R. A. Lutz

The Genesis hydrothermal vent at 13°N along the East Pacific Rise as it appeared in June 1990.

13°N Along the East Pacific Rise

Three major expeditions in 1982, 1984, and 1987 explored a variety of vent fields in the vicinity of 13°N along the EPR. During this five-year period, marked changes in vent activity and associated faunal composition, ranging from total cessation of vent flow and mass mortality of constituent vent organisms to the "rebirth" of an inactive field, have been reported by Daniel Desbruyeres (IFREMER, Institute Française pour Recherche et Exploitation de la Mar) and his co-workers. In 1990, three vent fields in the 13°N area (Totem, Genesis, and Parigo) were revisited and sampled. Noteworthy observations made during this cruise include:

- a vigorous level of vent activity and lush biological community present at the Genesis site, which was once known as "Pogomort," a vent field that had previously shut down and was named for the large number of associated dead tube worms (the vent tube worms were originally considered members of the phylum Pogonophora but were later placed in the recently erected phylum Vestimentifera),
- an increased dominance in 1990 (in contrast to 1987) of the tube worm *Riftia* relative to the tube worm *Tevnia* at the Genesis site;
- newly formed smokers heavily colonized by alvinellid polychaetes in the Genesis hydrothermal field; and
- a few isolated living mussels with no associated vent megafauna at the Parigo vent field, where no heat anomalies were encountered.

21°N Along the East Pacific Rise

A number of hydrothermal vent fields at 21°N along the EPR were visited during major geological and biological expeditions in 1979 (RISE—RIvera Submersible Experiments Expedition), 1981, 1982 (Oasis Expedition), and 1985. In 1990, *Alvin* visited five separate 21°N vent areas, four of which had been previously visited.

Clam Acres. Nineteen dives were devoted in 1982 to a variety of biological studies, most at an extensive vent field known as Clam Acres. At the beginning of this dive sequence, the area was dominated by large populations of *Calyptogena magnifica* and occasional isolated clumps of the tube worm *Riftia pachyptila*. As a result of the extensive sampling required by the multidisciplinary Oasis program, virtually every clump of tube worms had been "harvested" by the final dive of the series. When this area was revisited in June 1990, biologists were struck by the dramatic rejuvenation of the tube worm population; considerably larger and more numer-

R. A Lutz

Clam Acres, at 21°N along the East Pacific Rise.

ous *Riftia* clumps were present than had been encountered even during the beginning of the Oasis Expedition, and many of the tube worms within the clumps were more than a meter long. The clam population at this site remained extensive, and associated organisms collected were similar to those sampled in 1982.

Hanging Gardens. Visits in 1979, 1981, and 1985 revealed a lush biological community and one active black smoker at this site. During the return visit in 1990, no dramatic changes in community structure were apparent. The black smoker was still active and the vent field was dominated by two species of tube worms, *Riftia pachyptila* and *Oasisia alvinae*, and numerous clams, crabs, and limpets, all of which had been encountered during previous dives to the site.

National Geographic Smoker (NGS) Site. This vent area, named after a photograph of the site that appeared in the November 1979 issue of *National Geographic* magazine, appeared to have changed little over a 10-year period. Notes in *Alvin* pilots' records from 1981 described dead clam shells, inactive sulfide deposits, a tall, warm vent with white and dark smoke, and a few living clams, tube worms, and crabs. Numerous inactive sulfide deposits were found during the 1990 return visit along with a small (less than 2-meter high), *Alvinella*-covered smoker with temperatures exceeding 300°C. Other biological and geological observations were consistent with the conclusion that little had changed at this vent site since 1979.

OBS (Ocean Bottom Seismometer) Site. In 1981 this site was characterized by three tall chimneys, several dead clam shells, and a few large galatheid crabs (*Munidopsis* sp.), but no other specific vent megafauna. During both the Oasis Expedition in 1982 and the return visit in 1990, at least one of the three chimneys was vigorously active and the only indication of vent-associated organisms was again the presence of dead clam shells and occasional large galatheid crabs.

Northern Vent. Approximately 2 kilometers northeast of Clam Acres, this previously undescribed vent field was encountered by Rich Lutz and Daniel Desbruyeres. While few characteristic vent organisms were observed, tremendous numbers of an attached jellyfishlike organism (within the coelenterate order Stauromedusae) were concentrated around low-temperature vents and were also present in reduced numbers on adjacent basalt surfaces.

These tube worms were attached to a sulfide edifice in Guaymas basin.

Photo by Richard A. Lutz

Guaymas Basin

Unlike each of the other vent sites, the hydrothermal fields of Guaymas Basin are characterized by several hundred meters of soft sediment (with occasional outcropping sulfide edifices) through which vent fluids percolate. This region was extensively studied using *Alvin* in 1982 (10 dives), 1985 (40 dives), and 1988 (24 dives). In June 1990 the Magical Mystery Tour returned to find the region had not undergone substantial changes over an eight-year period. Bacterial mats, infaunal vesicomyid clams, and tube worms (*Riftia pachyptila*) on sulfide edifices remained the most conspicuous organisms associated with the vent fields. Empty shells of dead clams were scattered in localized regions throughout the areas of active (or previously active) hydrothermal venting, and black corals with associated terebellid polychaetes were retrieved from box core samples.

Juan de Fuca Ridge

South Cleft Segment. Organisms previously associated with vent fields along this ridge segment were described by Verena Tunnicliffe and A.R. Fontaine (University of Victoria) from photographs and limited samples taken during a 1984 *Alvin* cruise. During August 1991 two of the described vent areas, Vent 1A and 1B, were revisited, and associated vent organisms were sampled or photographed. While many tubes of the tube worm *Ridgeia* sp. were seen at Vent 1A (as they had been during the 1984 cruise) none appeared to contain living organisms and there was no evidence of active hydrothermal venting at the site. Similarly, there was no evidence of living vesicomyid clams at this site, despite the presence of many empty clam shells. Occasional spider crabs (*Macroregonia macrochira*) were the only living vent-associated organisms observed at the site. Approximately 100 meters north of this inactive vent area, a small amount of low-temperature venting was seen percolating through sulfide deposits along the west wall of the axial summit graben. Collections at this site included:

- a few living tube worms (*Ridgeia* sp.),
- two species of limpets, *Lepetodrilus fucensis* and *Clypeosectus curvus*,
- one coiled archaeogastropod species, *Depressigyra globulus*,
- one species of mesogastropod, *Provanna variabilis*,
- one mussel species, *Idasola* sp.,
- palm worms, *Paralvinella palmiformis*, and
- several unidentified polychaetes, a pycnogonid, and one specimen of a living vesicomyid clam.

Several crabs (*Macroregonia* sp.) were seen, though not sampled, and relatively sparse bacterial mats coated the surrounding basalt and sulfide rock surfaces. Vent 1B, which was approximately 300 to 400 meters north, was characterized by numerous, tall sulfide chimneys, several of which were vigorously active. Temperatures as high as 334°C were measured at one of the smoker orifices. Tube worms, other unidentified polychaetes, and sponges were common on the sides of active smokers, and numerous sponges were also seen around the base.

Tube worms, other unidentified polychaetes, and sponges were common on the sides of active smokers.

Axial Volcano. The Ashes Vent field within the caldera of Axial Volcano (Axial Seamount) was visited in 1984, 1986, 1987, and 1988. Biological community changes occurring between 1984 and 1988, particularly at an active sulfide mound known as "Mushroom Vent," have been described by Verena Tunnicliffe and are attributed largely to effects of sampling efforts and submersible maneuvering. In August 1991, this vent field was revisited; with the exception of an undescribed limpet species that appeared restricted to previously discharged submersible dive weights, all species sampled had been encountered during previous expeditions to this hydrothermally active region. Observations from the 1991 dive revealed a previously unreported substantial quantity of bacteria on basaltic and sulfide surfaces that may have reflected a recent increase in hydrothermal activity or a decrease in the rate of bacterial consumption by a variety of benthic invertebrates in the area.

North Endeavor Segment. A smoker (nicknamed "Godzilla"), the size of a 16-story building (50 meters high), numerous smaller smokers (one affectionately called "Bambi"), and isolated pockets of sediment in low-lying areas along the ridge axis characterized the North Endeavor Segment in August 1991. Sampling efforts on the sides and at the base of Godzilla yielded:

- three species of limpets (*Clypeosectus curvus*, *Lepetodrilus fucensis*, and *Temnocinclis euripes*),
- one coiled archaeogastropod species, *Depressigyra globulus*,
- the mesogastropod *Provanna variabilis*,
- two neogastropod species, *Buccinna viridum* and an unidentified cancellarid,
- one aplacophoran, *Helicoradomenia juani*,
- tube worms, *Ridgeia* sp.,
- numerous polychaetes, including three species of *Paralvinella* and the ampharetid *Amphisamytha galapagensis*,
- soft corals,
- hexactinellid sponges,
- anemones,
- a pycnogonid, and
- crabs (*Macrooregonia sp.*) with caprellid amphipods attached to their legs.

Many specimens of an unidentified vesicomyid clam were also collected from low-lying, sedimented regions of the axial graben just south of Godzilla.


Tube worms (upper left), mussels (center) and polychaetes (lower right) at the West Florida Escarpment cold seep.

Cold Seeps

West Florida Escarpment. Alvin visited this cold-water sulfide/methane seep site during geological and biological expeditions in 1984 and 1986. Barbara Hecker (Lamont-Doherty Geological Observatory), the sole biologist to dive at the site in 1984, returned to the seep area in 1990 to find little change in the biological community structure over the six-year period. Sampled or observed organisms included two unidentified mussel species (one of which was collected during both of the previous expeditions; the other was represented in the extensive 1990 samples by only a single individual), vesicomyid clams, the limpet *Paralepetopsis floridensis*, an undescribed coiled trochid gastropod, a turrid gastropod, numerous tube worms (*Escarpia laminata*), ophiuroids, and commensal polychaetes found within the mantle cavities of sampled mussels.

Louisiana Slope. While the first *Alvin* dives to the hydrocarbon seeps of the Louisiana Slope took place in April 1990, these methane-rich areas had previously been studied extensively by Jim Brooks (Texas A&M

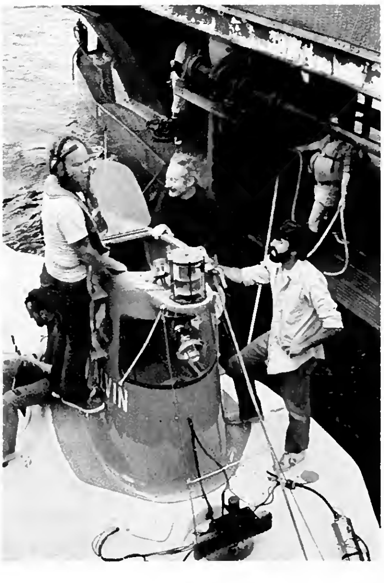
University) and co-workers using *Johnson Sea-Link, Pisces II,* and *NR-1.* Sampling efforts during the Magical Mystery Tour portion of the 1990 expedition were restricted to collecting two species of vesicomyid clams (*Vesicomya cordata* and *Calyptogena ponderosa*) and several new species of mussels, which are being described and systematically classified as part of ongoing genetic and taxonomic studies.

Guaymas Transform Ridge. Approximately 30 kilometers north of the active hydrothermal fields visited in Guaymas Basin, a transform ridge rises above the seafloor and crests at a depth of approximately 1,600 meters. In 1985, chemist John Edmond (Massachusetts Institute of Technology) and geologist Peter Lonsdale (Scripps Institution of Oceanography) explored the region and found buoyant hydrocarbon plumes and associated assemblages of biological organisms. In March 1991 Luis Soto (Universidad National Autonoma de Mexico) and I returned to the area and sampled several seep-associated organisms from large, depressed "pochmark" regions along the ridge crest. Retrieved specimens included:

- two species of vesicomyid clams,
- numerous specimens of a protobranch bivalve *Nuculana* sp.,
- two limpet species, *Lepetodrilus guaymasensis* and an unidentified species,
- two species of mesogastropods, *Provanna goniata* and *Provanna laevis,*
- several specimens of a heterobranch gastropod *"Melanella" lomana,*
- two unidentified species of tube worms,
- galatheid crabs *Munidopsis* sp.,
- ophiuroids, and
- a variety of miscellaneous polychaetes.

