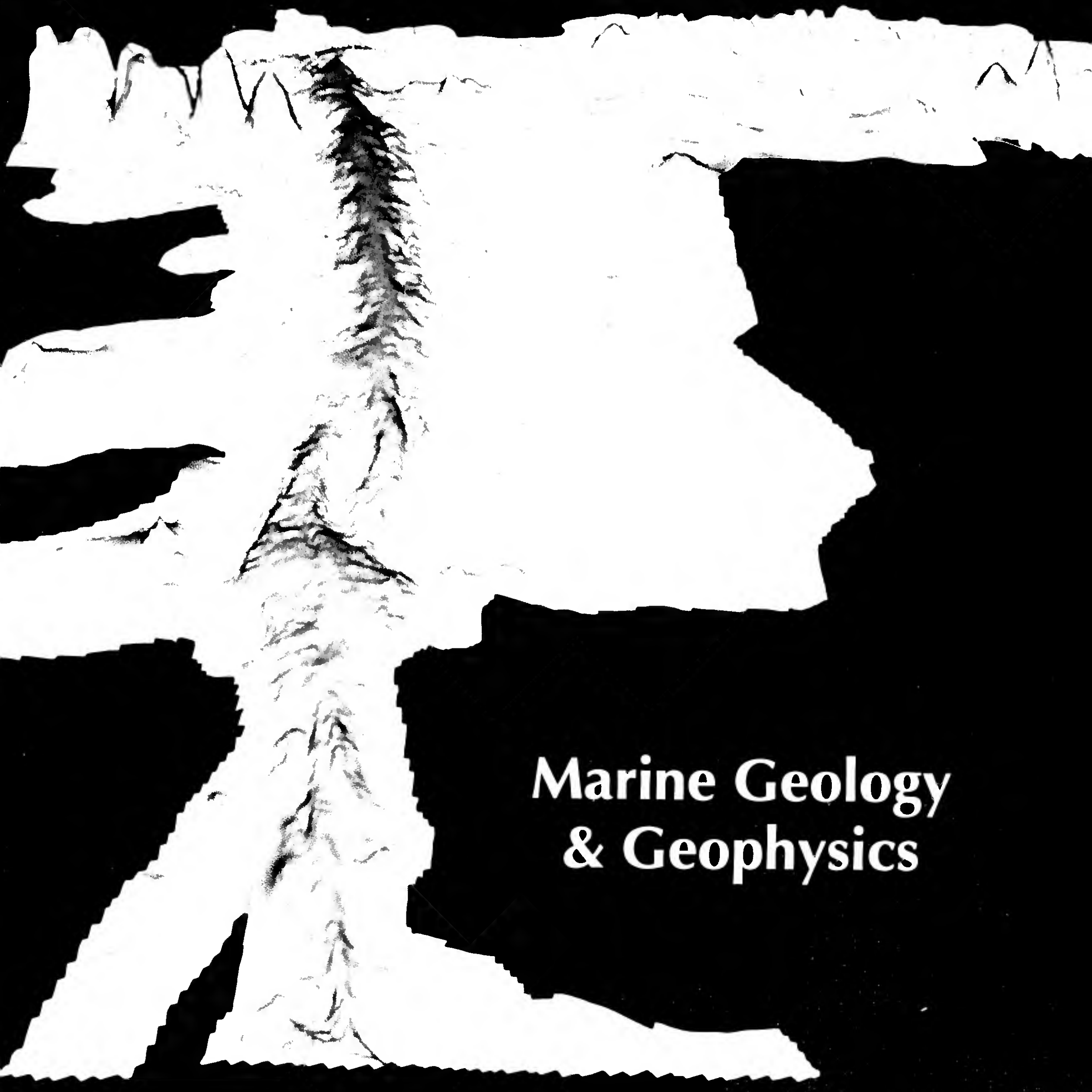
Oceanus

Volume 35, Number 4, Winter 1992/93



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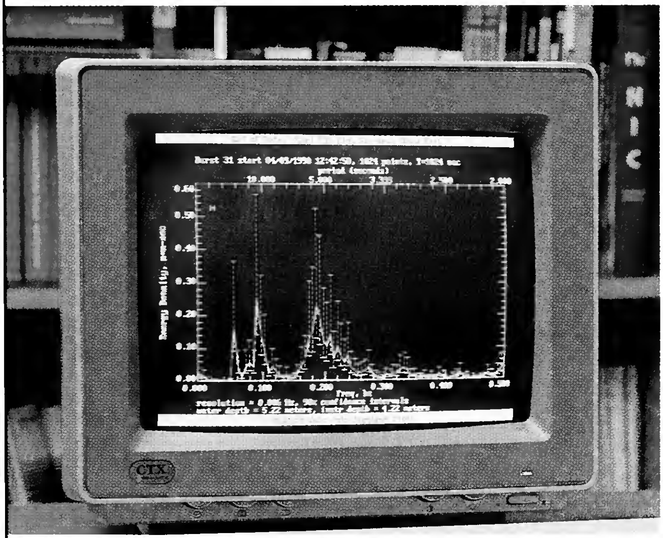
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MARINE GEOLOGY & GEOPHYSICS


Michael Rawson

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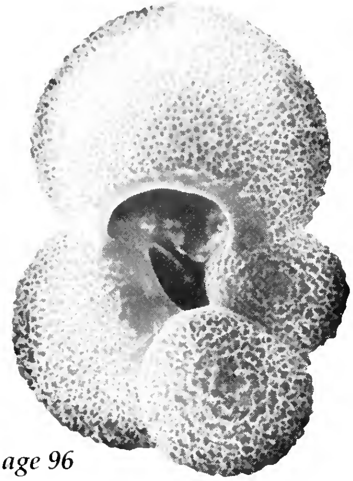
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Howard Spero

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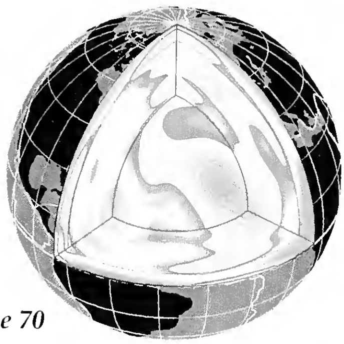

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ON THE COVER:

This image of the East Pacific Rise was computer generated at the University of Rhode Island's Ocean Mapping Development Center. For more information, see page 76.

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Oceanus

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Ocean Law & Policy

The Legal Odyssey of the Continental Shelf

Is it a Shelf? Is it a Slope? Is it Only a Legal Concept?

Keith Highet

In 1945, President Truman issued a famous proclamation that, for the first time in history, claimed sovereign seafloor rights for a coastal State. The proclamation stated that having in mind the "...long range worldwide need for new sources of petroleum and other minerals...the Government of the United States regards the natural resources of the subsoil and sea bed of the continental shelf beneath the high seas but contiguous to the coasts of the United States as appertaining to the United States, subject to its jurisdiction and control." This daring step was a product of the technological developments and security considerations of World War II. The Proclamation was careful, however, to add that: "...The character as high seas of the waters above the continental shelf and the right to their free and unimpeded navigation are in no way thus affected."

The Truman Proclamation was referred to at the time as the boldest and most successful land-grab in the history of the Union. But what was the meaning of "contiguous to the coasts?" What exactly did "the subsoil and sea bed of the continental shelf beneath the high seas" consist of?

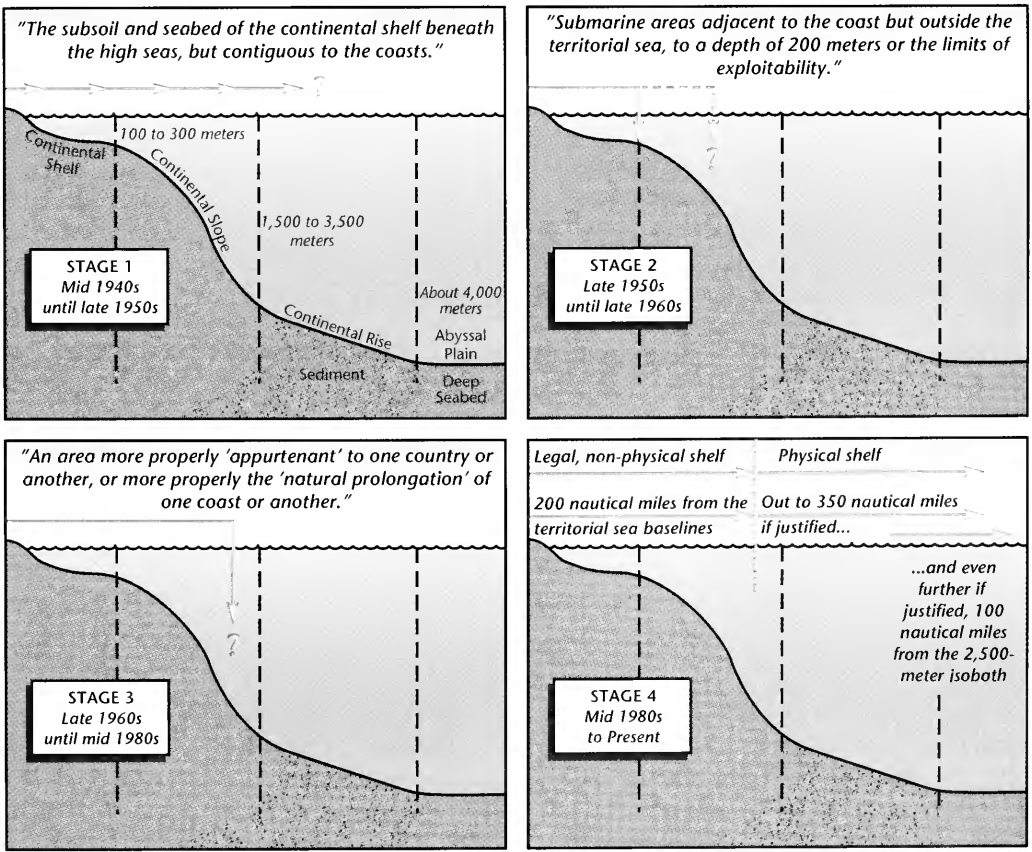
The continental shelf was defined in terms of how deep the water above it was, or whether people could get to it, but not what it *itself* was. Some years later there was an attempt to define the breadth of the continental shelf, in the 1958 Geneva Convention on the Continental Shelf. Article 1 stated that "the term 'continental shelf' is used as referring to...the seabed and subsoil of the submarine areas adjacent to the coast but outside the area of the territorial sea, to a depth of 200 meters or, beyond that limit, to where the depth of the superjacent waters admits of the exploitation of the natural resources of the said areas...." The definition of the shelf was thus provided by its "adjacency" out to a depth of 200 meters, or by the test—presumably a flexible and ever-changing criterion—as to whether it was accessible for exploitation. It still didn't define the shelf or tell how far out the shelf actually went.

Then came the lawsuits. They arrived in the context of five important cases, four in the World Court and one in a State arbitration. All were in the context of delimitation, or of drawing boundaries between States. In the first, the North Sea Continental Shelf Cases of 1969, the Court defined the shelf in terms that went beyond previous treaty provisions. It seemed to hint that the geological or geomorphological characteristics of the seabed and subsoil could provide a test or criterion for defining the shelf and determining to whom it might "belong." It must be noted that this was the World Court's first big case since the debacle of the South West Africa Cases of 1966, as a result of which the Court had endured much criticism in the United Nations and seen its workload shrink to almost nothing. Yet when Denmark, the Netherlands, and West Germany came to the Court in 1969 for help in delimitation of their continental shelves, the Court had only an incomplete legal definition to work with, in spite of its desire to be helpful.

The result was a long decision that hinted at a wide variety of ways in which the continental shelf of a country could be defined, including geological criteria (itself not defined) that might indicate whether the shelf in an area was more properly "appurtenant" to one country or another, or more properly the "natural prolongation" of one coast or another. As a result, for a period of a dozen years, between 1969 and 1982, the conventional wisdom was that the definition of the continental shelf would to some extent borrow from the lexicon of geology. Indeed, in a case coming eight years later (the Channel Arbitration of 1977 between the UK and France) the court of arbitration disregarded a trough between the British and French Coasts, but only because it was neither deep nor sufficiently marked to serve as a boundary for delimiting the respective shelves, and not because a trough would have no place in boundary delimitation.

Five years after that decision, the world community came to an historic agreement (with the egregious exceptions of the US, the UK, and West Germany as nonsigners) on a new ocean regime. The 1982 United Nations Convention on the Law of the Sea adopted the substantial innovation of the Exclusive Economic Zone (EEZ) extending 200 nautical miles from nations' coasts, as well as detailed provisions governing the continental shelf. Article 76 defined the shelf both in terms of distance from the coastline *and* in terms of its scientific composition. The distance was to be "the outer edge of the continental margin wherever the margin extends beyond 200 nautical miles," out to a total distance of 350 nautical miles from the territorial sea baselines, or 100 nautical miles from the 2,500-meter isobath. (Some difference from the paltry 200 meters of 1958!) The outer scientifically defined limits were set as "the outermost fixed points at each of which the thickness of sedimentary rocks is at least 1 percent of the shortest distance from such point to the foot of the continental slope" or "no more than 60 nautical miles from the foot of the continental slope" (the point of maximum change in the gradient at its base). The outcome was that the shelf was first defined in terms of distance pure and simple, as if one were to float a measuring tape on top of the water out 200 nautical miles from the coast, but extension beyond that limit depended on a new scientific definition.

How the Definition of "Continental Shelf" has Changed over the Years



Jack Cook/WHOI Graphics

However, at the very time that the 1982 Law of the Sea Treaty was being finalized, the Tunisia/Libya Continental Shelf Case was being argued before the International Court. In that decision the Court held (as the court of arbitration had done in the Channel Arbitration of 1977) that geological and similar features advanced by the parties as relevant to the issue of "whose shelf was whose" were insufficiently important to constitute boundary markers, but it went no further. It was not until 1984, in the Gulf of Maine Case, that a Chamber of the Court was faced with the fact that it was selecting a single maritime boundary—for both the new exclusive economic zone and the old and new continental shelf—and was therefore able to avoid geology inasmuch as it could have no relevance to the EEZ. Then in 1985 the Court, in its Libya/Malta decision, finally disposed of the geological foundations for the first 200 nautical miles of "continental shelf" by supporting the "distance principle" that had been so clearly expressed in the 1982 Convention.

The journey of the continental shelf, then, has been from that of a perceived scientific reality, to legal confusion, to a legal reality with no scientific basis coupled with a physical or scientific basis beyond the extent of that legal reality. The irony is that it is thanks to the 1982 Law of the Sea Convention's innovation of the exclusive economic zone that the first 200 nautical miles of the continental shelf has at last been given unequivocal legal expression.

Indeed, the Convention provisions articulate a more tolerant expression of sovereign rights than has been generally recognized. Why? Because countries such as Chile, fronting on the Pacific with virtually no "real" continental shelf but merely a huge drop-off into the deep ocean depths, are treated today as if they actually "had" a continental shelf, at least out to 200 nautical miles.

The world of the oceans is therefore now made up of continental shelves that are continental shelves and continental shelves that are not. The original shelf of the 1945 Truman Proclamation would still be recognized today, but if a State in 1958 did not possess a physical shelf that would have been recognized as such, that area of adjacent seafloor has been converted into a "legal continental shelf" by passage of time and the desire of nations not to discriminate against "geographically challenged" members of the world community.

Although the 1982 Convention has given States without significant continental shelves a uniform broad legal shelf of 200 nautical miles, it could not, by the nature of things, award landlocked States any such right, though landlocked States are given rights to fish in the exclusive economic zones of coastal States under certain conditions! Possession of a shelf still depends upon possession of a coast, although inroads on this concept have also been made by the most recent World Court case on the subject (1992), which awarded maritime rights in the Pacific to Honduras in spite of the fact that her coastline fronted on the waters of the Gulf of Fonseca and not on the Pacific Ocean proper. The Convention could thus reform some of the geographical inequities of the world, but not all of them.

Another paradox is that it is at the outer limit of the 200-nautical-mile "legal shelf" that the real continental shelf "kicks in" once again and, under the outer-shelf provisions of the 1982 Convention, can result in a State possessing an extended continental shelf that goes out all the way to 350 nautical miles or even further, such as the Russian sub-arctic continental shelf. What establishes this? It is a combination of technical examinations, of geology, and geomorphology. Forty years ago these elements were thought to be relevant to the nature and appurtenance of all the continental shelf. Today they are legally relevant only to its outer limits.

The continental shelves of all coastal States have been pushed far offshore, *regardless of whether* they exist in reality. Beyond 200 nautical miles, they may or may not continue, *depending only on* whether they exist in reality. The institution of the continental shelf has evolved from a physical fact to an intriguing blend of law and substance. Its evolution has been required not only by physical factors under the seas and the development of the law of the sea, but also by international political realities, and their attendant compromises, worked out—of course—on dry land.

Keith Highet is a Visiting Professor of International Law at the Fletcher School of Law and Diplomacy in Medford, Massachusetts.

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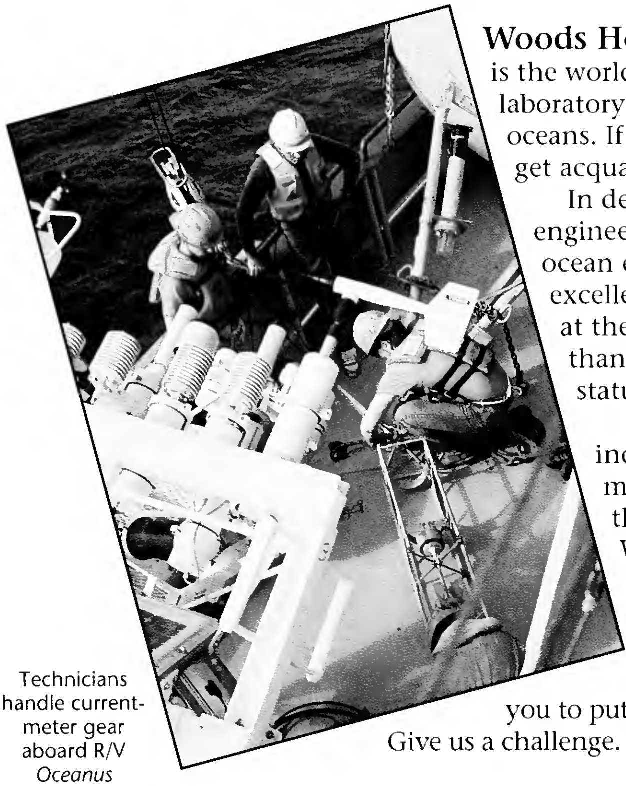

Technicians handle current-meter gear aboard R/V *Oceanus*

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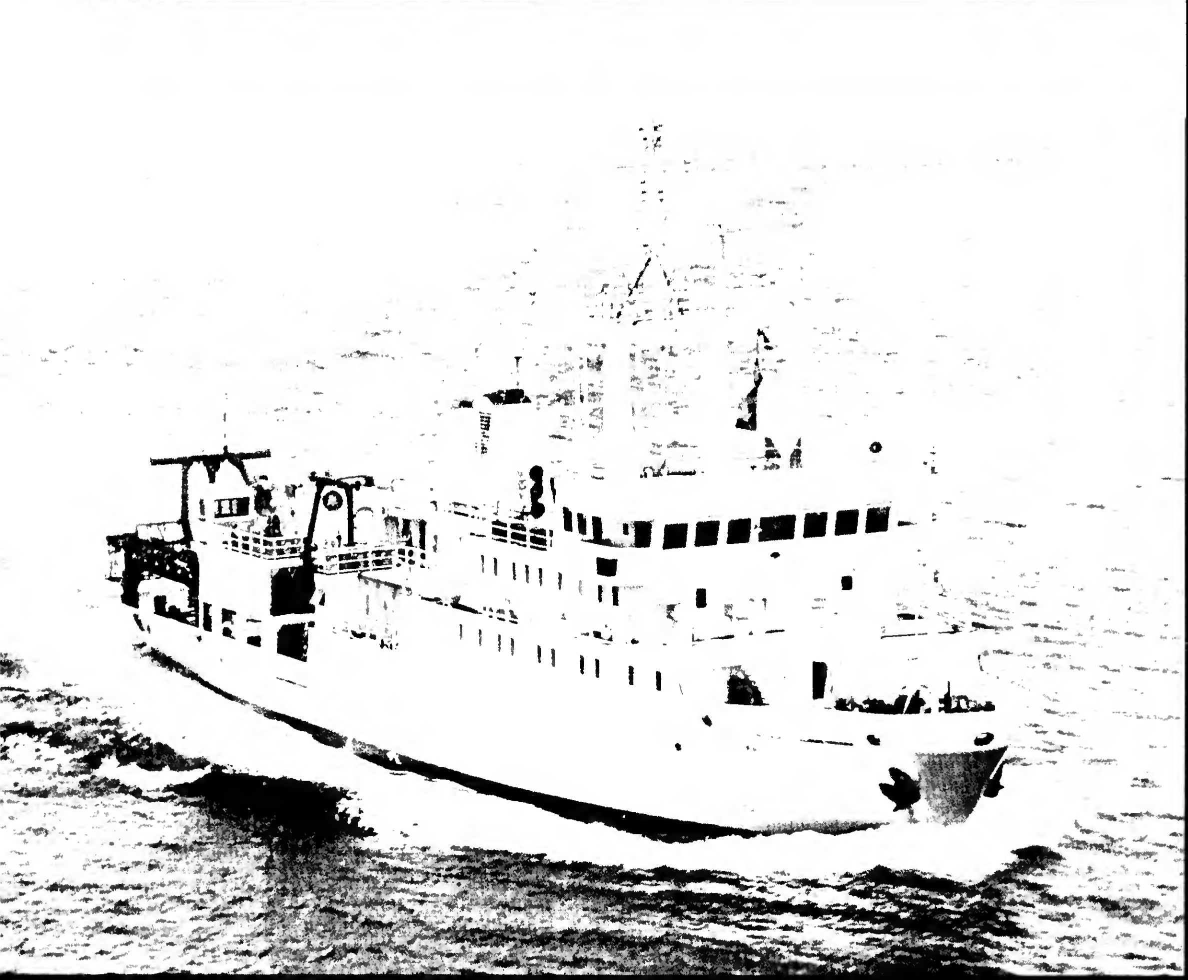


Michael Rawson

R/V *Maurice Ewing*

The research vessel *Maurice Ewing*, one of the largest and newest US oceanographic research ships, is owned and operated by the Lamont-Doherty Geological Observatory (L-DGO) of Columbia University. Built in 1983 for Petro-Canada Resources and named *Bernier*, the ship was purchased by L-DGO and reoutfitted in 1989/90 as a general-purpose research vessel with extensive marine geophysical capabilities. It was renamed for a pioneering marine geophysicist who founded the Observatory in 1949. The 70-meter ship accommodates a scientific party of 28 and takes a crew of 22. *Ewing* worked in the South Pacific during early 1992, transited the Panama Canal in May, then spent the rest of the year in and out of San Juan, Puerto Rico, Barbados, and Bermuda, before closing the year in the Gulf of Mexico. During 1992, Ocean Drilling Program site surveys were conducted at the Northern Barbados Trench and on the Ceara Rise east of the Amazon River fan. Other work included a survey of the Pacific Antarctic Ridge, Mid-Atlantic Ridge studies of the origin, structure, and evolution of slow-spreading ridges, and recovery and redeployment of ocean bottom seismometers that monitor the hundreds of earthquakes these instruments have recently confirmed occur daily on the Mid-Atlantic Ridge. Chief scientists hailed from L-DGO, the Massachusetts Institute of Technology, the University of Texas, the University of Washington, and the Woods Hole Oceanographic Institution. ■

An Introduction—
Down to the Sea in a Ship

William B.F. Ryan

The ocean bottom, its shape, its interior, its activity, and its origins stimulate the curiosity of geological and geophysical oceanographers. We are drawn to a subject that is remote and multifaceted, and that we investigate with a variety of technologies. We explore from oceanographic ships, satellites, airplanes, drilling platforms, and submersibles, and with robotic cameras and towed sensors. In moments of frustration, some of us would eagerly dispose of the overlying ocean once and for all. It gets in our way, is unforgiving to our instruments, and makes us miserably seasick!

In moments of frustration, some of us would eagerly dispose of the overlying ocean once and for all.

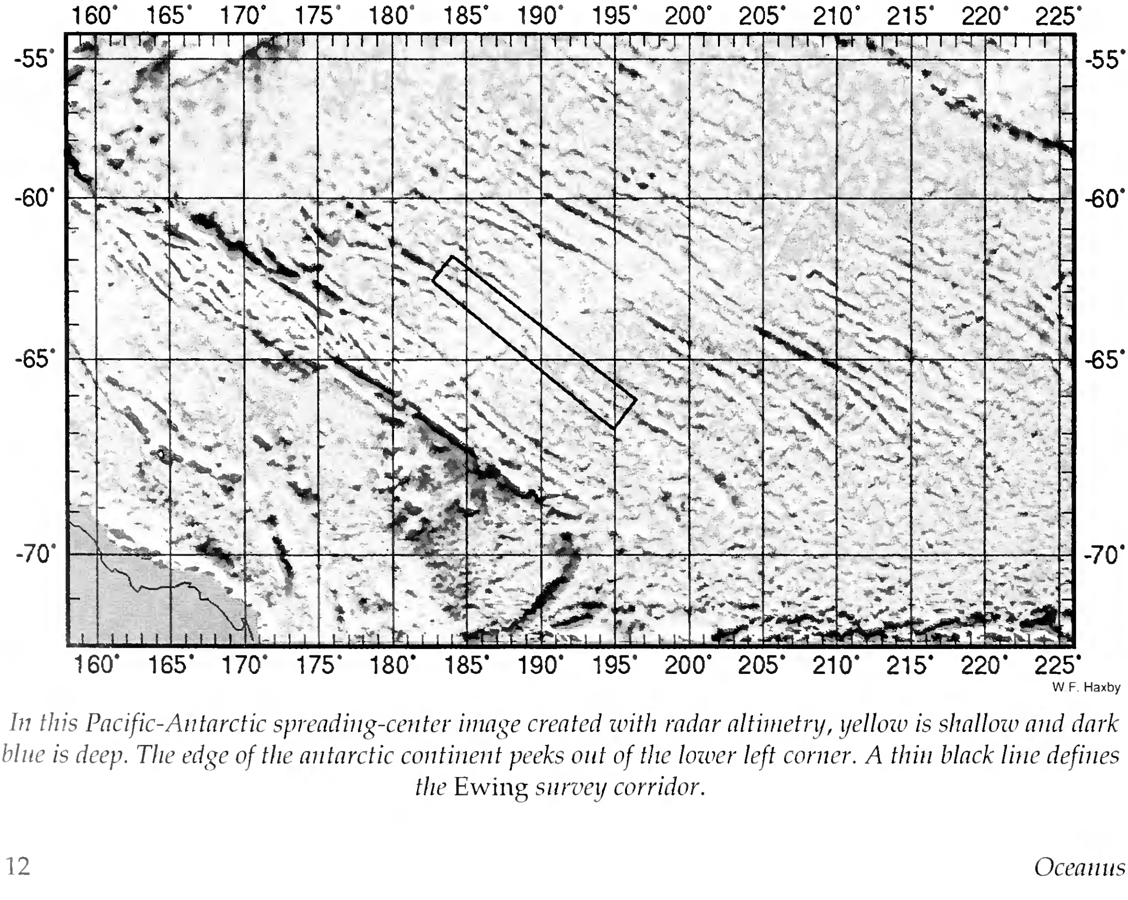
The vastness of the ocean and the secrets of its submerged landscape contribute to its mystery. Seawater is opaque to light beyond a few hundred meters' penetration. Hence, there are no mountain tops one can scale to directly gaze at vast expanses of the abyssal seafloor. Instead, we visualize the hidden seascape with digital data sets, picture element by picture element, as tiles of a growing quilt, each stitched in the course of month-long expeditions.

As an initiation to ocean-floor geology and geophysics, we join one of these expeditions as the guest of Bill Haxby, Steve Cande, and Carol Raymond, our co-chief scientists. Bill is a Senior Research Scientist at Lamont-Doherty Geological Observatory specializing in geodetic studies and plate tectonics. Steven has joined the faculty at the Scripps Institution of Oceanography, continuing with a career of using marine magnetics to study the shifting of earth's lithospheric plates. Carol is a Research Scientist at the Jet Propulsion Laboratory of the California Institute of Technology. She undertook graduate studies at Columbia University where she investigated the nature of the magnetization of oceanic crust and lithosphere using sensors from ships, airplanes, and satellites.

The expedition, funded by the National Science Foundation, occurs during the Southern Hemisphere summer of 1991 to 1992. Its objective is to survey a corridor across the limb of the world-circling Mid-Ocean Ridge that separates New Zealand from Antarctica. We are aboard the research vessel *Maurice Ewing*, a new member of the US oceanographic fleet equipped with specialized instrumentation for marine geology and geophysics. Prior to departure, Bill exploits satellite altimetry to generate an overview of the Pacific-Antarctic spreading center.

Satellite-borne radar measures sea-surface shape witha resolution of a few centimeters. Elevated seafloor displaces seawater, and the greater density of the crustal layer exerts a gravitational attraction to the adjacent ocean. In response, water is tugged toward the elevation to form a slight bulge in the sea. Over deeps, the ocean surface is slackened into a trough. Superior detail of a sea-surface shape materializes at high latitudes where satellite orbits converge. Bill has devised a method to convert the altimetry to a representation of seafloor shape. The pseudomap below portrays more than a dozen giant, deep scars that cut long trajectories through the broad Pacific-Antarctic Ridge. These scars are fracture zones, fossil traces of active faults that offset the spreading center at the Mid-Ocean Ridge axis.

Steve chooses one of these scars as the focus of our survey. His plan is to employ *Ewing*'s Hydrosweep multibeam sonar to image the seafloor to much finer detail than the altimetry provides (Beginning on page 74, Deborah Smith describes how this type of sonar tool advances our understanding of ocean-floor morphology.) The changing orientation of the scars is evidence of past shifts in the separation direction of the Pacific and Antarctic Plates. Some plate edges, most notably around the margin of the Pacific, sink back into Earth's interior. A major objective of our survey is to learn if fracture-zone bends correspond to a rearrangement of global plate motions caused by a large plateau clogging a trench. *Ewing* is equipped to measure the strength of Earth's gravity for a check against the gravity that can be calculated from the altimetry.



W.F. Haxby

In this Pacific-Antarctic spreading-center image created with radar altimetry, yellow is shallow and dark blue is deep. The edge of the antarctic continent peeks out of the lower left corner. A thin black line defines the Ewing *survey corridor.*

Carol is keen to probe the three-dimensional distribution of crustal magnetism. The many kilometers of water that float *Ewing* high above the oceanic crust act as a filter that removes the short-wavelength noise of Earth's past magnetic field intensity that is frozen into the volcanic bedrock when erupting lava chills into solid rock. Repeated flip-flops of Earth's magnetic field polarity back over a hundred million years are recorded in stripes of alternating strong and weak magnetism that strike parallel to the ridge axis (see page 82). If it were not for the fortuitous filter provided by the 3 to 4 kilometers depth of the ocean ridge, it is possible that the symmetry of magnetic stripes on either side of the Mid-Ocean Ridge would still not be recognized. The discovery of this symmetry in the early 1960s confirmed the theory of seafloor spreading and ignited the powder keg of the plate-tectonic revolution. The scar we map is named the Pitman Fracture Zone in honor of Walter C. Pitman III who realized in 1966 that these magnetic stripes could be used to predict the age of oceanic crust.

Benefiting from precise navigation based on the Global Positioning System's constellations of orbiting radio beacons the chief scientists directed *Ewing* back and forth across the spreading center on 650-kilometer-long adjacent tracks separated by 6 to 8 kilometers. We tow an array of air-driven guns that fire an explosive discharge every ten seconds. The sound travels into the seabed where it reverberates and reflects from layers of sediment and from discontinuities in the volcanic crust (see Mike Purdy on page 63). The returned echoes arrive at hundreds of sensors in a long streamer towed through quiet water far behind the ship.

The Pacific and Antarctic Plates are separating today at 60 millimeters per year. This is a rate midway between the slow Mid-Atlantic and Southwest Indian ocean ridges (see Henry Dick on page 26) and the much faster East Pacific Rise (see Bob Detrick and John Mutter on page 54). The magnetic stripes recorded by previous surveys show that the speed of separation and the rate of formation of new oceanic crust (a process the marine petrologist calls crustal accretion—page 74) has varied in the past, sometimes speeding up, sometimes slowing down. The spacing of the stripes on the two opposite flanks also indicates that at some periods more crust is accreted to one plate than to the other, so that the spreading is not symmetrical. Fast-spreading ridges generally exhibit smoother, more gentle relief and axial elevation, while slow-spreading ridges have rougher terrain and axial rift valleys.

Our co-chief scientists have strategically located our survey of the Pacific-Antarctic Ridge at a threshold between the fast and slow personalities. North of the Pitman Fracture Zone the spreading center seems to behave as if it is fast, and to the south it has some of the facade of a slow ridge. My contribution is to quantify the reflective strength of the sonar echoes bouncing back from the seabed. Using the reflectors, we generate a map that locates the most recently created crust and tells us how fixed the site of crustal formation has been though time.

What we don't understand with any confidence is the interior-earth physical process responsible for the changes in speed and the perceived asymmetry of the spreading. We employ theoretical modeling to simulate the ascent of Earth's ductile mantle as it floats upward to fill the void created by the diverging plates. As the hot mantle rises, it decompresses and some of it melts. The liquid melt is buoyant, and it percolates

We generate a map that locates the most recently created crust and tells us how fixed the site of crustal formation has been though time.

rapidly upwards into the shallow crust. Then it erupts in an astonishingly narrow belt along the axis of the ridge. This young strip of neovolcanic seafloor is glassy, and its bumpy lava surface reflects a multitude of points of light from the strobes and incandescent lamps of cameras towed overhead, or the illumination of robots and submersibles such as *Jason* and *Alvin*. Rock chemists, mineralogists, and those studying the mechanics of fluid flow are indeed impressed by the narrow focus of the upward flow of melt. Most of it collects into a thin magma lens no wider than a kilometer and no thicker than a few hundred meters (see Mike Purdy on page 63). Melt that escapes channeling to the ridge axis erupts only a few kilometers away where it is responsible for the short-lived growth of seamounts found in a range of heights and sizes that is probably linked to the depth of the magma conduits. The flow paths or "plumbing" of the melt as it moves upward through focused pipes and horizontally through the crust along fissures that bisect the ridge axis is one of the "hot" topics of current research (pun intended).

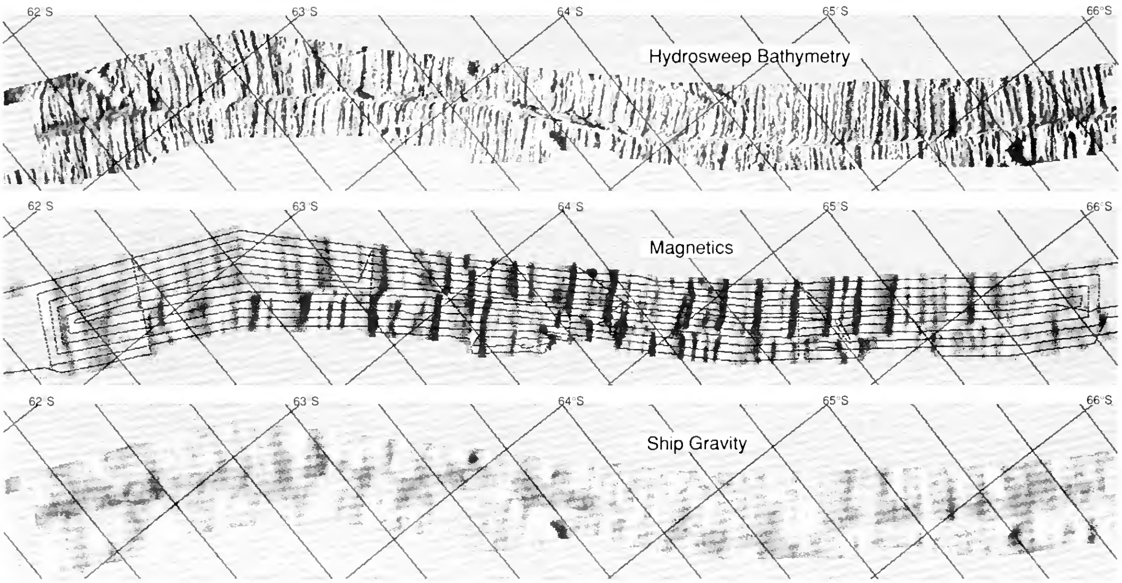
Magma reaches the seafloor in discrete events, one in 1991 perhaps only hours before a serendipitous visit by the submersible *Alvin*. The chemistry of the lava densely sampled by new rock-coring techniques is beginning to show some systematic patterns of spatial variation, both along the axis and away from it. These patterns represent changes in melt properties and melt delivery through time. Boreholes drilled deep into the crust pass though thick residues of multiple eruptions that sometimes occur in cycles, beginning with voluminous high-effusion-rate flows of hot, primitive, low-viscosity lava and terminating in small eruptions of slightly cooler, more evolved, viscous lava. This cyclic layering of upper oceanic crust is imaged with logging tools lowered into the boreholes.

This image of lumpy pillow lavas erupted at the Mid-Ocean Ridge axis was computer generated from stereo photos. The contours and coloring quantify the relief of the volcanic extrusions to a resolution of 1 centimeter.

Our cruise is the first to image what I call the "schizophrenic" ridge axis, where the visual appearance of the ocean bottom takes on different characteristics in response to small but measurable differences in the seafloor spreading rate. Being the first to address this issue, this cruise is carrying out the exploratory phase of research designed, in this case, to capture the full range of personality change. In the past, the problem has been defined by a reconnaissance cruise directed to cover a large area. Instead we have decided to limit the study area so that we might obtain full, 100-percent coverage of the ocean floor. Satellite altimetry is an invaluable asset, because it immediately saves us the enormous task of locating a suitable fracture zone. With its trace already fully delineated, we proceed to "mow the lawn," using adjacent swaths of the Hydrosweep sonar to fully cover the whole corridor so that we might return with a 20-million-year history of the rates, styles, and directions of crustal accretion.

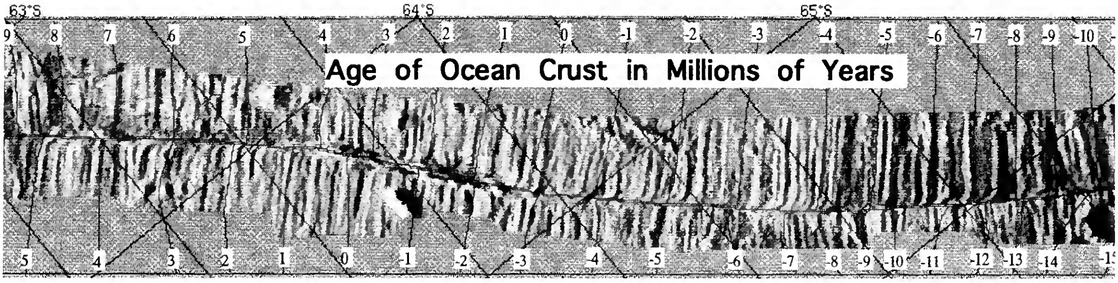
With complete coverage, our survey tracks are sufficiently close to one another that Carol's continuous sampling of Earth's magnetic field facilitates the creation of a high-fidelity image of the crustal magnetic intensity (the center image, below). Instead of picking inflection points along individual profiles (the traditional method for analyzing spreading rate), we can visualize the crustal growth with a time resolution improved by an order of magnitude. For the first time it becomes practical to superimpose lines that represent isochrones, that is, precise crustal ages, on the shaded relief of the seafloor. It quickly becomes apparent that between 3 and 4 million years ago the amount of new crust accreted to the Antarctic Plate was almost twice as wide as that accreted to the Pacific Plate, whereas the opposite is true for the period between 5 and 6 million years ago (see the figure on page 16).

Bill displays on his computer screen a composite image of the multibeam bathymetry with a horizontal sampling space of only 50 meters and a vertical resolution of better than 5 meters. Remarkably delicate abyssal hill lineations appear (as in the top image, below). Regions of densely spaced, high-relief hills are interspersed with regions of wider spacing and lower relief. The boundaries seem to correspond to the quickening and slowing of the spreading rate. I note bulbous shapes on the outward flanks of many of the hills that are characteristic of volcanic outpourings, whereas the inward (ridge-axis facing) slopes are strikingly linear and much steeper, as if they are faces of faults that vertically displace the crust.



In a segment of the Pitman Fracture Zone, the sun-illuminated relief reveals prolific abyssal hills (top). Some curve into the fracture zones, while some are abruptly offset. Sun-illuminated magnetic stripes of this region (center) show the polarity changes: light tan colors are positive anomalies corresponding to seafloor magnetized with normal polarity; dark blue bands are the seafloor formed during periods of reversed polarity. The thin black line is R/V Ewing's *track. The sun-illuminated free-air gravity anomaly yields more information still (bottom). Thin crust in the vicinity of the fracture zone results in a broad gravity trough that is breached in places where ridge volcanism was particularly robust. The breaching sites correlate with high-standing, broad, curved ridge tips.*

The fracture zone itself surprises each of us with its remarkably narrow and delicate-looking appearance. There are localities where the length of a single football field separates crust with an age difference of 4 million years! The shipboard-measured gravity field image (the bottom panel of the figure on page 15) shows the physical width of the fracture zone scar to be less by two orders of magnitude than its gravimetric counterpart. The gravity trough is not the zone of shearing between the two plates as they slide past each other, as some of us had mistakenly anticipated, but it is a representation of ridge-parallel crustal thickness and flexure. The variable width of the gravity trough becomes our first semi-quantitative and accurately dated record of the amount of melt delivered to the ridge axis. It appears that a large supply of melt produces long, robust, curved ridge tips and a narrowing of the gravity trough; a starved supply accounts for wispy, straight tips and a deep, wide gravity low.