Monterey Canyon. Alvin first visited the Monterey Canyon cold-seep area (located at a depth of approximately 3,400 meters) in October 1988, and returned two years later in September 1990. During both expeditions, the restricted areas of hydrocarbon seepage were characterized by dense populations of large vesicomyid clams with shells more than 20 centimeters long. While few other organisms appeared to be attached to or living among the clams, several empty shells of the protobranch bivalve *Soleyma* sp. were present in adjacent sediments, as were numerous small pogonophorans (phylum Pogonophora, former subphylum Perviata) that were likened by observers within the submersible to "fields of grass."

Note: *The author has prepared an informative chart listing the various vent and seep regions and their known resident fauna. If you would like a copy, free of charge, write to* Oceanus *at the address on page 4.*



The author (right) and Howard Sanders (center) prepare to enter Alvin *during an early dive to the Mussel Bed vent along the Galapagos Rift.*

Acknowledgments: *I wish to express my sincere gratitude to the pilots and entire crew of the* Atlantis II/Alvin *whose untiring dedication and competence made the Magical Mystery Tour a tremendous success. This is publication number D-32402-6-91 of the New Jersey Agricultural Experiment Station and contribution number 91-52 of the Institute of Marine and Coastal Sciences, Rutgers University, and is supported by state funds and NSF grants OCE-8716591 and OCE-8943896.*

Richard A. Lutz is a Professor in the Institute of Marine and Coastal Sciences of Rutgers University. He has been involved in a variety of ecological studies of deep-sea hydrothermal vent communities since the initial discovery of the Galapagos Rift vent fields in 1977. Presently he is Project Coordinator of a large interdisciplinary study of temporal changes in biological community structure at newly formed hydrothermal vents at 9° to 10°N along the East Pacific Rise.

Megaplumes

Edward T. Baker

The megaplume story has all the plot devices of a good detective yarn.

The megaplume story, like other engaging scientific puzzles, has all the plot devices of a good detective yarn: a continuing investigation cracked by a provocative and unanticipated event, a patient assembling of evidence from new clues, and a logical trail that leads to the suspected but long-elusive perpetrator. But since this is science, not Sam Spade, the puzzle solved leads not to a case closed but to newer, more intriguing puzzles.

The question at the heart of the megaplume story is one central to marine science: How does Earth's mantle evolve into rigid crust, and how does this evolution affect the deep oceans' heat and chemical budgets? The investigation began during the plate-tectonics revolution of the 1960s, when oceanographers first recognized the Mid-Ocean Ridge (MOR) as the birthplace of new ocean crust. Filtered by the broad time-and-space scales of geologic history, this creation process appears continuous, driven by the relentlessly separating plates of Earth's crust. On a human scale, however, the actual production of new ocean crust along plate boundaries is highly intermittent, and has been observed only at those few places, such as Iceland, where the MOR emerges above sea level. Less than 3 square kilometers of new crust is added yearly along the 70,000-kilometer length of the MOR. This increase is equivalent to only 5 percent of the MOR widening by just 1 meter every year.

Snippets of new crust are added to the axial crest of the MOR as the broad upwelling of mantle-derived magma is focused into a narrow ribbon of volcanic activity that is usually no wider than a few hundred meters. As the new crust cools, it shrinks and cracks. Seawater percolates downward through the cracks and porous new crust to where magmatic heat can raise its temperature to over 400°C. The transformed seawater gushes upward as geysers of "black smoker" hydrothermal fluids, building chimneys of precipitated metal sulfides and supporting a unique ecosystem of animals totally dependent on chemosynthetic bacteria. Oceanographers now realize that hydrothermal venting, unknown just 15 years ago, largely mediates the exchange of heat and chemicals between the Earth's crust and the ocean.

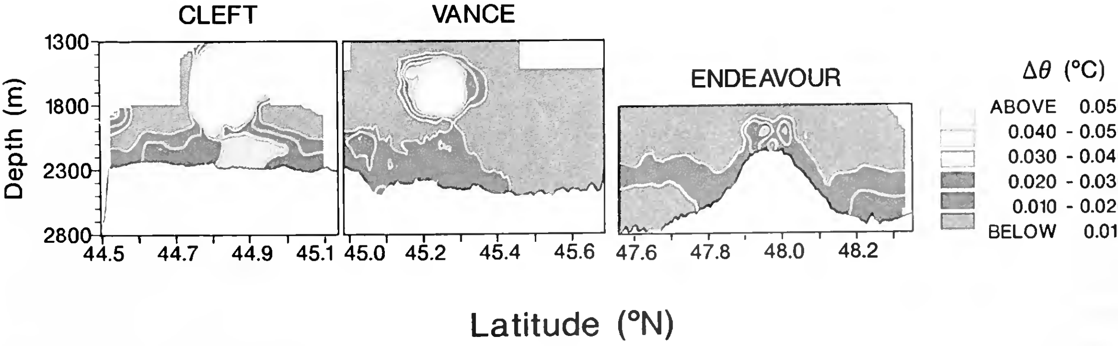
Marine scientists knew that studying a very recently active piece of the MOR would promote their investigation, but how could such a spot be found along its largely unexplored length? Since hydrothermal venting is powered by magmatic heat, some oceanographers reasoned that mapping the active-vent-field distribution on selected portions of the MOR might speed the search for sites of active spreading. Over the last few years the Vents Program of the National Oceanic and Atmospheric Administration (NOAA) has searched for vent fields along more than 80 percent of the Juan de Fuca Ridge axial crest, a 500-kilometer-long spreading center in the northeast Pacific that consists of six separate tectonic segments. It is now one of the few lengthy portions of the MOR where we know with confidence the distribution of vent fields.

We locate vent fields by slowly towing a conductivity/temperature/depth (CTD) sensor in a sawtooth pattern through the deep waters above the ridge crest. Hot hydrothermal fluids, diluted and cooled as they rise and mix with the surrounding seawater, form tenuous clouds that hang 100 to 300 meters above the vent fields, like chimney smoke from a 19th-century steel town. Investigators exploring small pieces of the East Pacific Rise and the Mid-Atlantic Ridge in the early 1980s hypothesized that vent fields should preferentially develop above the shallowest part of each tectonic segment, because injections of hot, low density magma would cause the crust to inflate. The Juan de Fuca Ridge results provide the most comprehensive support yet for this prediction.

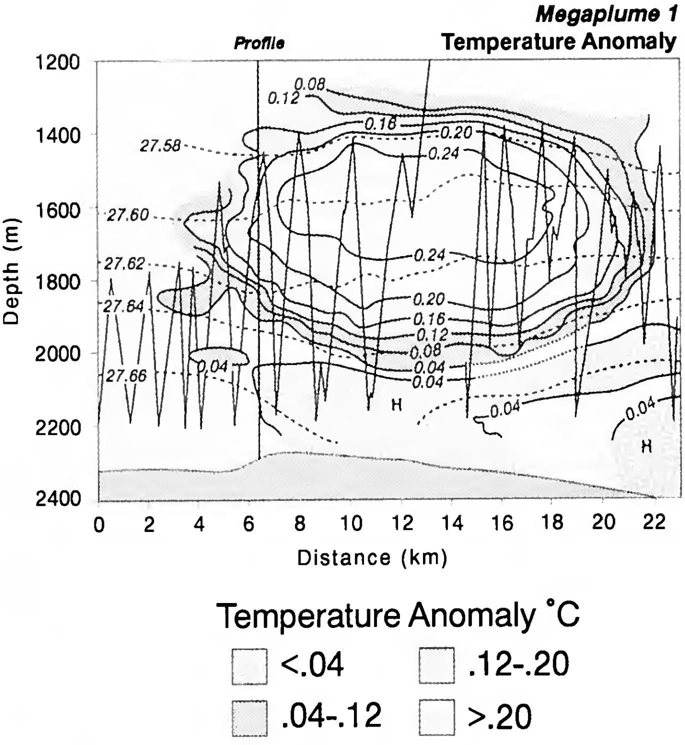
In the course of these hydrothermal explorations of the Juan de Fuca, we serendipitously discovered a plume so remarkable in its size, shape, and distance above the seafloor that it could only have been the product of fluid discharge far greater than any yet witnessed or anticipated. This plume, quickly dubbed the "megaplume," was found during an exploratory CTD tow along the northern end of the Cleft segment in August 1986. Although baffling at first, its discovery was quickly recognized as an opportunistic break in an investigation that was of increasing interest to a variety of scientific detectives.

The first and most startling new clue in the case was the unprecedented rise height of the megaplume. The rise height of a buoyant plume increases with the discharge rate of its source fluid, and all previously observed hydrothermal plumes had been found no more than a few hundred meters above their sources. The megaplume reached a stunning 1,000 meters above the ridge axis depth of 2,300 meters.

Abandoning a meticulously planned cruise agenda, we devoted several days to sampling this unexpected phenomenon. Subsequent data processing and laboratory analyses—forensic oceanography—established three important facts. First, a hydrothermal origin for the plume was confirmed. The plume waters were rich in several elements that are also in hydrothermal fluids, including manganese, iron, silicon, and helium-3, a rare isotope of the much more common helium-4. Second, abundant anhydrite crystals in the plume indicated a very recent, and thus local, origin. Anhydrite, which can crystallize only during the initial



Hydrothermal plumes along three tectonic segments of the Juan de Fuca Ridge in the northeast Pacific Ocean. Mixing of hot hydrothermal fluids with ambient seawater produces temperature anomalies that identify the plumes. Normal, steadily discharging, plumes rise about 300 meters above the seafloor and are most intense above segments (such as Cleft) or parts of segments (such as the midpoint of Endeavor) that are bathymetrically elevated. Megaplumes, shown in yellow, were found above the Cleft segment in 1986 and above the Vance segment in 1987.



A mug shot of a megaplume in cross-section shows density surfaces (dotted lines) superimposed on temperature anomaly contours. The zig-zag line is the path of the CTD tow-yo.

mixing of hot hydrothermal fluids and ambient seawater (before the temperature of this mixture falls below 125°C) subsequently dissolves within a matter of days in cold seawater.

Third, and most exciting, the plume was the residue of a brief but very massive discharge event, quite unlike the familiar steady flow from small chimneys. The megaplume's history was gleaned from detailed mapping that revealed an almost perfect three-dimensional symmetry. In geometrical jargon, the megaplume formed an oblate spheroid—a Frisbee—with a diameter of more than 20 kilometers and a thickness of 700 meters at its center. "Normal" plumes issuing steadily from a collection of chimneys in a vent field are imperfectly mixed and habitually asymmetric, growing erratically more dilute as deep currents sweep them away from their sources, like wood smoke from a lazy campfire.

The megaplume's precise symmetry implied a bomblike event, lasting only several hours to, at most, a few days.

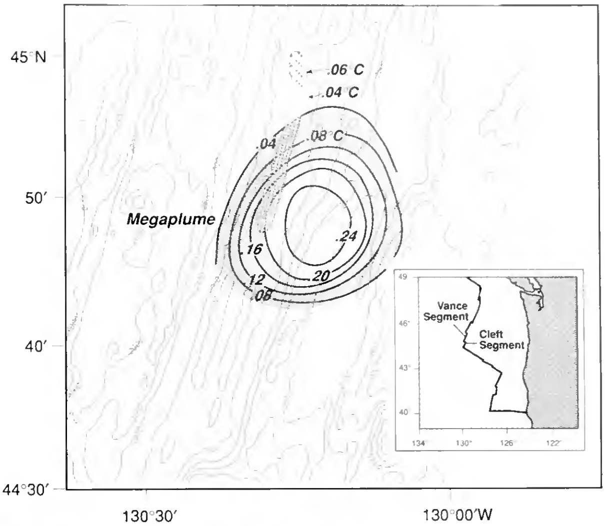
Searching for a Motive: Two Possibilities

With these clues in hand, the researchers working on the case next sought to construct a picture of the physical processes that created the megaplume: the suspect's *modus operandi*. Because the megaplume had known, symmetrical boundaries, we could confidently calculate its burden of hydrothermal heat and chemicals. Even though its average temperature increase above the surrounding seawater was only about 0.1°C, its volume of over 130 cubic kilometers contained about 2 x 10^{16} calories of hydrothermal heat, or enough energy to electrify New York City for almost a year. By knowing the hydrothermal heat content, it was possible to calculate the original volume of hydrothermal fluids: 100 million cubic meters at a temperature of 350°C.