Here the bathymetry of the survey corridor (red is shallow, blue is deep) is superimposed with contours of crustal age (in millions of years before present). The ages were determined from the detailed imagery of the magnetic stripes as visualized in the center image of the figure on page 15.

Our graduate students will undertake much more thorough analysis in the course of their dissertation research. This brief introduction gives you only a flavor of our science; I have not even touched on the continental margins (but see Debbie Hutchinson on page 34). However, the common thread to nearly all of the last decade's marine geology and geophysics research is the bold and successful implementation of new technology. This eagerness to take risks with sometimes untried tools has accelerated our understanding of the inner workings of Earth's seafloor and below. Although seagoing observationalists outnumber theorists by a hefty margin, a reading of this issue of *Oceanus* confirms that more attention is being given to computer simulation and numerical modeling than ever before. Data-sets are growing to enormous size—*Ewing* now processes up to 10 gigabytes of digital data per survey day. We expect that in the near future, this data will bring exciting new understanding to our field.

William B.F. Ryan is a Doherty Senior Scientist at Lamont-Doherty Geological Observatory of Columbia University. He began his oceanographic career in 1961 as a WHOI marine technician aboard R/V Chain *in an expedition across the Mid-Atlantic Ridge into the Mediterranean and back. He obtained his Ph.D. in geology from Columbia University in 1970. He has been a user of* Alvin *to provide ground truth to ocean-floor imagery obtained with new generations of sidelooking sonars and deep-sea cameras developed by his research group. His joys are expeditions with friends and colleagues at sea with tools that give transparency to the ocean and reveal the seafloor in its splendor, and the classroom teaching of marine geology and plate tectonics. "I find it a thrill that the generation of ocean crust at a spreading center continues to defy simple intuitive logic."*

Island Arcs, Deep-Sea Trenches, and Back-Arc Basins

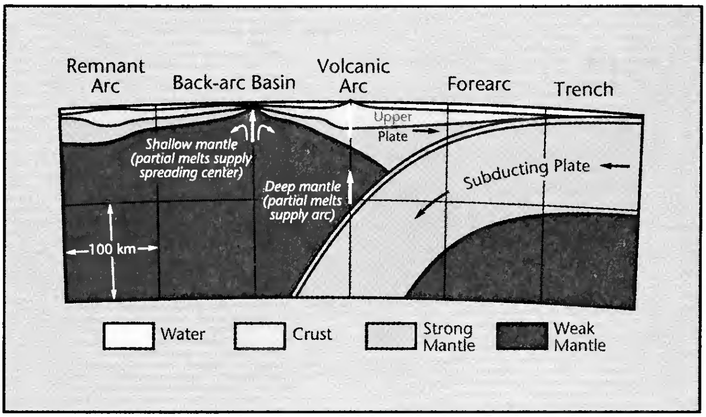
Brian Taylor

Chains of volcanoes, deep-sea trenches, and back-arc basins festoon the western Pacific rim from the Aleutian Islands to Indonesia to New Zealand (see figures overleaf). Land volcanoes such as Mt. Pinatubo in the Philippines, which erupted so spectacularly last year, are well known compared to most of the region's volcanism, which is submarine. In the last 10 years, exploration using new marine geological and geophysical techniques has changed our view of this seafloor and of the processes that occur there:

- Swath bathymetry and sidescan acoustic imagery provided the first detailed maps of large seafloor areas;
- Marine seismic studies of sub-seafloor structure and stratigraphy increased in resolution and penetration;
- Manned submersibles and remotely operated vehicles carried our eyes and experiments to the seafloor for precise sampling and observations; and
- Deep ocean drilling provided cores and downhole measurements of previously unsampled formations.

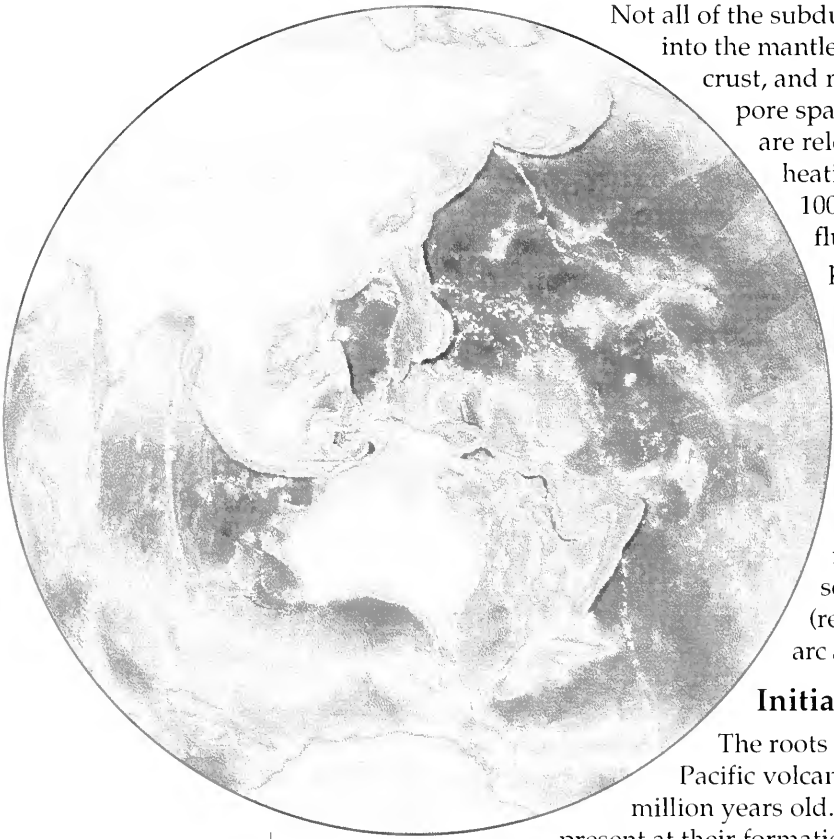
These studies have brought fundamental changes to our understanding of volcanism, crustal deformation, fluid circulation, and sedimentation in trench/arc/back-arc systems.

Subduction is the major recycling process for Earth's crustal materials. Oceanic crust, covered with sediments and dotted with seamounts, plunges at deep-sea trenches back into the mantle (from which it was derived at a mid-ocean ridge). Where sediments are thick, most of them are scraped off onto the leading edge of the overriding plate, like snow piling up on a plow blade, forming an accretionary prism. In other areas, part of the upper plate may collapse onto the subducting plate and be carried down with it.



The subduction zone is shown true to scale in this vertical cross section.

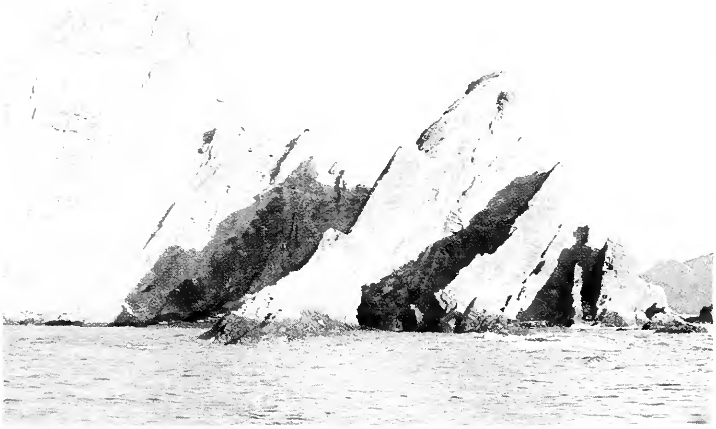
Jack Cook/WHOI Graphics



Not all of the subducted material is recycled into the mantle. Some underplates the crust, and most of the fluids in the pore spaces and hydrous minerals are released by squeezing and heating. At depths of about 100 kilometers, the expelled fluids lower the melting point of the overlying mantle rocks, forming magmas that rise to intrude beneath, and erupt at, island-arc volcanoes. Periodically, the island arc is stretched and splits. Seafloor spreading in the resulting back-arc basin separates an inactive (remnant) arc from the active arc and its deep mantle source.

Initial Arc Volcanism

The roots of the present western Pacific volcanic arcs are about 50 million years old. Had observers been present at their formation, two very different styles of volcanism would have been apparent. One type in Indonesia and Japan, for example, would have looked similar to today's volcanism. However, the volcanism that constructed the base of the intra-oceanic Izu-Bonin-Mariana and Tonga-Kermadec arcs was quite different, as confirmed by ocean-floor drilling there in 1989 and 1991. Volcanism during the first 10 million years of these arcs had characteristics intermediate between modern spreading centers and island arcs. It occurred over a vast terrain, covering up to 400 kilometers from the trench, rather

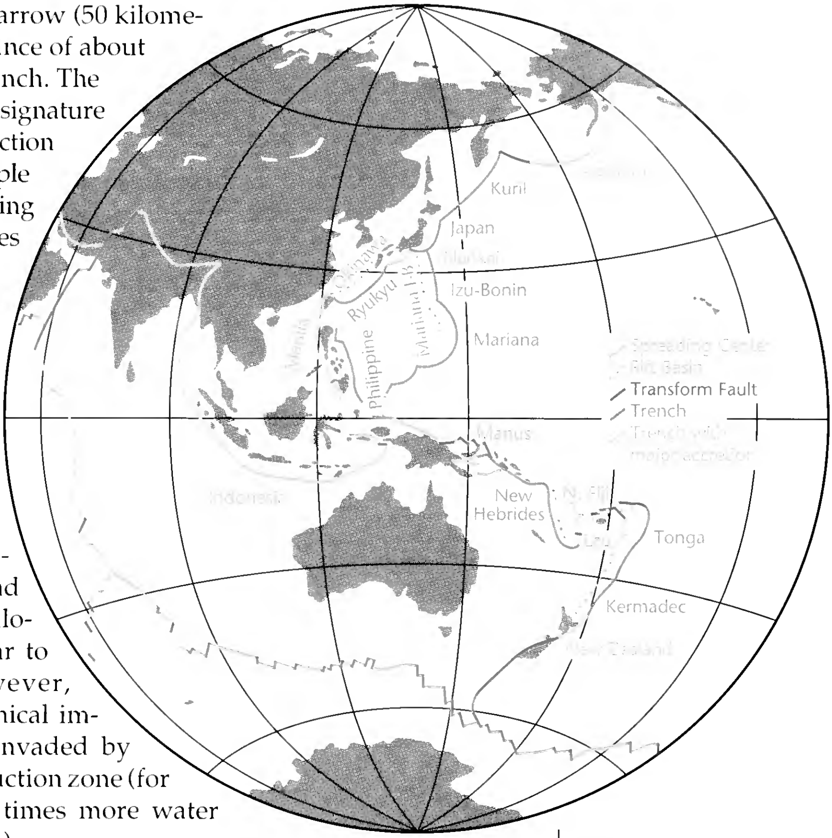


Barbara Keating/University of Hawaii

Dike swarms along the northeast coast of Chichi Jima, Bonin Islands, provide evidence of 40- to 45-million-year-old volcanism above a subduction zone but in an extending region.

than dominantly along a narrow (50 kilometers) volcanic line at a distance of about 200 kilometers from the trench. The old lavas have the chemical signature of volcanism above a subduction zone, but were fed by multiple dike intrusions in an extending region. Swarms of these dikes are exposed in the Bonin Islands, and one lava type from this environment, boninite, was named for the islands.

Boninites have a distinctive mineralogy and chemistry that requires their initial crystallization from melts at high temperatures (1,250° to 1,300° C) and shallow depths (3 to 10 kilometers)—conditions similar to spreading centers. However, boninites contain the chemical imprint of a source region invaded by fluids derived from a subduction zone (for example, they contain 10 times more water than mid-ocean ridge lavas).

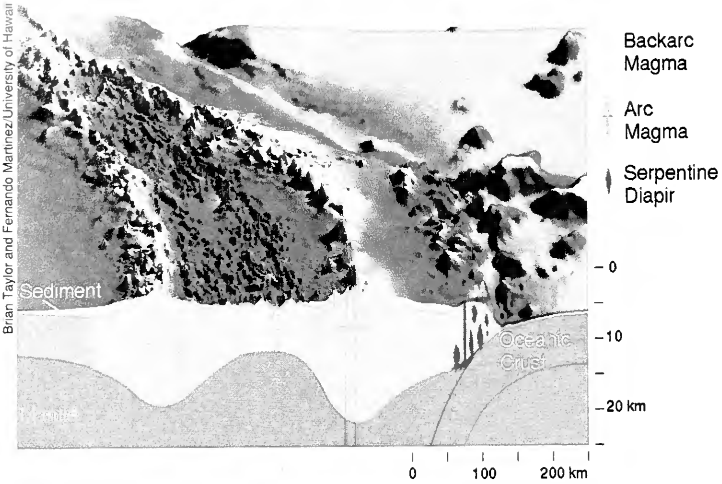


These equal-area projections reveal the location and topography of the island arcs, deep-sea trenches, and back-arc basins that rim the western Pacific Ocean.

Geologists have recognized many of these unusual characteristics in groups of seafloor rocks now exposed on land, called ophiolites. For many years, ophiolites were considered our best analogue of mid-ocean ridge crust. Their chemical distinctions from mid-ocean rocks were largely ignored, because they provided useful insights into the magmatic and structural processes thought to occur at spreading centers. Collecting the evidence and convincing the entrenched scientific hierarchy that such rock sequences typically form in a different tectonic environment is an ongoing battle. Many will now agree that most ophiolites formed above a subduction zone, but they still assume that it was at a (back-arc) spreading center. The concept that some might have formed in a broad immature arc terrain is hotly debated. The marine geoscience community also debates exactly how this might have occurred. All the models have problems, partly because some of the pieces of the puzzle (such as what was being subducted) have been lost, and there is no equivalent setting active today. One of the paradoxical inferences, however, is that there is a type of subduction initiation that does not cause compression of the upper plate, but, rather, extension and volcanism.

A Variety of Volcanoes

Ten years ago, the only detailed bathymetric maps of the western Pacific were classified. Although a few academics had clearance to see parts of the data, it was on a need-to-know basis and couldn't be discussed with colleagues. As small pieces of this data were released and as the scientific community conducted its own wide-swath mapping surveys, we



Brian Taylor and Fernando Martinez/University of Hawaii

The bathymetry of the northern Mariana Trench/arc/back-arc system is viewed here in shaded relief, from an elevation of 30°. A vertical cross section is in the foreground; the vertical exaggeration is 10. The pinkest oceanic crust in the cross section is the youngest. Arc volcanism occurs along the volcanic front and behind it. Magmas are also emplaced along the back-arc spreading center. Diapirs of serpentine are from seamounts in the forearc.

discovered that not only are there many more submarine volcanoes than previously thought, but in some areas there are also whole new classes of volcanoes in addition to the main line that parallels the trench. One class forms lines of volcanoes in the back arc, oblique to the main line. Others occur in the forearc, close to the trench. A series of geophysical mapping and dredge-sampling expeditions, *Alvin* dives, and ocean drilling investigations were made in the Mariana and Izu-Bonin arcs to discover more about what formed each of these two groups of volcanoes. The oblique lines of volcanoes are composed of lavas and volcanic sediments similar to those of the main line. Their distribution appears to be controlled by weaknesses in the upper plate, often inherited from the previous stretching of the arc, that allow arc magmas to erupt into the back-arc region. Nevertheless, we still know very little about the age, composition, and structural control of most of these volcanoes; there are hundreds awaiting study. The forearc volcanoes were an even greater surprise: most were not formed by lavas, but by green serpentine muds!

Serpentine Volcanoes and Diapirs

The forearc seamounts (mountains on the seafloor) are 5 to 30 kilometers across, 0.5 to 2 kilometers high, and occur within 100 kilometers of the trench. Most don't have the strong magnetic and gravity signal typical of volcanic seamounts; rocks dredged from them are composed primarily of the mineral serpentine. Serpentine is formed by the addition of water from the subducting plate to olivine in the peridotite mantle rock of the upper plate. This hydrated material, being less dense, is buoyant and slowly rises, often along faults in the overlying rocks. If these rising diapirs (upwardly mobile rock masses) reach the surface, they form seamounts with a range of characteristics. The finer-grained material with higher fluid content erupts onto the seafloor through a central conduit and forms a volcano of serpentine mud. The more massive, less mobile, material protrudes onto the seafloor like rising dough overflowing a small pan.

Fluids seeping through the surface of the serpentine volcanoes form chimneys up to 2.5 meters high, mainly composed of carbonate minerals. Near the surface the fluids are mixed with seawater, but their undiluted chemistry about 100 meters down into the volcanoes shows their subducted-plate origin. They contain light hydrocarbons (ethane and propane) and organic acids, as well as aromatic compounds (benzene and toluene) in fluid inclusions, that were produced by thermal maturation (baking) of organic matter subducted in sediments. The fluids are very alkaline, with a pH up to 12.6. Low strontium isotope ratios indicate that some of the fluids come from the crustal rocks beneath the subducted sediments.

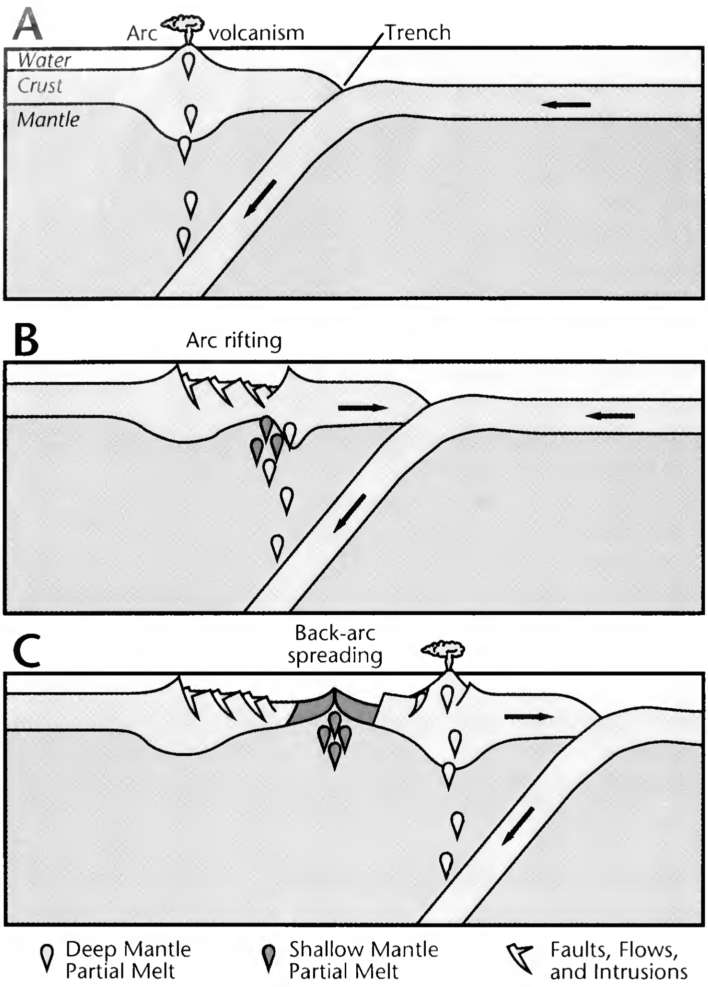
Serpentinized peridotite seamounts on the inner-trench slope indicate the presence of mantle, and therefore a thin crust, in the outer forearc above the subducting plate. Some crustal rocks are entrained into the serpentine diapirs as they rise, resulting in a mixed sample of rocks from all crustal levels. Most of these are arc rocks from the initial (40- to 50-million-year-old) stage of volcanism, however, some 100-million year-old mid-ocean ridge rocks have also been found in the Mariana forearc, both in the diapir samples and exposed on large-offset faults. These rocks require that some fragments of oceanic crust from the subducting plate have been added to the Mariana forearc.

Forearc Volcanism

The trenchward boundary of arc volcanism is termed the volcanic front. The main chain of island arc volcanoes lies along this front. Although some volcanoes occur behind this line (in the back arc) none are supposed to occur under normal circumstances in front of it (in the forearc, closer to the trench). The few exceptions to this rule have been associated with conditions of unusually high temperature gradients, produced by either the subduction of a spreading center or by "back-arc" basin formation in the forearc. None of these exceptional circumstances have influenced the Izu-Bonin, Mariana, or Tonga arc-trench systems in at least the last 25 million years. Very old (more than 100-million-year-old), cold, Pacific crust is subducted along all three trenches. Nevertheless, multichannel seismic data indicate the presence of lava flows or sills in the Izu-Bonin forearc. In fact, recent drilling found young arc lavas in the forearcs of all three systems; the youngest, in the Marianas, is 1.7 million years old.

This leaves us in quite a quandary. First, the volcanic front, one of our fundamental reference points for other features (such as "back-arc"), is no longer a simple boundary. It can still be defined by the amount, but not the presence or absence, of arc volcanism. For example, arguing that material has been removed from a forearc just because some arc lavas are too close to the trench is no longer viable. Nor is postulating a changed geometry of subduction in the geologic past just because a few lavas are found on the "wrong" side of the arc line. Second, our models for the genesis of arc magmas may be in need of serious revision. The experimentally determined solidus temperature (above which melting begins) of mantle rock under water-saturated conditions is about 1,000°C. Nowhere in the forearc wedge above the subducted plate are temperatures close to these reached—measurements at three forearcs drilled by the Ocean Drilling Program in 1989 and 1991 ranged only between 0.5 heat-flow units near the trench and 1.3 heat-flow units closer to the arc. There seem to be only two areas hot enough to generate arc magmas: beneath the volcanic front, or deep in the mantle of the subducted plate. Magmas from the volcanic front would have to move laterally 80 to 120 kilometers, perhaps as near-horizontal intrusions (sills), to reach the forearc sites of eruption. The alternative is that fluids circulate down to the hot mantle of the subducting plate where they might generate magmas that could ascend vertically. Both scenarios seem unlikely, but given the inferred low temperatures beneath the forearc we haven't yet come up with a better explanation.

The volcanic front, one of our fundamental reference points for other features (such as "back-arc"), is no longer a simple boundary.



Fernando Martinez and Brian Taylor/University of Hawaii

The origin of a back-arc basin. A: The thick, hot, crust of the volcanic arc is the weakest part of the upper plate. B: Sinking of the downgoing plate moves the trench and forearc to the right, pulling the arc apart. Shallow and deep, mantle partial melts are emplaced into the rift basin. C: With continued separation, the melt sources separate, a back-arc spreading center is established, and a new frontal arc builds along the rifted edge of the old one.

Arc Rifting and Back-Arc Spreading

When arcs are stretched they split, initially forming a rift (an elongate depression bounded by high-angle faults) and eventually a back-arc spreading center. The processes involved in arc rifting are similar to those involved in splitting continents, with the important difference of the presence of nearby arc volcanism. The causes of arc stretching are not fully understood, but we know some of the parameters. At a subduction zone the upper plate is horizontally coupled by suction to the downgoing plate. Most trenches migrate seawards as the subducting plate sinks, resulting in the upper plate being pulled seawards and stretched, depending on its other boundary conditions. Periodically, the stretching is sufficient to pull the upper plate apart. The weakest area of the upper plate is near the volcanic front, where the plate is both hottest and has the thickest crust (the stronger mantle is thinnest). The arc splits within about 50 kilometers of the volcanic front.

The resulting rift basins initially subside along a zigzag pattern (in plan view) of border faults. The rifts are often better developed between the arc volcanoes; magmatism, rather than stretching and subsidence, often fills the opening adjacent to arc volcanoes. The basins are rapidly filled by sediments shed from nearby volcanoes and are also intruded by magmas along faults. The magmas may be derived from the deep-mantle arc source or from pressure-release partial melting of the shallow mantle. The basins widen by continued stretching as well as by collapse of the weak arc margin. As they do, the zone of greatest subsidence and intrusion migrates with the retreating arc margin border faults. The result is an asymmetric basin in cross section, with a wider zone of stretched and intruded crust on the side away from the active arc. Activity along the volcanic front is often diminished, and sometimes ceases, as the frontal arc magma sources are bled off into the back-arc basin.

After continued stretching for 5 to 10 million years has produced a rift basin some 200 kilometers wide, the shallow and deep sources of mantle partial melts become horizontally separated. An organized spreading center, fed by the shallow mantle, forms in the back-arc basin, and the deep mantle arc magmas establish a new volcanic front along the rifted edge of the old one. This evolution is spatially transgressive; spreading is localized in some areas first and then propagates into adjacent rifting areas. Several variations on this model occur, depending on the interplay between the location, timing, and volume of back-arc and arc volcanism and the resulting strength of each region.

Volcanic-Hosted Massive Sulfide Deposits

A subduction signature distinguishes the sediments, lavas, and sulfide deposits of island arcs and back-arc basins from their mid-ocean equivalents. This same signature is associated with many ore deposits and their ophiolite host rocks, such as those mined in Cyprus, Oman, and the Kuroko district of Japan, suggesting that they formed in an arc/back-arc, rather than a mid-ocean, setting. Subduction-related volcanic rocks, including silica-rich lavas or intrusions, are common to all sites of major volcanic-hosted massive sulfide (VMS) ore bodies. Thus, studies of hydrothermal circulation and sulfide deposition at mid-ocean ridges cannot provide a comprehensive model of this important type of ore generation.

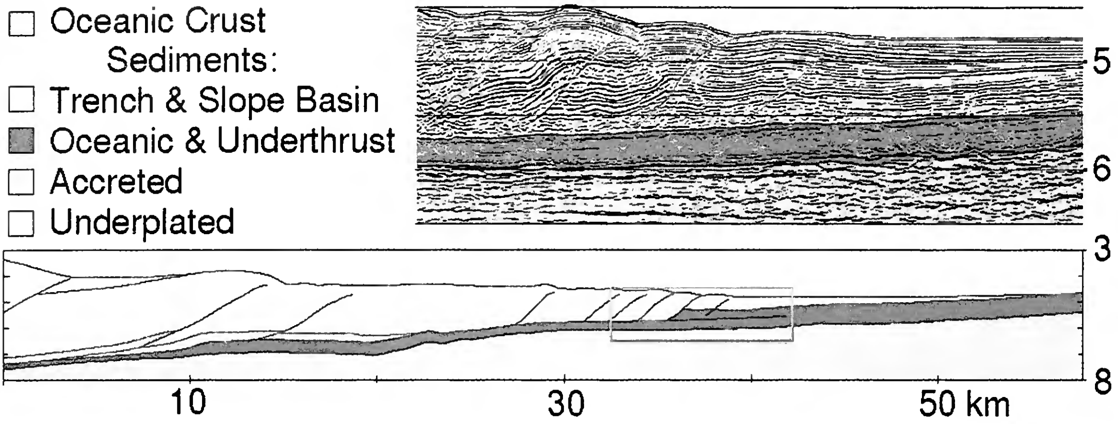
Therefore, Australia, Britain, Canada, France, Germany, Japan, Russia, and the United States have all sent expeditions to the western Pacific in the last five years to study arc/back-arc hydrothermal systems, and with great success. Dive programs, using submersibles from four nations, found active vents in all the regions investigated. The range of vent systems and sulfide types is much greater than at mid-ocean ridges, owing to the organic-rich volcanic sediments, and the silica- and volatile-rich rocks present in these environments. Modern Kuroko-type ore formation was discovered at depths of 1,300 to 1,600 meters in both the Okinawa and Izu-Bonin back-arc rifts. Silica, sulfate, and sulfide chimneys emitting clear, white, and black solutions at temperatures of 200° to 400°C were found on all the active back-arc spreading centers studied (Lau, North Fiji, Manus, and Mariana). The back-arc vent fluids have extremely low pH (2 to 5), and typically contain more zinc, barium, lead, cadmium, and arsenic than mid-ocean ridge vent fluids. The search for modern analogues of VMS ore bodies is over. The exploration and analysis of their diversity has just begun.

Aleksandr Lisitzin/Shirshov Institute of Oceanology

Golf-ball-sized snails cling to these high-temperature hydrothermal chimneys in the northern Lau back-arc basin.

Fluids in Accretionary Prisms

Thick sediments subducted at a trench respond like a wet sponge fed through a wringer; their porosity decreases and most of the fluids that form 50 to 70 percent of their volume are expelled. This occurs in at least two stages: initially, at the toe of the slope where the upper sediments are scraped off and, subsequently, at depth beneath the forearc where many of the lower sediments are underplated. The fluids flow through and out of the accretionary prism in several ways. Pervasive dewatering by diffuse flow may dominate in the toe of the prism, as indicated by data from drilling at the Nankai Trench. Focused fluid flow occurs along permeable sedimentary layers and faults. Flow along fracture systems becomes dominant as the sediments are consolidated and cemented. Diapirs of mud and shale may also pierce the prism.



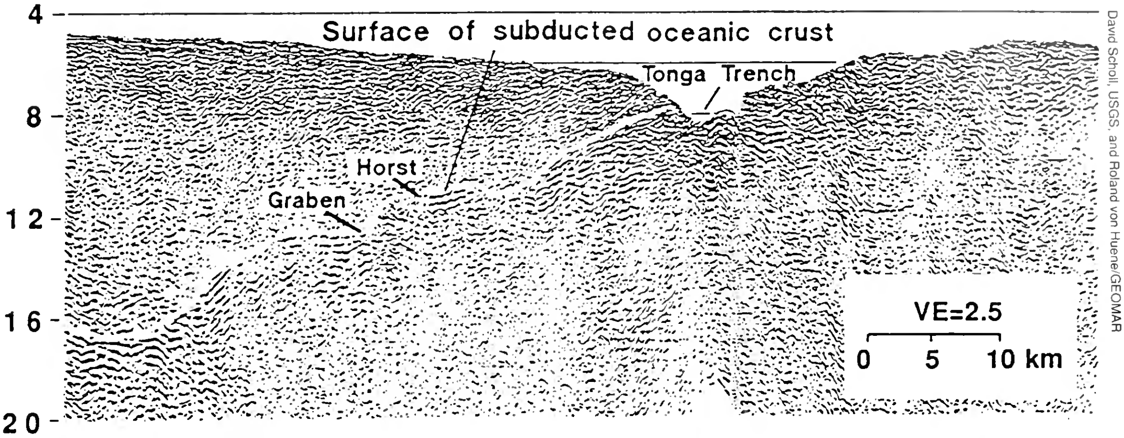
Brian Taylor and Greg Moore/University of Hawaii

Trench-fill sediments and some ocean-basin sediments are being folded, faulted, and structurally thickened to form a prism of accreted sediments at the Nankai Trench (bottom). Oceanic crust and a layer of basin sediments are not deformed as they pass beneath the toe of the slope, but some of these sediments are underplated into the accretionary prism at depth. A multichannel seismic profile (top) shows details of the structures in the red boxed area at the toe of the slope. The vertical exaggeration is 1.7.

Only in the last five years have the extent and effects of this fluid flux been recognized. Biological communities consisting of macroscopic organisms living symbiotically with bacteria that derive their energy chemically are dramatic markers of fluid seeps. The near-surface precipitation of carbonates and the formation of gas hydrates indicate substantial movement of carbon as methane and carbon dioxide, derived from the breakdown of organic matter. Silica is dissolved from strongly cleaved rocks and later precipitated in quartz veins. Fluids warmer and fresher than seawater have been detected moving laterally up from deep in the accretionary prism where they probably formed by the dehydration of clay minerals. Fluid pressures control the style of deformation and the shape of the accretionary prism. Episodic fluid flow is likely linked to episodic faulting, and hence to the generation of the largest earthquakes and tsunamis on Earth.

Subduction Recycling

We have only begun to characterize the flux of solids and fluids through a subduction system. We have order-of-magnitude estimates of the volumes, chemistry, and physical properties of the incoming materials. However, the changes in physical properties of this material and its partitioning between return flow to the oceans, addition to the crust, and absorption by the mantle is poorly known. The chemistries of the filtered fluids that escape to the ocean are extremely variable, ranging in pH from 2 to 12, for example. The mass flux of fluids of differing chemistries, and hence the chemistry of the residue crustal and mantle filters, are little constrained. So too are the fluid pressures and permeabilities in the rocks, which control the style of deformation and the earthquake cycle.



The surface of the oceanic plate (highlighted) can be traced landward of the Tonga trench on this seismic profile for nearly 50 kilometers. This is a typical example of a subduction zone at which no accretionary prism forms. Upper plate materials probably collapsed into, and are being carried down in, the troughs (graben) between the ridges (horsts) of the subducted plate.

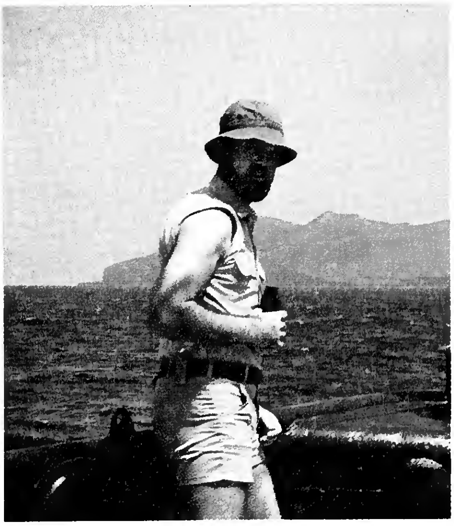
Both the scale of temporal variability and the long-term averages need quantifying. One estimate of fluid flux through subduction zones suggests that they recycle the global ocean volume slowly, about once every 500 million years. Nevertheless, they may form a significant link in the global carbon cycle, transferring most of the carbon in subducted organic matter back to the ocean.

Current models hold that continental crust grows by accretion of island arcs to continental margins. Yet little net growth of the terrestrial mass appears to have occurred in the last several hundred million years. The estimated volume of terrestrial material subducted into the mantle as unaccreted sediment and collapsed upper plate rocks balances the estimated volume of mantle melts added to arc crust (both about 1.6 cubic kilometers each year).

Our present understanding of trench/arc/back-arc systems is only good for the near surface and the recent past. The plumbing systems of volcanoes (of magma or mud) and their mineral deposits, the fault zones that generate major earthquakes, and the deforming lower crust of forearcs are critical areas that we have yet to accurately image or effectively monitor. Future marine geoscience studies, including three-dimensional seismic imaging, seafloor observatories, and deep drilling will investigate these sub-seafloor areas that shape planet Earth.

Brian Taylor is a Professor in the Department of Geology and Geophysics in the School of Ocean and Earth Science and Technology at the University of Hawaii. He is an Australian, married to a New Yorker, with a daughter born in Hawaii. Brian coordinated the US-Japan program of Alvin *dives in the Northwest Pacific and chaired the Western Pacific Panel of the Ocean Drilling Program. His research focuses on the tectonics, magmatism, and sedimentation of the circum-Pacific trench/arc/back-arc margins.*

The author on the bow of R/V Kana Keoki *in 1984, en route to sample Torishima arc volcano in the background, which last erupted in August 1939.*



A New Mandate for Deep-Ocean Drilling

Henry J.B. Dick

> *Each time certain properties of the sea floor were postulated on theoretical grounds, investigations in-situ have upset the picture.*
>
> —H. Kuenen, 1958

The only way to obtain direct and precise knowledge of the composition and structure of the oceanic crust is to drill into it.

A fundamental fact of life for marine geologists is that they know little of the composition and structure of the two-thirds of Earth's crust that underlies the oceans. While it has often been said that the surface of Mars is better known than the seafloor of Earth, the situation is far worse for the oceanic crust. Our knowledge is limited to inference from buckets of gravel dredged from the deep and remote geophysical sensing. The extensive covering of sediment, the technical difficulty of working beneath kilometers of water, the limited rock exposures, and the ubiquitous coverings of black hydrogenous manganese precipitated on the rocks from the water column have largely frustrated conventional geological techniques such as combining surface mapping with geophysical sensing at depth to interpolate Earth's deep structure. It is increasingly apparent that the only way to obtain direct and precise knowledge of the composition and structure of the oceanic crust is to drill into it.

The importance of this gap in our knowledge of the earth became evident with the confirmation of seafloor spreading, the acceptance of plate tectonics, and the completion of global seismic surveys in the 1960s. Despite widespread expectations to the contrary, the surveys proved that continental and oceanic crusts are fundamentally different. Whereas the continental massifs are old (billions of years, on average), thick, and composed of silica-rich rocks such as granites and andesite, the oceanic crust is young, thin, and composed of silica-poor magnesian lavas such as basalt. While continental formation has slowed or stopped, new oceanic crust continuously forms at the ocean ridges, driven by deep mantle convection. As the seafloor spreads and collides with continents and other ocean plates at island arcs, old crust is also continuously destroyed—overridden and mixed back into Earth's mantle at subduction zones. Thus, a direct and complete knowledge of the composition of the oceanic crust is required to understand the evolution and chemistry of the earth and to decipher how Earth's dynamic engine works.

After an initial debate in the late 1950s and early 1960s, a scientific consensus delineated a fairly straightforward "layer-cake" ocean-crust stratigraphy of uniform layers of gabbro, sheeted dikes, and pillow lavas atop the mantle and overlain by marine sediments. This model was based on a match of seismic wave velocities and densities and types of rocks dredged from the seafloor and found in on-land sections of fossil oceanic crust with the physical properties of the three principle ocean-crust seismic layers. Detailed geological models were then constructed by extrapolating the simple, observed, layered, seismic structure to the geology mapped in tectonically disrupted sections of fossil oceanic crust found on land and in island arcs.

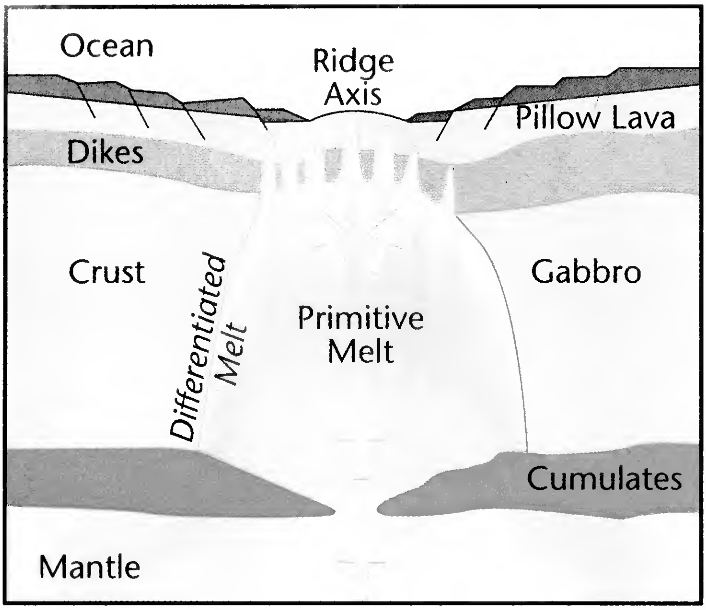
Based on this thinking the lowermost, and thickest, crustal seismic layer was believed to be uniform, consisting of coarse, stratified gabbroic rocks laid down on the floor, walls, and roof of a large magma chamber. Thus evolved the extremely attractive model of the "infinite onion (see illustration overleaf):" a large near-steady-state, continuous magma chamber underlying the global ocean ridge system, disrupted only by the largest of ocean fracture zones, from which layers of oceanic crust continuously grew at top, sides, and bottom to form a uniform layer of coarse rocks comprising the lower two-thirds of the oceanic crust (also see *Oceanus*, Winter 1991/92, page 36).

Two decades of additional observation of seafloor and oceanic crust and study of on-land fossil oceanic crust has thrown this model into question. Most, if not all, fossil oceanic crust on land is now believed to be atypical, formed in young rifts, around island arcs, and in marginal seas above subduction zones. These rocks simply cannot be taken as representative of the oceanic crust at large. Moreover, the structure of oceanic crust is now viewed as three-dimensional, highly dependent on the speed of seafloor spreading in any one region and the rate at which magma erupts from the mantle.

Most, if not all, fossil oceanic crust on land is now believed to be atypical.

Recent seismic results suggest no large steady-state magma chambers beneath ocean ridges—the linchpin of the layer-cake model. Observed seismic structure has become increasingly complex, with the lower oceanic crust varying in thickness near fracture zones and at small offsets in the ocean ridges. Compilations of dredge results and gravity lows centered over dredge segments also suggest that a continuous gabbroic layer simply does not exist at slow-spreading ridges, and that their internal stratigraphy is governed by ongoing faulting and deformation accompanied by hydrothermal alteration as cold seawater sinks into the crust, heats up, and reacts with the rock as much as by intrusion of new lava at depth and its eruption to the seafloor. Stephen Swift and Ralph Stephen of the Geology and Geophysics Department at the Woods Hole Oceanographic Institution have recently proposed that gabbro, generally believed to be the major constituent of layer 3, attenuates seismic waves too rapidly, raising the possibility that the composition of the lower ocean-crust layer could be radically different than we have supposed.

Deep-ocean drilling was first attempted, with some success, during the ill-fated Mohole Project in the 1960s. The project foundered in budgetary excess and the political process, but nonetheless gave birth to what must be the most successful international scientific cooperation in history: the Deep Sea Drilling Project and its successor, the Ocean Drilling Program. In two decades of drilling these programs produced remarkable results. The theory of plate tectonics was confirmed by demonstrating that the youngest oceanic crust is at the mid-ocean ridges and that it ages



E. Paul Oberlander/WHOI Graphics

The layer-cake model, also called the infinite onion model, has been accepted but nonetheless questioned for the last 20 years or so, and especially recently. In this model, a large steady-state, onion-shaped magma chamber underlies the ridge system. The chamber is disrupted only by very large fracture zones, where layers of oceanic crust continuously grow to eventually comprise the lower two-thirds of the oceanic crust.

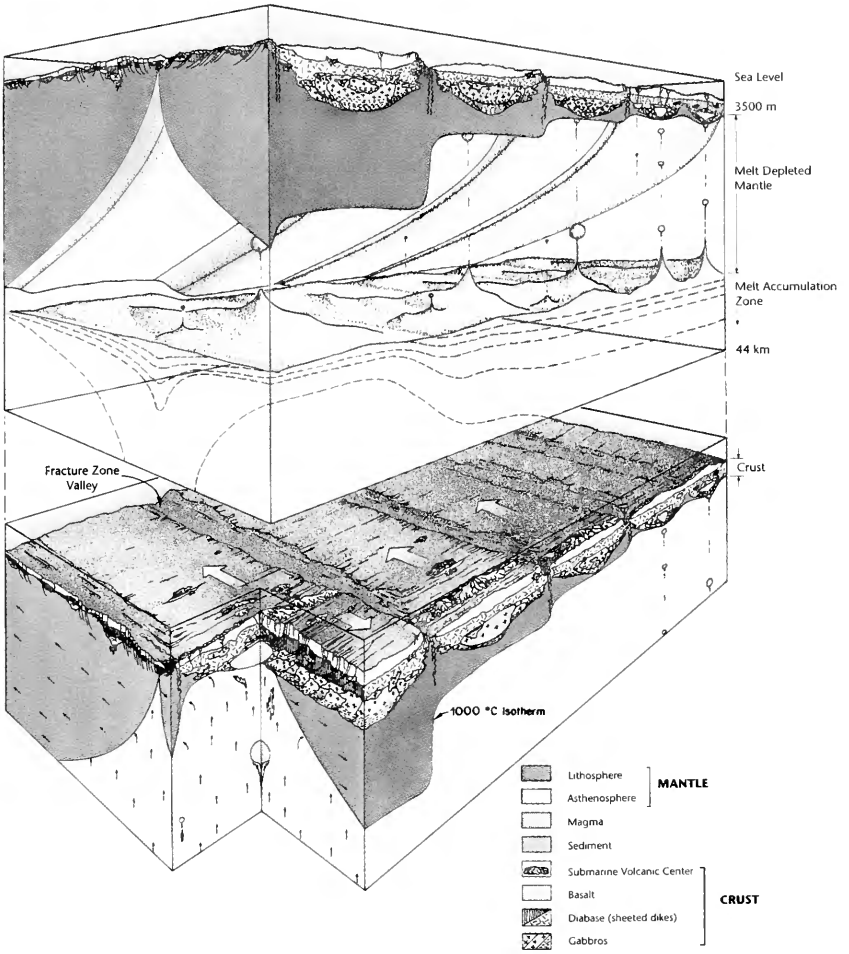
progressively toward the continents. Exploration of the continental margins and records of deep-sea stratigraphy provided an explosive stimulus for the relatively new field of paleoceanography, critical to understanding how the global climate has evolved and what controls it.

While crustal drilling in the oceans has dramatically confirmed and defined the nature of the shallowest ocean-crust layers, it has largely been unable to recover rocks from the deepest, largest layer. The composition, internal stratigraphy, and rock history of the lower oceanic crust, then, remains one of the fundamental unanswered questions of Earth science. Despite considerable effort by the drilling-program, the middle layer, composed of fractured, brittle, tough fine-grained basalt has proven technically difficult to penetrate at reasonable cost, postponing the long-standing goal of recovering a complete, intact section of oceanic crust and shallow mantle.

The 1987 drilling of 500 meters of gabbro in only 16 days by the drilling program's *JOIDES Resolution* at a tectonically exposed section of the lower oceanic crust on the southwestern Indian Ridge drastically changed our approach to ocean-crust exploration. The largely unanticipated success demonstrated that drilling lower-oceanic crust was totally different from drilling shallow-oceanic crust. Not only is it far easier, with nearly 100 percent rock recovery, but it requires no new technology. Moreover, this one long section confounded many in the geologic community. No evidence for a major magma chamber was found. While the compositional diversity of the rocks did closely resemble that found in fossil magma chambers exposed on land, these rocks were formed by a new and physically different dynamic process that involves close interplay of deformation and crystallization in semisolidified crystal mushes. Similar rocks recovered as gravel by dredges and submersibles, without their accompanying key stratigraphic and structural relationships, had led to opposite and entirely incorrect conclusions—demonstrating the inadequacy of studying oceanic crust without drilling.

This galvanized the geologic community. There was growing realization that a costly, single, deep hole through the oceanic crust would be insufficient to understand a laterally heterogeneous oceanic crust whose stratigraphy and composition varied radically from one region to another. This prompted a major international meeting, held in Woods Hole in 1989, to consider a new approach to oceanic deep-crustal and shallow-mantle drilling. The meeting report, *Drilling the Oceanic Lower Crust and Mantle,* proposed that while drilling a single deep hole through the oceanic crust should be a long-term goal, a major program of drilling directly into the lower oceanic crust and mantle should be done over the next decade. This report was then considered and endorsed by a working group reporting to the JOIDES (Joint Oceanographic Institutions for Deep Earth Sampling) Planning Committee and is now likely to occur if funding for the Ocean Drilling Program continues.

The strategy proposed, called offset drilling, borrows from that used by sedimentologists, using uplifted rock exposures as windows for drilling critical partial sections in the lower oceanic crust and mantle from which to reconstruct its overall composition and structure. This would be done in different regions that represent various conditions of



E. Paul Oberlander/WHOI Graphics

Contrary to the central tenet of the layer-cake model, recent seismic evidence implies that no steady-state magma chambers exist beneath ocean ridges, and there are no continuous gabbroic layers at slow-spreading ridges. What is becoming more and more apparent is that seismic structure is extremely complicated. Oceanic crust structure is believed to be dependent upon the rate of seafloor spreading and the rate of magma eruption from the mantle at each location. The thickness of the lower ocean crust varies near fracture zones and at offsets in the ridge. Internal stratigraphy is controlled by ongoing faulting, deformation, and hydrothermal alteration. The composition of the lower ocean-crust layer may be even more radically different than we have believed, because we now know it attenuates seismic waves too fast to be gabbro.

The composition, internal stratigraphy, and rock history of the lower oceanic crust remains one of the fundamental unanswered questions of Earth science.

ocean-crust formation, and would permit direct evaluation of models for crustal formation at slow- and fast-spreading ocean ridges and for crustal formation close to and near mantle hot spots. This strategy, while dependent on geologic interpretation of the sections to piece them together into an integrated model of ocean-crust formation, is far more scientifically sound than trying to interpret the whole from a single hole.

The first crustal-information drilling voyage is scheduled for November 1992 at an exposure of oceanic crust originally formed at the East Pacific Rise. This fast-spreading ridge is at the opposite extreme from the slowest spreading ocean ridges previously drilled in the Indian Ocean. We expect the rocks recovered will be strikingly different. They may reveal new processes for ocean-crust formation. This cruise will directly test for the first time the various new models for ocean-crust formation and fast- and slow-spreading ocean ridges. It is the beginning of a new era in the exploration of ocean basins.

This cruise will directly test for the first time the various new models for ocean-crust formation and fast- and slow-spreading ocean ridges.

Henry Dick is a Senior Scientist in the Department of Geology and Geophysics at Woods Hole Oceanographic Institution. He grew up in Oregon (and therefore considers himself an expatriate of a foreign country in Massachusetts). He obtained a Ph.D. in geology and geophysics at Yale University in 1976 by trekking through the remote Kalmiopsis wilderness in Oregon, which was purported to be a fragment of fossil ocean crust. It was rumored that he made a geologic map of the area while having a good time backpacking, trail biking, and swimming in the many mountain streams. Having debated the origin of the rocks he collected there with numerous other authorities on the ocean crust, none of whom, like himself, had ever actually even held a rock from the seafloor, he thought it might be a good idea to go take a look. The Institution has been stuck with him ever since; though several times it did send him to the bottom of the Atlantic and the Caribbean in Alvin, *and to many other strange places. He has kept coming back. His current ambitions include being on the ocean drill ship* JOIDES Resolution *when it first drills through the ocean crust into Earth's mantle, and to get his 16-month-old daughter to sleep through the night.*

Ocean Drilling Program

THE OCEAN DRILLING PROGRAM (ODP) sponsors an international partnership of scientists and governments to explore Earth's origin and evolution beneath the seafloor. Scientists sail the world's oceans in a continuous series of cruises aboard the drill ship *JOIDES Resolution* to retrieve long cylinders of sediment and rock samples, called cores, from beneath the seafloor. In addition, an extensive program in downhole measurements obtains geophysical data from the drilled holes.

On each cruise, ODP addresses specific problems concerning how the biosphere, atmosphere, ocean, crust, and mantle interact through time. The program's four broad areas of interest are tectonic evolution of passive and active margins, origin and evolution of oceanic crust, origin and evolution of marine sedimentary sequences, and paleoceanography.

The 143-meter *JOIDES Resolution*, officially registered as *Sedco/BP 471*, carries a scientific and technical party of 50 supported by a 68-member crew. The ship is outfitted with the most modern communications, navigation, computer, and geological and geophysical research equipment.

Plans for an ODP cruise begin many years before drilling. During the early stages, scientists from different disciplines meet to discuss both the geological theme of the cruise and the specific geographic area to be drilled. From these meetings, the scientists outline scientific objectives and propose drilling sites. Then they establish a general ship's track and begin formal plans for drilling. A survey is usually conducted by another research vessel to help select sites that are the most valuable scientifically and where no hydrocarbon accumulations will jeopardize the safety of the ship or the environment.

About a year before a cruise, ODP chooses two co-chief scientists, and then other cruise participants are identified based on their expertise and interest in a field important to the scientific objectives of the cruise. Several months after a cruise, a preliminary report is

Ocean Drilling Program

Vicky Cullen

Editor, *Oceanus* Magazine

Ocean Drilling Program

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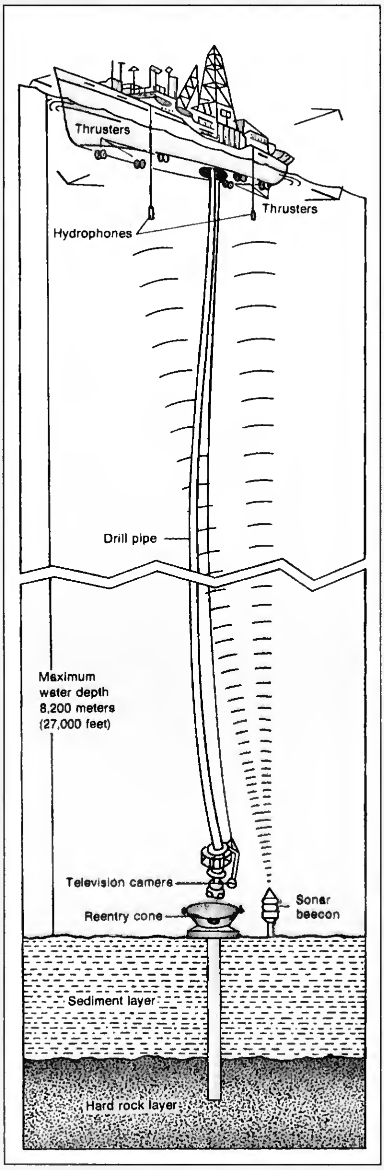


Relocation of a previously drilled hole is accomplished by bouncing sound waves between the ship's hydrophones and sonar beacons near the reentry cone while powerful thrusters hold the ship in place.

published in *Initial Reports of the Proceedings of the Ocean Drilling Program,* and some months later the scientific results of the cruise, including shorebased studies of samples and data, are published in *ODP Proceedings.*

ODP cruises generally last about two months. While on site, drilling continues 24 hours a day. Many lengths of 9.5-meter drill pipe are attached together to lower a large drill bit to the seafloor. This takes about 12 hours in 5,500 meters of water. Core barrels are then lowered through the drill pipe to receive and contain the core material. When a length of about 9.5 meters has been drilled, the core barrel is raised to the ship, where technicians recover the long cylinder of sediment or rock, cut it into 1.5-meter sections, and begin documenting and describing its origin, appearance, and contents. Deep holes may require several changes of drill bits; for each change, the drill string is brought back aboard the ship, pipe by pipe, and then reassembled as the new bit is lowered. A reentry cone facilitates relocation of the hole with a sophisticated system of scanning sonar equipment and an underwater television camera.

Seven laboratory levels occupy 1,115 square meters aboard *JOIDES Resolution* to provide space and equipment for studies in sedimentology, paleontology, petrology, geochemistry, geophysics, paleomagnetics, and physical properties. Following routine whole-core analysis, each core is split lengthwise and one half becomes the working section, the other the archive section. Small samples of the working half are removed according to the cruise sampling plan and the dictates of direct observation. The archive section is photographed and rigorously described before it is boxed for long-term, refrigerated storage. As technicians complete initial analy-

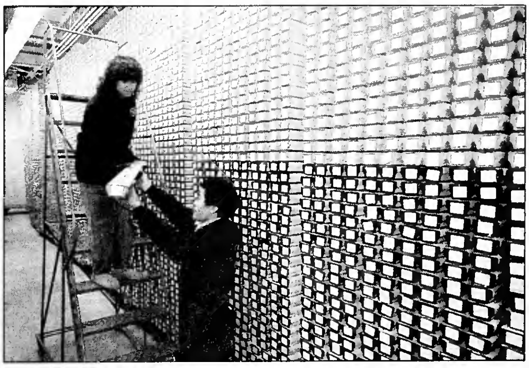
Figure and photographs courtesy of Ocean Drilling Program

Tiny flags mark sample locations in cores arrayed in a JOIDES Resolution *laboratory.*

ses of each core, the data are entered into the central computer for display on terminals throughout the laboratory complex. Scientists working anywhere on the ship can track the arrival of new samples and become immediately involved in their analysis.

Since 1985, ODP has recovered more than 77,500 meters of cores from 683 holes at 279 sites. Nearly 50 cruises have taken *JOIDES Resolution* to sites in the Atlantic, Pacific, northern and southern polar, and Indian oceans. Thousands of core samples have been distributed to investigators in more than 38 countries. ODP scientific accomplishments include new understanding of the causes and history of ice ages, the evolution of continental margins, Earth's tectonic processes, marine sedimentation, and the origin and evolution of oceanic crust. The US National Science Board recently recommended renewal of the program for another decade.

ODP is funded by the US National Science Foundation and contributions from 18 other ODP member countries. Nationally, 10 major oceanographic institutions comprise Joint Oceanographic Institutions Incorporated, which manages ODP. Internationally, a group of scientists provides overall planning and program guidance through the Joint Oceanographic Institutions for Deep Earth Sampling organization. Texas A&M University (TAMU) is the ODP science operator and ship manager, and the Lamont-Doherty Geological Observatory (L-DGO) maintains all aspects of wire-line logging data from *JOIDES Resolution* cruises and combines them with the archived data from the Deep Sea Drilling Project, ODP's predecessor. Cores are archived at TAMU, L-DGO, and the Scripps Institution of Oceanography of the University of California, San Diego.



Almost 80,000 meters of ODP cores are archived at three US marine institutions.

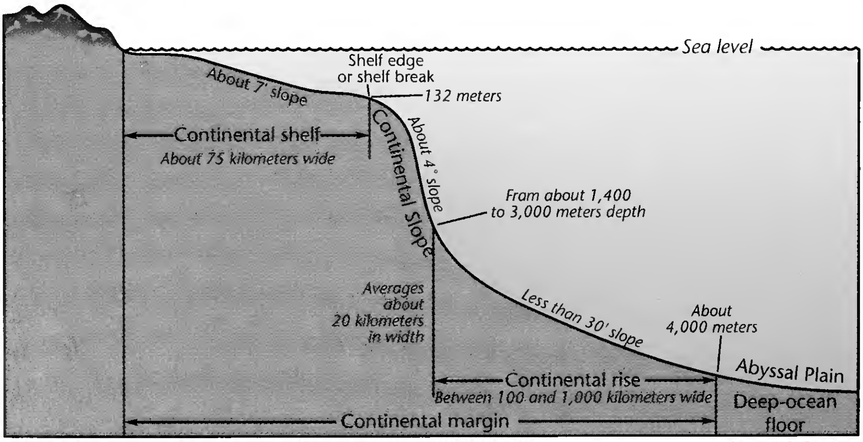
Continental Margins

Windows into Earth's History

Deborah R. Hutchinson

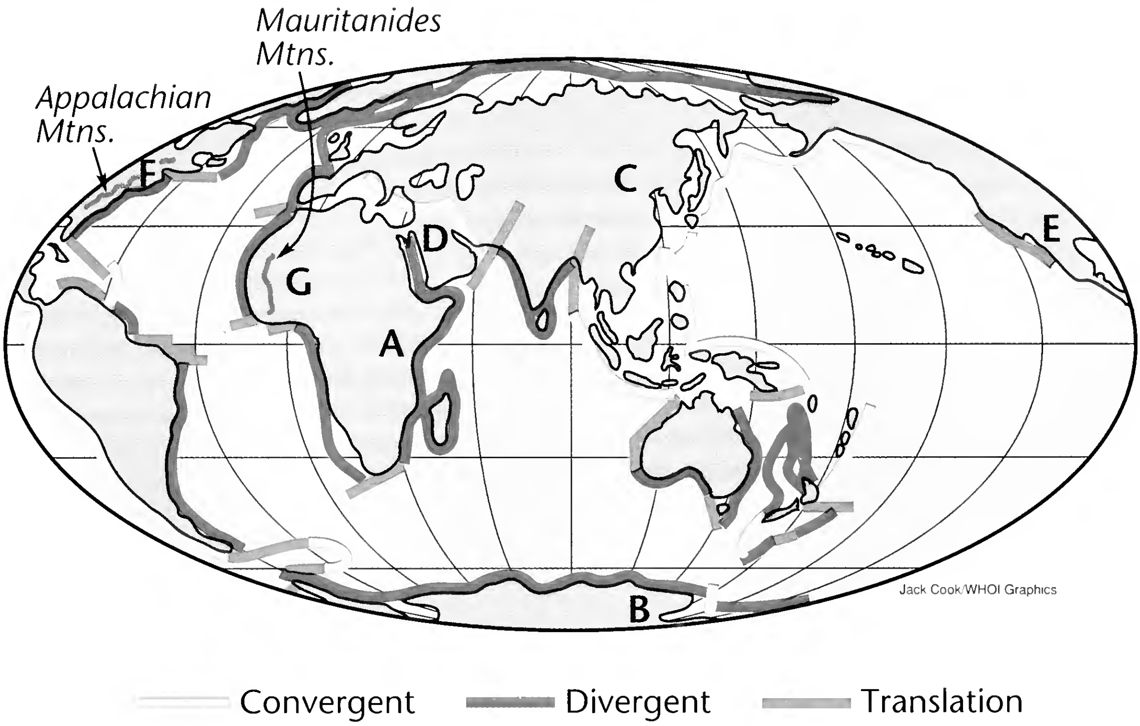
Continental margins are submerged platforms that surround continents and separate them from the deep ocean. As recently as two decades ago, this zone was geologically termed a "belt of ignorance," because land geologists tended to keep their feet dry and marine geologists typically stayed in deep water. Though it was the study of ocean geology that led to the theory of plate tectonics and revolutionized our understanding of how Earth works, the ocean basins are so effectively destroyed by plate motions that they do not offer a long-term historical record. Today, we know that continental margins preserve the history of continental erosion, oceanic subduction, climate variation, sea-level changes, biological productivity, and numerous other processes. Unlike ocean basins, the remains of continental margins are abundant in Earth's geological record, and knowledge of continental-margin formation provides the tools to understand a good portion of our planet's history.

Fundamentally, continental margins are transition zones. Here land meets water and shallow water meets deep water, less-dense continental crust meets more-dense oceanic crust, terrigenous sediments are interlayered with biogenic deposits of oceanic origin, and vertical crustal motions of continents are juxtaposed with horizontal motions of oceanic



Jack Cook/WHOI Graphics

The general morphology of a continental margin, showing the shelf, shelf-slope break, slope, and rise. Abyssal plains extend from the continental rise over the deep-ocean floor.



Jack Cook/WHOI Graphics

The global distribution of divergent, convergent, and translational continental margins. Letters indicate the locations of the East African Rift System (A); the West Antarctic Rift System (B); the Baikal Rift System (C); the Northern Red Sea (D); Baja California (E); the Appalachian Mountains (F); and the Mauritanides Mountains (G).

crust. The dynamic processes that shape the margins, such as wind, waves, tides, and currents, are often intense and focused. Changes in sea level can dramatically alter the depositional and erosional patterns on continental margins. The result is a region where there are large lateral and vertical variations in the physical and chemical properties of rocks. The sedimentary and volcanic rocks of continental margins contain a composite record of local, regional, and global geological processes. Scientists who study continental margins seek understanding of sea-level fluctuations, oceanic circulation, biological productivity, sediment flux, climatic variation, plate interactions, and mantle dynamics, as well as their relative influences on the margins.

Divergent Margins Form at Spreading Centers

Three types of continental margins are classified according to tectonic origin: divergent, convergent, and transform. Their distribution is shown above. Divergent margins, also called Atlantic or passive margins, result from continents breaking apart or rifting to form new ocean basins. Their history begins with the development of extensional faults, rift basins, and perhaps regional uplift and volcanism. Through processes not yet entirely understood, the rift evolves into an active plate boundary as volcanism increases to the point where seafloor spreading begins. The northern Red Sea and the Salton Trough in Baja California are two of the most thoroughly studied examples of the early phases of continental rifting. As the nascent ocean grows, the spreading center migrates away from the continental edge, leaving the continental margin in the stable interior of the growing plate. In general, the subsequent history of the margin is one of vertical subsidence caused by thermal contraction of the cooling crust and loading by a thickening sedimentary apron. This generalized history is modified by many processes, including changes in sea level and climate, and variations in sediment source.

A divergent margin consists of a gently sloping continental shelf (generally less than 130 meters deep), a steep continental slope (from the shelf edge to depths of 4,000 to 5,000 meters) that is sometimes dissected by submarine canyons, and a continental rise (where the seafloor gradient drops to below 1 meter in 40). The margin off the East Coast of the US illustrates some of the possible variability in morphology: off New Jersey, a well-developed shelf, slope, and rise exist; however, off Florida, the continental slope flattens into the broad, flat Blake Plateau at 800 to 1,000 meters, and then drops precipitously along the Blake Escarpment to 5,000 meters.

Although divergent margins are formed primarily by tension, their origin is thought to be shear between the crust and mantle. There are two models for continental breakup: *pure-shear extension*, in which the position of stretching of the crust and underlying mantle are coincident, and *simple-shear extension*, in which the position of crustal stretching is displaced from that of the mantle along a low-angle dipping detachment fault or zone of weakness. The two models have very different implications for the position of volcanism, the angle of faulting, the crust's strength during breakup, the size of rift basins, and the symmetry or asymmetry of the divergent margins.

One of the most astonishing discoveries of recent years is the tremendous lava outflow that can accompany the latest rift/ earliest drift period.

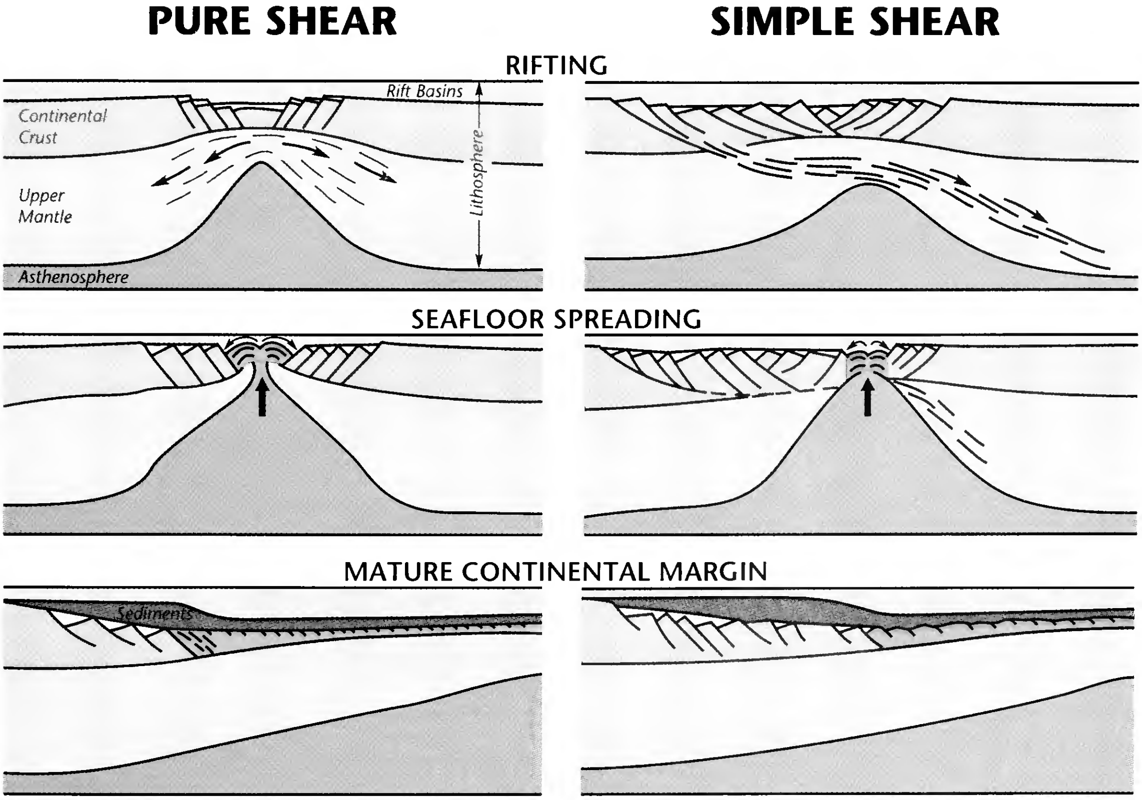
The basic structural units of divergent margins are the underlying crust, rift basins that form during continental stretching, and overlying sediments. The crust beneath divergent margins consists of, from land to ocean, prerift continental crust 30 to 40 kilometers thick composed primarily of granite, transitional rifted crust, and oceanic crust 6 to 7 kilometers thick that is mostly made up of basalt. Transitional rifted crust is only poorly understood at present. One of the most astonishing discoveries of recent years is the tremendous lava outflow that can accompany the latest rift/earliest drift period at some margins. In these "volcanic passive margins," the transitional crust is composed of as much as 20 kilometers of basaltic intrusive and extrusive rock, and the boundaries between thinned continental crust and normal (6-kilometer thick) oceanic crust are likely to be abrupt. The continental margins of Norway, East Greenland, and the US East Coast are examples of these volcanic margins. The composition and structure of transitional rifted crust beneath nonvolcanic margins, such as off eastern Canada and beneath the Bay of Biscay, are not well documented.

Rift basins occur shoreward of transitional rifted crust, and deposits in these basins record the early events that accompanied extension and continental breakup. The largest active continental rifts on Earth include the East African Rift, the Baikal Rift in Siberia, and the West Antarctic Rift system. Within divergent margins, most of the rift deposits lie deeply buried beneath a wedge of overlying sediments, but those still exposed provide a record of this stage in margin evolution. Along eastern North America, for example, there are outcrops from Nova Scotia to Florida of the Newark series of rocks formed from lake and river sediments and volcanic flows. These are the only directly observable rocks formed during the rifting event that separated America and Africa.

The most familiar and observable part of a divergent margin is the wide continental shelf and slope underlain by thick sediments. Some of the thickest sediment accumulations on Earth fill basins along divergent continental margins. The postrift sedimentary rock off New Jersey, for example, is approximately 15 kilometers thick in the Baltimore Canyon Trough. These sediments alone are slightly less than half the thickness of normal continental crust (40 kilometers) and more than twice the thickness of normal oceanic crust (6 to 7 kilometers). The sedimentary wedge that covers most divergent margins develops over millions of years. Its geometry and composition record variations in original breakup geometry, sediment source, sediment type, sediment supply, climate, ocean circulation, sea level, and dynamic sedimentary processes such as salt diapirism, compaction, burial diagenesis, landslides, and other mass-wasting features.

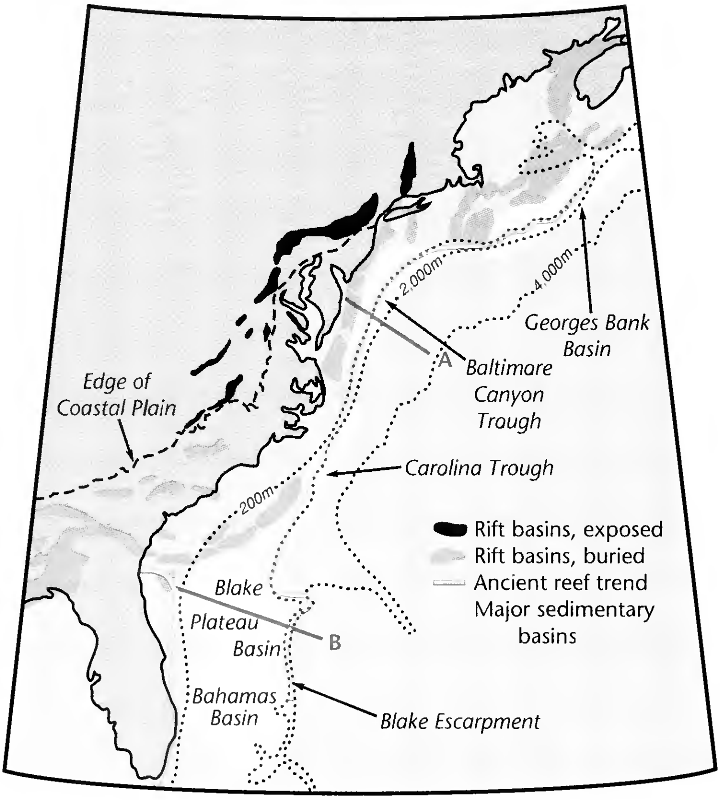
The US East Coast began forming approximately 225 million years ago when rifting from Africa first began. Numerous northeast trending detrital basins containing lakes and river systems developed in the rugged relief of the Appalachian-Mauritanides mountain chains now located in the US and Africa. The climate was mostly equatorial. As rifting progressed and the continents shifted northward, a more arid climate evolved. Large basins formed at sea level and filled with evaporites near the future axis of seafloor spreading. The spreading began 190 to 180 million years ago. The early postrift deposition was characterized by rapid subsidence and high accumulation rates caused by terrigenous

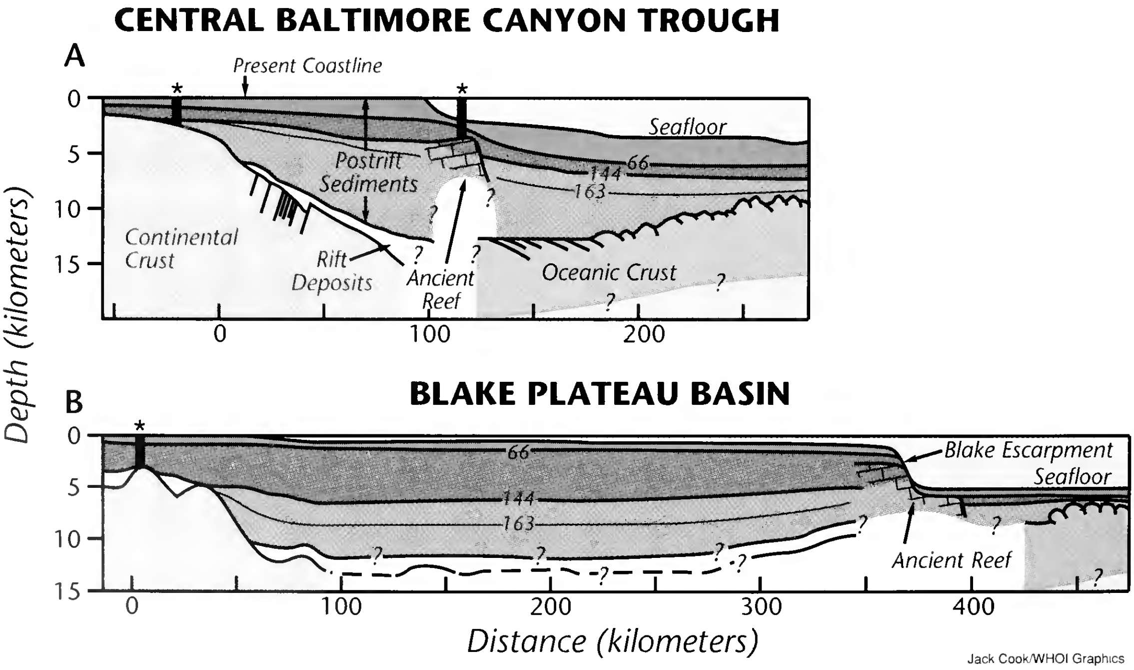
In the pure shear model, crust and mantle stretching are coincident, with brittle deformation in the upper crust occurring at the same place as ductile deformation deeper in the lithosphere. Rifts in this model tend to have steep fault dips and associated magmatism. In the simple shear model, initial stretching is displaced between the crust and mantle along a low-angle structural detachment. Rifts in this model tend to have faults with low-angle dips, and magmatism may be displaced from the position of the rift.



Jack Cook/WHOI Graphics

*Tectonic and basin elements along the Atlantic East Coast divergent continental margin (right). The edge of the coastal plain marks the landward limit of continental margin sedimentary deposits. Cross sections for lines A and B are shown (below). Wells are shown by * and a black bar. Color changes within the post-rift sediments coincide with time horizons at 144 and 66 million years. An additional horizon at 163 million years is shown. Zones of uncertainty are shown by queries. The greater width of the Blake Plateau basin may be due to a longer rifting period than that of the Baltimore Canyon Trough. Differences in the thicknesses of the corresponding sedimentary units can be explained by differences in sediment supply, climate, ocean currents, and subsidence rates, which have caused the ancient reef to be drowned in the Baltimore Canyon Trough and eroded in the Blake Platform. Slopes on the Blake Escarpment near 350 kilometers can exceed 40°.*





Jack Cook/WHOI Graphics

detritus from the Appalachians. From around 160 to 135 million years ago, sedimentation rates dropped and a huge barrier reef, similar to the Great Barrier Reef off Australia, grew along the East Coast and acted as a sediment dam. This reef formed the shelf edge for millions of years, is the single largest sedimentary feature beneath the Atlantic margin, and has been the target for much hydrocarbon exploration and drilling. A long period of generally high sea level and low sedimentation rates followed the reef's drowning until about 16 million years ago. With the onset of global cooling and glaciation at that time, sea level fell, oceanic circulation intensified, and sedimentation rates increased to the largest rate at any time in the margin's history. Most modern deposition bypasses the continental shelf and slope to form a thick wedge on the continental rise. Two examples of contrasting structural and depositional geometries are shown at left.

Convergent Margins Form Where Plates Collide

Convergent margins, also called Pacific or active margins, result from the collision and interaction of plates along a continent's edge. The basic plate-tectonic configuration involves subduction of an oceanic plate beneath an overriding plate carrying a continent. The resulting margin is a product of the two plates' histories and their relative motions. Convergent margin morphology is considerably more complicated than that of divergent margins: The shelf may be narrow and contain numerous islands, the slope may change frequently from steep to moderate dips, and a trough or trench often occurs at the base of the slope. Continental rises are rarely present. Also, sedimentary basins rarely fill with more than a few kilometers of deposits before being modified or destroyed by plate motion.

Rupture and plate subduction may begin along preexisting weaknesses in the crust or mantle, such as along boundaries between different crustal types, along oceanic fracture zones, or along fossil plate boundaries. After subduction begins, the margin develops characteristic domains that are, from ocean to continent (see figure overleaf):

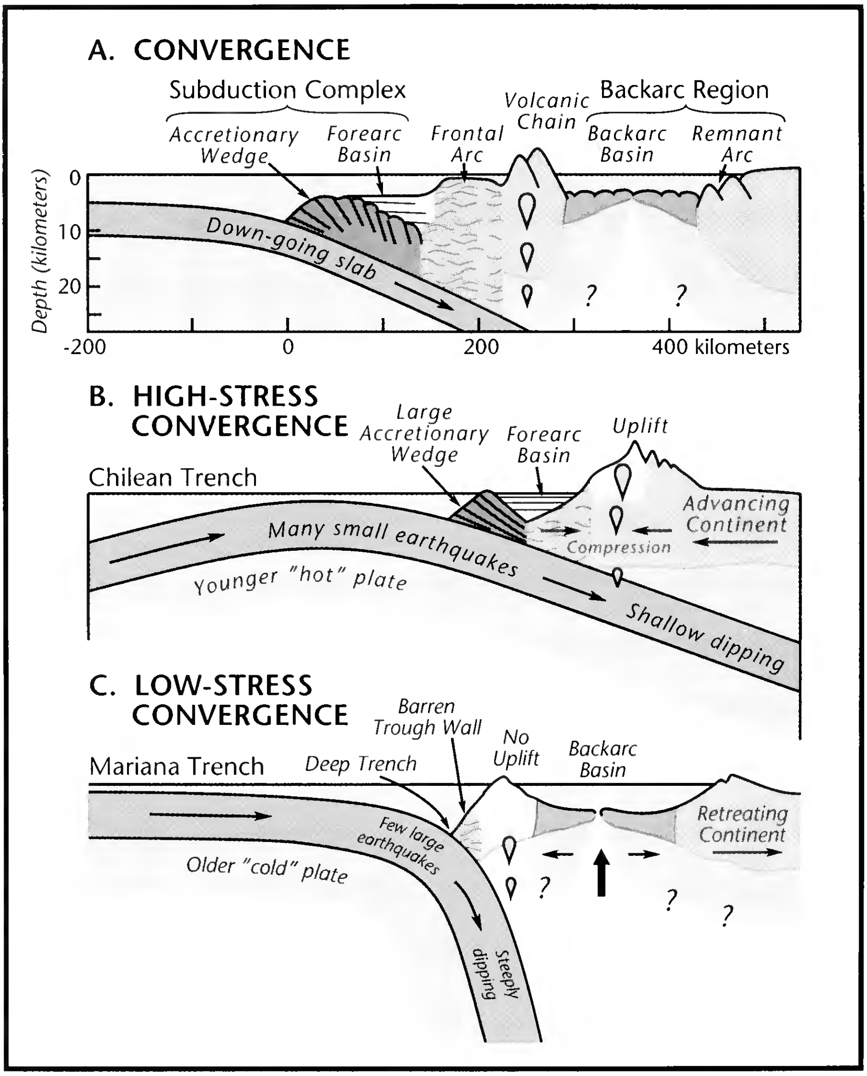
(1) the active trench, where the downgoing plate first interacts with the material on the overriding plate as it begins to descend into the mantle;
(2) the subduction complex, or accretionary wedge, where deformed rocks adhere as a result of subduction;
(3) the forearc basin on the landward part of the accretionary wedge containing less-deformed sediments;
(4) the frontal arc, a zone of uplift and deformation immediately between the accretionary wedge and the volcanic chain;
(5) the volcanic chain, a zone of active igneous activity; and
(6) the backarc region behind the volcanic chain that may contain marginal basins or inactive ancient arcs.

Together, these domains comprise what is generally called a volcanic arc, and contain some of the most dynamic tectonic environments on Earth. The trench, the subduction complex, and the forearc basin are commonly submerged and make up the continental margin.

There are high-stress and low-stress subduction zones. High-stress regime characteristics include a large accretionary prism, large shallow earthquakes, a wide range in the composition of the igneous rocks, and a

Around 160 to 135 million years ago, a huge barrier reef, similar to the Great Barrier Reef, grew along the East Coast.

shallow-dipping subducting slab. In a high-stress subduction zone, typified by the South American West Coast along the Peru-Chile Trench, the subducting oceanic crust is generally young (and therefore relatively thin and "hot") and the two plates are considered well-coupled. A low-stress subduction zone exhibits a small accretionary wedge, few large earthquakes, igneous rocks with a narrow basaltic compositional range, a steeply dipping down-going slab, and a well-developed backarc basin. Low-stress subduction zones generally occur where oceanic crust is subducting beneath oceanic crust, such as the Mariana Arc in the Pacific, and the subducting crust is generally old (and therefore relatively thick and "cold").