The megaplume event unleashed a staggering volume of hydrothermal fluid. By comparison, it would take 100 to 200 years for 100 million cubic meters to escape from a single familiar "black smoker" chimney. New ideas about fluid discharge from the seafloor were thus needed. A geologically attractive alternative proposed that the megaplume fluids erupted not from a forest of standard chimneys, nor from one yawning megachimney, but rather from a long but narrow fissure cleaving the vent field. Fissuring is common along the crest of the MOR, and pictures returned by a deep-towed camera sled revealed a prominent band of fissures cutting through the megaplume area.

The fissures imaged by the camera sled were, of course, only the exit ways of the kilometers-deep and tortuous paths through which hydrothermal fluids must slowly percolate to reach the seafloor. The normal concentration of pores and microcracks deep in the MOR's volcanic rocks is far too low to permit the fluid flow rate required by the megaplume. Ideas about what triggered the megaplume, therefore, had to have a common thread: the catastrophic rupturing of the crust beneath an ordinary vent field.

To speculate how crustal permeability can catastrophically increase, consider the megaplume fluids from two points of view: active and passive. An active model views hydrothermal fluids, circulating deep in the crust, as soup simmering in a pressure cooker afflicted with a stubborn safety valve. Crustal fluids fracture the imprisoning volcanic rocks when fluid pressure increases faster than normal venting can release it. Pressure can be raised past the critical point by a pulse of magmatic heat that raises the temperature of the fluids, or by a sudden release of magmatic gas.



The alternate view holds that a megaplume is the passive result of an impatient chef cracking open the pressure cooker while the soup is still boiling. An earthquake on the MOR fractures the crust, temporarily opening deep and spacious fluid pathways, releasing the trapped fluids as a gushing megaplume. This view evolves from a long history of observations at terrestrial volcanic sites. Most interesting are those from Iceland, a segment of MOR obligingly lifted above the concealing ocean. Records kept almost since the time of the Vikings show that every 100 to 150 years a years-long episode of crustal rifting and volcanic outpouring assaults Iceland. Careful measurements collected during the 1975 to 1982 episode indicate that intermittent crustal stretching was accompanied by subcrustal movements of magma and subaerial eruptions of molten lava.

DSVAlvin/Robert Embley, NOAA

A plan view of the comparative extent of the 1986 megaplume and the underlying "normal" plume along the axis of Cleft Segment is shown above. The size, symmetry, and hydrothermal temperature anomaly of the megaplume are all in sharp contrast to the steadily emitted normal plume. At left is the seafloor fissure the megaplume may have erupted from. Taken from DSV Alvin *(whose instruments are in the foreground), the fissure is several meters wide and perhaps 10 meters deep.*

Expanding the Investigation

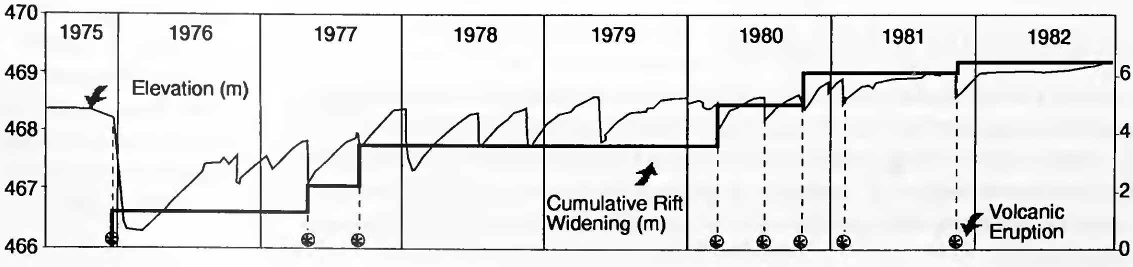
Several pieces of the puzzle were now in place, enough for tantalizing speculations, but too few to convince a sober jury of scientific peers. To find the crucial pieces needed for an airtight case, several investigators decided on a long-term stakeout of the megaplume area. After several years they hit pay dirt, in the form of two first-of-their-kind discoveries on the MOR.

Páll Einarsson

Within an hour of the beginning of two Krafla eruptions, a photographer in an airplane captured the image at right and the one on page 2. The eruptions began on October 18 and November 18, 1990, and lasted five days each. Both were similar, occurring on an 8-kilometer-long fissure extending from the center of the Krafla caldera, northword along the rift zone, and were part of a series of rifting and magmatic events at the divergent plate boundary in northeast Iceland that lasted from 1975 to 1984. Sudden decreases in the elevation of the Krafla caldera often corresponded to instances of crustal widening and volcanic eruptions (below). Volcanologists believe magma flows out of the caldera of the Krafla volcano, filling and sometimes overflowing the newly widened rift zone as the crustal plates separate. (After Bjornsson, 1985, and Tryggvason, 1984.)

The first solid evidence that the megaplume was a signal flare for magmatic activity appeared in annual analyses of water samples from the "normal" plume that always blankets the megaplume site. In August of 1986, immediately after the megaplume release, the ratio of helium-3 to hydrothermal heat in the normal plume exceeded by several times any value previously measured anywhere on the global MOR. The ratio then decreased every year until 1988, when it reached a level typical of other MOR vent sites, and of the megaplume itself. Such variability was no more anticipated than the megaplume itself. Upwelling magma from the mantle is the sole source of both helium-3 and heat, and work elsewhere on the MOR had found no evidence of a changing ratio. These new observations had an exciting explanation: a sudden change in a pocket of fluid magma had injected a surge of helium-3 into the hydrothermal fluids feeding the vent field. Laboratory experiments have demonstrated that magma can be rapidly stripped of helium-3 and other volatile gases both by bubble formation as rising magma depressurizes and by crystallization as magma cools.

The second discovery provided definitive evidence of the magmatic activity needed to produce a burst of helium-3. Magma can suddenly depressurize and cool when it intrudes into deep cracks opened in the upper crust by the retreating plates. Occasionally these dikes of intruding magma overflow their cracks, spreading in shimmering lakes or piling up in blocky mounds of fresh basalt on the seafloor. We know this happens: The evidence is the MOR itself. But not until 1989 at the megaplume site had oceanographers been able to identify and sample a specific lava flow newly emplaced upon the seafloor. Careful bathymetric mapping in 1987 and 1989, repeating survey lines originally run in



1981 and 1983, revealed a series of new lava mounds stretching for 16 kilometers along the trail of fissures that runs through the center of the megaplume area. The volume of the mounds is roughly 0.5 cubic kilometers, somewhat less than half the volume extruded during the Icelandic eruption episode of 1975 to 1982.

Revealing the Crime—and the Collaborators

A huge mass of hydrothermal broth imprisoned in pores and crevices was released almost instantly.

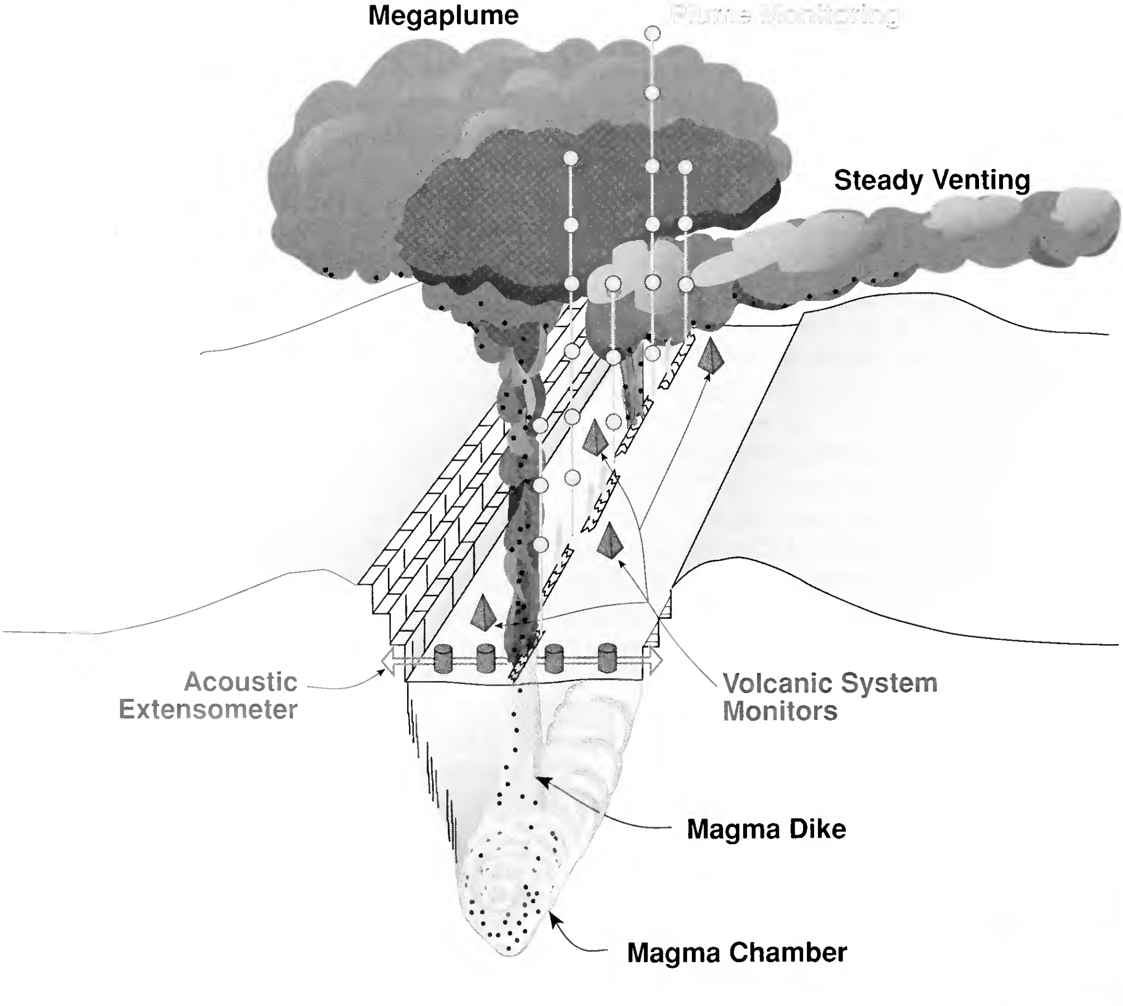
The discovery that the cataclysmic megaplume event of 1986 was closely associated with both an escape of magmatic gas and an eruption of fresh lava supplied enough pieces of evidence to make the case decipherable. A closing argument might sound like this: The separating tectonic plates on either side of the Juan de Fuca Ridge had been raising the tension along the axis of the Cleft segment for some time, perhaps decades. In mid-August of 1986, its crust failed and the width of the axial crest increased by a few meters. A huge mass of hydrothermal broth imprisoned in pores and crevices was released almost instantly. A several-kilometers-long line of hydrothermal heat and chemicals surged 1,000 meters above the seafloor, turbulently mixing seawater over a 300-square-kilometer area. The megaplume discharge ended abruptly as cold seawater filled the emptying fissures.

On the heels of this release, a slab of molten magma pushed upward through the cracked crust, lumping up mounds of fresh lava wherever it breached the seafloor. Helium-3 and other volatile gases dissolved in the magma were liberated as the magma rose and cooled. Newly forming hydrothermal fluids absorbed these gases, and soon afterwards the flow from seafloor chimneys contained extraordinary concentrations of helium-3. The magmatic dike reaching up from the base of the crust was only a few meters wide and stretched perhaps 20 kilometers along the fissure line running through the north end of the Cleft segment. By 1988 it had completely solidified, and extraction rates of helium-3 and heat were once again similar. New communities of vent creatures colonized the lava mounds, attracted by warm, chemical-rich water leaking up through the lava from the buried fissure system. A new sliver of ocean crust had been added to the seafloor.

This hypothesis of the events surrounding the megaplume release satisfied our puzzlement, while stimulating our curiosity with new questions. How common are megaplume events, and how important are they in the global budget of hydrothermal venting? Does volcano-tectonic activity on segments of the MOR follow the Icelandic pattern of several years of concentrated vigor separated by long quiescent periods? And, most basically, how can we test our hypothesis?

The importance of episodic events relative to the more familiar steady venting can only be surmised until we know more about the frequency of megaplumes. Megaplume observations are still understandably scarce. A second megaplume, somewhat smaller than the first, was found over the Juan de Fuca Ridge in 1987. The precise origin of that plume is unknown; when found, the plume was several weeks to months old and may have drifted far from its source. Researchers have also claimed evidence of a megaplume in the Fiji Basin just southwest of Samoa. More extensive evidence may actually exist in the geologic record, where the prevalence of hydrothermal breccias, deposits of fractured and fragmented debris, suggests that cataclysmic releases of hydrothermal fluids have not been uncommon along the MOR.