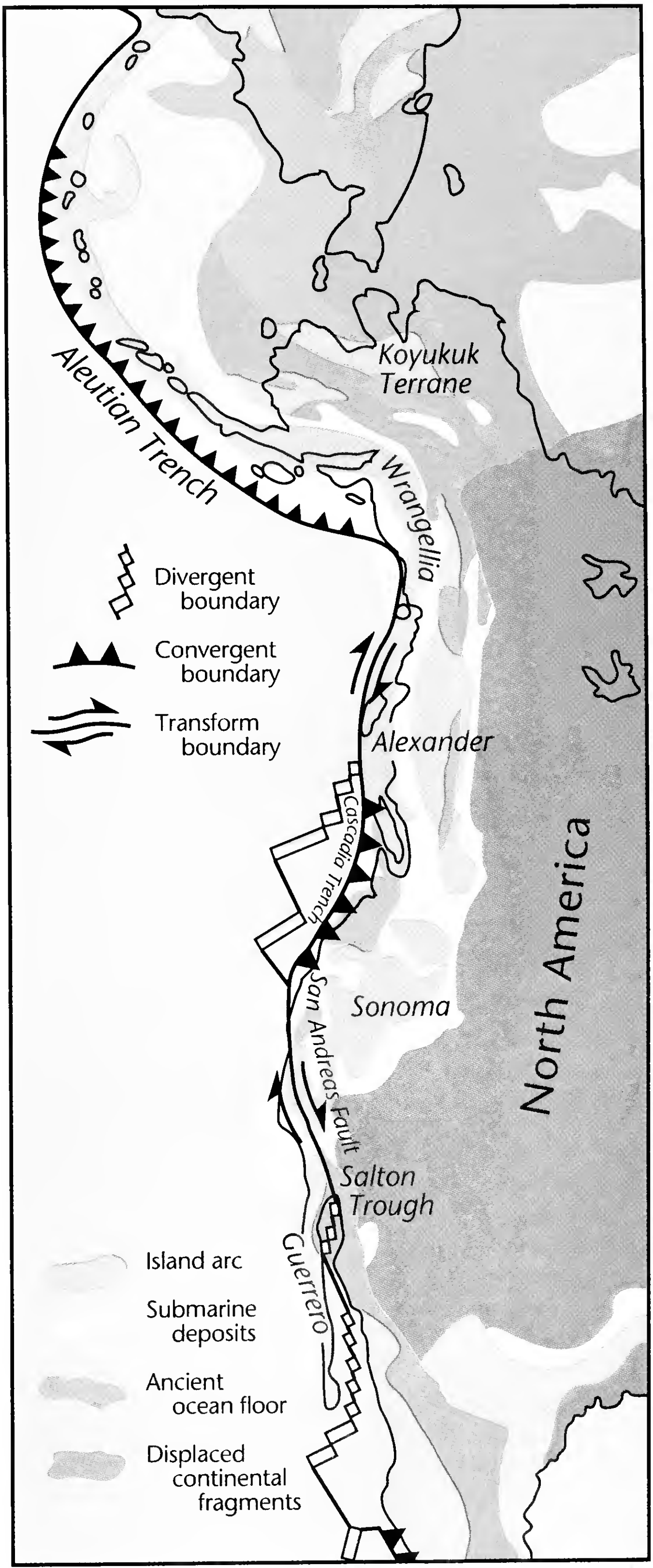


Jack Cook/WHOI Graphics

A typical convergent margin, with basic tectonic and depositional units, is shown at top (A). High-stress convergent margins are usually formed where oceanic and continental plates collide (B). Low-stress convergent margins are usually found where oceanic plates collide with each other (C).

Accretionary wedges have been extensively studied using seismic techniques and drilling, and these studies identify four major accretionary processes. Accretion occurs where oceanic sediments are scraped off a subducting plate and added to a large wedge on the edge of the overriding continental plate. "Kneading" describes large-scale, complicated folding and faulting ("mixing") of forearc-basin and accretingwedge sediments. Subduction erosion occurs where the front of the accretionary wedge migrates landward, presumably because of mechanical abrasion by the down-going plate. Sediment subduction occurs where sediment is carried down with the subducting slab. Variability in subduction, accretion, and volcanic processes has at different times been attributed to relative motions, ages, and temperatures of the descending and overriding plates.

The North American West Coast illustrates some of the complex geology that develops along convergent active margins and the differences between divergent and convergent margins. After millions of years as a divergent margin, around 200 million years ago the West Coast became a convergent margin and the site of active volcanic arcs (this was about the same time that the American-African supercontinent was rifting to form the Atlantic Ocean). An east-dipping subduction zone formed and North America became an overriding plate, a configuration that has persisted nearly to the present. After subduction began, a long history of accretionary events followed. Early on, a large continental fragment, Stikinia, arrived near North America on the subducting plate; it then collided with and became attached to the continent's western edge. Subsequently, at least three island arcs were pushed from their locations west of North America onto the continental edge. These are now identified as the Koyukuk Terrane (part of Alaska), Alexander Terrane (part of British Columbia), and Guerrero Terrane (Baja California).



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Tectonic, magmatic, and depositional elements along the West Coast of North America. Convergent, divergent, and translational margins all occur along the coast of California.

One of the largest continental fragments to be added to North America, Wrangellia (parts of Alaska and British Columbia), arrived by about 65 million years ago. The collage of terranes that forms western North America was mostly in place with the collision of Wrangellia. At that time, a trench-arc system was essentially continuous from Alaska to Mexico.

Modern tectonics of western North America have been dominated by the arrival and subduction of two mid-ocean ridge sections, one now off British Columbia, the other now off central California. As these ridge sections have been subducted, extensive strike-slip faults developed and fragmented the multiple components of the margin. The only intact portions of the previously extensive convergent margin are the Aleutian (off Alaska) and Cascadia (off Washington and Oregon) trench-arc systems.

The accretionary and tectonic events that shaped western North America continuously changed the shape and position of the continental margin. Through time, the margin shifted westward from the interior western mountains as new terranes and arcs became accreted. These tectonic events are the primary forces shaping the geometry of the margin, and other processes, such as climate, oceanic circulation, and sea level have been only secondary forces. The modern active margin is but the most recent evolutionary stage.

Continental margins provide a means to understand continental evolution, and then to reconstruct Earth's evolution.

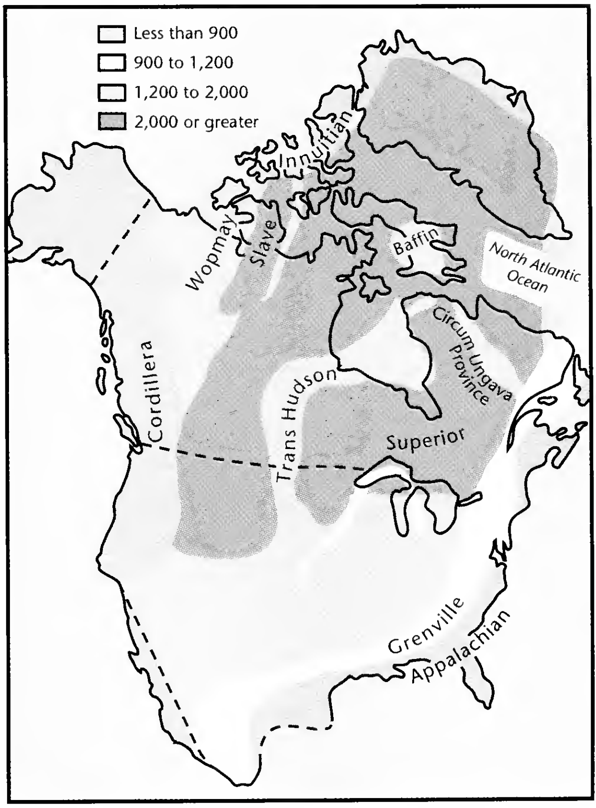
Plates Slide By One Another at Transform Margins

Transform margins form where two plates slide by each other or have slid by each other in the past. They can be associated with either divergent or convergent tectonic settings. The south-facing margin of West Africa began as a translational margin when South America and Africa first rifted apart. Likewise, the margin along southwest Newfoundland originated as a transform when Iberia rifted away. After the continents separated, these margins became passive in the sense that the transforms were inactive, but they are characterized by narrow shelves and narrow ocean-continent transition zones.

Convergent transform margins are numerous, and are generally characterized by a long and complicated history of translational and compressional movement. Parts of the North American West Coast became transform margins in the latest evolutionary stage. The San Andreas Fault, the largest of many strike-slip faults in a wide zone of deformation that includes the continental shelf, represents this kind of margin in California. To the north in western Canada, a transform fault connects the Aleutian and Cascadia trenches, and is the site where the Pacific plate slides past the North American plate. These margins are characterized by a shelf that can be as narrow as a few kilometers and a complex amalgamation of islands, banks, and basins that form in response to the geometry of the strike-slip fault zone. In transform convergent settings, most of the terrigenous sediment is trapped in the nearshore sedimentary basins, leaving the offshore basins to contain thinner layers of mostly biogenic sedimentation. Sediment thicknesses rarely exceed a few kilometers.

Earth's History is Written in Continental Margins

Continental margins provide a means to understand continental evolution, and then to reconstruct Earth's evolution. In a simple view, continental margins grow from both recycled continental material (sediments) and new mantle material (volcanic rocks). Through time, margins are successively incorporated into continental mass by plate collisions. Evidence for this includes the numerous remnants of divergent and convergent continental margins found in old mountain belts, and the progressive decrease in the age of rocks toward coastal areas. In North America, the oldest Precambrian rocks (1 to 4 billion years old) are found in the "interior shield" or mid-continent regions; Paleozoic sedimentary and volcanic rocks (several hundred-million years old) surround the shield—the Appalachian Mountains and parts of interior western Cordillera are examples; Mesozoic and younger sedimentary and volcanic rocks (less than 200 million years old) underlie the coastal borderlands.



Jack Cook/WHOI Graphics

The age and distribution of major crustal provinces in North America. Names provide geological designations of selected provinces. There is a trend toward younger ages of provinces in the exterior positions, reflecting the successive growth of the continent through time.

The identification of continental-margin deposits within mountain belts is an observation related to the Wilson Cycle, a theory about how oceans are born through rifting, mature through drifting, and eventually die by subduction and continental collision. Within the Appalachian Mountains, fossil passive continental margin deposits have been used to infer that a proto-Atlantic Ocean, known as the Iapetus Ocean, preceded the Atlantic Ocean. This ocean formed during a rifting event more than 600 million years ago, and the Iapetus passive margin lasted about 150 million years before becoming involved in oceanic subduction. The Iapetus Ocean may have disappeared by 400 million years ago, followed by several pulses of compressional tectonics that culminated with continental collision between North America and Africa, producing a mountain range whose remnants are the Appalachians in North America and the Mauritanides in Africa. Subsequent rifting started about 225 million years ago and led to the development of the present Atlantic Ocean. The Atlantic rift followed the general trend of the preexisting collision zone, although blocks of Africa became stranded in what are now known as Nova Scotia and Florida.

The oldest evidence for widespread development of continental margins comes from the proliferation of continental rifts about 2 billion years ago. The Circum-Ungava system of rocks in Labrador provides evidence for one of the oldest rifts, 2.0 to 2.3 billion years ago. These rocks are interpreted to represent a rift that opened into a small ocean basin that was later deformed, metamorphosed, and thrust back toward the continent. Prior to 2 billion years ago, the geological record is complicated by severe deformation and metamorphism, making interpretations of original rock successions and their tectonic environments equivocal. However, recent advances in dating techniques have produced ages for detrital zircons that suggest continental sedimentary rocks may have formed more than 4 billion years ago in Australia. In North America, the oldest known continental crust, located in northwest Canada, is about 4 billion years old. These data suggest that chemical differentiation of the Earth's mantle into continents and oceans may have begun shortly after Earth was born, but the record for these ancient fossil continents (and their surrounding margins) has mostly been obliterated by later meteor bombardment, erosion, and subsequent deformation. Therefore, the geological record of the widespread development of continents, continental margins, and tectonics indicative of plate interactions is so far only available to us for the second half of Earth's 4.5 billion year age.

Chemical differentiation of the Earth's mantle into continents and oceans may have begun shortly after Earth was born.

In many respects, the study of continental margins has matured in the past few decades. No longer are these regions of transition complete zones of ignorance. They are now recognized as "tape recorders" for many aspects of global evolution. Margins also hold promise as natural laboratories for studying dynamic processes affecting Earth's chemistry, physics, and biology. These processes include how igneous rocks contribute to crustal growth, crustal recycling, and heat and material transfer from the mantle; how faults can move catastrophically or by aseismic creep; or how fluids affect material, chemical, and heat transfer within the sedimentary column. If the past has revealed the mysteries of the morphology, architecture, and composition of continental margins, then the challenge of the future will be to define the deeper and more elusive secrets of global dynamics as we develop new technologies to measure and model the processes that construct and destroy these fundamental building blocks of the continents.

Debbie Hutchinson was introduced to geology through lab exercises in cow pastures of Vermont and through field trips across very old rocks of the Canadian shield of Ontario. After joining the US Geological Survey (USGS) in Woods Hole in 1974, she pursued studies on the tectonics of large inland lakes and of the Atlantic continental margin. With a degree from the University of Rhode Island, she is now firmly entrenched in marine studies of rifts and divergent continental margins, and currently heads the Framework Studies group for the Branch of Atlantic Marine Geology at USGS.

Glossary

Some definitions of less-familiar terminology found in this issue...

dike—a tabular body of igneous rock that intrudes preexisting structures

fracture zone—the 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

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

pillow lava—typically basaltic lava that frequently takes rounded pillowlike shapes, often indicative of submarine eruption or flow

scarp—sequence of cliffs resulting from faulting

sheet flow—flattened, rough-surface lava fields that result from extremely rapid delivery of fluid lava, generally on a steep slope

sheeting—ruptures in massive rocks characterized by tabular surfaces

subduction zone—area where oceanic plates plunge beneath a crustal plate into the asthenosphere

From the Gobi to the Bottom of the North Pacific

Rock Particles Travel from High Mountains to the Oceanic Abyss

Susumu Honjo

Earth's crustal materials are recycled by water, wind, ice, and fire. In order for this recycling to occur, crust must be moved from one region to another. How does this movement happen?

- On many land surfaces, the crust has been elevated by mountain-building tectonic forces, while part of Earth's surface is still rising due to loss of the weight of glacial shields that covered a great deal of land during the last glacial period.
- Glaciers and sea ice carry loads of rock particles, from boulders to the finest dust, and deposit them on the polar-ocean floor.
- The crust is constantly eroded, adjusting the heights of mountains.
- Rocks are crushed to finer sizes as gravity pulls them down-slope; a conveyer belt, driven by gravitational force, moves crustal material steadily down-slope until it comes to rest in the deepest basin of all, the deep seafloor.
- Rock particles are transported from arid lands to mid-ocean regions by aeolian transport (the wind's lifting of fine particles from continents and transporting them to the oceans).
- Earth's thermonuclear engine transports deep-sea sediment to the subduction zones where it is sucked down into the mantle hundreds of millions of years later, perhaps to rise again as volcanoes or massive mountains, thus closing the grand geodynamic cycle.

> ***Glaciers and sea ice carry loads of rock particles, from boulders to the finest dust, and deposit them on the polar-ocean floor.***

How Much Crustal Material is Being Moved?

Balancing the "budgets" of materials involved in planetary-scale processes is as difficult as balancing a government's financial budget. Balancing the supply of rock particles that originate on land with their deposition in ocean basins is no exception, because there are enormous variabilities and uncertainties in time and space in this process. Recent estimates of the rate at which rivers move rock particles from land to ocean edges range from about 18.5 to 20 billion tons per year. Coastal erosion also supplies rock particles to the ocean. Assuming an annual sea-level rise rate of 1.5 millimeters, we estimate that worldwide coastal erosion contributes half a billion tons of rock particles to the ocean each year. The amount of ice-rafted rock particles is estimated to be about 1.3 to 1.5 billion tons per year. Alexander Lisitzin (University of Moscow) estimates that global aeolian transport of rock particles to the ocean is 1.6 billion tons per year. Thus the total supply of rock particles from land to the ocean adds up to 21 to 23 billion tons per year. After the particles are acted upon by a variety of physical and chemical processes, they end up as fine clay minerals that form a majority of chemically stable sediments, including fine grains of quartz, feldspar, and other rock-forming minerals.

One method for determining the current sedimentation rate in deep basins is to examine the sediment already deposited there. Study of rock particles in the thick Holocene sequence (the most recent 10,000 to 11,000 years) in the Atlantic is muddled by the presence of abundant tiny shells of organisms that once lived in the upper layers of the oceans. In contrast, the Holocene sediment in the middle of the North and South Pacific is estimated to be as thin as several centimeters where the water is very deep; here the majority of biologically produced particles disappear due to dissolution during descent. Rock particles are concentrated in the "deep sea red clay" discovered by the H.M.S. *Challenger* expedition in the 1870s. Applying a number of assumptions, the estimated rate of rock-particle deposition in the red-clay area is on the order of 1 milligram per square meter per year. Lisitzin estimated the average global flux of deep-sea sediment through the Holocene period was 1.7 billion tons per year, which closely coincides with the estimate of aeolian transport.

The total supply of rock particles from land to the ocean adds up to 21 to 23 billion tons per year.

While these estimates are rudimentary, they clearly indicate that river-transported rock particles do not contribute significantly to deep-sea sedimentation, but rather the majority of the annual 20 billion tons of detritus that is eroded and transported via rivers and coastal erosion remains near the ocean edges. These studies lead us to hypothesize that rock particles are transported to the present-day central oceans primarily by aeolian transport.

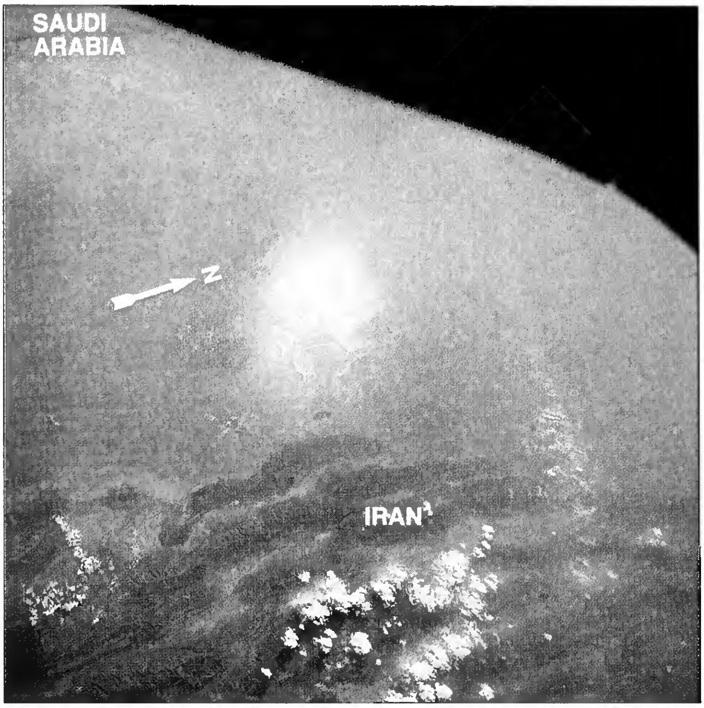
Aeolian Transport: Riding the Winds

In the 1950s, scientists estimated that about 36 percent of Earth's land is sufficiently arid to allow the wind to transport airborne soil as dust. Probably the total of global desert or desertlike area has increased in recent years due to greatly increased land cultivation. The largest region of arid land lies south of the Mediterranean and extends from the Indian Ocean to the Atlantic Ocean. Aided by the tropical upwelling of air, great plumes of Sahara Desert sand are blown into the atmosphere. Some of the particles are transported across the Atlantic by the trade winds—dust from North Africa often falls over Miami, Florida.

The North Pacific is also subject to wind-transported dust, but unlike the Tropical Atlantic, where most dust is transported seaward by easterly (blowing from the east) trade winds, Pacific dust clouds ride the westerly jet stream at high altitude: Dust lifted to high altitudes from the Gobi Desert and other east Eurasian arid lands travels the great distance to the North Pacific. Geochemical studies on dust fallout collected from

Pacific islands and deep-sea sediment attests to an extensive airborne rock-particle distribution, from arid, east Eurasian lands to the deep-sea sediment of the mid-latitude North Pacific. A classic example is that fine mica particles in Hawaiian soil were found to be as much as 180 million years old—the same age as Eurasian sand.

Volcanic eruptions often supply an enormous amount of ash to the open ocean. One of the largest and most violent incidents in human history was the eruption of Krakatau in 1883; scientists estimate that this eruption produced as much as 50 billion tons of tephra. Although it is not known how much of the erupted ash reached the stratosphere, a cloud encircled the earth in a few weeks and there was a full year of unusually red sunsets before it disappeared. These large volcanic eruptions significantly lower the atmospheric temperature by preventing part of the sun's radiation from reaching Earth. Airborne volcanic ash and any aeolian dust that has been lifted to stratospheric altitudes reflect heat, and contribute to the slowing of Earth's warming trend. Many scientists believe an asteroid—as heavy as a few trillion tons—hit Earth with tremendous impact about 65 million years ago. Clouds of particles produced by this impact were thousands of times thicker than the aeolian dust that normally falls into the ocean. This is an explanation of why almost all lineages of marine organisms, as well as dinosaurs on land, became extinct at the Cretaceous-Tertiary boundary.



NASA 41G-42-38

In October 1984, Space Shuttle Challenger *crew photographed this dust storm over the Persian Gulf. For centuries dust storms have been the subject of legend and scientific inquiry, but we are just beginning to understand how frequent they are and how much they contribute to the sediments on the seafloor. When this photo was taken the airborne dust layer was thin enough that eddies are apparent on the water surface; however, less than a minute later a huge mass of dust blew over the Gulf of Oman, completely obscuring the astronauts' view there through the next day.*

Sledding Along with the Ice

The distribution of ice-rafted rock particles is an important indicator of ocean environmental change through the glacial and Holocene periods. Dust blown out of the vast exposures along the thousands of glacial walls in the Canadian Arctic, Greenland, and Spitsbergen coasts fall on arctic sea ice. Large arctic rivers like the Mackenzie, Ob', and Yenisey carry a large quantity of soil particles to the arctic basin. Sediments from rivers and estuaries are incorporated into sea ice, which is pushed far off shore by wind. During summer, the ice surface melts, freeing dust that is blown onto arctic sea ice. The abundance of dust in the arctic sea ice makes the ice dark in color, often bonded in many hues. Arctic ice is often quite far from the image of a snow-white, pure-ice world! In Antarctica, on the other hand, erosion is limited to that caused by glaciers that grind base rocks.

Millions of ice floes are carried by the Transpolar Drift, a sea-ice conveyer that runs across the arctic basin from the Laptev Sea to the

Fram Strait. This drift is not only the largest body of heat transport on this planet, but also an efficient dust mover. Ice that travels with the Transpolar Drift melts along the east coast of Greenland and as it proceeds southward it annually dumps about a billion tons of rock particles onto the seafloor. Knowing this, one can understand why the annual flux of rock particles under the Transpolar Drift is as much as 3 to 4 grams per square meter, while the annual aeolian particle flux over the Greenland ice cap is only 50 to 100 milligrams per square meter. Great icebergs that separate mainly from the west coast of Greenland bring glacial boulders and sand very far south to the North Atlantic.

Directly Measuring Rock Particles in the Deep Ocean

A sediment trap (*Oceanus*, Spring 1992) can directly measure the amount of rock particles that arrive at great ocean depths far from their origins. A modern sediment trap, tethered to a strong mooring on the deep-ocean bottom, is programmed to open and close at regular intervals, trapping sediment particles that fall through the water column. The rate of particle arrival and deposition, known as the mass flux, can be calculated from the area of the trap's horizontal opening and the amount of time it is open to the water column. With these sediment-trap experiments at many ocean stations, scientists are beginning to understand the quality and fluxes of rock particles on the ocean floor during different seasons and years.

The seemingly crimson majesty of Mount Fuji is depicted in "Red Fuji" (right) by the Japanese artist Hokusai. Tephra, which erupted from a volcano into the high atmosphere, is transported throughout the earth. Beautiful red sunsets and dawns are caused by this atmospheric dust.

Sediment-trap studies show that annual rock-particle fluxes in the Pacific basin vary from 0.4 grams per square meter at a station located east of Hawaii (where there is probably one of the lowest rock-particle sedimentation rates in the world's oceans) to 8 grams per square meter at a station west of Panama. At the Panama station, annual rock particle flux ranged from 0.6 grams to 2.0 grams per square meter, but flux should progressively increase closer to the area where Saharan dust plumes pass; indeed, at a station to the east of Barbados, the annual flux of rock dust was about 6 grams per square meter. Under the antarctic Weddell Sea mixed-ice zone, lithogenic particle flux was only a trace (less than 1 milligram per square meter per year, the smallest rate ever recorded). But at an arctic counterpart station west of Spitsbergen, fluxes were as large as 14 grams per square meter per year because of the

黃塵萬丈

The Chinese characters above describe loam dust from the Hwang River area: "This high yellow dust cloud is a million fathoms high" (Huáng, Chen, Wàn, Zhàng). The dust particles from central Eurasia travel as far east as the middle of the Pacific.

Calligraphy by Hsiao-Ming Hsu/WHOI

phenomenon called "winter outburst," which is the flushing of rock particles from the fjords to the deep basin by heavy brine sinking during midwinter. The largest annual lithogenic particle flux recorded in an open ocean was about 28 grams per square meter from an open-sea station in the Bay of Bengal in 1988.

In the central Arabian Sea, annual rock-particle flux was measured at 4.4 grams per square meter in 1988, but it was only 1.0 gram per square meter during previous years. Rock-particle deposition rates are, then, highly variable in some areas, reflecting oceanographic changes from one year to another. It is important to continue flux measurements for many years so that we may understand these annual changes.

Rock Particles Help to Remove Atmospheric Carbon Dioxide

The term "rock particles" sounds very inorganic; it does not seem to indicate a major role in Earth's carbon cycle (including the planet's ability to deal with fossil-fuel-produced carbon dioxide), where all actors on stage appear to be chemical and biological processes. Sediment-trap experiments show that the flux of rock particles into the deep ocean is clearly correlated with the flux of organically produced carbon. Rock particles interact with the global carbon cycle in two ways. One is as a phytoplankton growth stimulator. Enhanced primary productivity (that is, when more organisms take up carbon) increases carbon dioxide removal from the atmosphere, just as tropical-forest trees help to keep Earth's carbon dioxide level low. The other form of interaction, of particular interest to oceanographers, is rock particles' role as ballast for removing organic matter and its load of atmospherically derived carbon dioxide to the deep-ocean interior. Unless organic carbon produced in the shallow ocean is removed quickly, oxidation by microbial processes returns the carbon dioxide to the air.

Sediment-trap experiments show that the flux of rock particles into the deep ocean is clearly correlated with the flux of organically produced carbon.

There are instances of aeolian dust enhancing productivity in the open sea. Shizuo Tsunogai (Hokkaido University), for example, found that the plankton *Trichodesmium* blooms in the Okinawa area and the Philippine Sea on the heels of "Kosa," dust clouds blown up from the Loess Plateau in northern China, which also create blood-red sunsets in far-eastern countries.

In the open ocean, far from land, iron is a critical element in chlorophyll synthesis (an integral part of primary production). The only fresh source of iron to the open ocean is the fallout of iron-rich aerosol. Therefore, John Martin (Moss Landing Marine Laboratory) and other scientists hypothesized that rock particles transported directly from arid lands may control the ocean's fertility on a global scale. The Southern Ocean, for example, is far less fertile, compared to its arctic counterpart, than it should be considering its abundance of major nutrients such as nitrate and phosphate. By studying ice cores recovered at Vostok, a Russian antarctic scientific base—the most remote from the coast of this ice-covered continent—Russian and French scientists revealed that the iron concentration in the dust found in the ice cores was sharply elevated during the last glacial maximum, 18,000 years ago, and that the carbon dioxide content of air trapped in ice bubbles of the same ice cores decreased during the periods when more dust accumulated.

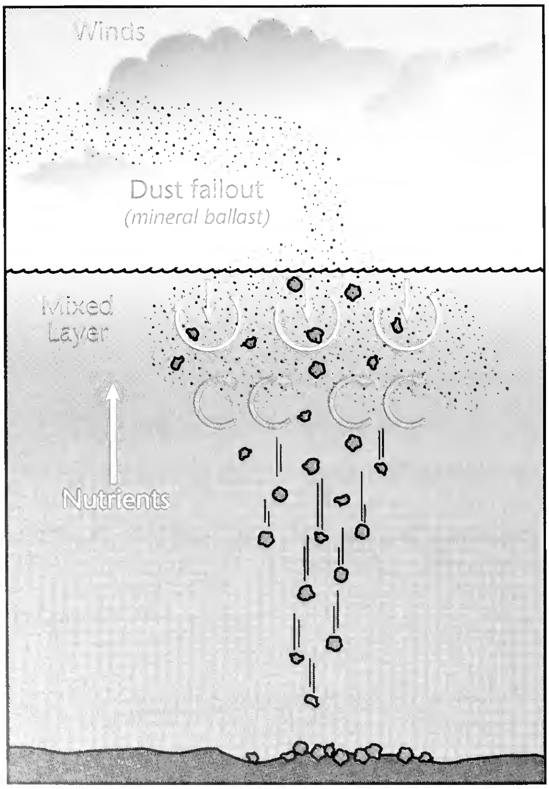
This relationship is explained as follows: During the glacial period, winds were far stronger than at present, and there were more arid regions. As a result, rock particles, which always contain iron-rich minerals, spread to a much larger area of open ocean than they do now, resulting in higher primary production, and more carbon dioxide being fixed to organic carbon. More organic carbon was being exported to the ocean interior and seafloor, thus reducing carbon content in the air. Today, the air parcel around the Southern Ocean and Antarctica is isolated by its own westerly wind system, which allows virtually no dust to reach deep into the continent, despite the fact that Antarctica is surrounded by many southern hemisphere arid lands. But 18,000 years ago, during the most recent glacial maximum, the wind was strong enough to break this air current system, bring dust storms as far as the center of the Antarctic continent, and perhaps enhance the primary productivity of the Southern Ocean as well as other global open oceans. At present, however, not enough paleoceanographic evidence has been gathered to support this hypothesis.

In areas such as the Arabian Sea, where the monsoon carries desert dust, organic matter is removed from the surface layers by the input of wind-borne rock particles. The result is increased biological production, particle aggregation, and sinking.

Fine Rock and Clay Particles Sink Surprising Rapidly

A discovery that went totally against scientific intuition is that tiny rock particles settle down through ocean layers at a speed a few hundred times faster than Stokes's law predicts. A piece of clay, for example, is typically a few micrometers in diameter. It settles less than half a meter in a day. In other words, it takes thousands of years to reach the deep-ocean bottom. However, surprisingly, the bulk sinking speed of fine particles (even in the 1-micrometer range) measured in the deep ocean is 120 to 250 meters per day. We make these measurements by deploying two or more sediment traps at both shallow and deep layers, then dividing the length of time it takes a particle species to arrive at the deeper trap (residence time) by the distance between the two traps. This gives us the settling speed. The settling-speed resolution is limited by how frequently a trap is opened and closed. A rapidly sinking particle does not move laterally while sinking, except in areas with fast currents, such as the Gulf Stream or the Kuroshio, and such currents are only strong in the upper several-hundred meters, a distance a particle can traverse in several days.

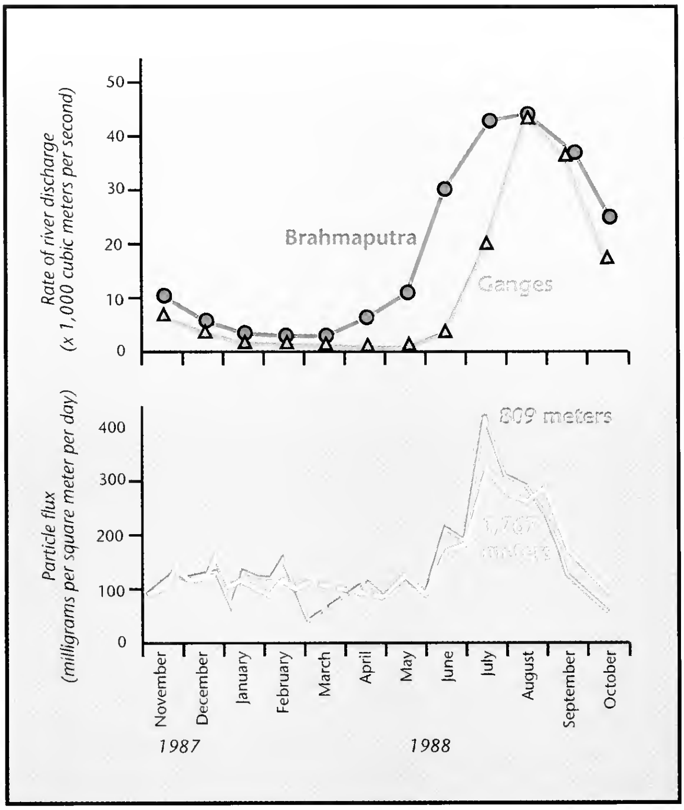
The pathway to the seafloor may, however, be complex. A network of surface ecosystem processes often controls the sedimentation rate. For example, many filter-feeding animal plankton ingest fine particles regardless of their nutrient value. Rock particles may pass through an organism's digestive system unchanged physically and chemically, but they render the organism's feces heavier than its original food. Thus they settle toward the seafloor in fecal pellets. The ocean's surface layer is also rich in mucus and other sticky stuff produced by



Jack Cook/WHOI Graphics

plants and animal plankton. Free particles are entrapped by these materials into aggregates typically half a millimeter in size. These aggregates, though not compacted and rather fragile, drastically decrease each participating particle's drag coefficient because the surface area of an individual particle is irrelevant when it is part of a larger aggregate.

The critical role of rock particles is to add weight and therefore a faster sinking speed to the host aggregate traveling from the surface layers. An aggregate disintegrates from its own shear speed as well as by being eaten up by bacteria and other single-celled organisms. Participating particles constantly fall off the aggregate host and become suspended, and are then picked up by other passing aggregates. Vertical transport of rock particles as well as other fine particles in the ocean is accomplished by many repetitions of this process, with the particles cycling between aggregation and suspension.



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Ittekkot's data show a close relationship between the discharge of the Ganges and Brahmaputra rivers (which increases during the monsoon) and the flux of particles in the northern Bay of Bengal. The red line indicates the particle flux at 809 meters depth, and the yellow line at 1,767 meters depth.

Monsoons, Arabian Dust, Himalayan Rivers, and Ocean Productivity

The Arabian Sea and the Bay of Bengal are two of the most productive areas in the world's oceans. Rivers transport large quantities of rock particles from the Himalayas to these areas, and twice a year strong monsoon winds bring abundant dust from the Arabian and African dry lands. Recent studies reveal the fascinating oceanographic roles played by rock particles in biogeochemical cycles.

Ravindrathan Nair (National Institute of Oceanography, Goa, India) and his international colleagues report that the variability of organic carbon flux and rock particles measured in the middle of the Arabian Sea and the variability of the southwest monsoon wind velocity were almost identical, corresponding in every detail. The monsoon wind causes vigorous upwelling of nutrient-laden bottom water, which increases primary production in shallow layers. The fallout of desert dust from arid African lands depends upon wind velocity and increased availability of ballast to force light organic matter to settle on already-abundant organic matter in the shallow layers.

On the other hand, Venugoplan Ittekkot (University of Hamburg) and others report that organic carbon flux in the Bay of Bengal also responded positively to the strength of the southwest monsoon, though the process was quite different from that in the Arabian Sea. Again, rock particles were a vital factor in the sedimentation processes. At a station in the northern Bay of Bengal, organic carbon flux was correlated to the variability of the discharge from two great Himalayan rivers, the Ganges and Brahmaputra, which peaked during the summer southwest monsoon. At a station farther south in the bay, east of Madras, the organic carbon flux peak overlapped with the arrival of dust from the Indian continent during the winter northeast monsoon, though input of the Ganges-Brahmaputra rivers from the Indian continent was quite obvious in summer. At the southernmost station, about the latitude of Sri Lanka, the variability of organic carbon was no longer correlated with river discharge but, similar to the Arabian Sea stations, was clearly related to airborne supply of particles associated with the southwest monsoons.

Recently ocean science has revealed that the processes of oceanic rock-particle sedimentation are strongly coupled with atmospheric carbon-dioxide removal.

Lateral Transport of Rock Particles

One other striking observation regarding the behavior of rock particles in the ocean is that their flux increases linearly with depth. It has been found that such a linear increase now occurs at almost all stations studied in the world's oceans. As of this writing, we do not have information from an Arctic Basin station established this past year, but we anticipate that it also will show this increase. The closer to the continental slope, the greater the rate of flux increase with depth. In the stations closer to the continental slope, rock-particle fluxes increased five times or even more. This increase is probably not directly related to the nepheloid layer, a "ground-fog-like" concentration of suspended particles extending from the ocean floor to a height of a few hundred meters, as a steady increase of lithogenic particle flux was observed in the Panama Basin water column, which lacks a nepheloid layer. Because rock particle flux increases linearly with depth, the gradient of this increase can be calculated by measuring the fluxes at two different depths; the gradient R (the rate of increase of rock particle flux) ranged from 17 micrograms per meter per day at the Panama Basin to a trace, about 0.13 micrograms per meter per day, at the mid-Pacific station east of Hawaii.

When rock particle fluxes are plotted against depth, the intersection of the flux with the ocean surface is the flux that enters the ocean from the air. (Fluxes of particles at near-surface layers are technically very difficult. They are disturbed by too much biological activity and waves.) The discrete aeolian flux can thus be estimated at a station where rock particle fluxes are measured at a minimum of two depths simultaneously. For example, an annual flux of rock particles from the air at a station in the Demerara Abyssal Plain was 4.5 grams per square meter per year, and 1.5 grams per square meter per day was added to the original aeolian flux. At two stations in the Atlantic where the measurement was made more precisely, about 1.2 grams of laterally transported rock particles were added to the aeolian fluxes.

We are looking for effective geochemical tracers as indicators for the origins of rock particles. The titanium and aluminum ratio, neodynium isotopic variations, produced by the decay of the long-lived radio isotope samarium-147 to neodynium-143, for example, seem to be useful to distinguish the origin of rock particles that settle in the ocean. But this is still an area of oceanography that science has just begun to explore.

Epilogue

Arriving at a more accurate and detailed budget of rock particles formed by land erosion and determining their rates of deposition along the coasts and basins of the ocean are critical to understanding the geodynamics of Earth's present and past. Recently ocean science has revealed that the processes of oceanic rock-particle sedimentation are strongly coupled with atmospheric carbon-dioxide removal. On the other hand, understanding the processes of transportation and provenance of rock particles that are constantly redistributed in the air and in the ocean provides practical knowledge of how to protect our ocean environment from industrial pollutants and waste disposal, from the coasts to the deep ocean basins. Such research will yield basic information to direct us in future uses of the ocean. A sediment trap left in the middle of the Black Sea caught radioactive dust almost instantly after the Chernobyl nuclear disaster. As Jim Lovelock says with his Gaia theory, Earth processes are all interconnected, as if the Earth is a living body. The Earth's mechanisms for transporting rock particles in the air and in water are certainly an important function of Gaia.

Marine geologist Susumu Honjo is a Senior Scientist and holds the Columbus O. Iselin Chair for Excellence in Oceanography at Woods Hole Oceanographic Institution. He does not hesitate to go anywhere in the world to bring back a part of the ocean to his laboratory, where he and his colleagues work hard, argue loudly, and ultimately enjoy research related to the biogeochemical cycles of matter in the world's oceans.

New Seismic Images of the Oceanic Crust

Robert S. Detrick and John C. Mutter

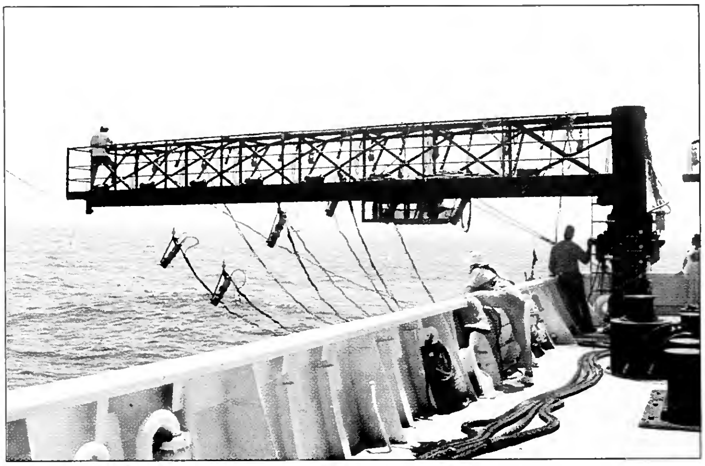
Recent multichannel reflection studies have yielded spectacular images of the internal structure of the oceanic crust.

How do we know what lies beneath the seafloor at an oceanic spreading center? There are a variety of approaches. The topography of the spreading axis must be an expression of processes occurring along the ridge, so by constructing detailed bathymetric maps of the seafloor it is possible to infer something about the structure of the underlying crust. Variations in the gravity and magnetic fields over a spreading center can also be used to map crustal and upper-mantle properties. The chemistry of lavas erupted at the seafloor and the composition of rocks dredged from steep submarine scarps provide a different type of window into the workings of a spreading center. However, all of these approaches are indirect in that they do not allow us to "see" the internal structure of a spreading ridge.

The closest we can come to directly imaging the structure of a spreading center is with images that the seismic reflection technique produces. Marine seismologists create these images using the same basic principles that allow obstetricians to obtain "pictures" of an unborn child in a mother's womb. In both cases, sound, rather than light, is used to create the image. Very-high-frequency sound is required to construct a sonogram of the fetus. Seismologists employ much lower frequency sound to record "echograms" from the boundaries between layers of rock deep within Earth's crust.

Because seismic energy travels as an elastic wave, it is both reflected from and penetrates through the seafloor and interfaces beneath. This enables us to simultaneously "see" the seafloor and the structure below. These reflections usually arise from relatively abrupt changes in seismic velocity and/or density. These contrasts may be caused by changes in rock composition (that is, from basalt or gabbro to peridotite), bulk porosity (between fractured and unfractured rock), or the physical state of the rock (molten to solid basalt). This reflected energy travels back to the surface, where it can be detected and recorded. These echoes are usually extremely weak, but the signal can be amplified by recording a large number of reflections from the same point on the seafloor using a long string of receivers arranged in groups. By measuring the time between the outgoing pulse of sound and the returning echoes, it is possible for seismologists to construct highly detailed acoustic "pictures" of the crust below the seafloor.

This technique, known as multichannel seismic reflection profiling, is widely used in the exploration industry to locate oil and gas in sedimentary basins both on land and along continental margins. Marine seismologists at universities and research laboratories have been using these same techniques since the mid-1970s to investigate the structure of igneous crust lying below the seafloor, and the tectonic and volcanic processes associated with the great shifting plates that make up Earth's outer layer. The world-encircling mid-ocean ridge system, where new oceanic crust is being formed as plates slowly slide apart, is one of the most difficult areas to conduct multichannel seismic studies. Because the seafloor is very rugged along this mountainous ridge system and little or no sediment covers the fresh, young basaltic lava, reflections and side echoes tend to obscure the structure of the crust below the seafloor. Despite these problems, several recent multichannel reflection studies have been conducted along the mid-ocean ridge and over older crust on the ridge flanks. They have yielded spectacular images of the internal structure of the oceanic crust that have changed some long-standing ideas about the origin and structure of oceanic crust.

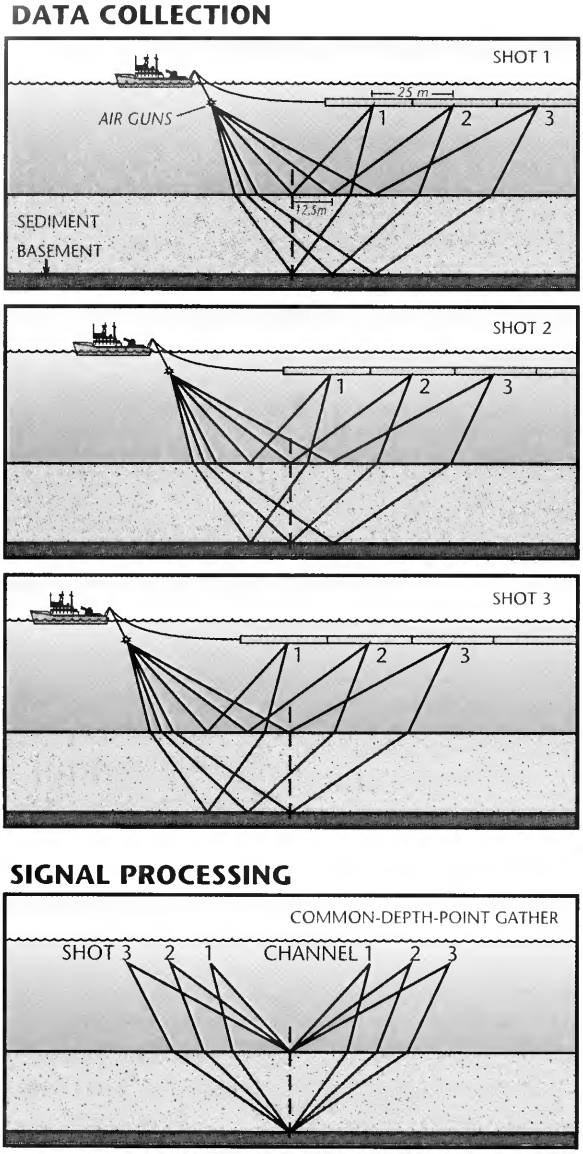


John Mutter/L-DGO

Air guns are being deployed for seismic reflection profiling from the starboard boom of R/V Ewing. *A total of twenty guns are deployed, eight from each boom and four from the stern A-frame. The guns are typically fired every 20 seconds.*

Creating a Reflection Image of Oceanic Crust

Modern seismic reflection profiling requires a specially equipped research vessel to acquire the original records, and sophisticated computer processing to construct the final acoustic images from hundreds of thousands of individual seismograms. The vessel used by most academic marine seismologists is R/V *Maurice Ewing* operated by Columbia University's Lamont-Doherty Geological Observatory. An extremely powerful sound source is required on vessels like this in order to image the entire oceanic crustal section. The base of the crust, marked by a boundary known as the Mohorovicic discontinuity (or Moho for short), generally lies at least 10 kilometers below the sea surface. Since high-frequency sound is rapidly attenuated in the earth, the source must be able to emit sound at very low frequencies, usually in the range of about 6 to 60 hertz. The initial sound pulse must also be relatively sharp, or the returns from closely spaced reflectors will overlap and blur the final image. The most commonly used sound source is the air gun, a device that suddenly expels a small volume of air under high pressure. The rapid expansion of this air bubble creates the initial pulse of sound. Rather than use one large air gun, an array of guns of different sizes, some quite small, are tuned to produce a sharp, powerful signal. In a typical *Ewing* array, 20 airguns are deployed from the stern A-frame and two booms extending about 10 meters out on either side of the ship. These guns release a total of 8,000 cubic inches of high-pressure air (approximately 2,000 pounds per square inch) every 20 seconds, creating a sound that can penetrate as much as 15 kilometers into the earth.



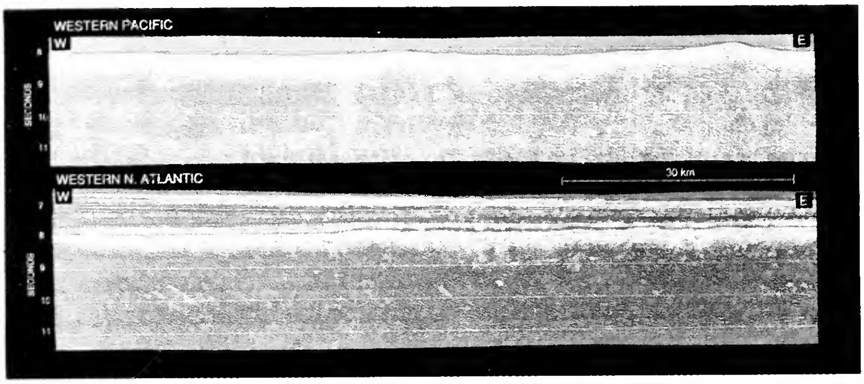
The multichannel seismic reflection system consists of a sound source (air guns) and a receiver (hydrophones in a long streamer), both towed behind a ship. After each shot, reflections from the seafloor and the underlying crust are recorded by different groups of hydrophones or channels within the streamer. Each channel records reflections from sound that has traveled along slightly different paths from source to receiver.

Jack Cook/WHOI Graphics

The weak echoes coming back from reflecting surfaces deep within the ocean crust are detected by sensitive hydrophones located in a long plastic tube or "streamer" towed behind the ship. This streamer, which can be thought of as a long acoustic "antenna," is filled with a low-density fluid and towed about 10 meters below the sea surface to isolate it from the acoustic noise produced by waves at the sea surface. The *Ewing* streamer is up to 4 kilometers long and has 4,000 individual hydrophones located at about one-meter intervals. These hydrophones are grouped together electrically to form up to 240 separate receiving channels spaced 12.5 or 25 meters apart. The acoustic return detected by the hydrophones in each channel is converted to an electrical signal, amplified, digitized, and transmitted up the streamer to the ship where it is recorded. Each channel is stored separately since each records a seismic signal from sound that has traveled along a slightly different source-to-receiver path, and bounced off different reflector points within the crust.

Multichannel seismic profiling generates prodigious amounts of data. Using the system described above, 240 separate data channels will be recorded every 20 seconds for each shot. Each of these records is usually at least 8 seconds long to ensure that echoes from deep within the crust are detected. The data from each channel is typically digitized at 250 samples per second (4 bytes per number) resulting in about 2 megabytes of data every 20 seconds. A 50-kilometer reflection profile is comprised of approximately 1,000 individual shots, and thus records about 2 gigabytes of data. That is about 25 times the capacity of the hard disk on an average desktop PC! A typical marine multichannel seismic survey may record some 3,500 kilometers of reflection data in a single cruise, resulting in nearly 150 gigabytes of data recorded on hundreds of magnetic tapes.

Extensive computer processing of the recorded data is required when the ship returns from sea in order to construct a reflection image of the oceanic crust. The reflections from deep crustal layers are usually very weak. Only a fraction of the original sound pulse is reflected back to the surface, and this echo is attenuated by its passage through many kilometers of rock. This signal can also be obscured by acoustic "noise" caused by towing the streamer through the water, wave action, or the sound of the ship's engines. This noise, however, is generally random while reflections have a coherent waveform from trace to trace. It is possible to cancel this noise by adding the signals from many different records with the same reflection point on the seafloor using a technique known as common-midpoint profiling. A general rule of thumb is that the signal-to-noise ratio increases as the square root of the number of traces added together. Thus if the 240 separate channels recorded by *Ewing's* streamer are all used, the amplitude of weak crustal reflectors may be increased by as much as 15 times. The thousands of traces generated by this process are plotted side by side to produce a final image like the ones shown above.



John Mutter/L-DGO

Seismic velocity structure varies with depth in oceanic crust. These two very different seismic reflection profiles are from crust created at fast-spreading (western Pacific) and slow-spreading (western North Atlantic) ridges.

These reflection images look like a vertical section or slice through Earth's crust. Strong reflections appear on these sections as dark and light bands. By mapping these events, geologists have been able to construct detailed models of what the sub-seafloor structure looks like. The following examples illustrate the unique contributions reflection imaging has made to our understanding of oceanic crustal structure and the processes of seafloor spreading.

Crustal Structure Varies with Spreading Rate

Spreading rates along the global mid-ocean ridge system vary from less than 15 to more than 150 kilometers per million years. These variations are typically accompanied by a systematic variation in topography at the rise axis. Where opening rates are slow, as along the Mid-Atlantic Ridge, the spreading axis is usually associated with a deep rift valley flanked by shallow, rugged rift mountains. At faster opening rates, like those along the East Pacific Rise, the rift valley disappears and the spreading axis is usually associated with a linear volcanic ridge that has relatively subdued flanking topography.

Conventional seismic refraction studies have shown that the thickness and gross seismic velocity structure of oceanic crust formed at fast- and slow-spreading ridges are similar, leading to the view that the structure of oceanic crust does not vary with spreading rate. However, images of the oceanic crust constructed from seismic reflection data challenge this assumption. Reflection profiles of crust created at fast-spreading ridges, like the East Pacific Rise, typically reveal an acoustically transparent crust with a strong, quasi-continuous reflection of about 2 seconds duration (some 6 kilometers) below the seafloor that is thought to be a reflection from the base of the crust. In contrast, the crust created at slower spreading ridges, like the Mid-Atlantic Ridge, is characterized by a wide variety of intracrustal reflecting horizons. Distinct, isolated, subhorizontal reflectors and steep dipping reflectors occur in the shallow crust while the mid-crust is often almost acoustically transparent. The lower crust is associated with a diffuse background reflectivity and distinct banded patterns of strong, linear or arcuate dipping reflectors with highly variable spacing. The base of the crust is not marked by a strong Moho reflection as at fast-spreading ridges, but is a comparatively indistinct boundary that is absent in many places.

The origin of this variation in crustal reflectivity is not well understood, but it suggests that important differences may exist in the architecture of oceanic crust created at ridges with different spreading rates.

Imaging Faults Within the Oceanic Crust

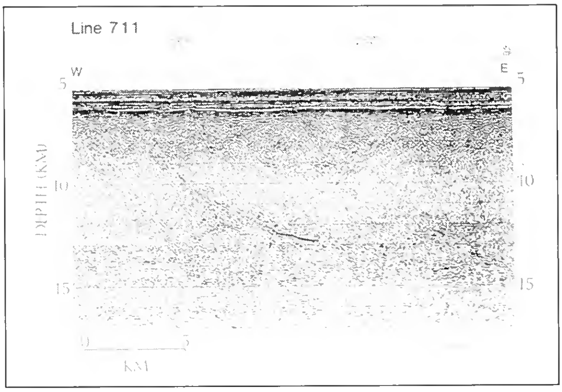
Multichannel seismic data collected in the western North Atlantic have shed new light on the nature of faulting at the Mid-Atlantic Ridge.

The separation of two plates along a mid-ocean ridge is accompanied by both volcanic activity, which creates new oceanic crust, and stretching and faulting of the newly forming lithosphere. The relative importance of faulting is greatest along slowly spreading ridges, like the Mid-Atlantic Ridge. High-resolution bathymetric mapping of the Mid-Atlantic Ridge reveals numerous small fissures and faults on the rift-valley floor and steep, linear slopes or scarps in the rift-valley walls and flanking rift mountains. The depth to which these faults extend in the crust and the amount of relative motion they accommodate are of considerable importance in understanding the structure of crust formed at slow-spreading ridges. The inferred dip and spacing of most faults suggests that they probably do not penetrate more than a few hundred meters into the crust. However, teleseismic earthquakes and microseismicity studies show that some faults rupture the entire thickness of the crust down to depths of 8 to 10 kilometers (see "Mid-Ocean Ridge Seismicity," *Oceanus* Winter 1991/92).

Multichannel seismic data collected in the western North Atlantic southwest of Bermuda have shed new light on the nature of faulting at the Mid-Atlantic Ridge. This 150-million-year-old crust preserves a record of the volcanic and tectonic processes that created it millions of years ago. The most striking features observed in reflection data from this area are the bands of dipping reflectors that cut through the crustal section. These events occur with equal frequency on lines shot perpendicular or parallel to the spreading direction. They typically dip 20° to the south on perpendicular profiles, and east at about 30° toward the paleo spreading center on parallel profiles although they often flatten out near the base of the crust. While generally confined to the lower crust, in a few cases these reflectors can be seen cutting through the entire crustal section.

Similar reflectors have now been observed in other areas, such as the Canary Basin in the eastern North Atlantic. These dipping events have been interpreted as the subsurface expression of major fault systems that have ruptured the entire crustal section down to depths of 8 to 10 kilometers, and provide strong evidence for the important role of crustal extension and faulting in shaping the crust formed along the Mid-

Atlantic Ridge. The most surprising, and still poorly understood, aspect of these data is the occurrence of these events on lines both parallel *and* perpendicular to the ancient spreading axis. If faulting occurs primarily along ridge-parallel normal faults, as many simple two-dimensional crustal accretion models predict, then these dipping reflectors should only be seen on ridge-perpendicular lines. The complex lower crustal reflectivity revealed in these data may indicate a more three-dimensional fault geometry with fault surfaces dipping both toward the ridge axis and away from major accommodation zones linking major boundary faults. Alternatively, these events may represent two different classes of faults that formed during different stages of the emplacement and aging of oceanic lithosphere. Resolving the true geometry of these events, and their origin, will ultimately require more detailed seismic imaging of the reflectivity and crustal structure.



Reflection image from the western North Atlantic showing dipping reflectors that are believed to be the subsurface expression of major faults cutting through the oceanic crust. The base of the oceanic crust is located at a depth of about 14 kilometers.

Imaging Crustal Magma Bodies at Spreading Centers

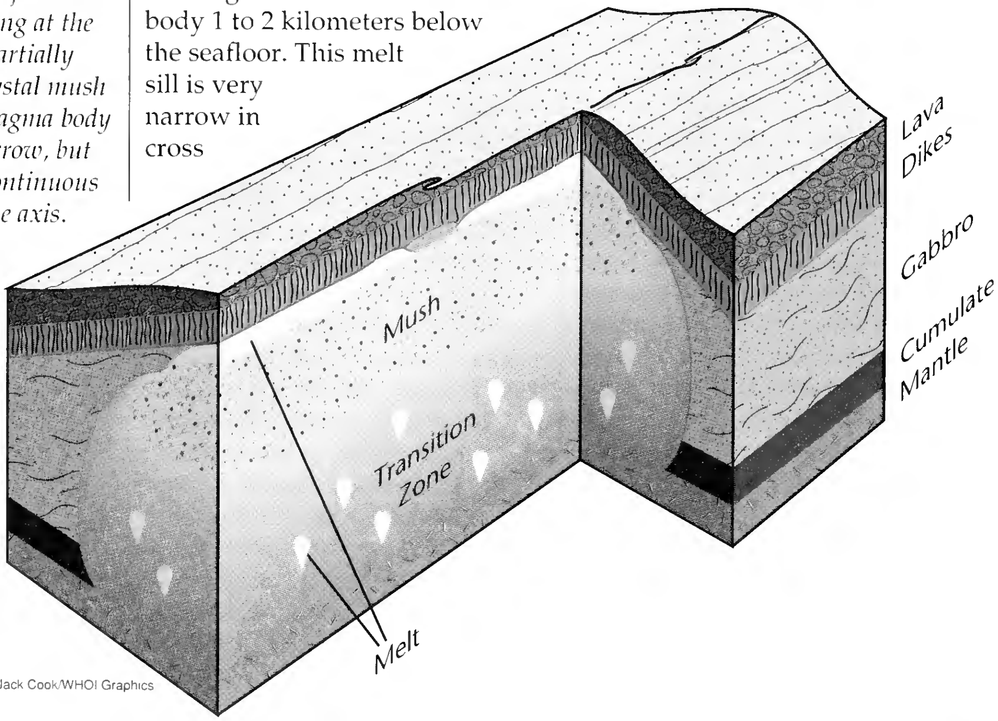
Along faster spreading ridges, like the East Pacific Rise, the magma supply is higher than at the Mid-Atlantic Ridge, and spreading is dominated by volcanic rather than tectonic processes. Geologists have believed for many years that fast-spreading ridges are underlain by molten reservoirs or crustal chambers that accumulate magma prior to eruption at the seafloor. Based on studies of ophiolites (fragments of oceanic crust found on land), most geologists envisioned these magma chambers as large bodies, up to 10 or 20 kilometers wide at their bases and several kilometers high, filled with melt (see "Onion and Leaks: Magma at Mid-Ocean Ridges" *Oceanus* Winter 1991/92).

Magma has a much lower seismic velocity than the solid rock surrounding it. At the roof of the magma chamber, the boundary between rock and melt is likely to be quite sharp and should be detectable in seismic reflection data. In the mid-1970s, a Lamont-Doherty group led by Tom Herron recorded a shallow reflector at the East Pacific Rise at about the same depth where refraction data collected earlier by John Orcutt of the Scripps Institution of Oceanography had indicated a zone of low crustal velocities. In 1985 and again in 1991, we and a Scripps group led by Orcutt and Alistair Harding conducted detailed multichannel seismic surveys of two portions of the East Pacific Rise. These surveys confirmed the presence of a shallow crustal magma body at the rise, but showed that it is far smaller than previously imagined.

Reflection profiles across and along the axis of the East Pacific Rise near 14°14'S show several different events. Two flat-lying events can be traced along the rise axis, one about 150 milliseconds (less than 200 meters) below the seafloor and another about 450 milliseconds (some 1,000 meters) below the seafloor. The shallower event, which occurs at the base of a layer that thickens rapidly off-axis, is not a true reflection but is due to refracted energy turning at the base of a near-surface layer characterized by very low seismic velocities. This surficial layer has been interpreted to be either a lava flow layer overlying a sheeted-dike sequence, or a high-porosity layer overlying lower porosities within the extrusive section. The off-axis thickening of this layer may be due to progressive thickening of the extrusive section by lava overlying the axial summit caldera. A remarkable, and unexpected, result revealed by the reflection data is the uniformity in thickness of this lava-flow layer along the rise axis.

The deeper event observed at the rise axis is a reflection off the roof of a shallow magma body about 1 kilometer below the seafloor. This body is quite continuous along the rise axis, but extremely narrow in the cross-axis direction. In this area it is typically less than 1 kilometer wide, and elsewhere along the East Pacific Rise it is never more than 3 to 4 kilometers wide. Analysis of the character of this reflector and coincident refraction data suggest that the predominantly molten part of this magma body is also quite thin—probably less than a few hundred meters thick and perhaps as little as a few tens of meters thick. Thus we have begun to refer to this body as a magma lens or melt sill. Whatever it is called, it is clearly much different than the large, entirely molten magma chambers once envisioned to exist at mid-ocean ridges. While relatively constant in depth along the rise crest, the melt lens is observed to shallow significantly at one location along the southern East Pacific Rise thought to be recently volcanically active. The combined thickness of the overlying extrusive and sheeted-dike section thins by several hundred meters in this area, providing an important new constraint on how the formation of the shallow crust section is related to magmatic activity.

These observations, recent seismic refraction studies at the East Pacific Rise (see "Tomographic Imaging of Spreading Centers," *Oceanus* Winter 1991/92), and petrological studies of volcanic and plutonic rocks from mid-ocean ridges have led to a new concept of what ridge-crest magma chambers look like. In this new view, the crust beneath the spreading center is mostly solid. The predominantly molten part of the magma chamber is a sill-like body 1 to 2 kilometers below the seafloor. This melt sill is very narrow in cross

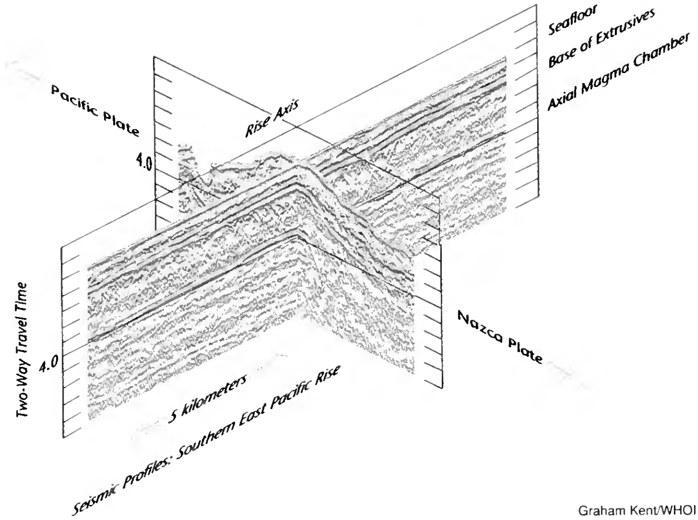


A cross section of the East Pacific Rise showing a model proposed by John Sinton of the University of Hawaii and Robert Detrick that is consistent with both geophysical and petrologic evidence for ridge-crest magma chambers. The magma chamber is viewed as a small, composite body consisting of a thin melt sill lying at the top of a partially solidified crystal mush zone. This magma body is quite narrow, but relatively continuous along the rise axis.

Jack Cook/WHOI Graphics

section (typically less than 1 to 2 kilometers wide) and quite thin (tens of meters of thick), but relatively continuous along the ridge axis. It grades downward into a partially solidified, crystal mush zone that is surrounded by a transition zone of solidified, but still hot and ductile, lower crustal rocks. Mid-ocean ridge magma chambers along fast-spreading or high-magma-supply ridges are thus seen as volumetrically small, composite bodies consisting of both melt and mush that are confined to the mid-crust beneath the rise axis.

This is very different from the old ophiolite-based models that viewed ridge-crest magma chambers as large, well-mixed, steady-state, essentially molten reservoirs. This new composite magma chamber model has broad implications for the composition of mid-ocean ridge basalts and how they vary along the ridge crest, the structure and formation of the lower oceanic crust, the circulation of hydrothermal fluids, and the longevity of mid-ocean ridge hydrothermal systems.



Graham Kent/WHOI

Two intersecting reflection profiles shot across and along the crest of the southern East Pacific Rise near 14°S are plotted. Amplitudes are color-coded with red indicating the highest amplitudes. Two observable reflectors are a shallow event that thickens rapidly off-axis and is believed to mark the base of a lava flow layer, and a deeper one that is the roof of a narrow magma sill located about 1 kilometer below the seafloor.

The Future

Multichannel profiling has proven to be a powerful tool for investigating the structure of oceanic crust and geologic processes occurring at divergent plate boundaries, especially along fast-spreading ridges. As more powerful sound sources and receiving systems are introduced and more advanced data-processing techniques become available, we can expect to see an improvement in our images of the oceanic crust, and we may be able to begin to resolve structure within the underlying mantle.

The reflection technique has been less successful in imaging crustal structure at slow-spreading ridges, primarily because of the rugged topography in that tectonic setting. In theory, given knowledge of seafloor topography and an accurate velocity model of the crust, it is possible to produce good images of the crust with appropriate processing; however, these approaches are so computationally intensive that they have not been widely used. With expected advances in computer technology, it is likely that we will see renewed efforts to image crustal structure using reflection methods in areas like the Mid-Atlantic Ridge.

The reflection method is also limited to mapping the seismic response to fairly sharp boundaries in the crust. Hence it is not very likely to tell us much about important questions such as the relative distribution of melt and mush in a crustal magma body or the size of the transition zone to a solidified lower crust. In contrast, seismic refraction and tomographic techniques are well suited for constraining vertical and lateral variations in seismic velocity, but generally lack the spatial resolution of seismic reflection techniques. Increasingly, we expect to see these techniques used in combination in experiments employing arrays of ocean-bottom instruments and dense two- or three-dimensional grids of seismic reflection profiles. The seismic images of spreading centers and oceanic crustal structure obtained in these experiments will undoubtedly lead to new insight into the tectonic, magmatic, and hydrothermal processes responsible for the formation of the oceanic crust that covers two-thirds of our planet's surface.

Robert S. Detrick is a Senior Scientist in the Department of Geology and Geophysics at the Woods Hole Oceanographic Institution. He has been studying mid-ocean ridges for most of the past 18 years and is currently Chairman of the Steering Committee of the U.S. RIDGE Program, a major, decade-long interdisciplinary research effort aimed at gaining a better understanding of the geology, physics, chemistry, and biology of the global mid-ocean ridge system.

John C. Mutter is a Professor of Geology at Columbia University and a Senior Research Scientist at Lamont-Doherty Geological Observatory, where he heads the multichannel seismics group.

Marine Seismology

G.M. Purdy

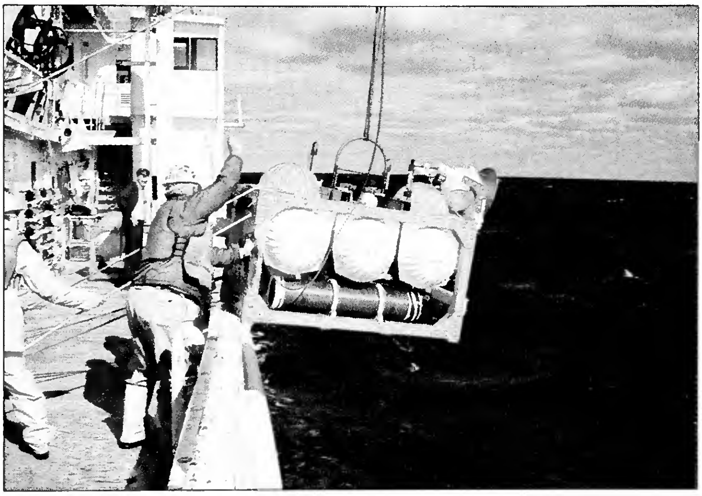
Seismology is the study of sound propagation in the earth. Research in continental seismology has been active since the late 1800s. When Croatian seismologist Andrija Mohorovicic published his landmark discovery of a shallow transition to a remarkably uniform layer of high sound (or seismic) velocities in 1909, he had, in fact, discovered the boundary between Earth's crust and upper mantle, which is now known as the Moho. But *marine* seismology did not become a significant endeavor until the 1930s. It then grew rapidly during World War II, fueled by the submarine-warfare-related need to better understand sound propagation in the oceans. Like almost all ocean sciences, then, seismology is a young and somewhat immature field: It is exciting, unpredictable—and fulfilling to the curious seeker of new truths about Planet Earth.

Understanding seismology requires knowledge of only the most basic laws of physics, but over the past 100 years it has provided fundamental insights into the structure of our planet, including:

- Earth has a liquid outer core surrounding a solid inner core;
- The outermost skin (or crust) upon which we live is about 30 kilometers thick beneath the continents, but only 6 to 8 kilometers thick beneath the deep oceans;
- The distribution of earthquakes around the globe (earthquakes are Earth's greatest sound generator) delineates narrow active zones that form boundaries between the rigid crustal plates (described by the plate tectonic paradigm); and
- The shelves beneath the shallow seas that bound the continents are formed of piles of sediment as much as 10 kilometers thick that have eroded from adjacent land.

These are but a few of the important facts about Earth that have been revealed through seismology.

In mapping Earth's interior structure, seismologists identify changes in the sound velocity that can be related to types and physical properties of rocks, and they map major boundaries that are sufficiently abrupt to actually reflect sound energy back to the surface. A minimal physical basis for seismology can be provided by

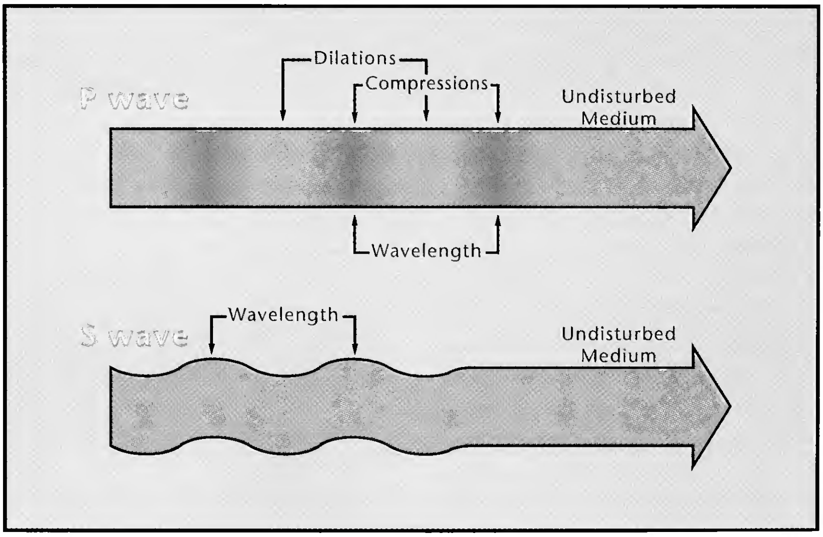


An ocean bottom seismometer is launched into the Atlantic Ocean from R/V Endeavor *(operated by the University of Rhode Island).*

David DuBois

conveying two simple principles: how sound (or seismic) energy actually propagates in Earth, and the simple principles of reflection and refraction of that energy. Seismic energy propagates either through the body of a material as "body" waves, or along boundaries with water or air as "interface" waves. For simplicity, here we will consider only body waves. When a disturbance occurs in a medium (be it an earthquake, an explosion, or simply hitting a table with your knuckles), energy propagates away in all directions in the form of particle vibrations in the medium. Particles vibrate either along the direction of energy propagation, when they are called compressional or pressure (P) waves, or perpendicular to that direction, when they are called transverse or shear (S) waves. Liquids cannot support shear, so shear waves occur only in solids. However, because it is possible to convert energy from P to S (and vice versa) at a liquid-solid boundary, shear waves remain important in ocean seismology even when man-made sound sources, which are frequently located within the water column, generate only compressional wave energy.

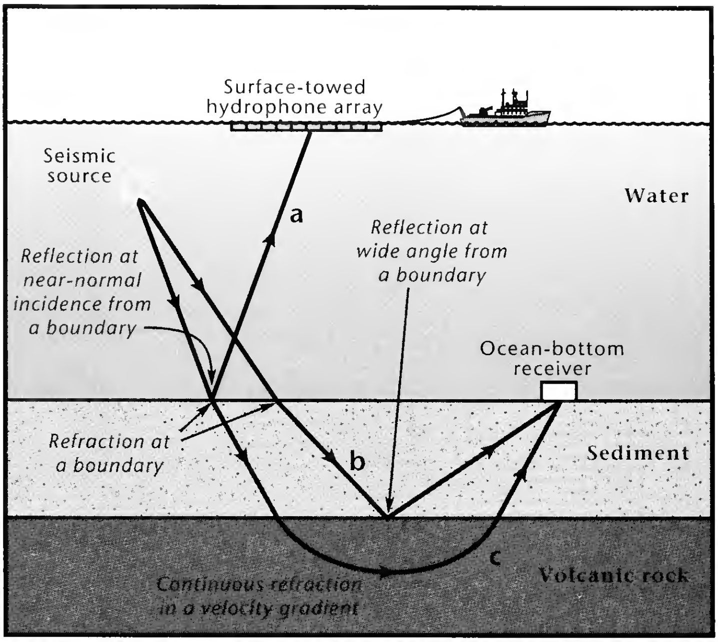
These waves of particle disturbances propagate radially from a source with characteristic wavelengths and frequencies. As they propagate, energy is lost to attenuation: The particle motions actually cause frictional heating (to an extremely small degree) within the medium. Attenuation is also caused by scattering from structural heterogeneities. Long wavelengths (with corresponding low frequencies) lose less energy to frictional heating and less to scattering because the long wavelengths do not "see" or sense small-scale structural changes. Therefore almost all Earth seismology employs very low-frequency sound. Studies in the uppermost 20 to 30 kilometers most commonly use energy in the 2- to 25-hertz band, which, given that the velocity of sound in crustal rocks varies between 2 and 7 kilometers, corresponds to wavelengths of 80 to 3,500 meters (using the simple relationship, velocity = frequency x wavelength). Using such large wavelengths results in a view of Earth's interior that lacks detail. We use these frequencies not by choice, but because the physics of energy propagation in a solid requires them. The



Seismic energy propagates through a solid in two different ways. In a compressional or P wave (top), the particle disturbances are in the direction the wave is moving. In a shear or S wave (bottom), the particles move perpendicular to the direction of propagation.

Jack Cook/WHOI Graphics

high-frequency energy that could contribute to a much more detailed picture of crust and upper-mantle structure is lost to attenuation: Nature guards its secrets well.



Jack Cook/WHOI Graphics

From a source to a receiver, seismic energy travels along three typical paths: Reflection at near-normal incidence from a boundary (a); reflection at a wide angle from a boundary (b); or a ray that has been continuously refracted in a medium where the velocity increases steadily with depth in such a way that the ray is turned back toward the seafloor (c).

As energy travels through the crust, it is reflected from boundaries and refracted by velocity changes. Reflection is discussed at length by Detrick and Mutter in their description of multichannel seismics beginning on page 54. In its simplest form, refraction can be explained in terms of the same Snell's law that is most commonly applied to optics. As sound velocity increases with depth (as it most commonly does), energy is continuously refracted until it is turned back to the surface and recorded. Precise navigation and accurate timing are of paramount importance to the marine seismologist, because to determine sound velocities we need to know both the separation and the travel time between sources and receivers as exactly as possible.

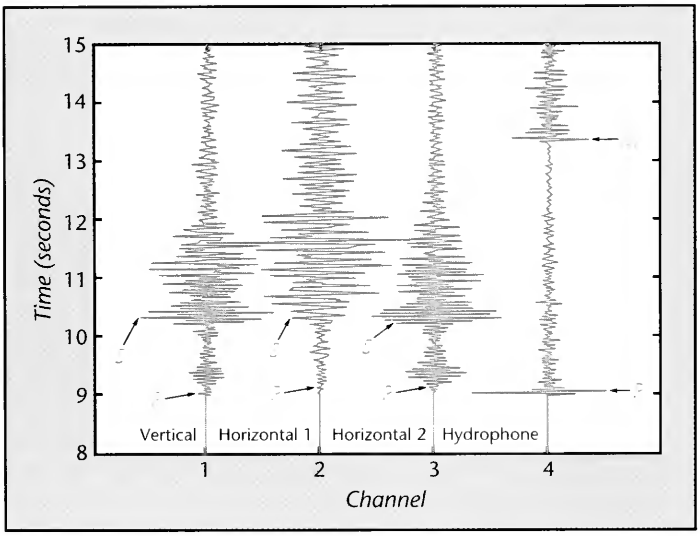
One of the greatest challenges of marine seismology is developing instrumentation for acquiring the necessary data. Sound sources range from simple packages of explosives (weighing from a few pounds to a ton or more) to complex arrays of air guns. Earthquakes are tremendously powerful sound sources. They are rich in shear-wave energy and occur within the crust—but, of course, have the disadvantage of being unpredictable in time, and to a lesser extent, in space. Recording systems can be hydrophone arrays towed astern of research vessels, or instruments with internal recording devices that remain on the seafloor for extended periods of time. One of the latter is shown on page 63. It is one of 30 available to the US academic community and one of 15 operated by the Woods Hole Oceanographic Institution (WHOI) Ocean Bottom Seismometer Facility. This $85,000 instrument is designed to remain on the ocean floor for as long as two months to record the output from three seismometers and a hydrophone on an optical disk. The seismometers record ground motion in one vertical and two horizontal directions, and the hydrophone records pressure waves in the water column. An accurate, low-power clock keeps time to an accuracy of 10 to 20 milliseconds over a two-month period, and two acoustic releases (only one of which needs to operate) assure reliable recoveries.

Imaging the Earth

In seismology, the fundamental unit of data is the seismogram. It is a time series, typically a few tens of seconds in length, that shows (in the case of hydrophone data) changes in pressure with time. To be useful, the various packets of energy that can be seen on the seismogram must be identified as refractions, reflections, P-waves or S-waves, etc., and there are many criteria to aid the seismologist in making these determinations. A typical modern experiment will involve several thousand of these seismograms. One of many interpretational approaches can then be taken to convert them into descriptive information about the earth. This information generally takes one of two forms: an image showing the location of reflecting boundaries, or a representation (frequently a contour map) of changes in velocity with depth.

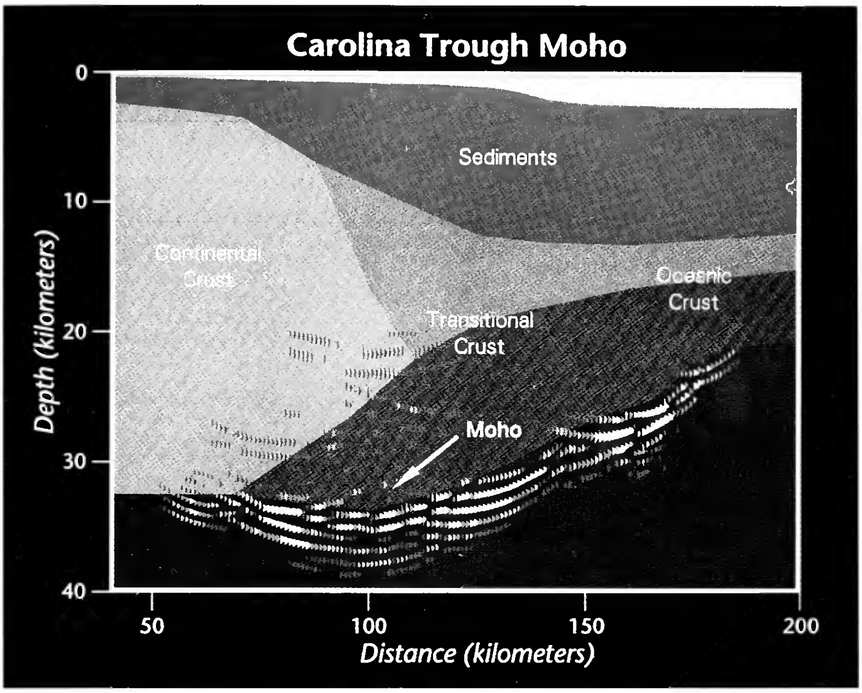
The most basic information contained in a seismogram is the absolute arrival times of various packets of energy at a receiver. Combining this with the knowledge of the instant that the sound source was triggered provides the energy's travel time along its ray path from the source to the receiver. Travel times for many different paths, from a spatially distributed set of shots to a network of receivers, can provide a three-dimensional determination of the location and nature of velocity anomalies within the crust and upper mantle. Doug Toomey has described a particularly successful example of this travel-time tomography in revealing structural details of the magma chamber beneath the East Pacific Rise (see *Oceanus*, Winter 1991/92, page 92).

Another approach is to generate a direct image of the location and geometry of the primary boundaries within the crust using the seismograms themselves. Although this is a straightforward task when dealing with near-vertical reflections, recent work indicates that using high-angle reflections from interfaces can provide information not visible any other way. However, when using such energy it is important to be able to reconstruct the position of the reflections to their real location within Earth. This process, called "migration," when applied by Steve Holbrook (WHOI) to wide-angle reflection data collected from the US East Coast using ocean bottom hydrophone receivers and large air gun sources, has produced the first direct image of the thinning of Earth's crust across the transition from continent to ocean. Like most first measurements, this result is crude and imperfect, but it is an exciting example of what is possible. The limitation on image quality is not physics or geology, but the density of crustal sampling by various ray paths from the



Jack Cook/WHOI Graphics

These seismograms are from a microearthquake recorded by an ocean bottom seismometer deployed on the Mid-Atlantic Ridge. The four seismograms are of the same event recorded by a vertical component seismometer (Channel 1), two perpendicular horizontal component seismometers (Channels 2 and 3), and a hydrophone. The first deflection on all traces is the compressional (P) wave arrival. The slower moving but more energetic shear wave arrival (S) is clearly observed on all three seismometer channels, but of course is not observed on the hydrophone that is sensitive only to pressure waves propagating in the water column. The second significant event on the hydrophone channel is the "water-column multiple" (M), the first arriving compressional wave arrival that has been bounced back to the receiver from the sea surface.



The first directly determined seismic image of the crust-mantle boundary (Moho) across the transition from continental to oceanic crust off South Carolina. The colored events are migrated wide-angle reflections that clearly delineate the thinning of Earth's crust from about 30 to about 6 kilometers. The boundary between gray shading and black marks the Moho as determined using less-robust forward-modeling methods to interpret the data. Agreement between the two solutions is clearly good. (After Holbrook, Reiter, Purdy, and Toksoz, 1992.)

source to the receiver. If more receivers were available, the detail of this image could be improved substantially.

Listening to the Earth Move

There is more to marine seismology than mapping boundaries and velocity anomalies in the crust and upper mantle. The richest data source for active processes is microearthquakes. Every day there are thousands of microearthquakes beneath the ocean floor, and each one, if properly recorded, can tell us about the nature, depth, and location of the cracking and faulting that occurs in response to plate-motion stresses. Unlike the velocity information described above, which must be interpreted before it is useful, earthquake data provides direct observations of Earth's processes and responses. Ambiguities associated with the interpretation of velocity anomalies, that is, conversion of sound-velocity information into geological inference, are profound. Microearthquakes, however, do not lie.