A few simple calculations can yield a rough estimate of the relative importance of large hydrothermal events. In terms of the power released by hydrothermal discharge on various scales, the megaplume is an awesome force. During its short lifetime, it releases heat at a rate equal to perhaps 10 percent of steady venting along the entire global MOR axis. In terms of global budgets, however, we should more appropriately compare the supply of hydrothermal emissions over a longer time period. On an annual basis, the contribution of hydrothermal elements such as iron and silicon from a single megaplume is about equal to that of an entire vent field, or about 0.1 percent to 0.01 percent of the global total. As a first estimate, then, the global supply of hydrothermal fluid from megaplumes would equal that from steady venting if every vent field produced a megaplume each year. What little experience we have suggests that this schedule is too ambitious, so megaplume events are unlikely to dominate the global budget. They may, however, be a principal contributor to the hydrothermal supply from MOR segments undergoing spreading episodes.



Cartoon of the hydrothermal and geological observation program of the Vents Program at the megaplume site. The geometry of the magma chamber and magma dike are conjectural.

Vents to Remain Vigilant

The progression from simple detection of megaplumes to a test of the complex hypothesis in which we have embedded them requires the establishment of a long-term observational program. The NOAA Vents Program is currently developing such a program at the site of the original megaplume. The seafloor observational system will initially include three components. Sensors on moorings along the ridge axis will monitor temperature and current velocity above the vent field, looking for perturbations that signal a sudden change in the distribution or intensity of steady venting, or the occurrence of hydrothermal events such as megaplumes. Volcanic system monitors resting on the seafloor will contain seismic recorders tuned to detect tremors indicative of magma rumbling through the crust, and sensitive inclinometers and pressure gauges to measure seafloor deformation caused by swelling or contraction of the magma chamber. Pilot deployments of these first two components began in 1991. The third component, an acoustic extensometer network, will be added in 1992. Acoustical beacons on either side of the rift zone will search for evidence of crustal spreading events by continuously monitoring the distance between themselves, much as a land-based laser-ranging system currently monitors movement along the San Andreas Fault system in southern California. In addition to these seafloor monitors, the Vents Program will tap into an existing array of military hydrophones throughout the Pacific to listen for the telltale underwater sounds, called T-phases, made by the cracking of earthquakes and the rumbling of magma.

The NOAA Vents Program is currently developing a long-term observational program at the site of the original megaplume.

In the world of pulp detective novels, the criminal always returns to the scene of the crime. Nature, however, may not so obligingly furnish another megaplume to the scientific Sam Spades now on a stakeout at the Cleft segment. But even without one, a long-term study of its birthplace will increase our understanding of the interrelationships of crustal rifting, magma movement, and hydrothermal activity, providing new puzzles and clues for the next detectives.

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Tomographic Imaging of Spreading Centers

Seismic tomography will help us understand plate-boundary mechanics.

Douglas R. Toomey

Since we cannot observe the vast regions beneath the seafloor directly, we must use remote-sensing methods such as sound waves to help us answer fundamental questions about the structures that make up mid-ocean ridges. We want to know the size, shape, and location of spreading-center magma-storage zones and the physical properties of the solid and molten rocks beneath the axis of accretion. We need to know the strength of ridge-building materials and the spatial and temporal relationships of various ridge components. Seismic tomography, a powerful method for mapping three dimensional physical properties within Earth's interior, promises to help us gain this knowledge, which in turn will help us understand plate-boundary mechanics. By analyzing the propagation of vibrational waves generated by earthquakes or man-made sources such as explosions, we can map seismic structure, that is, the travel speeds of different types of vibrational or seismic waves and their attenuation with distance due to frictional energy loss. One of the most frequently studied seismic waves, the P-wave, is similar to the acoustic waves we hear. A shock wave generated by a large explosion is a graphic analogue of a P-wave. By measuring the transit time of P-waves passing around and through an active spreading center, we can develop a three-dimensional image of the seismic structure beneath the plate boundary.

Seismic tomography can be used to image three-dimensional physical properties over a wide spectrum of length scales, including, for example, images at a scale of hundreds of meters of the upper-oceanic crust near regions of hydrothermal venting, reconstruction of kilometer-sized velocity anomalies characterizing axial magma chambers, and maps of physical properties within the zone of mantle upwelling and melt generation, located deep (10 to 100 kilometers) beneath seafloor-spreading centers. Several fundamental improvements in the descriptive and theoretical models of oceanic ridges await detailed, three-dimensional mapping of velocity structure.

The Importance of Seismic Imaging

Within a spreading center, the geology and morphology of the seafloor and the thermal and mechanical structure of the newly formed oceanic plate are controlled by the complex interplay of magmatic injection, tectonic rifting, and hydrothermal cooling. These dynamic processes all exhibit pronounced spatial and temporal dependencies. Moreover, while an individual process may express itself on the seafloor as a volcano, an uplifted mountain range, or a hydrothermal vent field, the majority of the dynamic activity invariably occurs at some depth beneath the seafloor. Understanding the nature of oceanic spreading centers requires knowledge of the behavior of these dynamic processes as they evolve directly beneath the axis of accretion.

In recent years, working models of oceanic spreading centers have evolved from two-dimensional, steady-state idealizations to more realistic three-dimensional, time-dependent systems (see the segmented Mid-Atlantic Ridge, page 11). The new dimension added to the working models is the pervasive along-strike variability of mid-ocean ridge processes, notably in the production of melt beneath the spreading center. Current hypotheses suggest that ascending melt within the mantle is focused into magmatic centers separated on the order of tens to a hundred kilometers. Each magmatic center supplies the greater portion of melt and heat to a single ridge segment. Within an individual ridge segment, processes such as faulting, hydrothermal circulation, and magmatic accretion vary systematically as a function of distance from the magmatic center. The hypothetical structural unit, consisting of a local maximum of magmatism bounded by along-axis minima, became known as a spreading-center segment or cell. This simple model of cellular segmentation provides an improved, but controversial, working hypothesis for mid-ocean ridge studies.

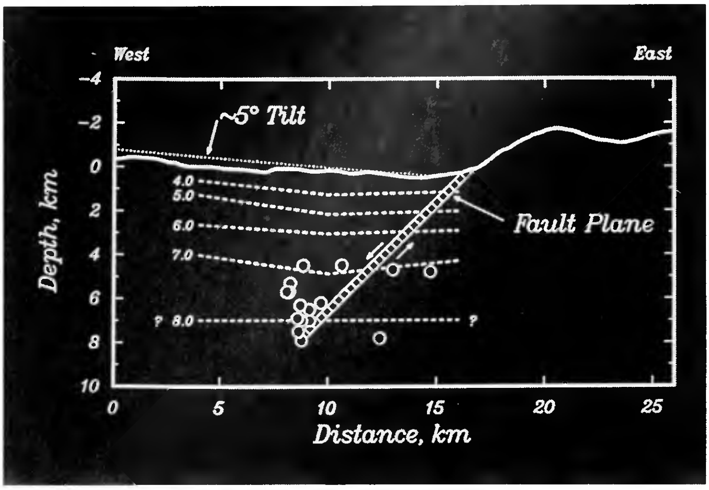
The majority of the dynamic activity invariably occurs at some depth beneath the seafloor.

What follows is a review of results of seismic tomography studies used to investigate the spatial variability of physical properties and processes deep within spreading centers. Divergent plate boundaries display several different structural forms, including the classic rift valley of the Mid-Atlantic Ridge, the pronounced *en echelon* or steplike structure of the Reykjanes Peninsula within southwest Iceland, or the more morphologically subdued East Pacific Rise. Each of these different spreading centers is the topic of a tomographic study. These investigations are unified by a common purpose: furthering our knowledge of physical structure beneath ridge axes, and using these observational constraints to improve working hypotheses of the mechanics of divergent plate boundaries.

Tomographic Images of Rifts and Rises

Mid-Atlantic Ridge

The cellular model of focused magmatic accretion is particularly apt for characterizing the rugged, slow-spreading Mid-Atlantic Ridge. Undulations in the ridge-parallel profile of axial seafloor depth are thought to result from variations in melt production. Magmatic centers presumably coincide with the shallower portions of the ridge axis, while the far ends of magmatic cells (regions of low melt production) are thought to correlate with the deeper parts of the ridge profile. Two recent studies conducted on the Mid-Atlantic Ridge by researchers from the Massachusetts Institute of Technology (MIT) and the Woods Hole Oceanographic Institution (WHOI), one within an axial low near 23°N and the other astride an axial high near 26°N, demonstrate the utility of tomographic imaging for characterizing crustal seismic structure throughout spreading-center cells.



This cross-section of the Mid-Atlantic Ridge median valley along-axis deep near 23°N, shows microearthquake hypocenters (circles) and contours of P-wave velocity (in kilometers per second) obtained from two-dimensional tomographic imaging. The seafloor bathymetry reveals the rift's relatively flat inner floor and rugged mountains to the east. A conjectural fault plane for recent large earthquakes is shown (see Mid-Ocean Ridge Seismicity, page 60). At the far end of this 40-kilometer-long ridge segment, tomography data shows nearly normal oceanic crustal structure.

The first application of tomographic methods to the study of mid-ocean ridge crustal structure occurred during an investigation of the seismicity and seismic structure of the Mid-Atlantic Ridge near 23°N, south of the Kane Fracture zone. The microearthquake study was located in an along-axis deep at the far end of a ridge segment approximately 40 kilometers long. During a two-week deployment within the rift valley, hundreds of microearthquakes were recorded by ocean-bottom receivers. In addition to locating the earthquakes, a tomographic analysis of travel-time data was conducted; the P-wave data comprised transit times from earthquakes and several man-made explosions (seismic refraction data) to the ocean-bottom receivers. By analyzing variations in the transit times among many different paths, images of anomalous volumes of seismic velocity were obtained. The two-dimensional seismic structure across the rift-valley inner floor and transecting the axial deep was similar to normal off-axis oceanic crustal structure, excepting a small decrease in mid-crustal (1 to 4 kilometers beneath the seafloor) velocities at zero-age crust. These low velocities quickly evolved with age (or with off-axis distance) within the first few hundred thousand years of crustal formation. The similarity in structure between axial crust within an along-axis deep and normal off-axis oceanic crust that had undergone extensive cooling as a result of aging was remarkable. From these and other observations we hypothesized that at this far end of a ridge segment, considerable time (about 10,000 years) had elapsed since an episode of significant magmatic accretion. Without the addition of new crustal material that results from magmatic injection, we also inferred that this rift-valley deep had undergone horizontal extension; in effect, the spreading of oceanic plates at the end of a ridge segment was accommodated by stretching and thinning of the axial crust.

A second study near the Transatlantic Geophysical Profile (TAG) hydrothermal field at 26°N was located close to an along-axis high near a ridge-segment center also approximately 40 kilometers in length. In contrast to the magmatically quiescent, cool crust beneath the along-axis deep at 23°N, the axial high of the ridge segment at 26°N is characterized by high-temperature, black smoker chimneys. At 26°N the two-dimensional seismic structure along the rift valley, including the region of the axial high, was remarkably heterogeneous in comparison with the structure near 23°N. Anomalously high velocities in the upper crust were detected near the axial high, and a low velocity anomaly was detected beneath an axial volcano. Both of these crustal velocity anomalies were interpreted to be the result of recent magmatic intrusion. In contrast, toward the axial deep at the southern end of the TAG ridge segment, the seismic structure is comparable to normal oceanic crustal structure, similar to the axial deep near 23°N. The axis-parallel velocity patterns near 26°N, including complex structures near the ridge segment center and a transition to more homogeneous, almost normal crustal structure near the segment's far end, appear consistent with the hypothesis that crustal accretion is focused centrally beneath a slow-spreading ridge segment.