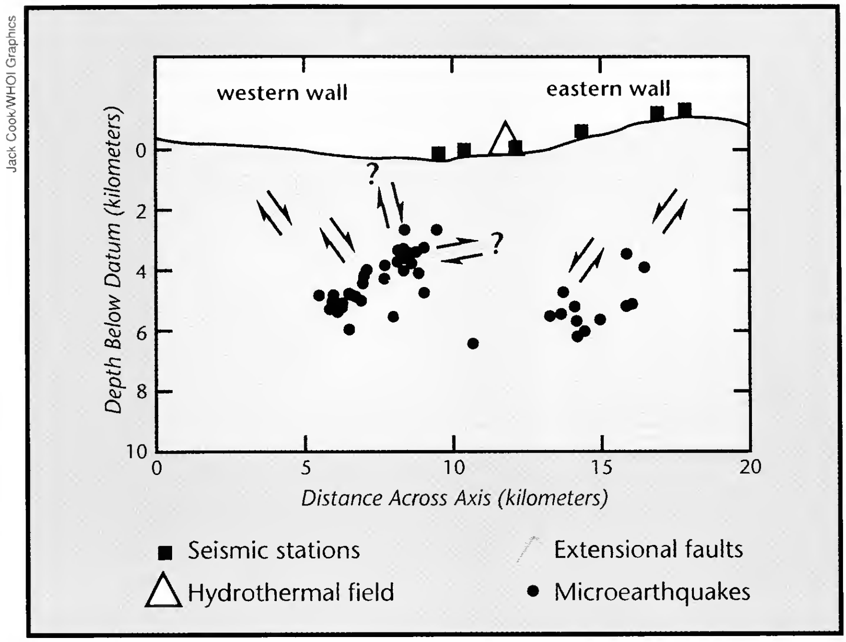
One powerful approach is to combine inferences from velocity-anomaly data with observations of faulting and active tectonics provided by microearthquakes. One of the few areas where sufficient data is available to attempt this is illustrated on page 69. This cross section of the Mid-Atlantic Ridge (MAR) near latitude 26°N is from WHOI/MIT Joint Program student Laura Kong's Ph.D. thesis. It shows the relationship between microearthquake locations beneath the MAR median valley and a volume of lower-than-normal seismic velocities. Because increasing temperature is known to lower velocities in common oceanic rocks, one reasonable interpretation of this figure is that this low-velocity volume represents a zone of anomalously high temperatures associated with the magma-emplacement process at the ridge. The microearthquake locations provide important supporting data for this—very few earthquake foci are present within the high-temperature zone because, we infer, the hot rock is too weak to support the stresses required to generate an earthquake. Surrounding this volume, however, where hydrothermal circulation has cooled the crust to a brittle state, extensional faults penetrate to depths of 5 to 6 kilometers. Above the high-temperature volume, shallow events have contrasting mechanisms. They are associated with the magma-injection process itself, not with extension. By combining these two powerful approaches, we are able to build a thorough and complete picture of the processes occurring at considerable depths below the seafloor.

It has been known for more than 15 years that many mid-ocean ridges are underlain by low-velocity zones. Velocities almost always increase with increasing depth below the seafloor, but in these instances, at depths between 2 to 5 kilometers, the velocity abruptly decreases with depth. On fast-spreading ridges like the East Pacific Rise, good evidence exists to prove that this phenomenon is associated with the presence of magma beneath the ridge crest. On slower spreading ridges, like the Mid-Atlantic Ridge, no steady-state magma body is thought to be present, so the velocity anomaly is interpreted to be a zone of substantially elevated temperatures (as described in the previous paragraph).

The seismic velocity results can now be interpreted in terms of the geological and physical processes that are occurring.

There appears to be a simple relationship between spreading rate and the depth to which hot rock or magma extends. On fast-spreading ridges where the magma heat supply is high, the velocity anomalies are shallow. On slow-spreading ridges, where the magma supply per unit of time must be substantially slower, the velocity (presumed to be temperature) anomaly is much deeper. This intriguing result, established from compilation of seismic data from many different mid-ocean ridge systems around the world, becomes even more significant when combined with the observation that the maximum depth of faulting beneath ridges (as revealed by large, globally recorded earthquakes) also increases with decreasing spreading rate. The seismic velocity results can now be interpreted in terms of the geological and physical processes that are occurring—and this is the important goal. The hypothesis is that a balance between heat supply (magma injection) and cooling rate (hydrothermal circulation) is being observed. If we accept that faults are important conduits for circulating cooling seawater deep into the crust, then in the figure opposite we see that on slow ridges, where the faults penetrate the deepest, the temperature anomaly is also at its deepest because heat is transported away by water circulating in the deep faults. On fast-spreading ridges the hot material can extend into the shallowest crust, because there are no deeply penetrating faults to transport the cooling water. This becomes a self-sustaining system, because cold, brittle rock is needed for faults to exist at all. On fast-spreading ridges that are kept hot by the high magma supply, faulting to significant depth cannot be initiated because hot, weak rock cannot support the necessary stresses.

Marine seismology has accomplished much in the last 20 years. We are beginning to understand the primary structural elements of the oceans. We know the basic architecture of oceanic lithosphere, and the primary structural characteristics of mid-ocean ridges, fracture zones, and continental margins. However, we know too little about their three-dimensional structure to adequately constrain process-oriented models for their formation and evolution, and our knowledge of structures within the upper mantle, where so much of our understanding of plate



A section across the crest of the Mid-Atlantic Ridge near latitude 26°N. The continuous black line is the seafloor and the solid black squares mark the location of bottom instruments implanted to monitor earthquake activity. The dots are recorded microearthquake locations and the red shaded zone is a volume of inferred low seismic velocities and elevated temperatures that is probably the source of heat that feeds the known active hydrothermal field (red triangle). The microearthquakes with their associated extensional faults are located in the colder brittle crust surrounding this hot zone. (After Kong, Solomon, and Purdy, 1992.)

interactions must lie, is minimal. Sound arguments can be made that mapping Earth's deep structure is best carried out from the oceans. Large-scale experiments are easier to plan and perform when national borders, roads, and towns can be ignored. And the thin, young, homogeneous oceanic lithosphere can be likened to a clear pane of glass compared with the frosty cracked window that is the old, heterogeneous continental crust.

Innumerable fundamental questions concerning our planet's deep structure remain to be answered. We have the ideas, the knowledge, and the energy to answer these questions: We lack only opportunity. In striving to create these opportunities, we are building new national research programs that include the Ocean Seismic Network, which is dedicated to the emplacement of permanent broad-band seismographic stations on the ocean floor, and the Ridge Interdisciplinary Global Experiments Program (see *Oceanus*, Winter 1991/92), which has as a primary element mapping of the seismic structure of the upper mantle beneath a fast-spreading mid-ocean ridge.

Seismology in the oceans is a young endeavor that moves quickly and unpredictably. We can be sure that our view of Earth will be greatly changed a decade from now, and this new vision will have been shaped in large part by the contributions of marine seismology.

Mike Purdy used to be a Yorkshireman, who traveled to Woods Hole in 1974 while on his honeymoon in search of a peaceful life in a small coastal town. The hectic pace of Cambridge (where he gained his Ph.D. in marine geophysics) and London (BS in physics and MS in geophysics) had convinced him that in order to thrive he needed a quiet habitat without the pressures of these large chaotic centers of learning. He has never fully appreciated the magnitude of this fundamental error in judgment, from which he is slowly recovering only because of the help of four extraordinary individuals: Alix, Christopher, Pippa, and Catriona.

Global Seismic Tomography

Adam M. Dziewonski

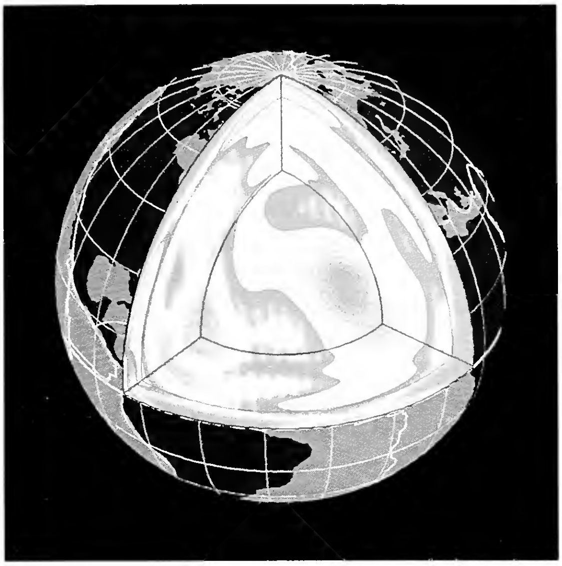
Our picture can be thought of as a snapshot of the temperature pattern in Earth's convecting mantle.

Scientists use seismic energy to map Earth's subsurface structure; for example, the Earth model at right was constructed using global seismic tomography (GST) data. The triangular cut into the globe shows deviations of shear wave speed in the planet's mantle from the spherically symmetric reference Earth model. The surface is the top of the mantle (the Mohorovicic discontinuity, see page 63), and the bottom is the core-mantle boundary (CMB). Green to blue colors indicate higher-than-average seismic wave speeds, and slower-than-average speeds are yellow to red. Seismic velocities decrease with increasing temperature: The inference is that the red areas are hotter than average and the blue, colder. Seismic wave speeds vary also with chemical composition, but there are strong indications that the thermal effect is dominant.

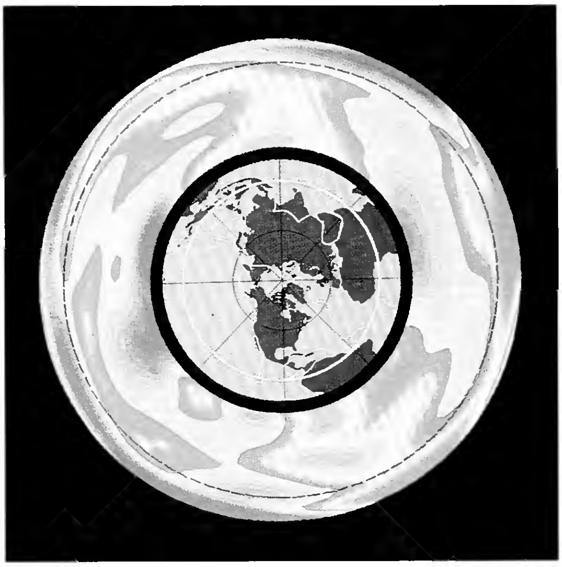
Density is also a function of temperature. Material hotter than average is lighter and, in a viscous Earth, tends to float to the surface; colder material is denser and tends to sink. Thus our picture can be thought of as a snapshot of the temperature pattern in Earth's convecting mantle. In particular, the picture implies a downwelling under North America and an upwelling originating at the core-mantle boundary under northwest Africa. Other cross sections of the model passing through this anomaly indicate that this upwelling may continue to the surface and be connected to the northern Mid-Atlantic Ridge.

Solving an "inverse problem" provides a three-dimensional model of seismic velocities. Like in optics, seismic energy propagates between two points (the earthquake and the seismograph) along the minimum travel-time path; because of the analogy with optics we often talk about "seismic rays." The travel time anomaly due to the small deviations from the reference-earth model is accumulated along the ray path. These are our data. What we need are the parameters describing the locations and sizes of wave-speed anomalies. To solve this, we must represent the properties of the medium using a finite number of parameters. The mathematics can get complicated. In the example shown above, basis functions (spherical harmonics in geographical coordinates and orthogonal polynomials in radius, both truncated at some degree) were used. Such basis functions vary smoothly with position in a way similar to that of the sine or cosine functions. Fortunately, there is evidence that the seismic spectrum of Earth's lateral heterogeneity is strongly dominated by very large wavelength features, so that truncating these basis functions does

The computer graphics used in this article have been developed by Wei-jia Su at Harvard University. The seismic models shown have been obtained at Harvard by Bob Woodward, Wei-jia Su, and Adam Dziewonski.



This three-dimensional plot of shear velocity anomalies in the mantle is viewed from an altitude of 37,000 kilometers (left). The arc length of each side of the cut's triangle is 10,000 kilometers. The bottom of the cut maps the velocity anomalies at the core-mantle boundary (CMB). A thin black line marks the 660-kilometer discontinuity, and plate boundaries are in yellow. The scale range is ±1.5 percent; the slowest velocities are in red, the fastest are in blue. There is considerable scale saturation in the upper mantle.

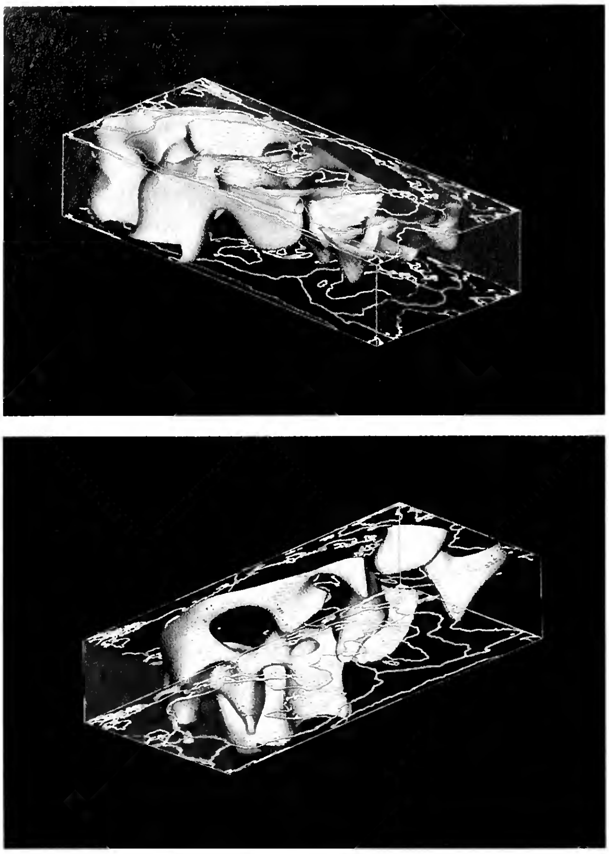


Great-circle cross section through the equatorial plane of a three-dimensional velocity model (right). The cross section is made along the heavy line in the inset map and passes through the center of Earth. The outermost ring is closest to Earth's surface, the innermost corresponds to the CMB. The depth of the 660-kilometer discontinuity is indicated by a dashed line. The scale ranges from −1.5 percent (red) to +1.5 percent (dark blue). Significant saturation of the scale is possible in the upper mantle.

not pose a serious source of error. The alternative, frequently used, approach is to solve for velocity perturbation in a three-dimensional array of cells, assuming that the velocity deviation within each element is constant.

There must be sufficient coverage of the mantle volume with criss-crossing paths to locate the source of the observed travel-time anomalies. If the data sampling a particular region exist for only one azimuth, the observed anomaly could arise anywhere along the ray path.

There is an important distinction between GST and medical tomography, for example, in which the location of wave sources and receivers can be chosen according to the objective. In GST we are limited by the distribution of globally detected earthquakes for wave sources and by the locations of seismographic stations for receivers. There is not much we can do about the distribution of seismicity, except that now and then an earthquake occurs in an unexpected place, so coverage is expected to improve with time. Generally, earthquake distribution is more even in the Northern Hemisphere. At this time, there are no permanent ocean-bottom seismographic stations for receiving the broad-band frequency signals we need, so the locations of the receivers are further limited to continents and islands. Significant progress has been made in recent years in the global deployment of state-of-the-art seismographic instrumentation. This has been accomplished through programs such as the Global Seismographic Network initiative in the US, and



In both of these images, the outer box spans 360° in longitude, split at 60°W. It extends from 75°S to 75°N latitude, and from the Moho to 660 kilometers depth; the vertical dimension is exaggerated 12.5 times. The outer box contains surfaces that correspond to –0.75 percent shear velocity anomaly. The inner surface contains even slower material and is shown in red; the outer surface is adjacent to material faster than –0.75 percent and is shown in amber. Plate boundaries are in blue. The top image shows the "box" from southwest at an azimuth of 225° from a point several thousand kilometers above Earth's surface. The troughs associated with the mid-ocean ridges and back-arc basins are clearly seen. Some of the features, such as the Pacific-Antarctic Ridge, extend from the surface to the 660-kilometer discontinuity. The bottom image is viewed from a northwest azimuth of 315°, several thousand kilometers below 660 kilometers depth. It is clear that anomalies associated with back-arc basins are relatively shallow. The red inner surface is seen where the –0.75 percent anomaly extends into the lower mantle. Notice a very large area off the North American West Coast. A top of an anomaly located in the lower mantle is just penetrating 660 kilometers depth under Eurasia.

GEOSCOPE in France. Complementary programs were established in Canada, China, Germany, and Japan. These digital seismographic networks were federated in 1986 to set common instrumentation goals and coordinate data exchange. However, without deployment of permanent ocean-bottom observatories, the distribution of receivers will remain inadequate, particularly in the Southern Hemisphere.

A workshop held at the Woods Hole Oceanographic Institution in April 1988 outlined the steps required to determine the feasibility of an Ocean Seismographic Network (OSN). Presently, the development of the necessary instrumentation and testing of background-noise levels at the ocean floor and in Ocean Drilling Program holes proceed in Japan, France, and the US. Even though the deployment and operational costs of a 15- to 20-station OSN would be high, its data are critical for improving the resolution of GST models and for other applications such as earthquake studies. Since 1977, when the first large-scale GST study was published, scientists have believed that three-dimensional images of lateral heterogeneity in the mantle will be essential to solve some of the fundamental geodynamics problems. Results accumulated since then confirm this belief. Here are some examples of the GST application to various problems in Earth sciences.

Mantle convection. The distribution of seismic anomalies represents the current configuration of thermal and compositional heterogeneity, and it imposes a complex set of constraints on possible modes of mantle convection. The figure at right on page 71 shows the equatorial cross section through the same Earth model as the figure to its left. Clearly, the dominating feature from the CMB to mid-mantle are the two slow and two fast regions indicative of a very large wavelength convection pattern.

Mineral physics. The in situ ratio of the perturbations in shear velocity and compressional velocity inferred for the lower mantle from GST in 1986 was much higher than determined, at relatively low pressures, in the laboratory. Only recently the mineral physicists were able to reproduce the tomographic value.

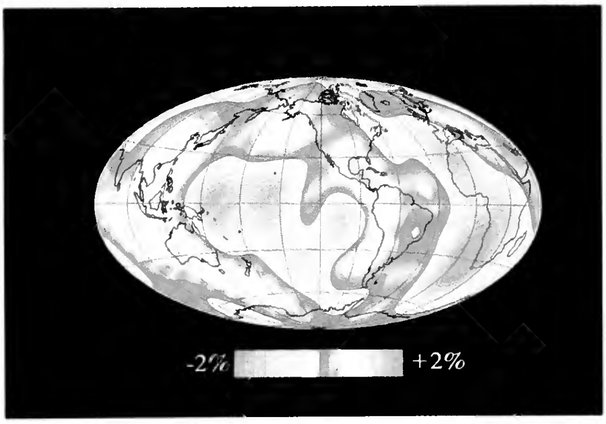
Gravity. Under the assumption that seismic anomalies are proportional to density perturbations, they provide constraints on the modeling of large wavelength gravity anomalies, the viscosity distribution in the mantle, and the ratio of density perturbations to velocity perturbations.

Petrology and geochemistry. The GST models have the potential to provide integral constraints on petrological and thermal models of the ridge systems. The top image on the facing page shows a perspective view of –0.75 percent contour of shear velocity anomaly in the upper mantle. The trough associated with the mid-oceanic ridges is deeply depressed, and on occasion extends into the lower mantle. On the other hand, the negative anomalies under the back-arc basins are relatively shallow. The negative velocity anomaly under the East Pacific Rise is much wider and deeper than those under the north and south segments of the Mid-Atlantic Ridge. Velocity anomalies associated with the continental shields confirm the hypothesis of "continental roots." The cross sections through the upper mantle of North America, Africa, and Europe (page 71, top) show that positive velocity anomalies extend to 400 kilometers or so. Correlation has been noted between low velocity anomalies near the core-mantle boundary, such as seen below, and the occurrence of large-scale isotopic anomalies.

Geomagnetism. Coincidence of regions with a high rate of secular variations and slow velocity anomalies (higher than average temperature) provides constraints on the thermal and mechanical coupling between the mantle and the core. Several recent papers point out that the virtual geomagnetic pole paths coincide with the two high-velocity regions circumscribing the Pacific and, effectively, connect the North and South poles.

Geodesy. GST models of velocity anomalies and topography of major discontinuities (CMB, 660 kilometers) can be compared with the data on Earth's rotation obtained by other techniques, such as very-long baseline inferometry.

In addition to the ever-present goal of improved resolution, the most urgent challenge in GST modeling is deriving comparable quality results for P- and S-wave heterogeneities, which is necessary to distinguish between the thermal and compositional variations.



This map reveals shear velocity anomalies at a depth of 2,850 kilometers—just above the core-mantle boundary (CMB). Comparing this figure with those on page 71 indicates that many of the large-scale features seen near the CMB extend throughout the lower mantle. They can be considered "megastructures in Earth's deep interior." Some are named high-velocity features, such as Pangea Trough extending through much of the lower mantle under North and South America, Tethys Trough from the Macquarie triple junction to the Straits of Gibraltar, China High, and North Pacific High. Low-velocity features include the Equatorial Pacific Plume Group and the African Plume Group.

Adam M. Dziewonski received his education in Poland at the University of Warsaw and the Academy of Mining and Metallurgy in Cracow. He arrived in the United States in 1965 and has been at Harvard since 1972. Even though his official title there is Professor of Geology, most of his work is in the area of global Earth structure, including one of the first tomographic studies in 1975. Having run out of data provided by the land-based stations, he started several years ago with G.M. Purdy of Woods Hole Oceanographic Institution and John Orcutt of Scripps Institution of Oceanography, among others, promoting the concept of the Ocean Seismographic Network. As an early warning of the possible consequences, he was appointed a co-chief scientist of ODP Leg 136, during which a hole off Hawaii was drilled for future experiments with a broad-band seismographic system.

Illuminating the Seafloor

Deborah K. Smith

The ocean is so effective at concealing the bottom that we know more about the topography of Venus than we do about Earth's ocean floor.

If we could empty the ocean basins and obtain a clear view of the seafloor, we would learn a great deal about Earth's interior processes. We would see volcanoes erupting and building, and be able to map their distribution along the Mid-Ocean Ridge axis and off its axis. We would also see new oceanic crust forming at the ridges, being chopped up by faulting, and moving away from the ridge. Such observations would provide insight into magmatic and tectonic processes. However, the seafloor remains hidden from our direct view, except for brief excursions to the ocean bottom in manned submersibles or through the "eyes" of remotely operated vehicles. Its topography currently must be inferred from data collected by remote sensing instruments deployed from ships on the ocean surface.

Because ship tracks are sparse, most seafloor topography is still poorly known. This is especially obvious in small-scale bathymetric maps of South Pacific regions where water-depth contours resolve to circles that are centered on widely spaced tracks. Nevertheless, statistical interpretations of measurements collected during ocean-basin crossings reveal many things. For example, submarine volcanoes far outnumber their terrestrial counterparts. Because of their inaccessibility for study, however, the factors that control the formation of submarine volcanoes are largely unknown, and several first-order scientific questions remain to be answered, such as How do their abundances and size distributions vary geographically within and between ocean basins? and, How do volcano morphologies differ, and what do they indicate about eruption processes? The ocean is so effective at concealing the bottom that today we know more about the topography of Venus than we do about Earth's ocean floor.

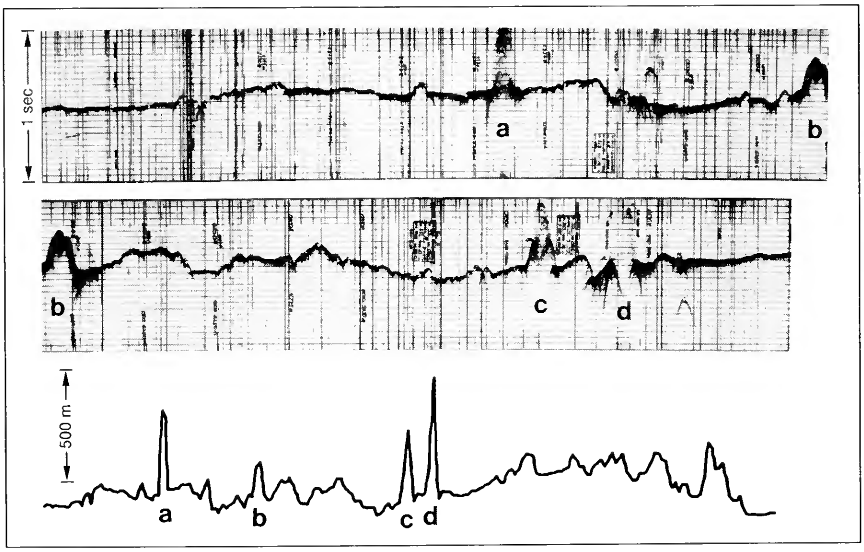
Recent advances in instrument capabilities are beginning to allow marine geologists to investigate submarine topography in much the same way terrestrial geologists study land features. Using new high-resolution sonar systems, we can observe seafloor features in three-dimensional detail. Historically, technological advances in surveying tools mark stages in the advancement of our understanding of the seafloor and the underlying processes controlling its formation and evolution.

Early Views of Seafloor Topography

Laying of the first transatlantic submarine telegraph cable in the 19th century sparked interest in seafloor morphology. Before then, the ocean basins were thought to be vast featureless plains covered with huge amounts of sediment shed from the continents. The seafloor's shape was only known in the shallower areas of the continental rise where it was necessary for navigation.

In 1872, H.M.S. *Challenger* sailed from England on what is considered to be the first scientific oceanographic expedition. In three and a half years, *Challenger* circumnavigated the globe stopping every few thousand kilometers to collect samples and measure water depth by unreeling a sounding line. These widely spaced soundings showed that the seafloor was not featureless, but instead contained large topographic features. The nature and frequency of such features remained unknown, however, for quite a while.

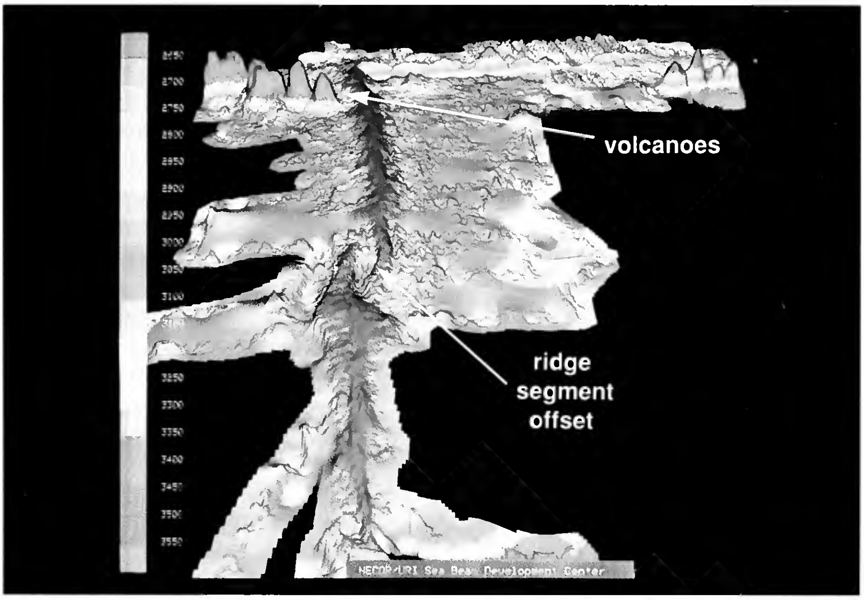
Little more was discovered about the seafloor until the echosounder was developed in the 1920s. These instruments illuminated deep-ocean-basin mountain ranges, valleys, and other morphologic features similar to those observed on land. An echosounder measures the time it takes a sound pulse generated at the sea surface to return to the surface after reflecting off the seafloor; its travel time is then converted to water depth using a velocity-depth curve for sound through the water column. As the ship moves across the ocean, a profile of the bottom is assembled from the "echoes." The area of the seafloor reflecting the sound pulse is proportional to the echosounder's beam-width and the water depth: The larger the beam width and the deeper the water, the larger the resulting area. A traditional widebeam echosounder sends out a pulse that spreads outward as a sphere so that in water depths of 4,000 meters (an average ocean depth), a widebeam profiler samples a piece of seafloor with diameter of about 4,600 meters. A single depth represents this large patch of seafloor, and because the depth recorded is from the nearest acoustic reflector in this patch, an echosounder typically records the depth of the tallest feature, even if that feature is off the ship's track.



A widebeam echogram collected in the Northeast Pacific is displayed above a computer-generated plot of water depth versus time, generated from soundings digitized at about 5-minute intervals. Approximately 10 hours of data are shown, which corresponds to about 180 kilometers. It is impossible to know whether these features are below the ship or off to one side. In addition, it is hard to obtain information on the shapes of features from these echograms.

Because the first echosounders had low spatial resolution and poor vertical depth resolution, only the gross character of features was recorded. Therefore, emphasis was placed on charting features rather than determining their shapes, but seafloor mapping had begun.

Systematic coverage of the Pacific Ocean increased dramatically in 1935 when the US Navy, following a National Academy of Sciences recommendation, began rerouting ships to areas that had never been sounded. The need for oceanographic data in World War II's Pacific theater brought an exponential increase in ocean soundings as Navy ships stationed in the Pacific routinely collected depth data. A turning point for marine geology occurred when Harry Hess, a Princeton University professor and commanding officer of USS *Cape Johnson*, studied bathymetric profiles collected during transits between Hawaii and the Mariana Islands. He discovered curious flat-topped peaks that he named "guyots"for the 19th century Princeton geologist Arnold Guyot. In 1946 Hess suggested that these peaks are drowned ancient islands whose tops were planed off at sea level by wave action and erosion. The idea of vertical island motion was not new. In 1842 Darwin had proposed that atolls are formed from islands as Earth's crust subsides. However, the discovery of flat-topped features in the middle of the Pacific, 1 to 2 kilometers below the sea surface, was exciting. This discovery, and the hypothesis for their origin (which turned out to be correct), stimulated marine geologic exploration for some time to come.



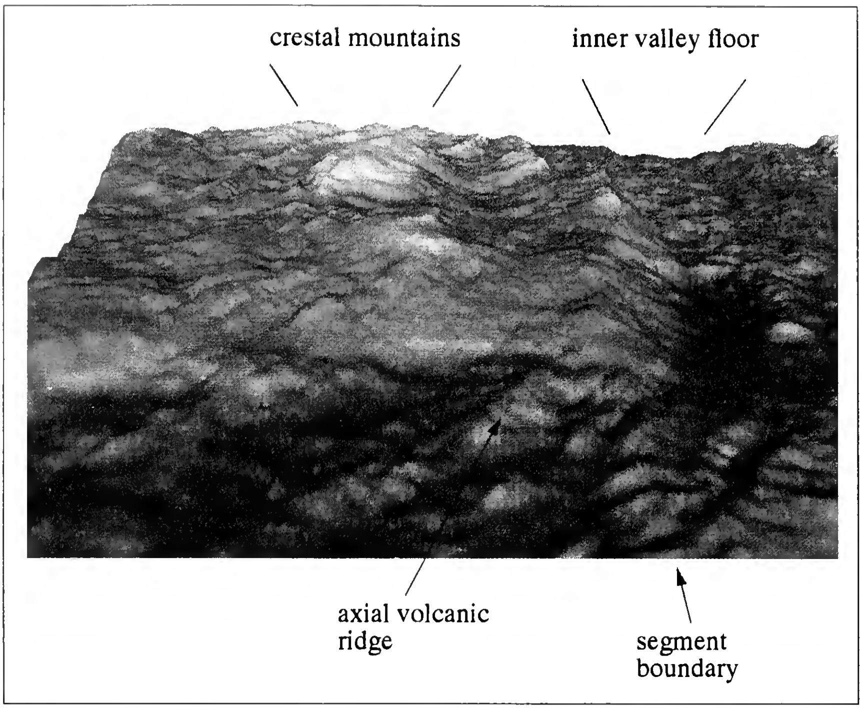
Ocean Mapping Development Center/University of Rhode Island

In this relief map of the fast-spreading East Pacific Rise near 9°N, the ridge axis (red) is offset to the east near the middle of the figure. The axial high, typically a few kilometers wide, can in general be mapped in a single bathymetric swath. It would easily fit on the inner valley floor of the slow-spreading Mid-Atlantic Ridge, and has the same dimensions as the axial volcanic ridges observed there. The axial high of the East Pacific Rise is composed primarily of fissure-fed sheet flows.

New Tools Improve Seafloor Topography Definition

The 1950s brought the introduction of the precision depth recorder, capable of measuring water depths with a resolution of approximately 1 fathom (1.8 meters). Collecting bathymetric profiles then became standard procedure on most oceanographic expeditions. By the late 1960s marine geologists had accumulated broad knowledge of the North Pacific and North Atlantic seafloor morphology. Topography maps constructed from these data became an integral part of synthesizing ideas that led to the theory of plate tectonics.

Also during these years, the concept for collecting bathymetric data changed from reconnaissance to detailed surveying, and interest focused on major bathymetric features such as plate boundaries. These included



Sea Beam data was used to generate the bathymetry of the median valley of the slow-spreading Mid-Atlantic Ridge near 29°N. Depths range from about 4,000 meters in the dark-blue regions to less than 2,000 meters in the red regions of the crestal mountains. Two spreading segments are shown with an easterly offset between them. The inner valley floor of the northern segment is 5 to 7 kilometers wide. In contrast to the fast-spreading East Pacific Rise, volcanic eruptions on the valley floor of the Mid-Atlantic Ridge form small volcanic edifices that pile on top of each other to build prominent axial volcanic ridges.

spreading ridges where new oceanic crust is generated, fracture zones that offset the spreading ridges, and subduction zones, where oceanic crust is consumed back into Earth's mantle. Again, an advance in instrument capabilities preceded this new focus. High-resolution multibeam and sidescan sonars began to provide a far more detailed picture of the seafloor. The Sea Beam multibeam echosounder joined the suite of oceanographic research tools in the early 1970s. This system covers a seafloor swath whose width is approximately 75 percent of the water depth, and returns up to 16 cross-track depths: Each depth represents a patch of seafloor approximately two and two-thirds degrees on a side. In 4,000-meter water depths, the "footprint" is about 200 meters on a side, much more focused than the larger area (4,600 meters in diameter) sampled by a widebeam echosounder. Another important early 1970s advance occurred when ships began to use satellites for navigation—accurate navigation is essential in correlating bathymetry between ship tracks and in developing coherent maps.

Multi-narrowbeam echosounders such as Sea Beam, and more recent systems that cover wider swaths, revolutionized marine geology. In a 30-day cruise, tens of thousands of square kilometers of the seafloor can be mapped. Such high-resolution, two-dimensional swath maps reveal seafloor details not readily obtained from bathymetric profiles, such as the shapes of features. With a one-dimensional bathymetric profile, for example, it is impossible to discriminate between a ridge and a circular volcano because both appear simply as peaks. The first Sea Beam cruises confirmed that most ocean-basin topography is highly lineated. For the first time, the orientation and the length of these abyssal hills could be accurately measured. Abyssal hills are generated by faulting near the spreading ridge, and their orientation parallels that of the ridge axis at the time of their formation. Thus, changes in the abyssal-hill orientation provide us with information about how processes at the spreading ridge change through time.

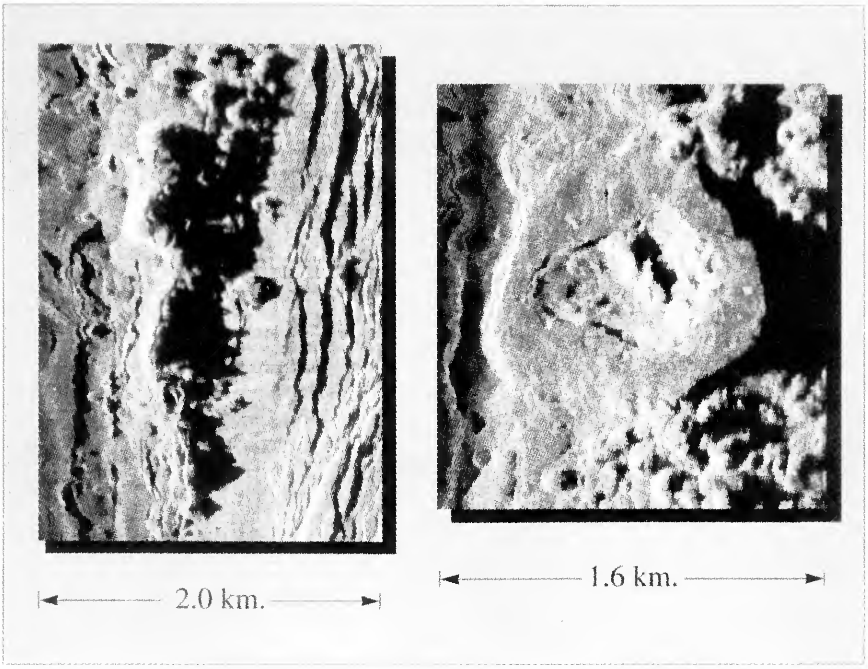
Deeply towed sidescan systems such as Deep-Tow, operated by the Scripps Institution of Oceanography, were also available for use in the early 1970s. These types of sonar systems are towed about 100 meters above the seafloor, typically cover a 1-kilometer-wide swath, and produce high-resolution (spatial resolution of less then 10 meters) seafloor images that allow investigation of small-size topography. For example, several faults imaged by Deep-Tow may appear as one large fault on Sea Beam data, because they cannot be resolved by the Sea Beam system. The finer resolution information is vital for understanding such things as how the oceanic crust responds to stresses induced by seafloor spreading.

In addition to these instruments, the new 1970s submersible capability to dive to mid-ocean depths led to firsthand observations of the deep-ocean bottom. Submersible dives offer a number of significant advantages including the ability to distinguish different styles of eruptions by observing and mapping the morphology of individual lava flows, the ability to assess the importance of processes such as mass wasting (that is, debris flows and landslides) in shaping topography, and to collect samples from specifically targeted locations.

The new 1970s submersible capability to dive to mid-ocean depths led to firsthand observations of the deep-ocean bottom.

Many studies of the seafloor have now taken advantage of these mapping and sampling capabilities to further expand our knowledge of spreading ridges and their distinctive topography. Since the 1960s when marine geologists and geophysicists accepted the theory of plate tectonics, and, in particular, that new crust is generated at oceanic spreading centers, it has been known that topographic signatures change from spreading ridge to spreading ridge. This variation seems to be most strongly associated with spreading rate. Our current view is that fast-spreading ridges such as the East Pacific Rise (which opens at a rate of about 80 millimeters a year) are distinguished by an axial high or ridge 1 to 2 kilometers wide. Tectonic faults caused by extension are on the order of tens of meters high, and low-relief lava flows are common. By contrast, most slow-spreading ridges, such as the northern Mid-Atlantic Ridge (which spreads apart at about 25 millimeters a year) contain a major axial rift valley 30 to 45 kilometers wide. The median valley has an inner-valley floor 5 to 12 kilometers wide that is the primary site of volcanism and crustal construction. The valley floor is bordered by walls where numerous faults chop up the crust as it moves vertically 1 to 2 kilometers into the bounding mountains. Typically, eruptions on the inner-valley floor build small (1 to 2 kilometers in extent) volcanic edifices that pile upon one another to form prominent axial volcanic ridges. These ridges can be several hundred meters high, 1 to 5 kilometers wide, and tens of kilometers long.

In the late 1960s scientists recognized that the data density and coverage of mid-ocean ridge axial zones was insufficient to understand the processes that create new oceanic crust, and Project FAMOUS (French-American Mid-Ocean Undersea Study) was organized. The Mid-Atlantic Ridge near 37°N was chosen as the study site because it was thought to be typical of slow-spreading ridges. Investigations began with regional-scale surveys of the ridge axis using multibeam echosounders and surface-towed sidescan sonars. Then selected subregions were



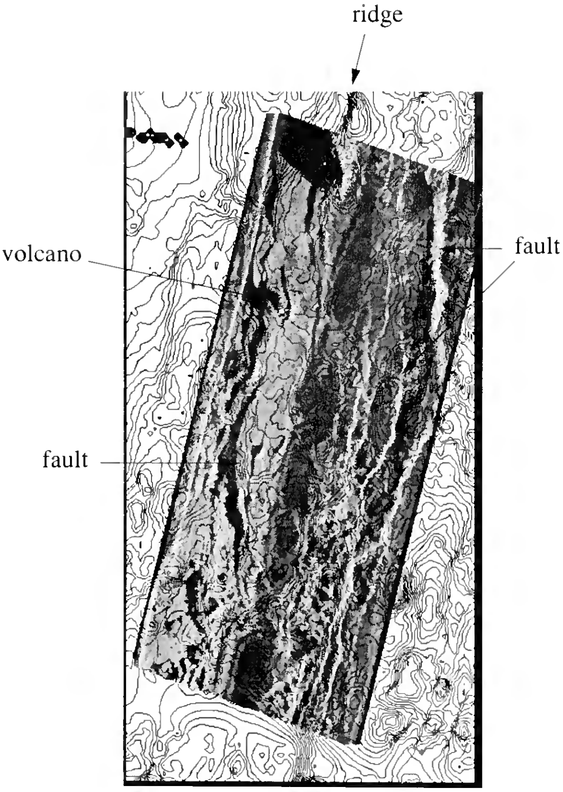
M. Dougherty Boise State University

Small volcanic edifices coalesce and pile upon one another to form the oceanic crust at the Mid-Atlantic Ridge. To the left is a tadpole-shaped ridge about 30 meters high. Its orientation mimics the orientation of neighboring faults, and it probably erupted along such a fault. It has a fissure along its crest. To the right is a flat-topped circular volcano about 70 meters high. The summit crater is filled with what appears to be small cones. It is surrounded by a flow composed of small rounded mounds. Volcanic edifices such as these form a patchwork that builds the larger-scale axial volcanic ridges.

surveyed at increasingly greater detail with deep-towed sidescan sonars and cameras. The final component was submersible dives on particular targets. Project FAMOUS included collecting bathymetry, magnetic, gravity, and seismic data, as well as camera runs and dredge samples. There were more than 25 cruises and dives in the FAMOUS area between 1971 and 1974.