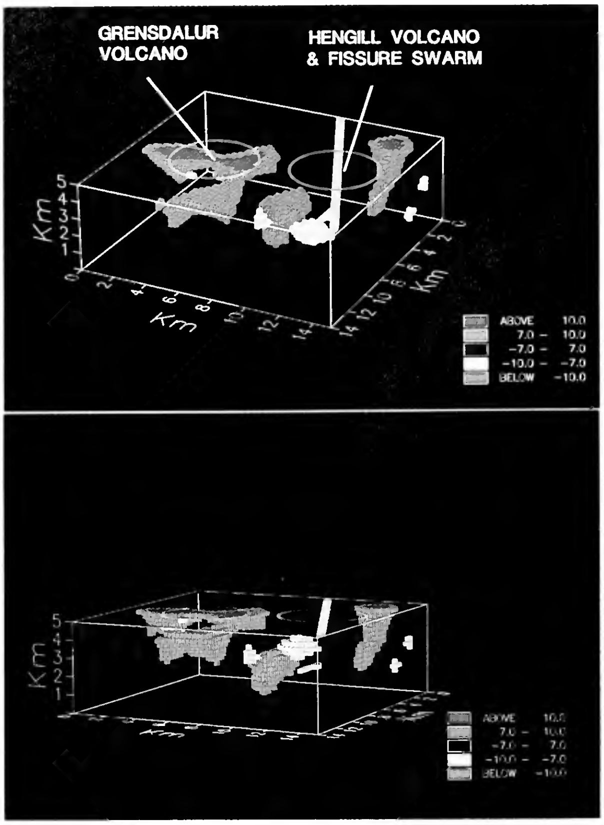
We don't yet know whether or not the observed variations in axial seismic structure are fundamentally related to axial segmentation and focusing of magmatic accretion. Current models of mid-ocean ridge processes suggest that slow-spreading Mid-Atlantic Ridge segments of equal length, such as the 23°N and 26°N ridge segments, are magmatically fed by either upwelling plumes of similar size or volumetrically similar amounts of melt. If the model predictions hold true, the tomographic images resulting from these two microearthquake experiments may begin to characterize the seismic structure near the axial high and axial low of a 40-kilometer-long ridge segment.

A dense distribution of sources and receivers permits structural resolution to within approximately 1 and 2 kilometers.

Reykjanes Peninsula, Iceland

A tomographic study of the Hengill-Grensdalur volcanic field in southwestern Iceland provides further indication of the power of seismic methods for imaging the interior of active spreading centers. Working with Gillian Foulger of the UK, we resolved the anomalous three-dimensional crustal structure underlying the magmatic center of a slow-spreading Icelandic rift segment. Geologic maps of the area show that the magmatic center or central volcanic region incorporates the recently active Hengill Volcano, the inactive Grensdalur Volcano, and the high-temperature geothermal field associated with these features. To either side of the Hengill central volcano, and extending to the far ends of the rift segment, are a set of fissure swarms indicating the locus of past eruptions. Our scientific objective was to tomographically image the seismic structure of the center of this magmatic cell. These results also aided the Icelandic Energy Authority in their search for volumes of anomalously hot rock beneath the spreading center and to evaluate this volcano's geothermal energy potential.

A significant advantage of land-based surveys is the ease of recording seismic data for a longer period of time than is typically possible for marine seismic experiments. A longer recording period provides a larger data set, and thus more extensive sampling of the study volume; as expected, higher resolution tomographic images are obtained when larger quantities of data are available. Using P-wave travel times recorded during a four-month period by over 20 seismometers, we tomographically imaged seismic velocities within a 14-by-15-by-6-cubic-kilometer volume that underlies the high-temperature Hengill-Grensdalur geothermal field. A dense distribution of sources and receivers permits structural resolution to within approximately 1 and 2 kilometers in the vertical and horizontal directions, respectively. The



Three-dimensional tomographic image of P-wave velocity beneath the Hengill-Grensdalur volcanic complex, Iceland. The color scale denotes percentage difference in velocity from the regional structure. For display purposes, the model is represented by constant-velocity cubic blocks of dimension 0.25 km. Two views of the tomographic image are shown; both views are from the northeast. Positions of the surface expressions of the Grensdalur and Hengill volcanoes (red circles) and the axis of crustal accretion (solid bar) are shown.

final model of the area's structure is characterized by distinct bodies of anomalously high velocities: Two of these bodies are continuous from the surface to about 3 kilometers depth, and each is associated with a site of past volcanic eruption; the third body of high velocity lies beneath the center of the active geothermal field at a 3- to 4-kilometer depth.

The volcanic features we directly observe on the surface are clearly the expression of igneous processes occurring at great depths. They include the crustal-level storage of molten magma and the cooling of such bodies to form magmatic intrusions or plutons. For crustal-level rocks, the P-wave velocity varies little at temperatures below 500°C and decreases rapidly at temperatures in excess of 500° to 800°C (basalt begins to melt at about 800°C). We thus infer that neither molten magma nor rock hotter than about 500°C exist presently in large volumes beneath the Hengill-Grensdalur volcanic and geothermal field. The presence of hot springs and fumaroles at the surface with water temperatures between 300°and 370°C, however, indicates the presence of intrusive rock at similar temperatures. We interpret the tomographic images of anomalously high velocity to be the result of recently solidified magmatic intrusions into the upper crust. Furthermore, those intrusions beneath active geothermal fields, while solid, are most likely hot enough (about 400°C) to provide a usable source of thermal energy.

The tomographic image of the Hengill-Grensdalur volcanic field may provide an analog to the type of three-dimensional seismic structures possibly present beneath the TAG area of the Mid-Atlantic Ridge. Both sites are coincident with the center of a ridge segment, and both are characterized by profound structural heterogeneity suggestive of recent crustal-level intrusion of magma.

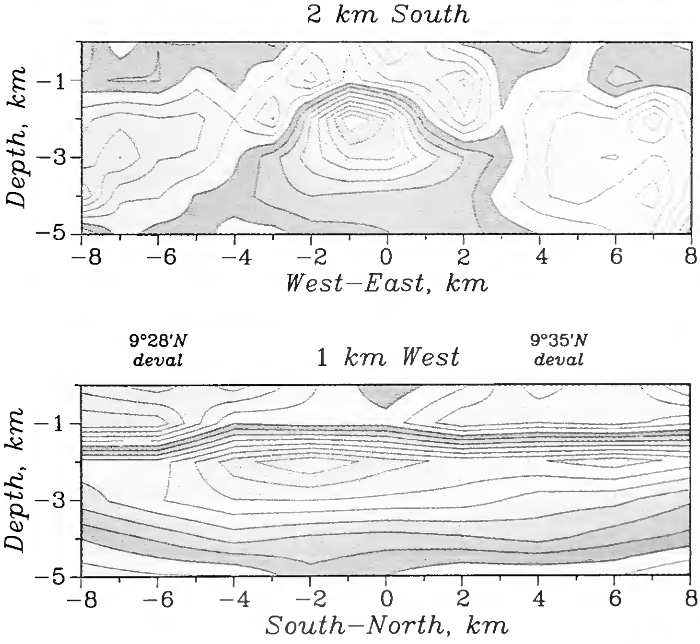
East Pacific Rise

Long-standing fundamental questions surround models of the size, shape, and physical properties of mid-ocean-ridge axial magma chambers. Mid-ocean ridge magmatism is a significant function of spreading rate, and at faster spreading rises, such as the East Pacific Rise, the volume of melt and the amount of heat delivered to the crust greatly exceeds that of the slower-spreading Mid-Atlantic Ridge. Consequently, thermal models for mid-ocean ridges predict that shallow crustal temperatures are generally higher, and axial magma chambers are generally larger and more long-lived along faster spreading rises. To test these models, a seismic tomography experiment was recently conducted on the East Pacific Rise (EPR) near 9°30′N by MIT and WHOI. It employed

A man and his charge: Beecher Wooding of WHOI prepares to launch an explosive charge (in the cardboard box) during the 1988 East Pacific Rise seismic tomography experiment aboard R/V Washington.

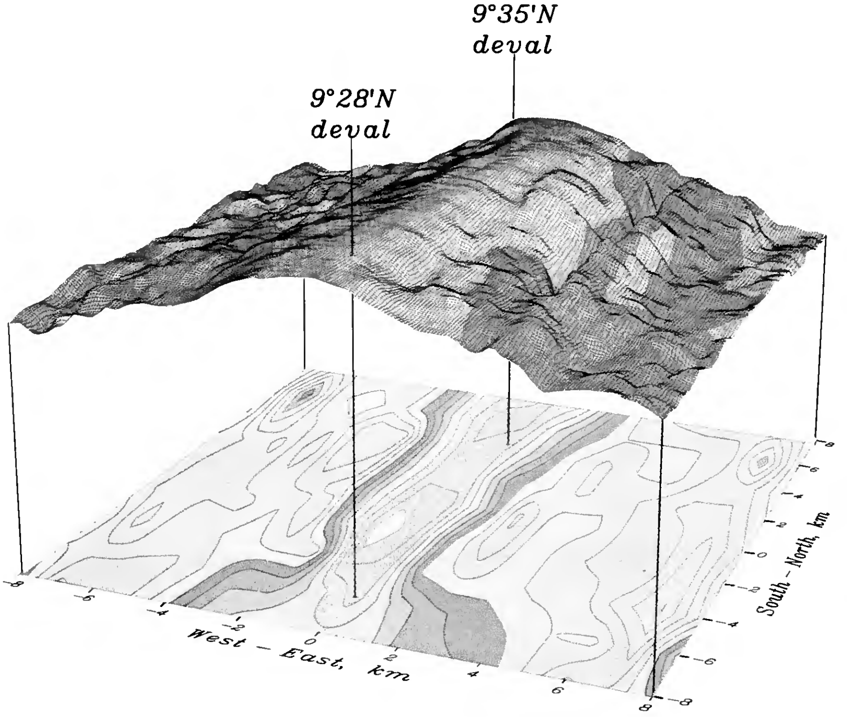
15 ocean-bottom receivers and over 450 shots to image for the first time the three-dimensional seismic structure of an axial magma chamber. The 15 receivers included ocean-bottom hydrophones and seismometers, designed and built by engineers and technicians at WHOI and MIT. Unlike the so-called passive tomography studies of the Mid-Atlantic and Icelandic rifts that used P-waves generated by local earthquakes, the EPR experiment was an active seismic-imaging experiment that used P-wave energy generated by explosives. We deployed the individual explosive shots in a dense grid to ensure good sampling of the crustal volume beneath an 18-by-16-square kilometer area centered on the EPR axis. Over 7,000 seismograms were recorded, each providing some measure of the crustal seismic structure along a different path connecting a source to a receiver.

A vertical section (at right) of the EPR tomographic reconstruction shows the anomalous P-wave structure across the rise axis and cutting through the axial magmatic system, which appears primarily as the anomalously low seismic velocities (orange and red areas) about 2 to 4 kilometers beneath the seafloor. From laboratory studies of



These vertical cross sections through the P-wave velocity structure were obtained by tomographic imaging of the East Pacific Rise. The top and bottom sections are transverse and parallel to the rise summit, respectively. The colors show departures of the three-dimensional model from an average one-dimensional, depth-dependent velocity structure: blues are faster than average and greens to reds are slower than average. The contour interval is 0.2 kilometers per second. Two deviations in the along-axis trend of the rise summit (devals) are shown on the rise parallel section. Both images pass through the axial magmatic system.

P-wave velocity with increasing temperature we infer that the subaxial crustal region comprising low seismic velocities is extremely hot, with temperatures well over 500°C. We think the concentration of lower seismic velocities near a 2-kilometer depth results from the accumulation and storage of molten magma within a thin melt-filled sill; this magma lens is frequently observed by other types of seismic experiments and its maximum cross-axis width and thickness are inferred to be 1 to 2 kilometers and less than a few hundred meters, respectively. The estimated volume of melt stored within this sill is comparable to that of a typical seafloor lava flow, suggesting that a volcanic eruption along a fast-spreading ridge draws melt from this region. The tomographic images also show a large region of low seismic velocities that presumably envelope the much smaller magma lens near a 2-kilometer depth. In general, the seismic velocities throughout the larger volume encompassing the melt lens are consistent with elevated temperatures, but not necessarily with molten rock. The size and shape of the seismic anomalies across the rise axis strongly constrain the size and shape of the axial magmatic system.



Juxtaposing the EPR seismic tomography results and the seafloor bathymetry permits a perspective view. Two map-view sections through the three-dimensional model are shown, one near the seafloor and the deeper one at a depth of 2 kilometers beneath the rise summit; the deeper section passes through the lowest seismic velocities of the axial magmatic system. The colors show variations in seismic velocity structure; blues are faster than average, greens to reds are slower than average. The three-dimensional mesh depicts undulations of seafloor bathymetry; the axial summit is depicted by shallowing of the seafloor. The location of two devals are noted, as is the vertical projection of these seafloor features down to the depth of the axial low-velocity volume.