From the FAMOUS investigations, a consistent model for the creation and evolution of the rift axis of the Mid-Atlantic Ridge was advanced. Studies of inner-valley floor volcanic structures led marine scientists Robert Ballard (Woods Hole Oceanographic Institution, WHOI) and Tjeerd van Andel (then at Oregon State University) in 1977 to suggest that the inner-valley floor is produced by volcanic activity that forms axial volcanoes. They hypothesized that major volcano-building episodes alternate with periods of reduced volcano construction. Entire axial volcanoes migrate laterally away from the rift axis, and are lifted out of the inner-valley floor by faults. The goal of surveying the entire width of the FAMOUS area's broad axial zone, however, limited coverage along the axis of the spreading ridge. Therefore, the resulting models for crustal generation were mainly two-dimensional, focusing on the evolution of the topography as it moved away from the crustal accretion zone. The next step was to incorporate the third-dimension, along-axis variations into our thinking.

After Project FAMOUS, intense investigative attention turned to the East Pacific Rise because of its simpler structure. The narrow axial zone of the East Pacific Rise can be completely mapped in a single multibeam bathymetry swath. Based on these investigations our view of crustal construction and evolution changed from a two-dimensional to a three-dimensional perspective, and the wide variability in ridge-crest processes along a spreading axis was first understood. Extensive surveys along the axis revealed that the ridge axis is partitioned into segments that are tens of kilometers long. It was also realized that there are intrasegment signals within segments: For example, segments shallow near their midpoints and deepen at their ends. This trend has recently been related to discrete regions of mantle upwelling that concentrate at a segment's center. Ultimately, from this new view of mid-ocean ridges, marine scientists recognized the three-dimensional dynamic variability of spreading ridges.



A TOBI deep-towed sidescan image is overlain with Sea Beam bathymetric contours. The sidescan image is 6 kilometers wide, and the track of the instrument is down the middle. The image is similar to what would be seen if a flashlight were swung back and forth across a patch of seafloor: bright is a reflection, dark is a shadow. The sidescan images give smaller-scale information necessary to understand the processes acting at the ridge axis to form the oceanic crust. For example, Sea Beam does not resolve the numerous small-scale faults found in the sidescan data, nor does it show that the small volcano is faulted.

Recent Work Brings Sharper Focus

Until recently there was no equivalent high-resolution along-axis mapping of the Mid-Atlantic Ridge, and the nature of ridge-axis segmentation at the Mid-Atlantic Ridge remained poorly known. The axial zone at this slow-spreading ridge is so wide that a major mapping effort was needed to obtain the necessary along-axis coverage. During 1989 and 1990, scientists from WHOI's Department of Geology and Geophysics spent two months mapping over 900 kilometers of the Mid-Atlantic Ridge between about 24° and 32°N. These surveys are the first to clearly reveal the segmentation at the northern Mid-Atlantic Ridge, and the along-axis variability in topographic characteristics similar to that at the East Pacific Rise. These data are yielding much information about the processes of faulting and volcanism at a slow-spreading ridge.

One of the most important capabilities of swath-mapping sonars is that large areas of the seafloor can be surveyed during one cruise. It is clear, however, that to fully understand the processes that shape the seafloor, we must obtain detailed surveys at many different scales. Systems such as Sea Beam are now considered to be the lower resolution instruments that provide valuable overviews of a region. This was apparent when Joe Cann (University of Leeds) and I recently used Sea Beam data to make inferences about small-scale volcanic edifices. We suggested that the inner-valley floor of the Mid-Atlantic Ridge was littered with small volcanoes, and the question was raised whether such interpretations made from Sea Beam maps are valid. For example, it was suggested that some of the circular highs on the bathymetric map that we identified as volcanoes may instead be circular flow fronts. To address this and other questions, a joint British-American cruise went back to the ridge axis in February

1992. We used the newly developed British deep-towed sidescan system TOBI (Towed Ocean Bottom Instrument) to survey large areas within the Sea Beam coverage. TOBI has an approximate resolution of 2 meters across-track and 12 meters along-track, providing a much higher resolution seafloor image than can be obtained from the Sea Beam echosounder. It is towed 400 to 600 meters above the seafloor, covers a total swath of 6 kilometers, and so provides detailed images of large sections of the topography.

The results of this cruise corroborate our hypothesis that small volcanoes are widespread at the axis of the Mid-Atlantic Ridge. In addition, we find that small volcanic features pile up to form the axial volcanic ridges that dominate the larger topography of the spreading segments. This style of volcanism is very different from that observed at the fast-spreading East Pacific Rise, where we observe sheet flows that spread out from fissures, and has important implications for magmatic processes at a slow-spreading ridge. The next step in our investigation is to return to the Mid-Atlantic Ridge to survey and sample individual volcanic features in an effort to understand the relationship between small volcanic features built on the seafloor and the magma bodies that feed them.

After a successful 33-day cruise, the author and fellow scientists and crew fall out for a much-needed swim call. This cruise was a seafloor survey of the Mid-Atlantic Ridge, aboard RRS Charles Darwin.

Our "view" of the seafloor has changed radically with our capability to image it. One hundred years ago we believed that the oceans were featureless plains drowned in sediment. Thirty years ago we began to accept the new theory of plate tectonics. Today, as we obtain higher resolution images of seafloor topography, we are discovering the complexity of the system that creates it. This complexity has much to tell us about the processes occurring within Earth. Our goal in the 1990s is to understand the processes that combine to generate the oceanic crust at spreading ridges. We have yet to answer many basic questions about this system, including how magma is supplied from the deep mantle, how and where magma is stored in the crust, and what controls the eruption of lavas at the seafloor. The technology that brings us our new and ever-changing view of the seafloor will help us answer these fundamental questions.

Deborah K. Smith is an Associate Scientist in the Department of Geology and Geophysics at the Woods Hole Oceanographic Institution. She developed her interest in the oceans while sailing a small boat from San Francisco to New England, and has continued to go to sea ever since.

Micro-Magnetic Field Measurements Near the Ocean Floor

Maurice A. Tivey and Hans Schouten

agnetic measurements provide information about the rock composition of Earth's upper crust. Igneous rock bodies—volcanoes, for example—can be identified by their distinctive magnetic properties, which depend mainly on how much magnetite the rock contains, the thickness of the rock body, and its depth below Earth's surface. Magnetization is also a function of the direction and strength of Earth's magnetic field when the rock cooled, because its iron minerals became permanently aligned with magnetic north at that time.

Marine magnetic reversal anomalies provide a virtually continuous record of Earth's magnetic field for the past 200 million years.

The study of marine magnetic anomalies played a major role in the discovery and understanding of plate tectonics. In the early 1960s Earth scientists found through dating and paleomagnetic studies of terrestrial lavas that Earth's magnetic field, which is created by the circulation of core materials, had reversed polarity frequently and regularly in the past at intervals of about half a million years, with each reversal probably taking only a few thousand years. (During periods of "normal" magnetization, the north-seeking end of a compass needle would behave as it does now; during periods of reversed magnetism, the "north-seeking" end of the needle would point south.)

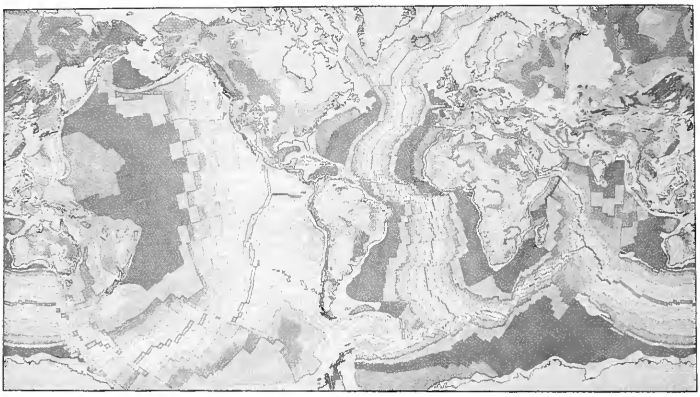
Meanwhile, marine scientists noticed that the newly discovered mid-ocean ridges were marked by significant magnetic anomalies that persist away from the ridge crests in a systematic pattern of "magnetic stripes." These two observations led Frederick Vine and Drummond Matthews (Cambridge University) to hypothesize in 1963 that the ocean crust acts as a sort of tape recorder that preserves Earth's magnetic field through time. The Vine & Matthews hypothesis begins with the magnetization of newly formed mid-ocean ridge crust as it cools. This crust then moves out of the formation zone through the process of seafloor spreading to become part of an oceanic lithospheric plate. The positive magnetic stripes form during normal polarity periods and the negative stripes during reversed periods.

This pivotal idea provided confirmation of the theories of plate tectonics and continental drift. Unlike on land, the marine magnetic reversal anomalies provide a virtually continuous record of Earth's magnetic field for the past 200 million years. Correlating the sparse but well-dated terrestrial magnetic-reversal time scale with the continuous marine magnetic-reversal record produced the Geomagnetic Polarity Time scale, which allows scientists not only to accurately date the ocean basins and unravel their tectonic history, but also to obtain a detailed record of Earth's magnetic-field behavior.

Although marine magnetic anomalies are now an indispensable tool in marine geophysics, important issues remain unresolved. For example, the crustal source region of these anomalies is a subject of continued controversy. Some models define the uppermost volcanic extrusive layer (about 500 to 1,000 meters thick) as the source layer, whereas other models suggest a significant contribution from the deeper intrusive dike and gabbro layers that compose the remainder of oceanic crust. Another fundamental question that remains to be answered is the source of Earth's magnetic field itself. No convincing models of the geodynamo that satisfy all of the observations have yet been demonstrated.

Ships Measure Broad-Scale Magnetic Anomalies from the Surface

Typically, a marine magnetic survey involves a ship towing a sea-surface magnetometer at speeds between 4 and 10 knots. The spatial resolution of the magnetic signal is approximately equal to the water depth, typically about 3 or 4 kilometers. For seafloor created at a medium spreading rate of 30 kilometers per million years, a 3-kilometer wavelength is equivalent to a time interval of about 0.1 million years. Since the average reversal rate is approximately 0.3 million years, sea-surface measurements provide an adequate measure of Earth's magnetic-polarity reversal history. Spectral analysis of marine magnetic anomalies also shows that the magnetic signal due to seafloor topography contributes significantly to the magnetic field at wavelengths less than 2 kilometers. Thus, the sea-surface data are relatively free from the effects of topography. It is clear, however, that short polarity events (on the order of 0.1 million years or less) are severely filtered when measured at the sea surface. This missing signal is important to understanding the source of the geomagnetic field. For example, are these short-wavelength magnetic anomalies crustal in origin, reflecting the processes of crustal construction and evolution? Or, are they geomagnetic, reflecting rapid reversals or intensity variations of Earth's magnetic field? If these short-wavelength anomalies are geomagnetic, they provide another constraint on geodynamo models for the generation of Earth's magnetic field.



The oceanic crust (bedrock) becomes older as it spreads away from ridge crests in a symmetric fashion. Colored patterns in the ocean basins depict the history of this seafloor spreading over the past 180 million years of geological time. The bright red pattern outlines the ridge-crest axes and the oceanic crust formed in the past 1 million years. This bright red grades to cooler colors indicating older oceanic crust. The oldest (blue) portions of the ocean basins formed in the Jurassic period, and are 135 to 180 million years old.

(From *The Bedrock Geology of the World* by Larson, Pitman, Golovchenko, Cande, Dewey, Haxby, and LaBrecque. W.H. Freeman & Co., NY, NY, 1985.)

Thus while sea-surface magnetic surveys are fast, easy to accomplish, and provide a good first-order understanding of the history of Earth's magnetic field, we need more detailed information to resolve short-wavelength magnetic anomalies and, ultimately, the sources of these anomalies.

Submersibles and Towed Vehicles Survey Near-Bottom Magnetics

Near-bottom surveys provide an opportunity to improve the resolution of marine magnetic measurements by measuring the anomalies closer to their sources. To date, this kind of measurement has been accomplished using either deep-towed vehicles or manned submersibles. There are a number of advantages to both of these methods but also several logistical disadvantages.

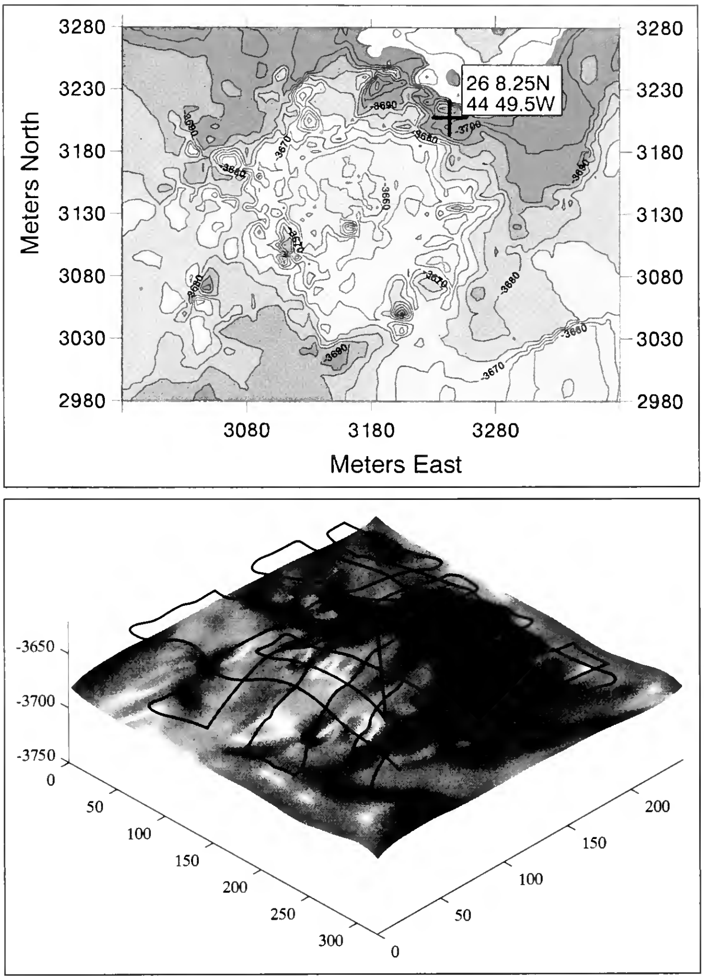
The advantage of getting closer to the magnetic source is that the spatial filtering effect is reduced to hundreds of meters instead of 3 or 4 kilometers (or several thousands of years compared to 0.1 million years at a 30-kilometers-per-million-years spreading rate). This finer resolution provides a more accurate record of the polarity reversal history than is possible with sea-surface data. Being closer to the source also means stronger signals, which is more important in equatorial regions where diurnal magnetic variations (daily magnetic variations due to the sun) can be of the same magnitude as the crustal magnetic signal. Although the magnetic signal is improved, a greater percentage of this signal is "contaminated" with topographic and shallow crustal magnetic variations. Significant post-processing is required to analyze these near-bottom data sets and separate the various signals. Furthermore, the two-dimensional assumptions used in analyzing the sea-surface data must be used with caution in the near-bottom environment where topography becomes more three dimensional. Logistically, deep-towed surveys are complicated operations. The long cable lengths, cable drag, slow tow speed (1 to 2 knots), depth control, navigation, and difficult maneuvering around turns make deep-towed operations a challenge. Without a dynamically positioned ship and tow-fish system, near-bottom surveys over rough topography or along scarp faces are virtually impossible to achieve.

Emory Kristof © National Geographic Society

Nautile *is launched from her mother ship,* Nadir.

Though limited in range and expensive to operate, manned submersible surveys offer the ability to negotiate such terrain. In addition, submersible-mounted magnetometers offer the opportunity to link seafloor observations such as rock type and tectonic structure directly to magnetic-field measurements.

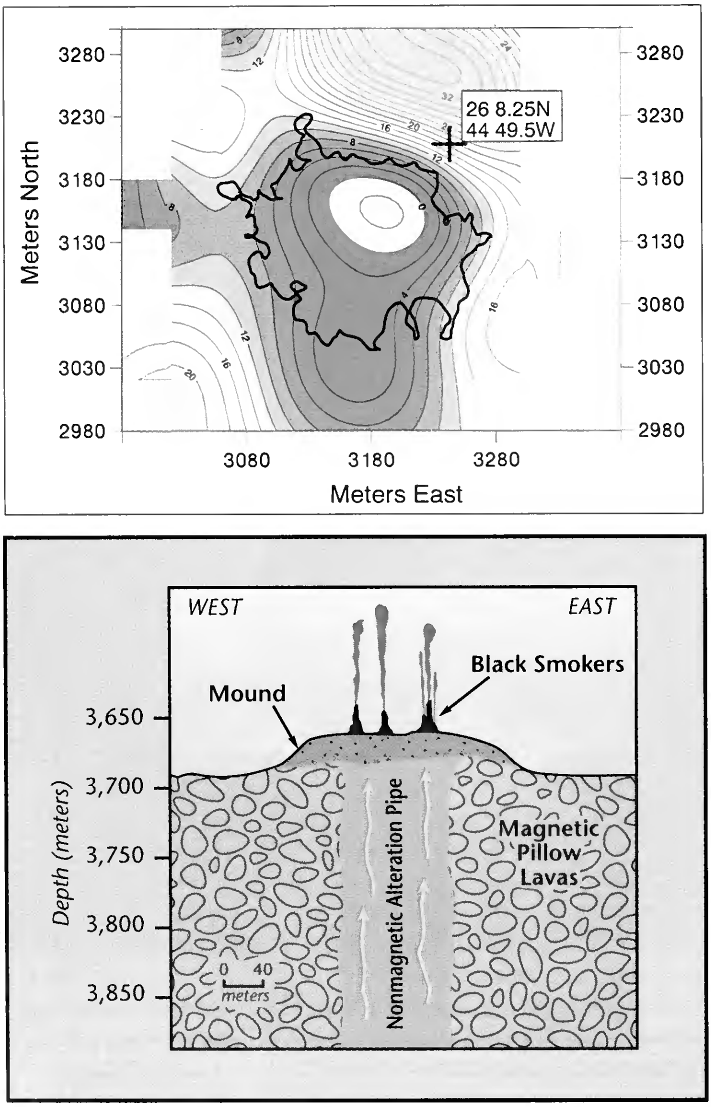
Recently, the capabilities of the US deep submersible *Alvin*, operated by the Woods Hole Oceanographic Institution, and the French deep submersible *Nautile*, operated by the Institut Française pour Recherche et Exploitation de la Mer, provided the opportunity to conduct two different types of surveys. The 1990 *Alvin* survey focused on the actively venting TAG (Trans-Atlantic Geotraverse) hydrothermal mound on the Mid-Atlantic Ridge at 26°08'N, 44°49'W. This survey was designed to define the effects of hydrothermal alteration on the basaltic rocks of the upper crust by carrying out a grid-like survey over the entire mound. The 1991 *Nautile* survey consisted of vertical magnetic traverses up a fracture-zone wall in order to map the vertical magnetic structure of the ocean crust. Both surveys used a three-axis fluxgate magnetometer mounted to the sample basket of the submersible. The magnetometers were calibrated on each submersible by having *Alvin* and *Nautile* actively spin on descent and ascent, so the magnetic effects of the submersibles themselves could be determined and necessary corrections applied. We used new data-analysis techniques that promise to expand the use of submersible and near-bottom magnetic surveys in the future.



The bathymetry of the TAG active hydrothermal mound was measured by Alvin *during the 1990 magnetic survey (top). The contour interval is 5 meters. A three-dimensional representation of the mound looking northwest has the submersible's track lines superimposed in black (bottom).*

The Alvin *TAG Magnetic Survey.* Hydrothermal mid-ocean-ridge vent systems first discovered in 1977 represent a significant source of mass and heat exchange between the oceanic crust and the surrounding ocean. Many of the world's major metallic ore deposits appear to have formed in this kind of environment. The initial magnetization of oceanic crust can be virtually destroyed by thermal and chemical processes at work in such vent systems. At the TAG site, for example, a significant hydrothermal vent system appears to be coincident with a sea-surface magnetic anomaly that has a clearly three-dimensional morphology. The resolution limitations of the sea-surface data can only resolve the size of the source body to an area smaller than 4 by 4 kilometers. The 3,760-meter-deep central vent region consists of a 50-meter-high, 200-meter-diameter mound. *Alvin* carried out a detailed, near-bottom magnetic survey at an altitude of 20 meters over the actively venting mound on grid lines that were 40 meters apart and 400 meters long.

The magnetic results suggest that a zone of reduced magnetization exists beneath the mound. This 100-meter diameter magnetization low is consistent with the highly altered upflow zone of a hydrothermal vent system that feeds the actively venting mound. This low is not sufficient to account for the anomaly observed at the sea surface, which suggests that there is also a deeper and broader zone of low magnetization beneath the mound (too broad to be detected by the *Alvin* survey) that is the source of the sea-surface anomaly. The overall model of crustal magnetization at a hydrothermal field with discrete zones of demagnetization in the upper crust and a broader zone of demagnetization at depth is consistent with studies of hydrothermal systems in ophiolites (remnants of ocean crust that are now exposed to land). These studies show narrow upper-crust alteration pipes that feed the seafloor vent deposits and pervasive alteration at depth, both of which are commonly associated with late-stage intrusive bodies.



Jack Cook/WHOI Graphics

The crustal magnetization of the TAG active hydrothermal mound was calculated from the Alvin *magnetic survey. Contours are in amps per meter. There is a zone of nonmagnetic crust that is centered directly beneath the mound region outlined by a solid black line, indicating the presence of an alteration pipe at depth. A schematic cross section through the TAG mound (bottom) shows this alteration pipe that is thought to be responsible for the magnetic low.*

Nautile *Survey of Blanco Scarp.* The Vertical Magnetic Profiling project (VMAG) was designed to determine the vertical magnetic structure of ocean crust using newly developed survey methods and analysis techniques. In a modification of conventional near-bottom magnetic survey methodology, *Nautile* surveyed a vertical cross section of ocean crust on the Blanco Scarp at the western end of the Blanco Transform (part of the Juan de Fuca Ridge, in the northeastern Pacific). This scarp had previously been mapped with high-resolution sidescan sonar on a 1987 cruise with John Delaney (University of Washington) as chief scientist. The 1991 *Nautile* dive was led by Thierry Juteau (Université de Bretagne Occidentale, Brest, France) aboard *Nautile*'s mother ship, *Nadir.*

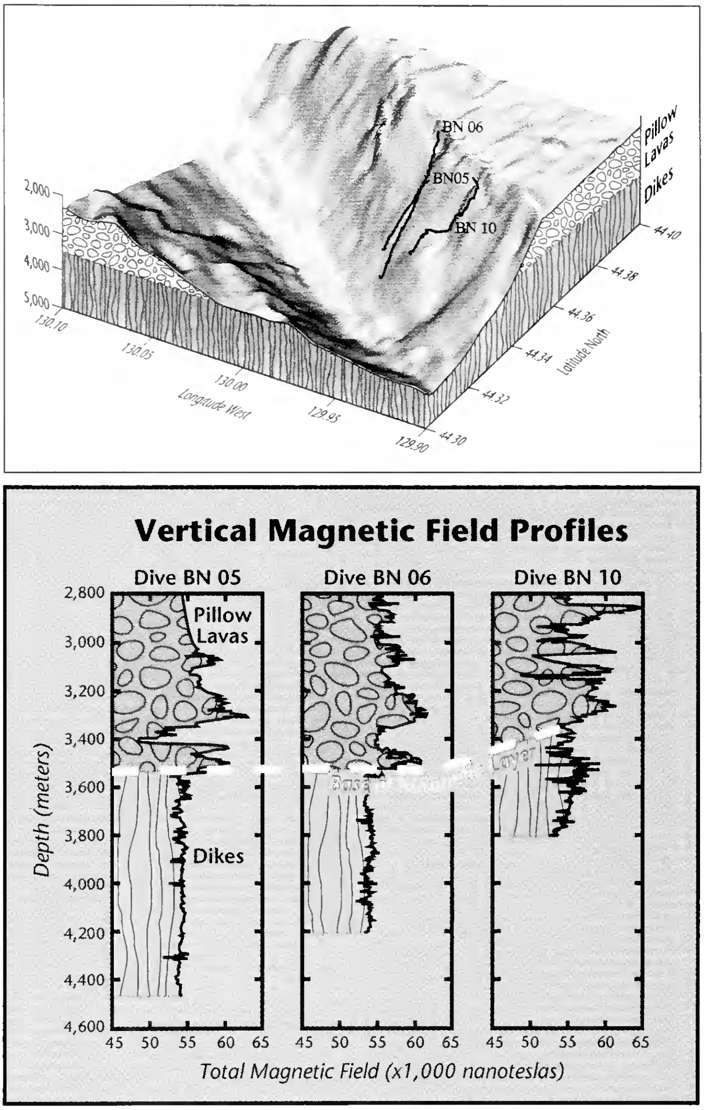
Out of about 24 *Nautile* dives, 13 were focused on the scarp face itself. Magnetic data were collected on 14 dives, and 242 rock samples were recovered. Navigation was provided by a transponder system, and the 1987 sidescan map provided an excellent "base map" for planning dives and navigating the submarine. The geological and petrological observations of the dive program divide the scarp into:

- a lower intrusive dike section, from the base of the scarp to 3,400-meters depth,
- a rubble slope where some highly fractured pillow-lava flows outcrop, and
- an upper basaltic pillow-lava section, from 3,300 meters to the top of the scarp at 2,200 meters.

These studies provide an excellent geological framework for interpreting the magnetic data collected. The magnetic data show a remarkably coherent picture. The figure below shows the total magnetic field recorded during three vertical traverses up the Blanco Scarp face. The most outstanding feature of these profiles is the dramatic increase in the magnetic field at approximately 3,400 meters depth. This magnetic anomaly coincides perfectly with a transition from dikes to pillow lava that was observed from the submersible, and the magnetic character is consistent with models of a highly magnetic pillow-lava section and a relatively low-intensity intrusive-dike section, and with data collected from the surface. Preliminary analysis indicates, then, that a majority of the source of the sea-surface magnetic anomaly pattern lies with the extrusive section, at least for 1-million-year-old crust.

We conclude from these two case studies that near-bottom magnetic field studies utilizing a submersible platform can provide new information on the nature and structure of oceanic crust that is not currently obtainable any other way. The results of the *Alvin* magnetic survey show the presence of a narrow, pipelike body of demagnetized crust directly beneath the mound, inferred to reflect the upflow zone that channels the hydrothermal fluids to the surface there. The *Nautile* magnetic survey shows the occurrence of a distinct anomaly at the pillow-dike transition on the scarp, and provides new constraints on the source of the "magnetic

Three of Nautile's *dive tracks are superimposed on this relief view of the Blanco Scarp, looking northwest. Observations from the submersible indicate that the crust is composed of pillow lavas and dikes as shown schematically below the relief (top). Magnetic field measurements made along these dive-track lines are shown (bottom). The sharp increase in magnetic field intensity (between 3,400 and 3,500 meters depth) correlates almost exactly with the change from dike rocks to pillow lavas. This magnetic-field boundary is thought to represent the base of the magnetic source layer that creates the magnetic stripes of the ocean floor.*



Jack Cook/WHOI Graphics

stripes." Both surveys demonstrate the value of measuring the near-bottom magnetic field during submersible dives on oceanic crust to complement conventional observations from the sea surface.

Editor's Note: As we went to press, author Tivey was participating in another set of *Nautile* dives to measure the magnetism of deep oceanic crustal layers (gabbros) exposed in the Kane Fracture Zone on the Mid-Atlantic Ridge.

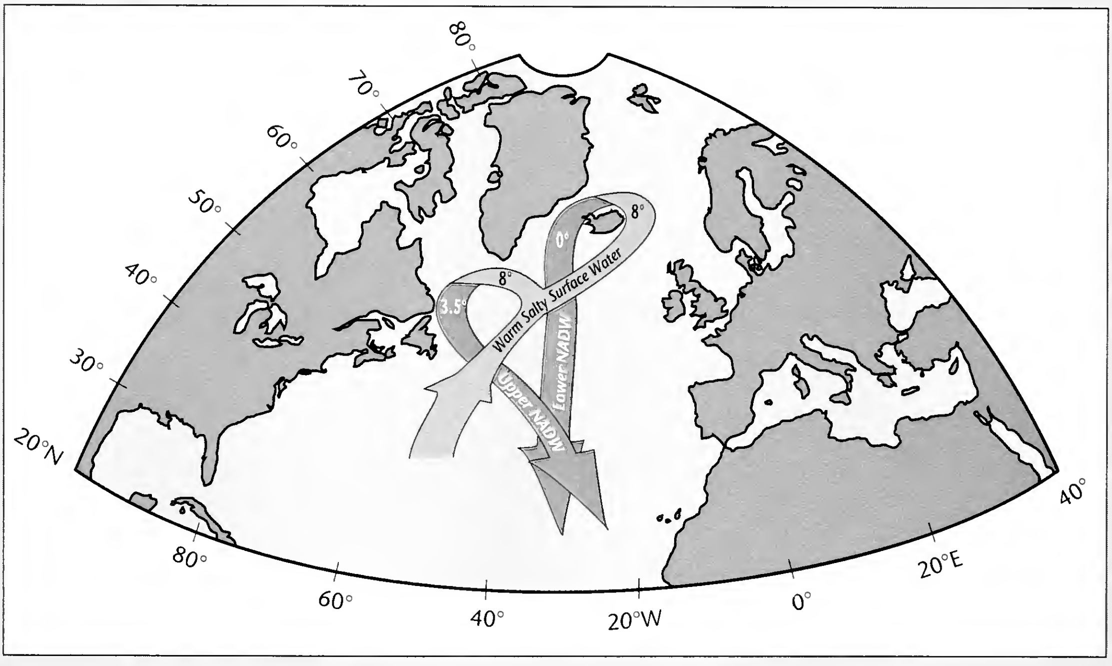
Maurice Tivey, the son of a 22-year veteran of the British Royal Navy, was told by his father not to choose a life at sea—it was an arduous life. Armed with this advice he opted to study geology at Dalhousie University in Nova Scotia and rock magnetism at the University of Washington in Seattle. Little did he realize that this course of study would lead to 18 major research cruises and a position on the staff as Assistant Scientist at the Woods Hole Oceanographic Institution.

Hans Schouten was educated in Holland and received his marine geophysical training aboard Dutch freight ships carrying Heineken with great urgency and speed (16 knots) to Caribbean isles and South American republics and dictatorships. He left this frantic pace for a more sedentary science in the US where he began applying fast Fourier transforms to the magnetics and roughness of the seafloor. Since then, he has quit smoking, collected 10 children, and has become obsessed with rapidly rotating microplates.

Deep-Sea Sediments Reveal...

ONE IMPORTANT PREREQUISITE for understanding humankind's impact on Earth's climate is making a determination of the nature and causes of substantial climate changes known to have occurred in the past, prior to human intervention. Although often difficult to obtain, information about ancient climates is recorded in deep-sea sediments, lake sediments, and ice. For instance, recent studies of Greenland ice cores revealed that large, swift changes in atmospheric temperature occurred at the end of the Last Ice Age. Average temperatures changed about 7°C in 50 years, a rate of more than 1°C per decade. Similar shifts characterize the ice-core record every few thousand years between about 80,000 and 8,000 years ago, and thus appear to be a characteristic feature of Earth's climate. Though temperature changes can be caused by orbital variations that affect the amount of solar radiation Earth's surface receives, this phenomenon occurs too slowly to account for the frequency or abruptness of the changes seen in ice cores.

According to a theory popularized by Wallace Broecker (Lamont-Doherty Geological Observatory), sudden transitions between warm and cold climate may have been driven instead by changes in the heat-carrying capacity of the Atlantic Ocean, at the driving end of



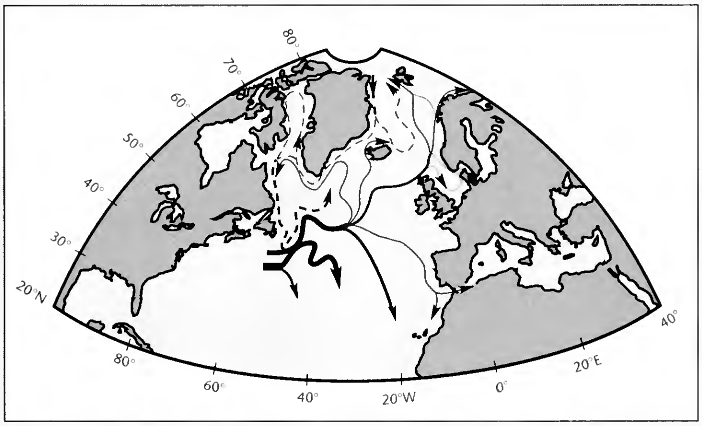
Jack Cook/WHOI Graphics

The "driving end" of the Great Ocean Conveyor shows the conversion of warm, salty Gulf Stream waters to cold, salty deep waters. Heat lost to the atmosphere during this conversion warms the circum-Atlantic region. North Atlantic Deep Waters round the Antarctic continent and then upwell at various locations in the Pacific to return to the Atlantic as surface or near-surface currents, thus completing the conveyor circuit.

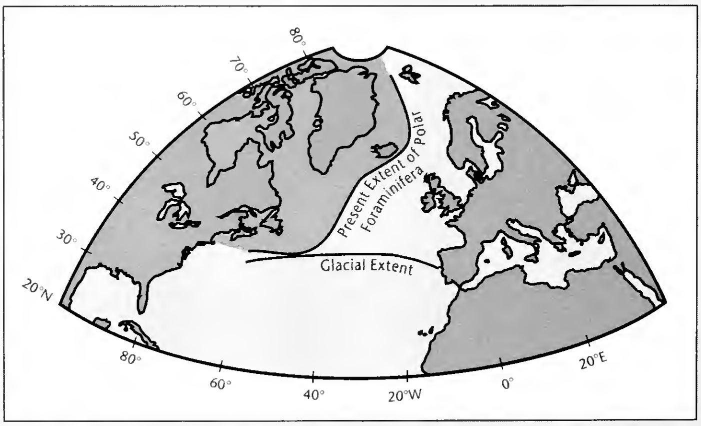
SCOTT J. LEHMAN AND LLOYD D. KEIGWIN
Woods Hole Oceanographic Institution

...the History of the Great Ocean Conveyor

a whole-ocean circulation scheme he has called the "Great Ocean Conveyor." The conveyor's major features are set up by sinking of northward flowing, warm Gulf Stream waters in the northern Atlantic Ocean and Norwegian Sea. Gulf Stream waters become enriched in salt due to evaporation as they pass through warm latitudes. As these waters flow toward cooler latitudes they release heat to the atmosphere, become dense, and sink. The newly formed deep waters flow south (Upper and Lower North Atlantic Deep Water), filling much of the deep ocean, and more warm water is drawn northward at the surface to replace the water exported at depth. This "heat engine" drives the northward penetration of relatively warm surface waters in the northeastern Atlantic Ocean and Norwegian Sea, and results in the presently hospitable conditions in Britain and Norway, as contrasted to those at equivalent latitudes in Greenland and Canada. However, under the conditions that prevailed during much of the Last Ice Age, certain elements of the conveyor were shut down, depriving the northern Atlantic region of ocean-borne heat. If Broecker is right, and shutdowns of the conveyor promoted the sudden temperature changes seen in ice cores, they ought also to be evident as changes in deep-sea sediments. Until now, however, directly verifying these changes has not been possible because typical oceanic sediments accumulate much too slowly to resolve such brief events. However, by studying sediments recovered from a deep channel off the southwestern coast of Norway, where mud accumulated at rates some 100- to 500-times greater than the ocean average (due to glacial erosion on the adjacent continent), we have recently been able to read the record of the shifting conveyor.



The present-day flow of relatively warm surface waters into high-latitude regions of the Atlantic Ocean and Norwegian Sea (solid line, above) corresponds to the limited range of polar Foraminifera (dark-blue area, below). At the height of the Last Ice Age, polar Foraminifera extended their range greatly, indicating that the poleward flow of warm water was cut off. At the close of the Ice Age, the front between polar and temperate waters swept back and forth to produce the time-dependent changes seen in Norwegian Channel sediments reflecting air temperatures over Greenland. These changes are compared graphically on the facing page.

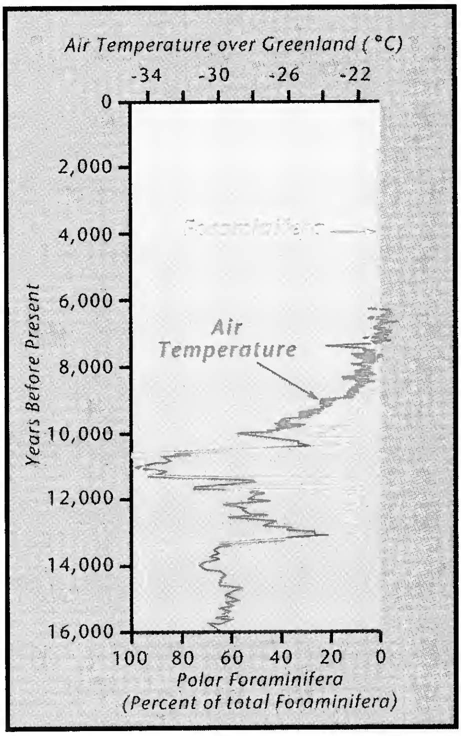


Jack Cook/WHOI Graphics

Planktonic Records Help Reconstruct Conveyor History

To track past changes in the Gulf Stream's strength and trajectory, we use a conventional technique based on the present-day temperature tolerances of living communities of planktonic Foraminifera (microscopic shell-forming animals living near the surface of the open ocean; see page 98). Today the action of the conveyor draws warm Gulf Stream waters, and hence temperate Foraminifera, into high latitudes in the northeastern Atlantic Ocean and eastern Norwegian Sea. The frigid waters around Greenland and in the Arctic support only polar Foraminifera. By counting the abundance of different types of foraminiferan shells in sediments deposited throughout the northern Atlantic during the Last Ice Age, other researchers have shown that polar Foraminifera had greatly extended their range to the south; the Gulf Stream must have then flowed more-or-less straight across the Atlantic toward Portugal, rather than northward, toward Norway. This largely cut off the poleward flux of oceanic heat, contributing to the establishment of frigid air temperatures and the growth of continental ice caps and sea ice.

Our studies of planktonic Foraminifera in sediments from the Norwegian Channel revealed changes in surface circulation during the recovery from the Last Ice Age with almost unheard-of resolution. We dated the changes in Foraminifera using a recently developed radiocarbon-dating technique called accelerator mass spectrometry, which permits direct counting of carbon-14 atoms in the shells (see Oceanographer's Toolbox, page 93). Using the carbon-14 dates to plot our results against age, we found that the history of circulation change was remarkably similar to the air-temperature changes recorded in Greenland ice cores. Even more remarkably, we found that the most abrupt transitions in our record spanned fewer than 40 years of sedimentation. As polar Foraminifera live only in waters colder than about 10°C and constitute more than 95 percent of the population in waters colder than about 5°C, the largest changes in Foraminifera correspond to temperature shifts of 5°C or more. Using these estimates along with the dating, we calculated rates of sea-surface temperature change in excess of 1°C per decade! These phenomenal rates of change are similar to those recorded in the ice cores and, now, in



Jack Cook/WHOI Graphics

There is correlation between air temperatures over Greenland (deduced from oxygen-isotope variation in ice cores) and radiocarbon-dated changes in abundance of polar Foraminifera (expressed as a percentage of total planktonic Foraminifera) in a marine sediment core from the Norwegian Channel, in the northeastern corner of the North Atlantic. The larger faunal shifts correspond to sea-surface temperature changes of more than 5°C and occurred within fewer than 40 years.

models of ocean circulation played out on supercomputers.

Why Does the Great Ocean Conveyor Change Over Time ?

Early in his effort to understand the machinations of abrupt climate change, Broecker noted that the salt content of Gulf Stream waters was critical to the sinking and deep-water formation that drives the conveyor. Perhaps excess freshwater runoff (from increased precipitation, decreased evaporation, or melting of snow and ice) might reduce surface-water salt content to levels below those compatible with sinking, turning off the conveyor and the associated northward flow of heat. Following his lead, ocean modelers found that once they were able to simulate deep-water formation on their computers, only very slight freshening of the surface brought the conveyor to a halt. The models are likely to be more sensitive than the real ocean; left unattended they run too fresh and tend not to form deep water (so much so that at an international meeting, Broecker presented one of the leading modelers with a household salt shaker!). Nevertheless, the models point out that fresh water may have a powerful influence on the conveyor's vitality.

Of the various limbs of the ocean conveyor, the Norwegian Sea limb is most effective in warming the atmosphere as surface waters undergo a larger degree of cooling (heat release) prior to sinking. It may also be the most vulnerable. Our studies show that as the Last Ice Age was coming to a close and continental ice caps were melting, the Norwegian limb of the conveyor was periodically shut down, leading to sudden shifts in sea and air temperatures. The open-ocean limb appears to have survived in some form even during ice ages. One possible explanation for this difference is that runoff is concentrated in the restricted basin of the Norwegian Sea rather than being mixed by the currents of the open Atlantic Ocean.