A vertical section parallel to the EPR axis shows a variation in seismic velocity suggestive of an along-axis segmentation of the crustal magma chamber and the axial thermal structure. Again, the elevated temperatures associated with crustal-level magmatism are effectively mapped as the regions of lower seismic velocity. Along this section of the EPR, the observed seismic structure is noticeably segmented on a scale of about 10 kilometers, with the lowest velocities observed immediately south of the experiment center; from this we infer that thermal structure is segmented in a similar manner.

The along-axis segmentation of the axial magmatic system gives rise to an observed segmentation of seafloor morphology. During the experiment, we mapped seafloor bathymetry over a 3,600-square-kilometer area. Inspecting these maps we found that along axis the trend of the EPR axial summit was variable; within the aperture of our seismic experiment, the rise summit was easily divided into three adjacent linear segments. Our seismic tomography images included one complete 12-kilometer-long linear segment and parts of the bordering rise sections. At either end of this linear segment, the axial summit deviates from linearity, a seafloor morphologic feature referred to as a deval. The along-axis tomographic section shows that the axial devals coincide with a relative increase in along-axis seismic velocities near a depth of 2 kilometers. The interpretation is that at mid-crustal depths the temperature is highest in the center of the morphologically defined linear-rise segment, and lowest at the segment ends. The correlation of seafloor bathymetry with subseafloor thermal structure shows that magmatic processes occurring at great depths strongly affect surface geology.

Correlation of seafloor bathymetry with subseafloor thermal structure shows that magmatic processes occurring at great depths strongly affect surface geology.

A perspective plot (opposite page) shows a different view of the seismic tomography results including anomalous seismic velocities near the seafloor and 2 kilometers beneath the seafloor; variations in seismic velocity are indicated with color. As in the other figures, anomalously low and high seismic velocities are indicated by warmer and cooler colors, respectively. Seafloor bathymetry undulations are represented by a three-dimensional mesh, clearly showing the shallowing of the seafloor that demarcates the axis of seafloor spreading. Seismic velocities near the axial summit seafloor are notably high (shown as blue colors). Two bathymetrically defined devals are shown as vertical lines penetrating the seafloor and continuing downward to the horizontal section at a 2-kilometer depth. The deeper section lies near the depth of the melt-filled sill and through the core of the axial magmatic system. Our interpretation is that melt generated in the mantle tens of kilometers beneath the seafloor is injected into the shallow crust at intervals of about 10 kilometers along the rise axis, giving rise to magmatically defined rise segments of similar length. The segmentation of crustal-level axial magmatism and its relationship to segmentation of seafloor morphology is an important new observation made possible by seismic imaging.

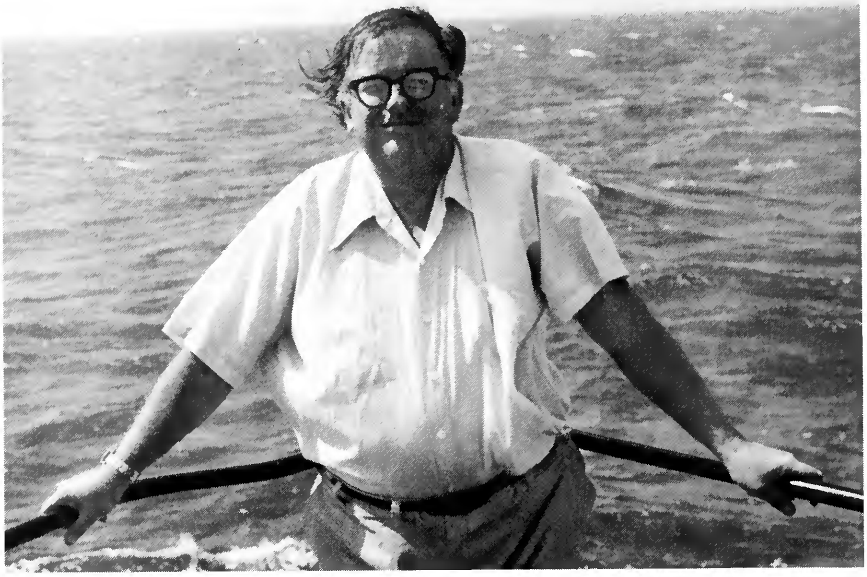
Tomographic studies of seismic velocity structure beneath local segments of the East Pacific Rise, the Mid-Atlantic Ridge, and the Icelandic rift represent a new and powerful approach to the seismological study of divergent plate boundaries. Future seismic tomography experiments will continue to provide images of the physical properties deep within spreading centers, and the study of these images, in conjunction with other geological and geophysical data, will greatly improve models of the tectonic, magmatic, and hydrothermal processes responsible for the formation of oceanic regions.

Acknowledgements: Much of the research reported here was done in collaboration with G. Michael Purdy (Woods Hole Oceanographic Institution) and Sean C. Solomon (Massachusetts Institute of Technology). The results from the TAG area of the Mid-Atlantic Ridge are from the Ph.D. thesis of Laura Kong (MIT/WHOI Joint Program in Oceanography/Oceanographic Engineering).

Douglas R. Toomey is an Assistant Professor in the Department of Geological Sciences at the University of Oregon, and a graduate of the MIT/WHOI Joint Program in Oceanography/Oceanopgraphic Engineering.

Bruce C. Heezen

A Profile



Bruce Heezen, aboard Vema, *in the 1970s.*

Paul J. Fox

Bruce Heezen died prematurely at the age of 54 in June of 1977, as he was preparing to dive aboard the Navy research submarine *NR-1*. His intended destination was the Mid-Atlantic-Ridge axis, a limb of the world-encircling ridge system where oceanic crust is created. Bruce had been fascinated with the Mid-Atlantic Ridge since he first studied and explored it 30 years before, as an undergraduate research assistant for Maurice Ewing at Woods Hole Oceanographic Institution (WHOI). Bruce's passing was untimely, and marine geology and geophysics lost one of the great visionary minds of the science, but the way he died was in a sense heroic: He was at sea, poised to enter the abyss in his never-ceasing quest to better understand how Earth works. If asked, I cannot imagine that he would have scripted his death any differently.

It is a daunting task to adequately profile the depth of character of a man who contributed more than 300 publications and two books to marine geological literature, who was the mentor and colleague of 13

Ph.D. students, who spent more than eight years at sea pursuing knowledge about the seafloor, and who, through these achievements, changed the way we think about the processes that create and modify the seafloor. I will try, however, to focus on a few highlights of his early years, his science, the particular gifts that allowed him to see further than most, and the generosity and wisdom that made him such a memorable teacher.

As the son of a successful turkey farmer in Iowa, Bruce Heezen spent a great deal of his childhood outdoors, rambling about the countryside attending to agrarian chores and developing a keen interest in the natural sciences, a focus encouraged by one of his grandfathers. He entered the University of Iowa as World War II drew to a close, with a desire to study science and an intention to never have anything to do with turkeys, whether it be their care or their consumption. I cannot help but believe that Bruce's intense dislike for these creatures contributed to his desire to distance himself from the Iowa turkey pens and seek the sea's far shores and mysteries.

His path to the sea, however, was indirect, and conditioned by serendipitous twists. His initial focus while an undergraduate geology major was paleontology, the study of fossil plants and animals. An outstanding undergraduate, he was selected to spend a summer in the western US helping a graduate student collect specimens for his Ph.D. thesis. Bruce later said that at this stage he had no doubt he would go on to graduate school seeking a Ph.D. in paleontology and spending his summers out west in search of fossils.

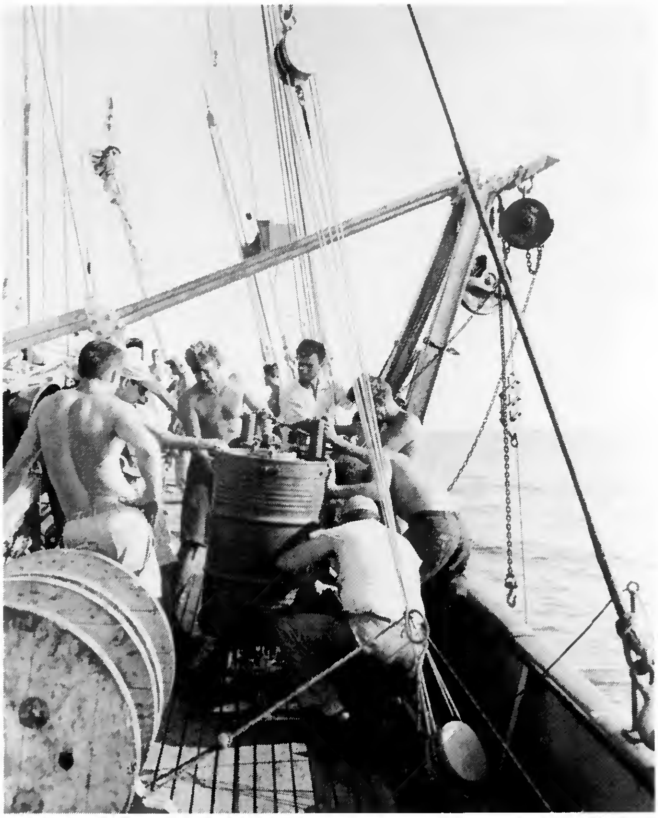
By the 1940s the study of the fossil record was a mature science with a 100-year record of scholarship; advances came slowly and only after a great deal of careful work. This characteristic was clear to Bruce during the winter term of 1947, as he labored on a study of toothlike fossil elements called conodonts, sampled from 300-million-year-old rocks around Iowa. When Maurice Ewing, a geophysicist from Columbia University, arrived on campus as a visiting lecturer and spoke about the vast *terra incognita* that lay beneath the obscuring blanket of the world's oceans and the exciting science to be done at sea, Bruce was intrigued at the seemingly great opportunities for discovery in this young science. It was no coincidence that Ewing emphasized the romantic qualities of oceanographic research: He was looking for undergraduates to join him for a summer of work. During a tour of the geology department after the lecture, Bruce was introduced to Ewing over a tray of fossils. Out of this came a seductive invitation to join a National Geographic-sponsored

Aboard Atlantis *in the North Atlantic, Bruce Heezen arms a surplus World War II bomb for a seismic refraction experiment. This photo was taken in the late 1940s or early 1950s.*

cruise aboard WHOI's R/V *Atlantis* to explore a long linear swell, the Mid-Atlantic Ridge, that lay along the North Atlantic's center line.

The opportunity to participate in an investigation of the first-order properties of an unknown mountain range beneath the sea offered a refreshing change in perspective and scale from the microscopic study of subtle changes in conodonts. Bruce accepted the invitation and arrived in Woods Hole in June to join Ewing's team preparing for the cruise. For the first several weeks, they worked feverishly to fabricate equipment for the voyage. Bruce constructed a photographic laboratory on *Atlantis*, helped to build several deep-sea cameras, and searched Harvard libraries for literature about the Mid-Atlantic Ridge. At that time, almost nothing was known about the Mid-Atlantic Ridge excepted that it existed.

It came as a shock and a surprise to Bruce when Ewing told him, during a walk home late one evening in Woods Hole, that he was not to go on *Atlantis* to the Mid-Atlantic Ridge. Instead, he was to be chief scientist aboard a small Navy ship, *Balanus*, that had unexpectedly become available. He was to use one of the newly constructed bottom cameras to take photographs of the submerged continental margin off the east coast, an environment that had never been photographed. Even in those expansive days of oceanographic science following World War II, it was most unusual to be chief scientist on one's first cruise. Ewing must have sensed that despite his inexperienced state, Bruce could be counted on to do the job.



Again on Atlantis *in the North Atlantic, Bruce Heezen (right, facing) with Maurice Ewing (left, facing) arms an explosive charge.*

This change in plans proved providential: It set the stage for Bruce's uncompromising love for the seafloor and the processes that shape it. The stomach of a flatlander from Iowa was in no way prepared for the lively nature of a small ship at sea, and Bruce experienced terrible seasickness. He reflected later that had he gone to the ridge with Ewing aboard *Atlantis*, he would have been the youngest of a large number of students and, as just one of many under Ewing's tutelage, would have lacked the incentive to rally against relentless seasickness. Instead, he was put in charge of a ship and given the responsibility of carrying out a program. He persevered that summer, successfully taking 200 bottom photographs of the uncharted abyss. He took these photographs home with him that fall, and spent his senior year at the University of Iowa trying to understand and interpret them. Bruce found that he had more questions than he had answers, and the photographs became a catalyst for dedicating his professional career to the study of the seafloor. The following summer he returned to the sea with Ewing, this time as a beginning graduate student, and spent two months aboard *Atlantis* continuing the Mid-Atlantic Ridge investigation. In the fall of 1948 he joined Ewing and his growing entourage of graduate students at Lamont Geological Observatory at Columbia University to begin his formal training. Marine geology was never to be the same.

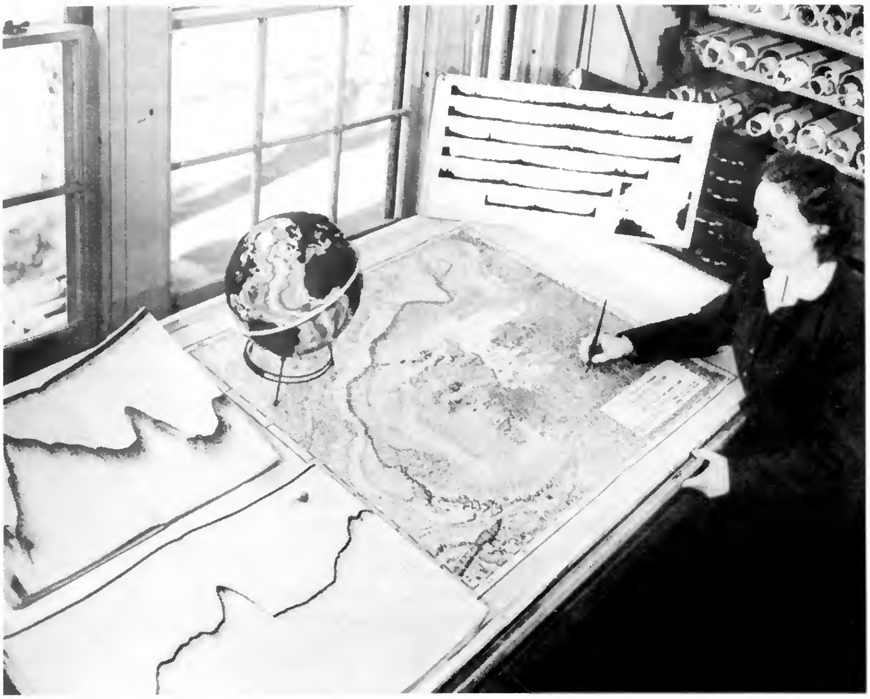
Like many talented people, Bruce was blessed with a very quick, multidimensional mind and an exceptional memory. He had an insatiable appetite for books on all aspects of Earth science. These characteristics combined to form an ability to see and think imaginatively about linkages both between and across different, but complementary, investigative results.

Bruce's disdain for all things turkey remained inviolate for over 20 years until an oceanographic cruise in the late 1960s. The cook aboard the ship had his roots in southern cuisine and all animal and most vegetable products were fried in a cavernous deep-fat fryer that seemed never to be turned off. After six days of nothing but fried foods, one's interest in meals was low indeed. Finally, at lunch on the sixth day we arrived in the mess to find a roasted turkey on the menu; roasted, because the 20-pound bird was too big for the fryer. Bruce, who had not eaten turkey for over 20 years, hesitated, stared, poked, and then descended ravenously upon his portion.

One of the great breakthroughs in our understanding of the Mid-Ocean Ridge system provides a good example. When Bruce started working with investigators at Lamont on the data from *Atlantis* cruises to the Mid-Atlantic Ridge, the existence of a world-encircling ridge system was unknown. However, a ridge of some kind was known to extend the length of the Atlantic based largely on results from English and German oceanographic studies carried out before World War II. These investigations showed the bottom water of the eastern and western basins to be different and, therefore, separated by a barrier with unknown properties. Also, investigators sailing under flags of a variety of countries before World War II had documented, with widely spaced soundings, the existence of the Albatross Plateau in the equatorial eastern Pacific (known today as the East Pacific Rise) and the Carlsberg Ridge in the northeastern Indian Ocean.

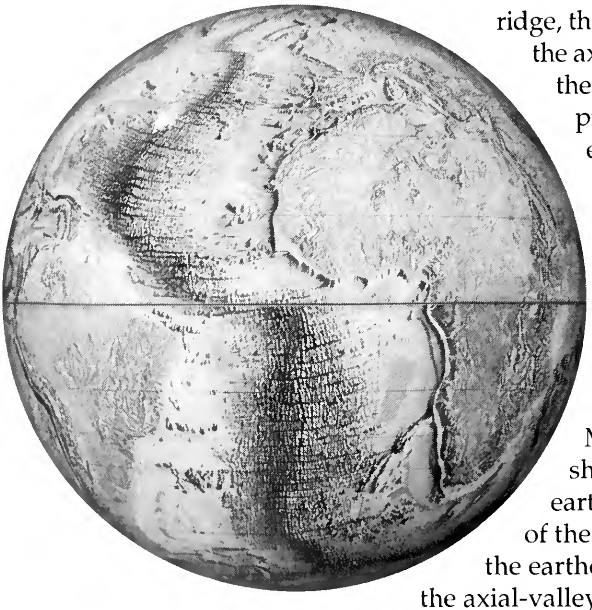
Bruce's initial project at Lamont was to compile all the available sounding profiles across the ridge in the Atlantic, in an attempt to characterize its spatial properties. He was assisted in this task by Marie Tharp, a new research assistant, who had recently completed an M.S. in geology at the University of Michigan. Marie tackled the tedious and demanding task of creating coherent profiles from noisy sounding data. She compiled six widely spaced profiles across the ridge in the North Atlantic and made the interesting observation that on each profile, the crest of the ridge appeared to be notched by a several-thousand-meter-deep valley that was 40- to 60-kilometers wide. Bruce was skeptical about the existence of such a valley at a regional scale, but intrigued by the notion.

Coincidentally, Bruce was working with Ewing on another project evaluating the linkage between underwater avalanches of sediment, called turbidity currents, and earthquakes. For this study, Bruce created a plot of earthquake epicenters on a North Atlantic map drawn to the same scale as Marie's sounding-profile map. This was no coincidence; Bruce believed that plotting different kinds of data at the same scale facili-



Marie Tharp (in about 1956) working with the first-edition physiographic map of the North Atlantic. The famous six profiles across the Mid-Atlantic Ridge are on her right, two sounding records on her left, and an early globe that she and Bruce created of ridges in North and South America is at center. In collaboration with National Geographic, Marie and Bruce made a physiographic globe of the earth in the late 1960s (below).

tated comparisons. Laying the epicenter map over the profiles revealed that the earthquakes defined a broad belt of activity down the center of the North Atlantic, and in the six profiles Marie plotted across the ridge, the earthquake locations fell within the bounds of the axial valley. The occurrence of earthquakes along the Mid-Atlantic Ridge had been recognized previously, but the association of the seismic events and the axial valley Marie proposed was startling. Bruce became convinced that Marie's insightful observation about the existence of a rift valley was correct.



The coincidence of the valley and earthquake activity, which is an indicator of rupturing of the earth's brittle yet elastic outer shell in response to forces that exceed the shell's strength, indicated to Bruce and Marie that this feature was dynamic and shaped by currently active processes. The earthquake belt was continuous along the length of the North Atlantic, leading them to speculate that the earthquake-belt location could be used to predict the axial-valley location in the absence of sounding data. As they slowly accumulated sounding profiles across the North Atlantic, their plots began to reveal a deep axial valley coincident with the seismic belt along the crest of the Mid-Atlantic Ridge. Ewing and Heezen then embarked on a project to plot the locations of earthquakes in ocean basins throughout the world, and noted once again the coincidence between belts of earthquakes and the crests of known, but seemingly separate, ridge segments scattered about the ocean basins. In addition, the earthquake locations defined a diffuse but continuous belt that linked the known ridges in the Atlantic, Indian, Arctic, and Pacific oceans, leading them to suggest that the world was encircled by a mid-ocean system of ridges that by their very existence, scale, and continuity, were central to the history of the ocean basins. They also observed that when sounding profiles crossed a branch of the ridge system, earthquake epicenters fell within the boundaries of the axial valley that was interpreted to be an active rift zone. In 1956, they published their idea for a continuous ridge system, and were met with some skepticism. Cruises were planned to test their predictions by surveying unexplored portions of the southern Pacific and Indian oceans to see if, indeed, a ridge existed where proposed—and a ridge was always found.

During this global synthesis, Bruce noticed that a limb of the mid-ocean seismic belt could be traced across the northwestern Indian Ocean into the Gulf of Aden, where it linked with a north-south trending zone of continental seismicity in East Africa. This belt of continental seismicity was associated with the network of East African Rift valleys that contained the great lakes of Africa, such as Victoria and Rudolf, and where fieldwork by British and German geologists had documented that the earth's crust was being extended in an east-west sense to create a north-south trending rift system. Bruce and Marie constructed topographic profiles across the rift valleys of East Africa and compared them with profiles across the Mid-Atlantic Ridge. The similarity of the profiles was striking. This, along with the continuity of the seismic belt, indicated to Bruce that the axial terrain of the ridge and the rift valleys of East Africa are genetically related. He proposed that the crust along the axis of the Mid-Ocean Ridge system is stretched at right angles to the axis. By the late 1950s, evidence for large displacements of the continents (based on paleomagnetic studies of rocks by British investigators) was compelling. Bruce suggested that these displacements were accommodated by the creation of crust at the ridge axes, and that the history of continental displacements were recorded in the seafloor's structural fabric. With this, a major pillar in our understanding of how the earth works was in place.

Earthquake locations defined a diffuse but continuous belt that linked the known ridges in the Atlantic, Indian, Arctic, and Pacific oceans.

During this phase of exploration and insight, Bruce and Marie realized that it was difficult to create improved maps of the seafloor because of the vast scale of the underwater terrain and the slow rate of sounding data acquisition. Following the techniques developed by continental cartographers, they created physiographic diagrams of the seafloor. Unlike a contour map that links points of similar depth with lines, a physiographic diagram creates an interpretive three-dimensional view of the seafloor. Such a presentation also allowed Bruce and Marie to extrapolate the seafloor's textured variations between widely spaced sounding lines. They finished their first physiographic diagram of the North Atlantic in 1956, and it was followed over the next 20 years by a series of physiographic maps that, in one form or another, covered all the world's oceans. These maps are remarkable because Bruce and Marie had an ability to visualize seafloor morphology in three dimensions and intelligently extrapolate trends and relationships into areas of sparse data to create depictions that have since been shown to be remarkably accurate. This collection is probably the most widely distributed set of seafloor maps. As such, it has provided a pictorial gateway to the earth's last frontier and captured the imaginations of students and researchers around the world.

Bruce was happiest when he was at sea learning something new. He was indefatigable in this environment, where he seemed to derive the strength he needed to work night and day by feeding off the realization that a major discovery was in the making if he could collect the right kinds of data in the right way. Given the great expanse of unexplored ocean, more was always better—and Bruce worked himself, his colleagues, the ship, and its crew to the limit. Data were not mindlessly accumulated; each new observation of interest was studied and assessed for telling clues about the seafloor. With each new insight came hypothesis testing and cruise-plan modification to create a more effective investigative strategy. To be a student working with Bruce at sea under these conditions (which I had the fortune to be during several cruises) was at once exhilarating and fearful: exhilarating in that I learned so much because the arrival of new information in the form of a sample, photograph, or profile always precipitated lively and intense discussions about all the data's aspects and implications, and fearful because Bruce asked penetrating questions and expected intelligent answers. I knew when I had run aground with an idea if Bruce likened me to one of his feathered friends from his early days in Iowa.

Bruce became an avid and enthusiastic user of submersibles in the late 1960s when this technology became available and permitted manual presence in the deep sea. One day, during an explanation to a graduate student about what to expect when this student made his first dive, Bruce found his descriptions about the experience to be lacking. In mid-sentence, he jumped up from his desk, turned off the lights, grabbed a flashlight and crawled under his desk. From his confined quarters under the desk, Bruce held the flashlight above his head and pointed the narrow beam out across the floor slowly sweeping the shaft of light across one partially illuminated object after another. About this time his secretary opened the door to a darkened room to find Bruce squeezed under his desk, shining a light about the room with a silent but bemused graduate student standing off to one side. Her look was incredulous, but before she could say a word, Bruce announced that he was diving in a submersible and was not to be disturbed.