Our results provide direct evidence that changes in the Great Ocean Conveyor governed air temperatures around the Atlantic region. The magnitude of these changes was some three- to five-times greater than experienced during the Little Ice Age (generally considered to be 1450 to 1890), a time during which those who were not starving enjoyed good skating on the Thames and ice fishing in Scotland. We marvel at the development of human civilization during the climatically quiet times of the last eight millennia, and we take for granted the constancy of the oceans. But our results indicate that there have been times when the ocean dealt hard. It will be interesting, and possibly scary, to see how the ocean will respond to the new "greenhouse world." Such changes in atmospheric chemistry have not been witnessed since the end of the Last Ice Age. ❄

In response to ineluctable demographic forces, Scott Lehman was conceived not far from New York in an atmosphere of post-war euphoria. Life was comfortable but boring in suburbia. Following a somewhat-delayed pubescence, the growing tide of testosterone was sublimated in the mountains (which even his parents admitted was more constructive than burning down ROTC buildings). Climbing and a few other minor personality flaws have confounded his academic and personal life ever since. He is currently an Assistant Scientist in the Geology and Geophysics Department at Woods Hole Oceanographic Institution (WHOI).

Lloyd Keigwin is an Associate Scientist in the Geology and Geophysics Department at WHOI, and a sometime naval officer. With undergraduate training at Brown University and graduate degrees from the University of Rhode Island, he grew up by the sea and likes chowder—two things that should never be admitted to when applying to graduate school in oceanography.

Oceanographer's Toolbox

Accelerator Mass Spectrometry

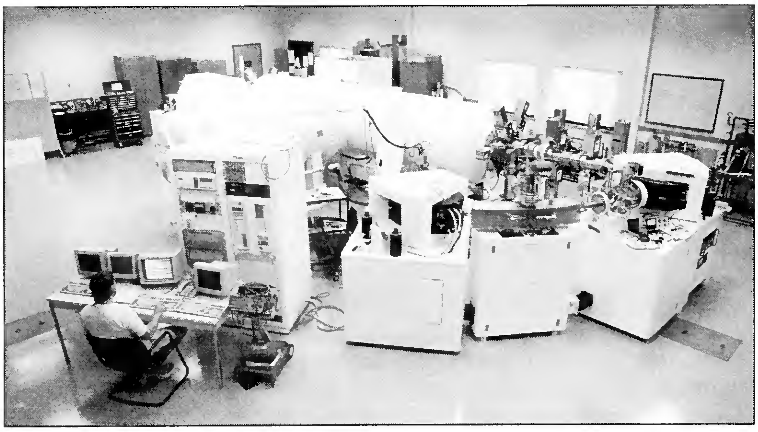
Tracking Carbon in the Marine Environment

Robert J. Schneider and Glenn A. Jones

The latest in accelerator technology is now available to marine scientists interested in the oceanic carbon cycle. At the National Ocean Sciences Accelerator Mass Spectrometry Facility at Woods Hole Oceanographic Institution, scientists can trace oceanic circulation, determine the age of seafloor sediments, and track nutrient flow from surface waters to the benthic environment with unprecedented precision and accuracy. Known as accelerator mass spectrometry (AMS) since its development at the University of Rochester in 1977, this technique combines classical mass spectrometry, which separates atoms or molecules by mass, with a high-voltage accelerator, which dissociates them into atomic ions of different charge states. AMS actually counts atoms of a selected mass and charge state from suitably prepared samples. It is practically 1,000 times more sensitive than counting radioactive decays from a carbon-containing sample, the method developed by Willard Libby in 1950.

In the global carbon cycle, the major reservoirs are the oceans (including ocean sediments), the terrestrial biosphere (plus sedimentary rocks), and the atmosphere. Carbon occurs in nature almost entirely as carbon-12, with only 1.1 percent as carbon-13 and one part in 1,000,000,000,000 as carbon-14 for modern materials. The origins of these three isotopes are quite different. The stable isotopes, carbon-12 and carbon-13, are derived from Earth's mantle, and released when carbon-bearing rocks weather at the surface. Organic matter deposited millions of years ago and used today as fossil fuel (oil, natural gas, and coal) contains only these two carbon isotopes. Small differences in the stable-isotope ratios result from diffusion and photosynthesis, and lead to lower carbon-13 levels in fossil fuels and vegetation than in the atmosphere and oceans. Stable-isotope mass spectrometry measures these subtle differences, a few parts per thousand, and distinguishes organic from inorganic carbon in the marine environment.

The unstable isotope, carbon-14, is produced continuously in the upper

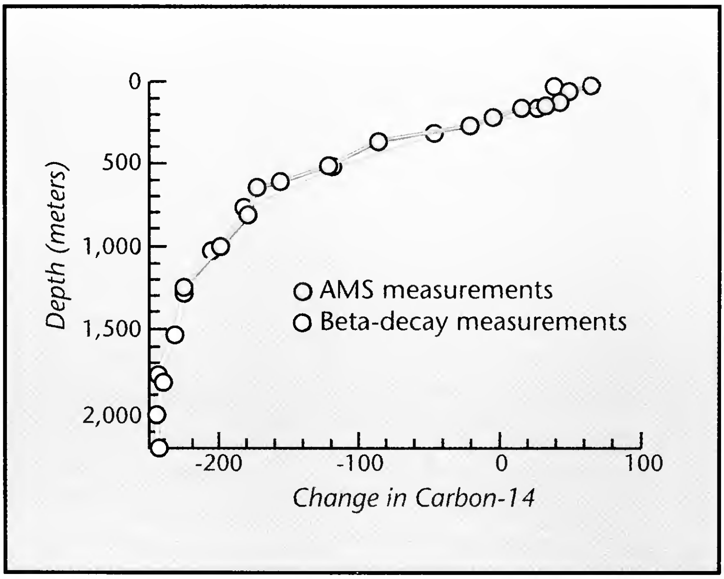


Tom Kleindinst/WHOI

A view of the Accelerator Mass Spectrometry Lab. Samples are loaded into the ion source at the extreme left. The long tank is a pressure vessel, containing the 3-million-volt accelerator with its power supply. The emerging ions are analyzed by the magnets in the foreground.

atmosphere, mostly by the interaction of cosmic rays with nitrogen. In modern times, it has also been produced as a byproduct of nuclear power and nuclear weapons testing. Its half-life of 5,730 years makes it useful as a tracer and for dating purposes, with limits set only by the available concentration and the sensitivity of the measurement technique. Since the 1960s, the carbon-14 (and also tritium or hydrogen-3) injected into the atmosphere and ocean by nuclear weapons tests has been useful for studying oceanic/atmospheric mixing and ocean circulation. A 1-milligram sample of organic carbon from the "prebomb days" contains about 50,000,000 carbon-14 atoms. In an hour, on average, only one of these atoms decays back to a nitrogen atom. Radiocarbon dating by counting the electrons emitted during these so-called beta-decays therefore requires a large sample and a long counting time to obtain enough detector counts for a precise age estimate.

The modern AMS technique is equivalent to counting the atoms in the sample and sorting them into three bins, according to their mass and charge. This requires them to be dissociated from any molecules and ionized into a unique charge state. It relies on the fact that carbon-14 readily forms a negative ion, whereas nitrogen-14, its closest competitor for mass selection, does not. (In fact, the early workers were looking for negatively charged nitrogen-14 when they realized the importance of this fact.) Samples can be prepared from any carbon-containing material, whether a shell carbonate, dissolved inorganic carbon dioxide in seawater, an organic fraction from a sediment, or an archaeological artifact. The sample is acidified or combusted to produce carbon dioxide, which is then completely reduced to solid graphite at high temperature in a small reactor. The solid graphite is then placed into the cathode of a device called a cesium sputter ion source. Negative ions are emitted when the graphite is bombarded by cesium.



Jack Cook/WHOI Graphics

The samples for this depth profile for carbon-14 concentration in the North Pacific Ocean were collected on a WOCE cruise in 1991 from a station at 47°N, 152°W. The red circles are AMS measurements on 0.5-liter samples, and the yellow circles are large-volume (242-liter) samples that were counted with the beta-decay method for comparison. The measured carbon-14 concentrations are expressed as differences in parts per thousand from a modern (1950) standard.

Carbon atoms and molecules such as CH and CH_2 (called hydrides) emerge from the ion source as a beam of negatively charged ions. A series of magnets splits the beam, permitting only particles with masses 12, 13, and 14 having a single negative charge to be injected into the accelerator. The three masses are simultaneously injected into the first acceleration region where they are accelerated to an energy of 2.5 million electron volts. There they pass through an argon gas canal where collisions with the argon atoms cause four electrons to be removed from each atom. Any molecules (such as hydrides) are also broken down into atoms at this point. Losing electrons converts each atom into a triple-charged, positive ion. The ions then pass into the second half of the accelerator region and obtain a kinetic energy of 10 million electron volts and a velocity 4 percent of the speed of light (12,000 kilometers per second). At this point the ions exit into the analyzer region. The beam is magnetically split again: Positively charged carbon-12 and carbon-13 ions are detected in charge collectors (called Faraday cups) while carbon-14 ions pass through more electrostatic and magnetic filtering and into an ultrasensitive gas ionization detector. There they are individually counted. The counting rate for a modern sample is about 80 per second (or 288,000 per hour), compared to 1 beta decay per hour using the old technique.

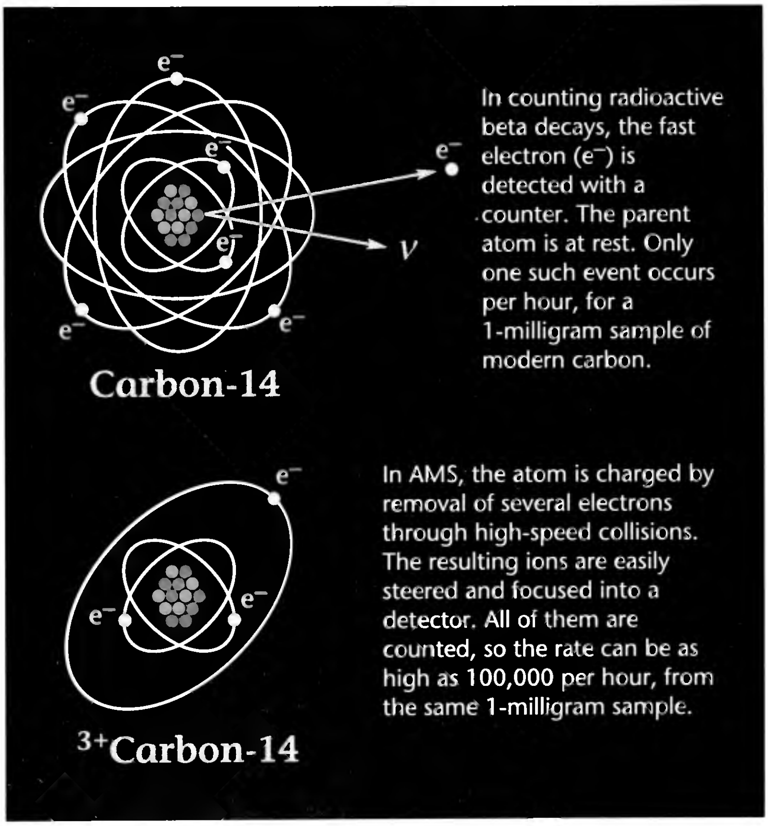
The AMS system at Woods Hole became operational in 1991, and has already demonstrated 0.5 percent precision for measuring modern carbon-14/carbon-12 ratios. Only 1 milligram of carbon is required, an amount small enough to make AMS useful in a wide range of applications. For instance, 240-liter barrels of seawater are no longer necessary for radio carbon analysis, as they were 20 years ago. Also, the dating of small quantities of plankton and Foraminifera is now possible.

The most ambitious AMS sampling program to date is under way with the World Ocean Circulation Experiment (WOCE). Scientists in this program are collecting seawater samples from many depths at stations across the world's oceans. Dissolved inorganic carbon dioxide is extracted from water samples as small as 100 milliliters, then reduced for analysis to a few milligrams of graphite. These carbon-14 measurements will provide scientists with a three-dimensional picture of ocean circulation, as well as details on ocean/atmosphere exchange processes.

In addition to seawater samples, the AMS system has been used to measure carbon-14 concentrations in coastal and lake sediments, shell carbonates, and corals. Together with known temperature ranges of certain marine species, these data can yield climate-change information going back almost 50,000 years, the current limit of the technique. As an example, planktonic Foraminifera extracted from different depths in a box core collected from the Norwegian-Greenland Sea were dated to identify the time and locus of Northern Hemisphere deglaciation.

All of these data will provide marine scientists and those who model climate change with the ability to measure carbon-exchange rates between the environmental reservoirs. The facility was established and is supported by the National Science Foundation, Division of Ocean Sciences.

Robert J. Schneider is a Senior Research Specialist and Glenn A. Jones is an Associate Scientist in the Geology and Geophysics Department at Woods Hole Oceanographic Institution.



In counting radioactive beta decays, the fast electron (e^-) is detected with a counter. The parent atom is at rest. Only one such event occurs per hour, for a 1-milligram sample of modern carbon.

In AMS, the atom is charged by removal of several electrons through high-speed collisions. The resulting ions are easily steered and focused into a detector. All of them are counted, so the rate can be as high as 100,000 per hour, from the same 1-milligram sample.

Carbon-14 atoms are produced in the upper atmosphere when cosmic-ray neutrons interact with nitrogen-14 nuclei. During the next 5,370 years, known as the half-life, there is a 0.5 probability that the carbon-14 will decay back to a nitrogen atom, by a process known as beta decay, where a neutron within the nucleus gives off an electron (e^-) and a neutrino (ν) to become a proton. Normally a carbon atom has six electrons surrounding the nucleus, which neutralize its six protons. If it has an extra electron, it is called a negative ion. If it loses electrons it is called a positive ion. Ions can be guided by electric and magnetic fields.

Creature Feature

So You Thought Extinction was Forever?

Richard D. Norris

Imagine living in glue. You swim in it, breathe it, release waste into it, and try your hardest to catch your lunch in it. All the while the stuff adheres tenaciously to you. That's life in the world of the Protozoa, an enormous group of diverse microscopic, mostly single-celled creatures. It is tough enough for us to swim in the ocean, but to a creature half the size of the period at the end of this sentence, water is as sticky as Elmer's glue. Turn off the engines on the *Queen Elizabeth II* and she coasts for a kilometer or so before stopping, but a microbe jerks to a halt the instant it stops swimming. A microbe's world is an alien place. Equally curious in this alien world is the peculiar evolution of one group of marine Protozoa, the planktic Foraminifera.

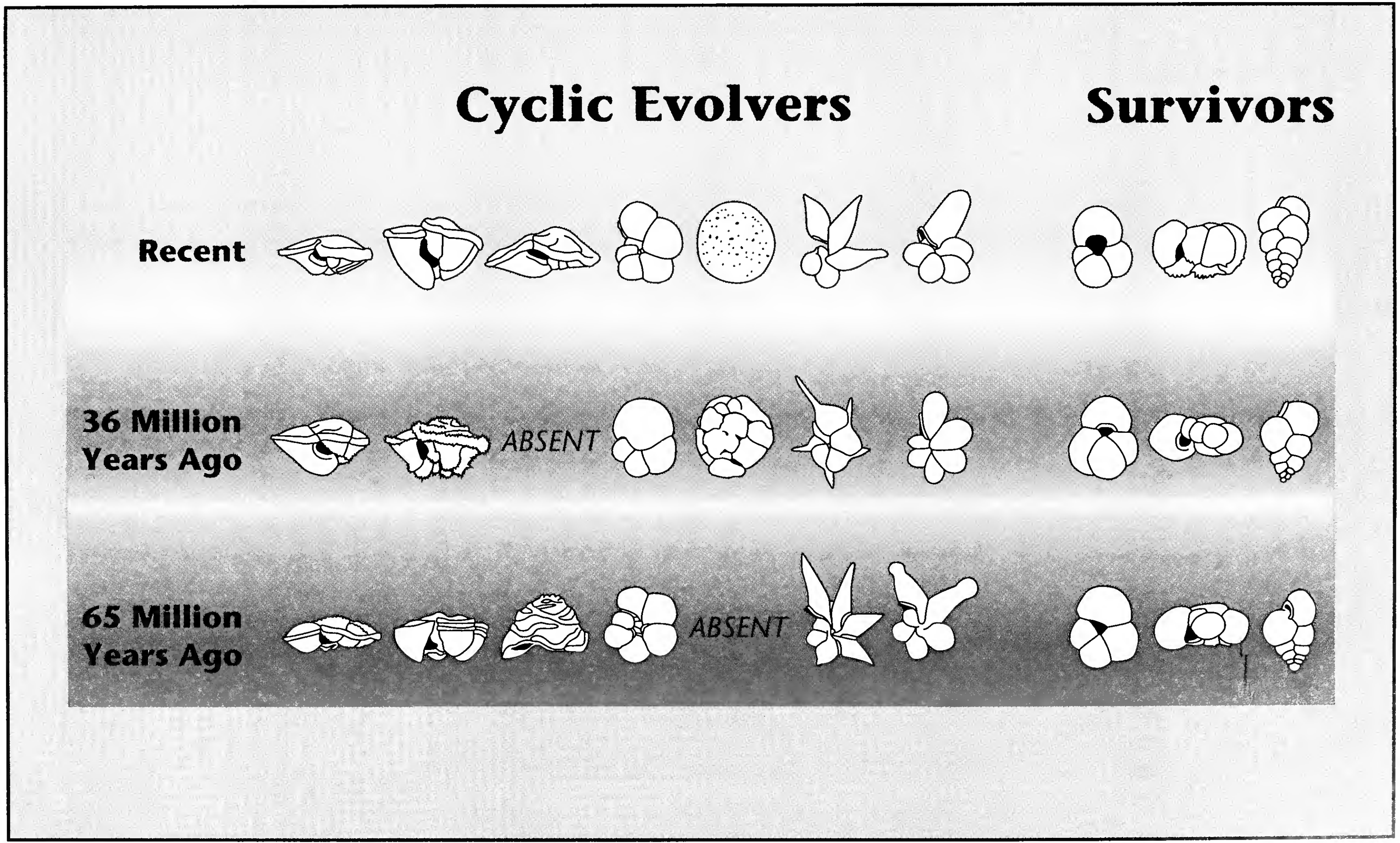
Like dedicated customers, planktic Foraminifera have stuck with the tried-and-true. These microbes suffered massive extinctions that repeatedly wiped out nearly all species. Yet when the dust settled, they bounced back to recreate the same body shapes and evolutionary patterns that had vanished in the previous mass extinction.

Planktic Foraminifera use long extensions of their cytoplasm to snare tiny photosynthesizing protozoans and microscopic animals for food. They float in the plankton their entire lives, then die and settle to the seafloor where they form the ubiquitous foraminiferal "ooze" that coats the sea bottom. "Foraminifera" refers to the openings, or foramina, that connect the individual chambers in the shell of each organism. Their microscopic shells are extremely abundant in deep-sea sediments. Indeed, a blob of sea-bottom mud contains millions of fossils. The sequence of changes in these fossils over time is an important tool for dating events in the history of the oceans.

The cyclic evolution of planktic Foraminifera went unnoticed by early workers on these protozoans in the 1930s and 1940s. It was thought that several living groups were extremely old, some closely related to look-alike ancestors that first appeared over 160 million years ago. This view began to change in the 1960s when it was discovered that there had been major extinctions about 65 million years ago and again about 36 million years ago. At both times, nearly the entire variety of skeletal shapes of these plankton became extinct. The party nearly ended for good 65 million years ago. Apparently only two or three species survived this extinction—the same event that swept away the dinosaurs.

However, like Lazarus, the Foraminifera seemingly rose from the dead. After each period of extinction, a few survivors repopulated the oceans, replicating the general shapes of their predecessors from before the extinction. Although not identical, the skeletal shapes from these repopulations are similar enough to duplicate the variety of body types that evolved earlier, and in many cases they are very close matches.

The similarities do not stop with a general correspondence between skeletal shapes. It is well known that some types of organisms die out less often than others: For example, clams become extinct relatively rarely

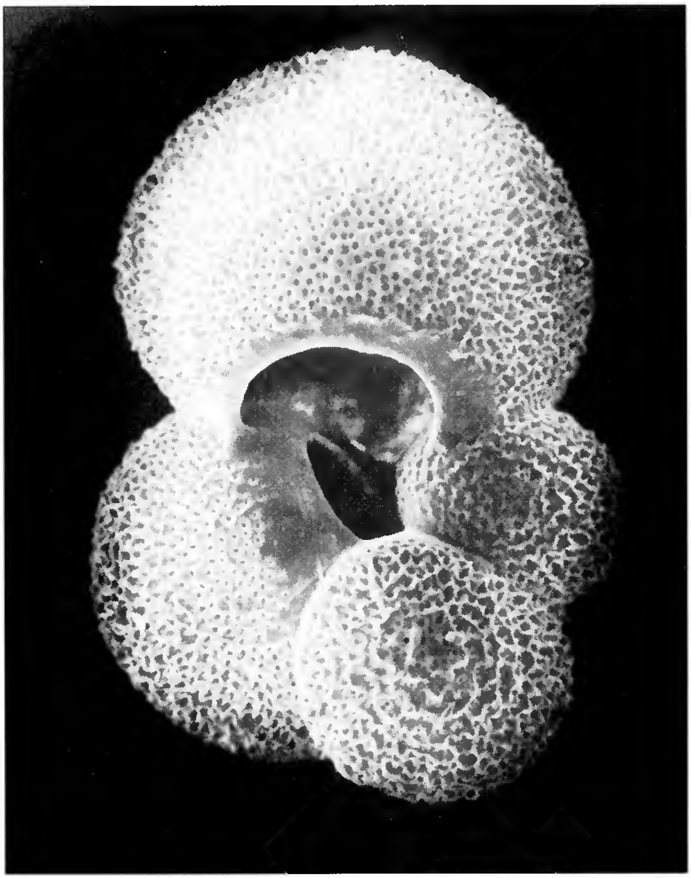


Jack Cook/WHOI Graphics

During the last 100 million years, three major radiations or "repopulations" of planktic Foraminifera have occurred. Representative species from each of these repopulations are shown. "Survivors" are species and body shapes that survived from one repopulation to the next, then served as founders to a succeeding repopulation. "Cyclic evolvers" are species and body shapes that became extinct, then independently evolved during each repopulation phase.

compared to mammals. As a group, planktic Foraminifera fall between these extremes. However, when grouped by their body shapes, some appear and disappear much faster than their relations in other groups. Species with globular skeletal shapes tend to last a long time—on average, about 12 million years—while their peers with more discoidal shapes last only about half as long. In each of the three major periods of repopulation that planktic Foraminifera have experienced, a species' shape and longevity are linked. Not only that, but their size ranges are also predictable. Survivors of the extinction 65 million years ago were hardly larger than the diameter of a human hair, but from these diminutive ancestors evolved species as much as a millimeter long—giants by protozoan standards. Similar patterns of evolution from small-sized survivors to larger descendents also followed the other evolutionary expansions.

Why all the duplication? Might it be that Foraminifera are just tracking cyclic changes in their environments? Attractive as this idea may be, there does not seem to be strong environmental cyclicity to explain the patterns. Oceans of 70 million years ago were vastly different from those of today: They were more like warm puddles than cool, free-flowing seas. There were no large glaciers at the poles to cool polar waters and drive the flow of cold, deep waters that we see today. Deep-ocean water temperatures have declined with fits and starts during this entire time, giving no hint of cyclicity.


Howard Spero/University of California, Davis

At the end of a foraminiferan's life cycle, it slowly drops its spines and releases reproductive gametes. After gamete release, the shell is empty and it gradually settles to the ocean bottom, where it becomes part of the fossil record. This is Globigerina bulloides *after it released gametes in the laboratory. The actual shell size is .35 millimeters.*

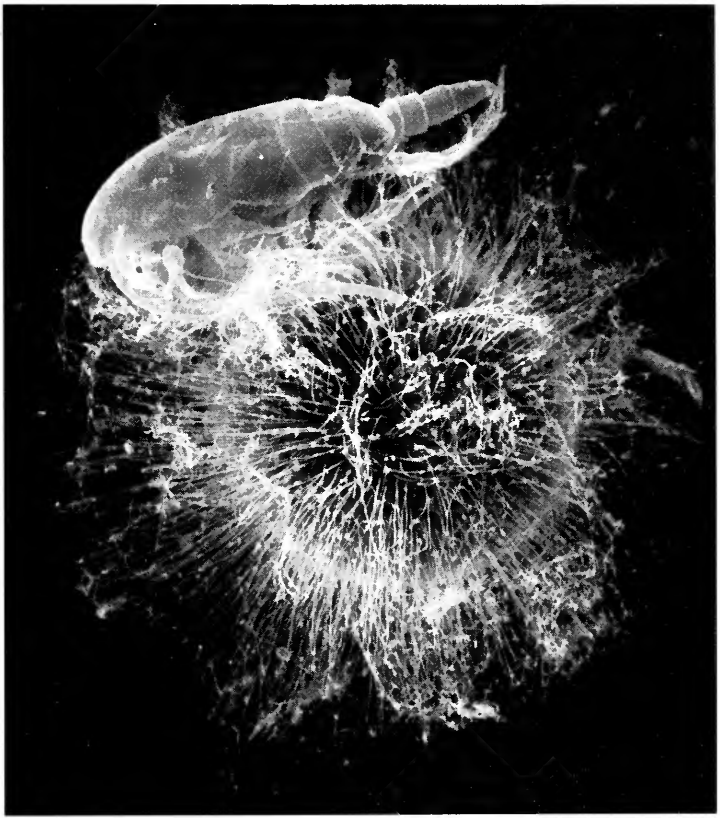
Perhaps instead of cyclic controls, we should look to features that have displayed little or no change over time. After all, Foraminifera have not seemingly changed much, at least in their general shapes and evolutionary patterns. To them, water has always been as thick as molasses, the oceans have generally been layered by differences in temperature and saltiness, and there has been a range of habitats, from rich coastal waters overflowing with life to blue-water "biological deserts." Hence, a similar array of opportunities for life has almost always existed in the protozoans' world.

When planktic Foraminifera nearly became extinct 65 million years ago, the survivors reemerged into a world similar to the one they had known before the cataclysm. This extinction has been firmly linked to the impact of a meteorite, the debris of which has now been found the world over. The biological world was turned upside down, but the basic variety of physical habitats was reestablished quickly. Planktic Foraminifera invaded these environments anew after a readjustment period that lasted several million years.

The extinction around 36 million years ago lasted about 10 million years, and was seemingly triggered by a wholesale switch in ocean circulation and the initial formation of large glaciers on Antarctica. These changes temporarily altered the variety of habitats in the oceans' surface waters and lead to the demise of species accustomed to living in warm waters. With the renewal of such habitats by roughly 20 million years ago, planktic Foraminifera expanded their range of body shapes once again. This repopulation happened despite the permanent switch from a "greenhouse" world prior to the extinction to the "icehouse" world we now call home.

Planktic Foraminifera are not unique in their tendency to duplicate earlier patterns of evolution. The ammonites, whose pearly spiral shells closely resemble those of the chambered nautilus, repeatedly came close to extinction and then repopulated the oceans. Like the Foraminifera, each phase of evolutionary expansion replicated conch shapes that had disappeared for a time. The same thing has also happened in oysters, which have repeatedly evolved massive, boat-shaped shells appropriate for resting on muddy bottoms.

All of these groups repeatedly arrived at the same solutions to exploit persistent opportunities. It may also be that life in "glue" limits the variety of shapes Foraminifera can assume, or perhaps their simple genetic organization holds them back. Whatever the explanation, to these microbes the world has always been a sticky place—unappealing to us, perhaps, but sufficiently attractive to a protozoan to warrant going back time and time again.



Howard Spero/University of California, Davis

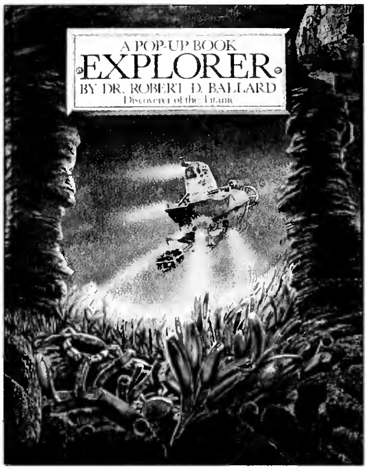
Orbulina universa *is a spinose planktonic foraminiferan whose spines are typically 2 to 2.5 millimeters long, and are covered with a thin layer of sticky cytoplasm. Marine organisms (such as the calanoid copepod shown) that accidentally swim into the foraminiferan's spines are snared by the stickiness, and are slowly drawn to the shell surface where they are digested. The shell of this individual is .5 millimeters.*

Richard D. Norris has been a condor-watcher in the California foothills, director of a land reserve in the Mojave Desert, and a collector of beat-up clam and snail shells while studying long-dead things at the University of Arizona. A thesis on cyclic evolution of marine protozoans at Harvard led him to Woods Hole, where he is currently an Assistant Scientist in the Department of Geology and Geophysics.

Editor's Note: Rich Norris uses "planktic," derived from the Greek word for "floating around," in preference to the more-familiar (but incorrectly translated) "planktonic" found in most American dictionaries.

Explorer

A Pop-Up Book



By Robert D. Ballard, illustrated by James Dietz, 1992. Turner Publishing, Inc., Los Angeles, CA; 20 pp. - $19.95.

Robert Ballard, director of WHOI's Deep Submergence Laboratory and leader of cruises in 1985 and 1986 that led to the discovery and exploration of the sunken oceanliner *Titanic,* is a legendary figure to thousands of young children across the country.

Many children who know of his work wish they could accompany him on his exploits, to go where he has gone, to see what he has seen. His new pop-up book provides ample fuel for some armchair fantasizing. Each spread in the book describes a different underwater mission in which he has been involved. The pop-up format is highly interactive. On the spread about the discovery of the *Titanic,* for example, there are no fewer than four separate activities, including one that explains the movements of ROV *Jason, Jr.* (the mini-telerobotic vehicle that traveled all over the doomed luxury liner, videotaping the condition of its ruined majesty). A flap that can be lifted shows both what *Titanic* looked like before it sank, and a map of where it met its end. A three-dimensional pop-up illustration shows the hull of the ship, with tiny DSV *Alvin* traveling beside it. And a movable depth chart shows how far down *Alvin* had to travel to reach *Titanic.* Altogether, there are sixteen different "interactive illustrations." Topics covered include Project FAMOUS, explorations of hydrothermal vents and the Cayman Trough, a mission on *NR-1* (the world's smallest nuclear-powered submarine, operated by the US Navy), and the JASON Project, in which Ballard and others have offered live satellite transmissions of deep-sea explorations to groups of children across the US.

Usually pop-up books appeal to younger children, from the ages of four to six. I would recommend this for somewhat older children, such as Alex (age seven) who found it fascinating. Indeed, I'd recommend it for anyone who would enjoy a crab's eye view of deep-sea exploration.

—Deborah Kovacs
Author, childrens' literature and Editor, *Ocean Explorer,* the newsletter for Young Associates of the Woods Hole Oceanographic Institution

The Beaches Are Moving

A Video Featuring Orrin Pilkey

1990. Environmental Media, Chapel Hill, NC; 60 min. - $29.95 (home use)/$69.95 (institutional use).

Publicity on the greenhouse effect and its possible acceleration has focused interest on sea-level rise, and its potential effects on the world's coasts. Recent severe storms (in the US, Hurricanes Hugo and Bob, as well as the severe Halloween storm of 1991) have emphasized the exposure of development along the coast to damage and destruction. Debate continues to rage over what is the rational human response to the continued threat of coastal damage.

The Beaches are Moving, a video featuring well-known coastal geologist and beach activist Orrin Pilkey, presents a clear view of coastal development and its dangers, based on a scientific perspective that is certain to stir debate among those interested in continued coastal development. Excellent photography, good computer graphics, and effective narration all combine to make this video a powerful statement of Pilkey's view of coastal development.

Focusing on North Carolina, with its low-density coastal development and prevalence of highly malleable and constantly changing barrier islands, the video provides useful background on coastal processes applicable to many areas besides the target audience in North Carolina. Pilkey's narration on coastal processes, combined with excellent graphics, provides valuable insight about how beaches work and how they respond to ocean forces. There are, however, some generalizations about beaches that may be true for North Carolina, but not elsewhere, and these have the potential to confuse viewers from other areas. For instance, loss of sand from the beach to greater depths offshore is not universal; in some areas, the offshore area is a significant source of sediment to the beaches, rather than a sink. Because the viewer is not always warned about site specificity of some of the concepts, this film must be viewed as a useful perspective on beaches, but not necessarily as an authoritative film on beach processes applicable in detail to all coasts. Perplexing is the strongly intuitive (but erroneous) concept that since swimmers are swept rapidly alongshore by wave-driven currents in the surf zone, so will sand be swept alongshore. Since the density of a human body (which floats) and a sand grain (which sinks) are vastly different in water, this comment introduces needless technical error in the interests of analogy.

Following his highly instructive discussion on the behavior of barrier beaches in North Carolina, Pilkey departs from a scientific discourse on natural processes and considers the effects of human activities on natural beach processes. By contrasting the coast at fully developed Seabright, New Jersey, with the less-developed and open coasts of North Carolina, the negative effects of attempts to stabilize the coast are clear. This powerful comparison, while ignoring the history of how New Jersey reached its present condition, provides excellent fodder for thought. The contrasting roles of seawalls and other shore-protection devices in protecting upland behind beaches, while increasing the loss of beach fronting those structures, is shown clearly.

Pilkey's more activist side emerges in a scathing attack on the US Army Corps of Engineers. He suggests that by keeping the Corps under control, the beaches could be saved. Perhaps a better balance would have been reached by acknowledging that the intense desires of the public to live or vacation at the coast, and the developers' eagerness to meet that desire, are the roots of the problem. This vitriolic attack detracts from the effectiveness of the film, in my opinion, marring what otherwise is a useful and relatively instructive view of barrier islands.

Pilkey's final comments are germane, stating here, as he has in his numerous books, that the public must learn to live *with* the coast and not just *on* the coast. He provides several useful suggestions for such a harmonious relationship.

—David G. Aubrey
Senior Scientist, Department of Geology & Geophysics, Woods Hole Oceanographic Institution

Books & Videos Received

OCEANOGRAPHY

The Arctic Seas–Climatology, Oceanography, Geology, and Biology edited by Yvonne Hermen; 1992; Van Nostrand Reinhold, Florence, KY; 816 pp. - $92.95.

Basins on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution edited by J. Parnell; 1992; Geological Society Publishing House, Avon, England; 470 pp. - $120.

Coastal and Oceanic Buoy Engineering by Henri O. Berteaux; 1992; Henri O. Berteaux, Woods Hole Oceanographic Institution, Woods Hole, MA; 285 pp. - $58.

Oceanography in the Next Decade: Building New Partnerships by the National Research Council; 1992; National Academy Press, Washington, DC; 216 pp. - $39.95.

Oceanography and Seamanship - Second Edition by William G. Van Dorn; 1992; Cornell Maritime Press, Centreville, MD; 496 pp. - $39.95.

Ophiolites and their Modern Oceanic Analogues edited by L.M. Parson, B.J. Murton, and P. Browning; 1992; Geological Society Publishing House, Avon, England; 330 pp. - $92.

Primary Productivity and Biogeochemical Cycles in the Sea edited by Paul G. Falkowski and Avril D. Woodhead; 1992; Plenum Publishing Corporation, New York, NY; 550 pp. - $125.

Upwelling Systems: Evolution Since the Early Miocene edited by C.P. Summerhayes, W.L. Prell and K.C. Emeis; 1992; Geological Society Publishing House, Avon, England; 520 pp. - $110.

ENVIRONMENT

Earth in the Balance: Ecology and the Human Spirit by Senator Al Gore; Houghton Mifflin, New York, NY; 407 pp. - $22.95.

Ecology of an Underwater Island by Robert Schmieder; 1992; Cordell Expeditions, Walnut Creek, CA; 200 pp. - $22.

Global Climatic Changes in Water and Heat Transfer—Accumulation Processes by S.G. Dobrovolski; 1992; Elsevier Science Publishers, New York, NY; 280 pp. - $108.50.

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Hydrological Aspects of Accidental Pollution of Water Bodies by the World Meteorological Organization; 1992; American Meteorological Society, Boston, MA; 208 pp. - $40.

Animal Biomarkers as Pollution Indicators by D. Peakall, 1992; Chapman and Hall, New York, NY; 291 pp. - $77.50.

The Right Climate for Carbon Taxes: Creating Economic Incentives to Protect the Atmosphere by Roger C. Dower and Mary Beth Zimmerman; 1992; WRI Publications, Baltimore, MD; 39 pp. - $9.95.

Saving the Oceans by Joseph MacInnis; 1992; Key Porter Books, Toronto, Ontario, Canada; 180 pp. - $50.

Wetlands of North America by William A. Niering; 1992; Thomasson-Grant, Charlottesville, VA; 160 pp. - $39.95.

YOUNG PEOPLE

The Ocean Alphabet Book by Jerry Pallotta; 1992; Charlesbridge Publishing, Watertown, MA; 30 pp. - $14.95.

Manatee, A First Book by Donna Corey; 1992; Sundiver Productions Company, Crystal River, Florida; 48 pp. - $5.

The Seal by Joelle Soler; 1992; Charlesbridge Publishing, Watertown, MA; 28 pp. - $6.95.

S'GANA, The Black Whale by Sue Stauffacher; 1992; Alaska Northwest Books, Bothell, WA; 224 pp. - $15.95.

Snorkeling for Kids by Judith Jennet; 1992; National Association of Underwater Instructors, Montclair, CA; 56 pp. - $8.95.

GENERAL INTEREST

Charting the Sea of Darkness: The Four Voyages of Henry Hudson by Donald S. Johnson; 1992; International Marine, Blue Ridge Summit, PA; 256 pp. - $22.95.

Continents in Motion, The New Earth Debate, Second Edition by Walter Sullivan; 1991; American Institute of Physics, Colchester, VT; 425 pp. - $50.

Growing Up in a Shipyard: Reminiscences of a Shipbuilding Life in Essex, Massachusetts by Dana A. Story; 1991; Mystic Seaport Museum, Mystic, CT; 139 pp. - $15.

The Flood from Heaven—Deciphering the Atlantis Legend by Eberhard Zangger; 1992; William Morrow & Co., New York, NY; 256 pp. - $25.

John Isaacs and His Oceans by Daniel Behrman with John D. Isaacs; 1992; American Geophysical Union, Washington, DC; 210 pp. - $16.

Journeys Through the Inside Passage—Seafaring Adventures Along the Coast of British Columbia and Alaska by Joe Upton; 1992; Alaska Northwest Books, Anchorage, AK; 189 pp. - $12.95.

***Challenger* at Sea—A Ship That Revolutionized Earth Science** by Kenneth J. Hsu; 1992; Princeton University Press, Princeton, NJ; 417 pp. - $35.

To the Editor...

To the Editor:

We wish to clarify an important point in the article entitled "Marine Biotoxins at the Top of the Food Chain" that we wrote for your Fall issue (Vol. 3, No. 3, 1992). An editorial change altered the intended meaning of a sentence concerning the risks associated with the occurrence of "paralytic shellfish toxins" in fish and may lead to confusion among your readers as to the risk for humans.

The toxins occur only in the viscera of fish. Thus the third sentence at the top of page 60 should have read, "So the risk is confined to animals that eat whole fish, including the viscera, such as other fish, marine mammals, and birds." On rare occasion, humans may be affected in this manner. In Southeast Asia there have been a few instances of human poisoning from these toxins following consumption of whole fish. We wish to emphasize, however, that there is no evidence of risk to humans from eating fish flesh, even during red tide events.

Donald M. Anderson
Biology Department
Woods Hole Oceanographic Institution
Woods Hole, MA

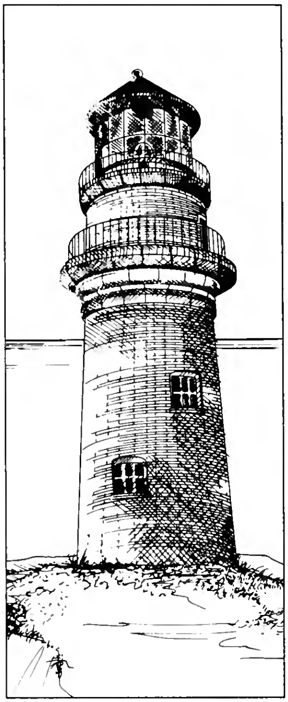
Alan W. White
Northeast Fisheries Science Center, National Marine Fisheries Service
Woods Hole, MA

COMING UP NEXT

Coastal Science & Policy

Volume 36, Number 1, Spring 1993

Oceanus authors will address many aspects of Coastal Science and Policy in the Spring and Summer 1993 issues. Seiches, tides and their effects, coastal erosion, and competing uses of the coastal zone will be considered in the first issue. The controversial Boston sewage outfall is scheduled for discussion, along with related topics such as decision making in the face of uncertainty and the role of citizens' groups in environmental issues. We'll offer a 120-year history of hurricanes blowing into Florida, a look at the National Oceanic and Atmospheric Administration's coastal programs, and features on a special creature and an interesting lighthouse. Don't miss these fascinating—and most important—discussions!



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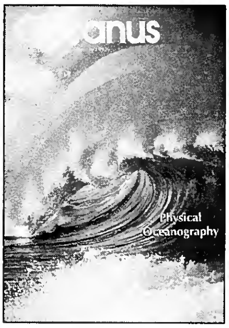

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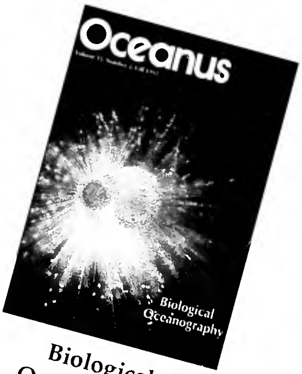

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