Bruce was a marvelous advisor to his graduate students. He understood and respected the sanctity of research and the freedom to follow one's own ideas. He exposed incoming students to the broad venue of research possibilities that lay between the shorelines of the world's oceans, and gave them free reign to choose problems of interest. He recognized the importance of exploring unknown and untested avenues of research and the time-consuming nature of this process. He had as many as 11 Ph.D. students at one time, all working on a broad range of problems, and, given his many involvements, he only had time to measure a student's research progress every few months. When the call did come, however, his students knew they had better be prepared, because Bruce would expect to be challenged by new observations and ideas. The sessions were often lengthy, as Bruce explored every aspect of the student's work. I always left these encounters exhausted but enlightened, because his probing questions and great depth of knowledge had provided new insights about my results, opening up new avenues of exploration. No matter how thoroughly I had analyzed a problem, Bruce always seemed to see farther.

The science of the seafloor was Bruce's life, and the boundary between his work and everything else that constituted his being was invisible. When your goal is to map the world-ocean floors and understand how this great expanse was formed, you need a great deal of space, more than Bruce found available at the Lamont Observatory, so certain mapping and writing projects were carried out at his or Marie's homes. Over a period of years, both homes evolved into laboratories with drafting tables, a multitude of maps, and books piled everywhere. Because these environments were quieter than the chaos of his offices and laboratory space at Lamont, where technicians and graduate students swirled about, he would often work at one house or the other, and this is where a student might go to work with him, especially when preparing a manuscript. These gatherings could go on for hours as Bruce probed every sentence for clarity and insight, oblivious of the time. I remember that when projects were under way, there was always a welcome place at the dinner table. After dinner, typically a very rare meat and an excellent bottle of Bordeaux, the manuscript honing would continue long into the night. Bruce would reluctantly loosen his grip on our text when he observed that I had fallen asleep.

On an expedition to the Caribbean in the early 1970s, Bruce Heezen discusses a dredged limestone sample with students aboard R/V Eastward.

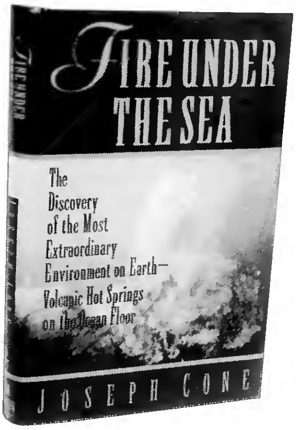
During his career Bruce received awards from many scientific societies for his fundamental contributions to marine geology and our understanding of the earth. He was a man for his time, because his wide-ranging interests and probing intellect were free and unconstrained by the lack of disciplinary boundaries found only in new fields of science. Today, marine geology and geophysics is a much more mature science with rigorously defined investigative disciplines, and it is difficult, if not impossible, to work on and contribute to the range of problems that Bruce examined. We were lucky to have him when we did.

Paul J. (Jeff) Fox is Professor of Oceanography at the University of Rhode Island Graduate School of Oceanography. He was one of Bruce's graduate students at Lamont-Doherty Geological Observatory of Columbia University and worked with him at sea and in the laboratory from 1964 until Bruce's death. Under Bruce's tutelage, he was introduced to the intriguing mysteries and romance of the Mid-Ocean Ridge system; it is a love affair that continues to this day.

Fire Under The Sea

By Joseph Cone, 1991. William Morrow and Company, Inc., New York, NY; 286 pp. - $25.

The discovery of hot springs on the seafloor is one of the most dramatic findings in marine science in the last 15 years. From the formation of mineral deposits to the existence of previously unknown biological communities, studies of these hot springs have had profound effects on our understanding of ocean floor processes. In *Fire Under The Sea*, Joseph Cone traces their exploration in an action-packed story that not only conveys the challenges and excitement of exploring the ocean bottom, but also provides a glimpse into the lives and work of sea-going scientists.



Addressing the field in general, Cone concentrates on the exploration of hot springs on the northwest coast of the United States. The book opens aboard the research vessel *Atlantis II* off the Oregon coast on a typical morning as scientists prepare to dive in the submersible *Alvin* to the ocean floor for a day of observations and sampling. This is the first of many "dives" the reader makes during the book's course and, through the thoughts and comments of the scientists, the story captures the essence of being part of an oceanographic expedition.

Cleverly interwoven into the story of hot springs on the Gorda and Juan de Fuca Ridges is an account of the development of modern ideas of seafloor spreading and continental drift. As in any good mystery story, a number of unconnected pieces—in this case, studies done independently by continental and marine geologists and geophysicists—have been fitted together to produce a model of the Earth's surface plates created at mid-ocean ridges. From the time when Alfred Wegener first noted the "fit" of the continents of South America and Africa early in this century, the reader is led through scientists' work as they developed new ideas, designed experiments, and debated their results. Although the story is full of information, Cone manages to keep the reader's interest with anecdotes that illustrate the personalities of those involved. By the 1960s, the plate tectonics paradigm had gained general acceptance. Against this background, scientists predicted the occurrence of hot springs on the ocean floor and took on the challenge of proving their existence.

Apart from the highly visible aspects of scientific discovery, there are many other important facets—from the technological developments that frequently pave the way for exploration, to the policy decisions necessary when new, potential mineral resources are found. Whether describing the development of sophisticated echo-sounding techniques or Law of the Sea negotiations, Cone's writing is authoritative, easy to read, and without jargon.

In writing *Fire Under The Sea*, Cone interviewed an impressive list of scientists and consulted a large number of references, both of which are presented in the book. The inclusion of a chronology of events at the beginning is helpful, and eight pages of color photographs illustrate the strange chimney structures and unusual organisms associated with seafloor hot springs. *Fire Under The Sea* is an entertaining and compelling account of discoveries in a young and exciting field, and should be of interest to anyone curious about the ocean.

—Susan Humphris
Dean, Sea Education Association
Woods Hole, Massachusetts

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Oceanus welcomes and occasionally publishes letters from readers regarding editorial content or other ocean-science issues. Please write to the address on page 4.

4000 Meters Under the Sea

By Films for the Humanities and Sciences, Princeton, N.J. 1991. 28 minutes - purchase $149/rent $75.

This 28-minute video, made by NHK (Japan Broadcasting Corporation) and distributed by Films for the Humanities and Sciences, concerns a 1987 joint US-Japan expedition to study the geology and biology of the Marianas Trough spreading center. The film depicts the findings of hot vents and associated fauna at the accreting plate margin in the trough using the deep submersible *Alvin* and R/V *Atlantis II*. It is aimed toward the lay audience.

The film nicely captures the essence of a multidisciplinary expedition and the use of *Alvin* as a research tool. A voice-over commentary identifies the principal investigators, Bob Hessler and Jim Hawkins of Scripps Institution of Oceanography, and their Japanese colleagues, but, regrettably, with the exception of a closing sentence from Hessler, we do not hear first-hand from the scientists. The film quality is good with some excellent close-ups of the vents and the vent communities. The development of the film's theme—the finding of and questions regarding hot vents—is well done (with some reservations that I will discuss later), and draws the audience along nicely. It makes for an interesting 28 minutes.

There are a few, minor irksome aspects: Principally I found it most annoying to be continually told in the introduction, and near the end, that the expedition was to the Marianas *Trench*. Presumably this assertion, accompanied by continual references to the deepest part of the world's oceans, is an attempt to add glamour and excitement—certainly not needed here. In actuality, some excellent graphics clearly show the Marianas Trough and its relative position to the Trench. These graphics were so good and visually striking, I regretted that they didn't spend a couple of minutes more explaining the spreading center and its relevance to the Trench, plate motions, etc. The other irksome aspects were in the commentary: Generally it was well done, but a little better quality control could have avoided small things like referring to the *Alvin* manipulators as "magic hands" or, more importantly, reference to the planktonic food falling to the seafloor and being converted *into* bacteria (rather than *by*).

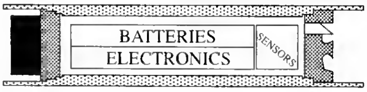
On the whole, the scientific aspects were well covered and well explained. A few errors slipped through: References to "magma in the venting solutions making them cloudy," rather than products of rock-water interaction; the chimneys or smokers being alluded to as "cooled molten lava," rather than precipitates of sulfides and sulfates; the observed minerals being "crystals of iron, copper, and zinc," rather than sulfides of these elements. I think the interaction of seawater with the rocks, subsequent extraction of metals, gases, etc., and how they reach the sea surface had the weakest coverage, but the main points did come through.

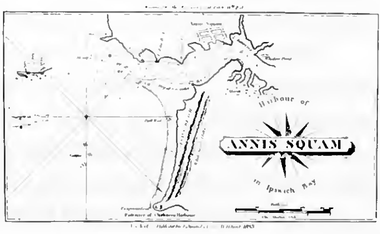
While recognizing the educational and

entertainment aspects needed for this kind of video, I was most disturbed by the implicit (and at times explicit) suggestion that this was the *first* discovery of vents, and the expression of great "surprise" to find life at this depth; similar vents and life had been discovered and investigated in many locales, and at similar depths, before this expedition. The questions being addressed (implicitly for the first time): Where does the hot water come from? Could the cloudy waters be the key to life? How does it sustain life? How do the animals feed? All these have been previously investigated at other vents and are known to some degree. The really important aspects of the Marianas Trough vents were not made clear—their setting in a back-arc basin as opposed to a mid-ocean ridge, and their biological community that is slightly different and dominated by new species (hairy gastropods) compared to other vents. This is never spelled out, and previous work is not properly referenced, except for one comment from Hessler about how exciting it was to find "new friends" (animals) as well as "old ones" (previously discovered vent fauna) at the Marianas vents.

All in all, in spite of my minor misgivings, I found it an interesting video. It should excite the lay audience, and the shots of the vent communities are certainly worth a look by serious submarine-hot-spring researchers.

—Geoffrey Thompson
Senior Scientist, Chemistry Department
Woods Hole Oceanographic Institution





Glossary *continued from page 8*

strike-slip fault—a fault showing predominantly horizontal movement parallel to the strike; vertical displacement is absent

subduction zone—area of crustal plate collision where one crustal block descends beneath another, marked by a deep ocean trench caused by the bend in the submerging plate. The downward movement of the subducting plate results in earthquakes, volcanos, and intrusions on the far side of the trench.

swath mapping tools—instruments installed on a research vessel that use sound reflected from the seafloor to map the shape of the seafloor along a band or swath that extends as far as 1 to 5 kilometers on either side of the vessel's track. Common instrument names are GLORIA, Hydrosweep, Sea Beam, and Sea MARK.

tectonics—the forces and movements that create Earth's larger features

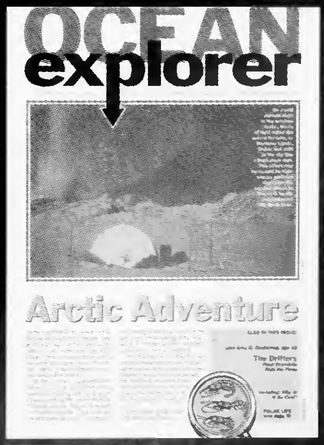
terrane—the area or surface over which a particular rock or group of rocks prevails

transform fault—a strike-slip fault of a particular type where displacement stops abruptly, especially associated with offsetting of mid-ocean ridges

transverse feature—a geological feature whose strike is generally perpendicular to the general structural trend of the region

vent—place where water heated and altered by circulation through porous volcanic rock erupts from the seafloor, precipitating minerals and supporting sulfide-dependent biological communities

The *Oceanus* staff acknowledges the valuable aid in assembly of this glossary of *The Facts on File Dictionary of Geology and Geophysics* (© 1987 by Dorothy Farris Lapidus, Facts On File Publications, New York, New York, and Oxford, England).



CREATURE FEATURE: These photographs represent the many interesting animals found in the colonies that thrive around mid-ocean ridge hydrothermal vents. (For a broad look at recent work on vent communities, please see The Biology of Deep-Sea Vents and Seeps...by Rich Lutz on page 75.) The large photo is a field of tube worms, *Riftia pachyptila,* on the Galapagos Rift, and the upper right inset is a closeup of these animals. The lower left inset is an *Alvin* camera view of giant clams, *Calyptogena magnifica,* and scavenging galatheid crabs, *Munidopsis* sp. At upper left, a line of crabs marches along the edge of a bed of mussels, *Bathymodiolus thermophilus.* At lower right, the Pompeii worm, *Alvinella pompejana,* was photographed on the surface with the tube it calls home. (Large photo by Kathleen Crane, small photos clockwise from lower left by *Alvin* exterior camera, Robert Hessler, Dudley Foster, and John Porteous.)

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